Analysis of Pressure System PS-PHY-08-005

Overview

Pressure System PS-PHY-08-005 is the collection of Documents in Docushare associated with Legacy Pressure System PS-007-00-024. The Pressure System includes both Liquid Helium and Liquid Nitrogen Circuits. The Helium System consists of both a pressure vessel (the toroidal shaped coil vessel(s)) and connection piping (Figure 1) while the nitrogen circuit is defined as just pressure piping because its flow circuits never get above that of a 6-inch pipe (Figure 2).

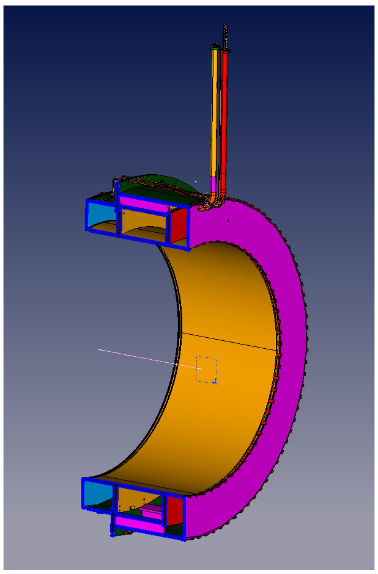

Figure 2 Helium Vessel & Piping (Coil 1)

As is discussed below, we define the Pressure Boundary for this entire system as the vacuum vessel surrounding these Systems. (Figure 3) The Pressure Boundary stops at the top flanges of the helium and nitrogen circuit adaptors inside the vacuum vessel bellows flange as they all interface to the bottom of the Service Unit that supplies cryogenic fluids. These Units are called the Cryo Can for the Coil Tests and the Cryo Box for the Hall D installation. Two configurations of the Pressure System are encompassed by this analysis. The first configuration is the Individual Coil Test at the Test Stand in the Test Lab (Building 58) and the second is for the final installation of all four coils in the complete Solenoid Magnet in Hall D. (Figures 4 & 5) All drawings cited in the calculations are located in the Document Control drawing archive. The list of drawings is in Appendix 6.

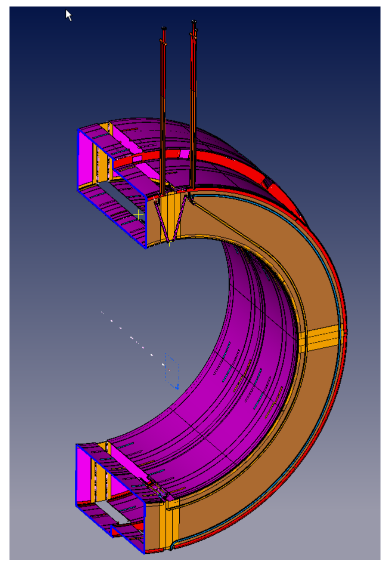

Figure 1 Nitrogen Shield & Piping (Coil1)

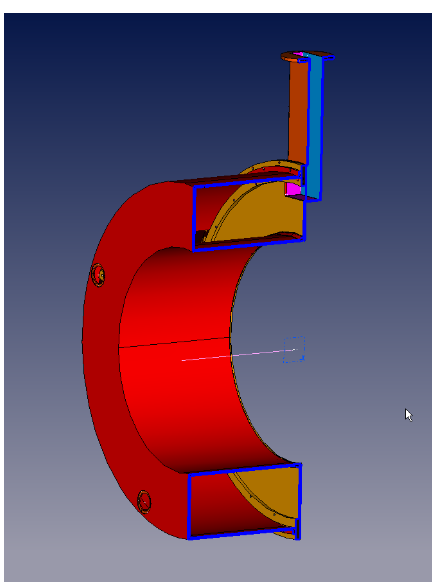

Figure 3, Vacuum Vessel & Chimney (Coil 1)

The Hall D Solenoid consists of four superconducting magnet coils within a series of steel yoke rings. Each coil consists of a stainless steel liquid helium vessel containing a superconducting coil and liquid nitrogen cooled shield panels made of expanded copper sheets and connected by brazed stainless steel tubing (or just stainless steel panels with welded tubing for Coil 3). These cryogenic fluid containers are within a stainless steel vacuum vessel consisting of a ring cake-pan-like cover bolted to a large washer-shaped flange mounting plate. The outer surface of the nitrogen panels and the surface the helium vessel are covered in multilayer insulation within the insulating vacuum volume. Stainless steel tubes connect the nitrogen shield panels and the helium vessel to the Cryo Can/Box located above the coil(s) through Adaptor Tubing Assemblies. The vacuum boundary connection to these service units is through rectangular extensions to the vacuum vessel known as a Chimney. The configuration of the Coil Test is one coil at a time, inserted into its own Yoke Ring, sandwiched between the end yoke rings and serviced by the Cryo Can.

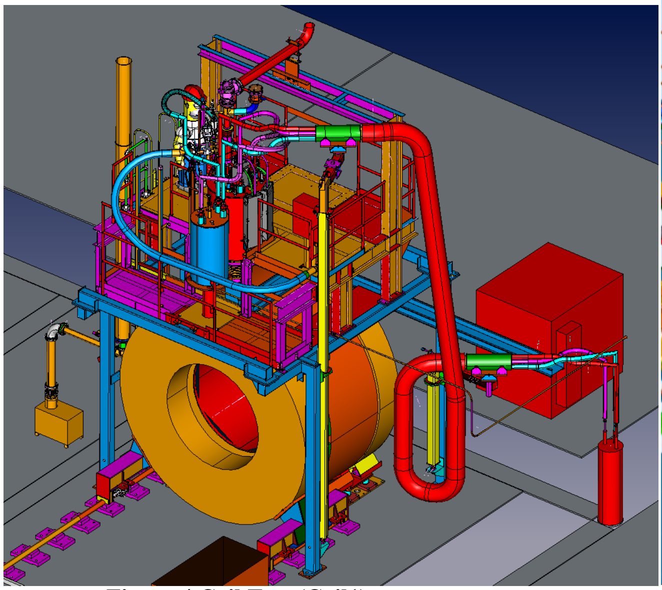

Figure 4 Coil Test (Coil1)

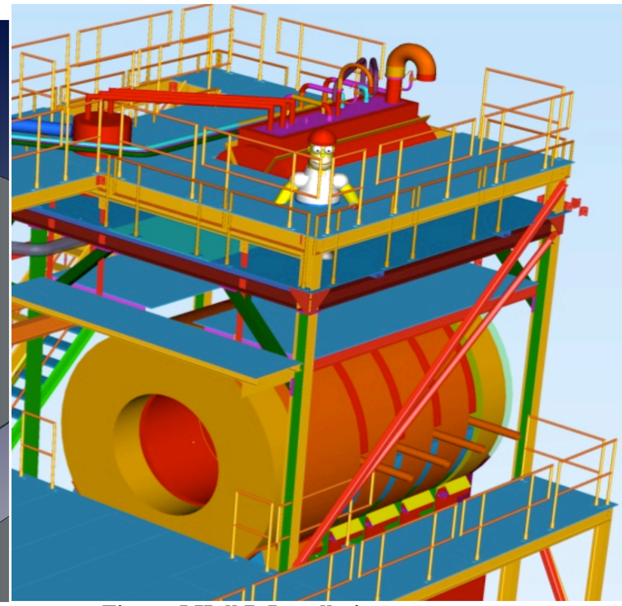

Figure 5 Hall D Installation

Helium Vessel and Piping Description

In 1971, the coils were wound at Stanford Linear Accelerator Shops on bobbins that formed the inner shell of a toroidal helium vessel. Consaco of Oakland Ca, a shipbuilder, made the vessel parts. Further assembly at SLAC added the outer shell over the inner bobbin shell after the coil was wound. The shells conform to ASME strength requirements for a minimum of 110 pound per square inch (psi) range (See Calculation Summary Table Below for all calculations). Washer shaped flat heads, welded to the inner and outer shells complete the toroidal vessels. These heads are relatively thin and the welded joints are small, reducing the actual **Maximum Allowable Working Pressure (MAWP) of the helium system to 30 psi (absolute)** as is explained below. The piping to these vessels is all small diameter (2 inch maximum) and generally with walls of .049 and .065 that have design pressures of over 1000 psi.

There is a nod to the ASME Code in the manufacturing specification of the Helium Vessel parts. They have a MAWP of 30 psia in the contract specification (See PS-PHY-08-005 3 Manufacturing Folder. The specification required ASTM grade (not ASME) materials and Steve St Lorant, one of the project leaders, claims that only the "Clips" (see below) were Chary Impact tested cold (>80K) with a reading over 100 ft-lb. We have the vessel weld quality certifications. (See PS-PHY-08-005 3 Certifications in the Manufacturing Folder)

Nitrogen System Description

The nitrogen system of each coil is robust. The shield panels are made of two, .08 inch copper sheets, brazed to each other in a spot pattern. The space between spots is hydraulically expanded at many hundreds of psi to form small channels that consider to be "Piping". The expansion pressure is unknown but is assumed to be greater than the 1.1x the System Pressure below. Tubes connecting the panels are all small diameter, (3/4 inch OD or smaller) and made of stainless steel. No formal System Pressure was found in the coil records. **We assign a System Pressure of 75 psia.**

Calculations supporting this choice are summarized in Table 2 below and are available in Appendix 2. Note the newly made stainless steel panel system used in Coil 3 (Drawing Number D000000402-2019 & 2020) was manufactured to ASME rating of 100 psia.

Vacuum Vessel

Both nitrogen and helium systems are contained within another, robust Stainless Steel Vessel – The Vacuum Vessel, nominally rated at 15 psig and well vented. Analysis is summarized in Table 3 below and calculations are in appendix 3.

Cryo Can/Box (Cryo Can Assembly Drawing D000001313-1000)

The Cryo Can/Box (not part of this Pressure System but mentioned because the two system's relief piping flows through it) acts as the source for the cryogenic fluids and the electric current to drive the coil(s). Both Helium and Nitrogen systems within the Cryo Can are built to ASME Code specifications to a 95 psia MAWP. (Figure 6) The Cryo Can/Box contain (1) U-Tube Bayonet Sockets to connect to Cryogen sources, (2) vessels that maintain liquid levels, (3) control valving for cool down and normal running, (4) overpressure relief vent outlets and valves for helium and nitrogen (5) vapor cooled magnet current leads that minimize heat leak and (6) instrumentation leads and connections. The Cryo Box is being designed to ASME Standards.

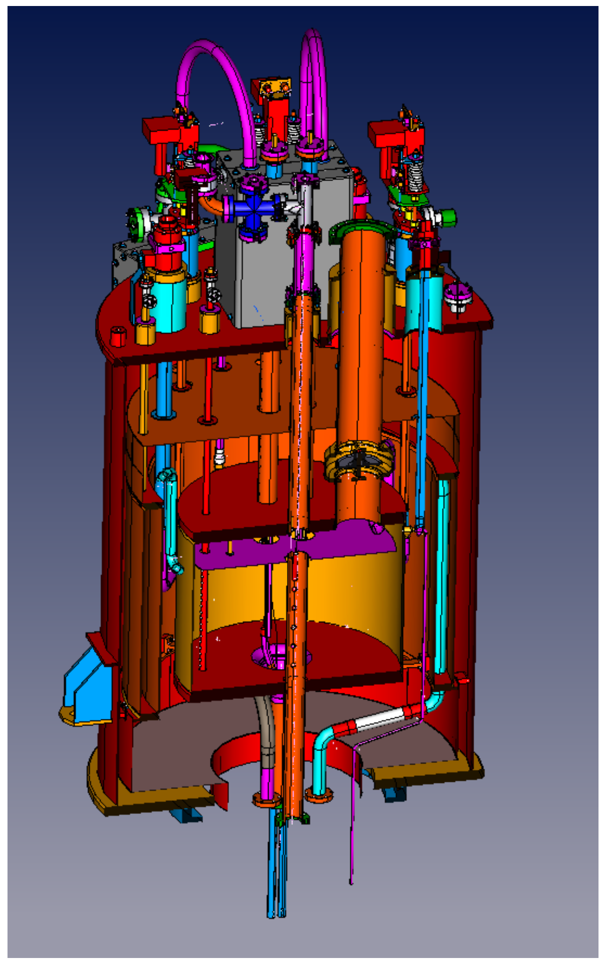

Figure 6 Cryo Can Cut-away

Detailed Pressure Analysis of Systems

Normal Operation

Both Helium and Nitrogen Systems operate just above atmospheric pressure ~18 psia with respect to the vacuum insulation volume. Small (several psi) pressure spikes are expected during filling and other normal transient operations.

Each helium vessel is vented by two, 2-inch diameter tubes leading from the coil helium vessel to a second helium vessel in the Cryo Can/Box that, in turn, is vented by a 4-inch pipe connected to a vent valve system. One of the two-inch tubes contains the current leads and instrument cable that are a restriction to venting flow in that tube. The other tube has only a small instrument cable that is ignored in the pressure drop calculations. The vent valve system handles the inventory venting easily. The vent valve system (Figure 7) consists of two relief valves and a rupture disk. The first small valve vents into the warm return helium pipe at 10 psia. It is meant to respond to any minor pressure spikes in the system while maintaining the helium system integrity and purity. The second valve, designed for full capacity, vents to atmosphere at the higher pressure of 16 psig. The valve is pilot operated, responding directly to the pressure in the helium vessel(s) via a separate tube that is not part of the flow circuit. A back up, full flow rupture disk vents at 25 psig to atmosphere. Also shown in the figure is the vapor cooled leads (green) and their vent system which are part of the Cryo Can Pressure System PS-PHY-10-003.

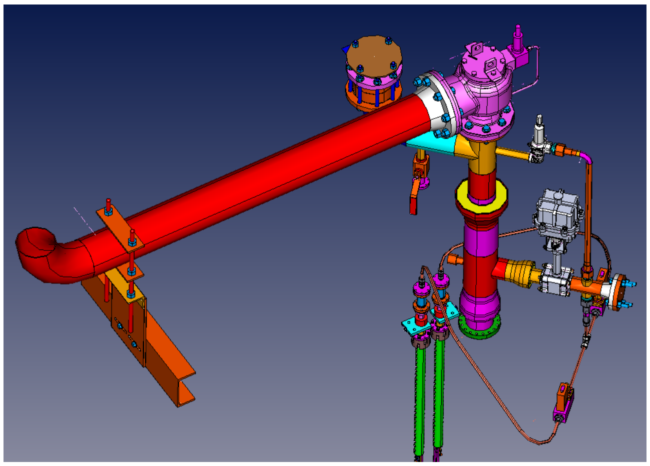

Figure 7 Helium Vent System

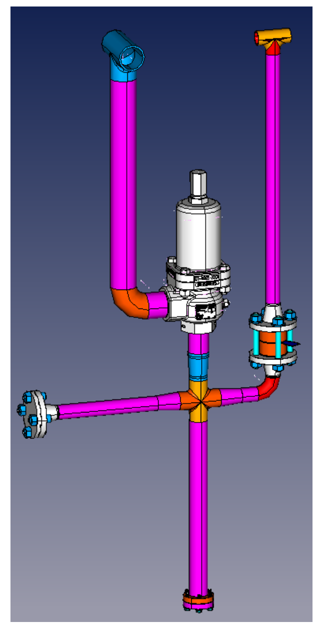

Figure 8 Nitrogen Vent System

The valve and rupture disk combination (Figure 8) connected to the nitrogen reservoir in the Cryo Can/Box vent the nitrogen system to atmosphere at 60 psig and 73 psig respectively.

Features of the helium and nitrogen systems are qualified for these pressures as shown by the calculations in the appendices except for the Helium Vessel Corner joints explained below.

Inner Shell to Head Joint

The corner junctions of the helium vessel heads to the inner and outer vessel shells are not conventional pressure vessel design. (Figure 9) These heads are welded to the inner and outer shells, not using an ASME mandated full penetration weld. Rather, a two-component joint is used. A standard, reliable, but low strength edge weld (normally used on vacuum hardware) performs the sealing function. This joint is thin and not able to restrain an attempt to impose a

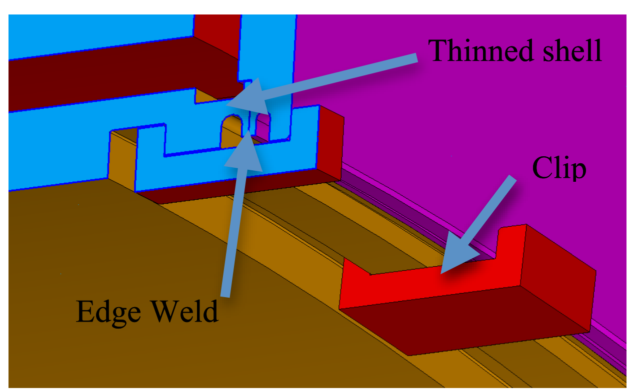

Figure 9 Close up of Inner Shell Joint at a Clip

moment. Clips made of A286, high strength stainless steel, contacting shelves in the shells and a machined land on the head, are meant to add strength to the joint. There is an additional load (~30 psi) imposed on inner portions of the head by the spring system that compresses the coil. We performed finite element, inelastic analysis of these joints using the spring load and as built dimensions using ANSYS. We observe the following characteristics:

A. The flat, washer-form heads are thin with respect to the rating of the shells. Under pressure, they balloon to an arch between shells, superposing a bending strain on the head to shell joints.
B. Many lips of the seal weld are diminished or gone, ground away during repairs. The lips for the seal weld on the downstream heads of all coils were partially or fully ground away during openings of the vessels to fix shorts. The repair seal weld is further inboard and some are made with just the addition of filler metal to what is the crack between the parts. The slight bellows-like flexibility of the lips is not operative at these repair joints. In the repaired joints, the clips only take their assigned pressure load if there is considerable tensile stretch in the weld material. Analysis shows that in the repaired configuration, the clips actually cause increased weld joint stress during pressurization, adding to the tensile stress in the welds as well as in other vessel features.
C. The Clips are reverse loaded. The pivot for the head's arching is the seal weld. The line of action of the clip restraint contact falls radially outboard of this pivot when the lips of the seal weld are ground away. Outboard of the pivot, the head's edge tilts axially inward, bringing the clip grab surface closer to the shell's clip shelf. If the clips were attached by an interference fit they would fall off. But, tack welds attach the clips. Nominally meant to be unstressed, the tack weld of the clip to the head experiences high tensile and shear stresses during this reverse loading. In reaction, the seal weld joint in the vicinity of the clip experiences higher tensile loading than if the clip was not there.
D. The inner shell has an extraordinary thinned portion. The original manufacturer moved the outer profile of the inner shell's edge radially into the vessel in order to "clean up" out-of roundness of the shell and changed the inner diameter of the head to match. This change further thinned the already thin portion of the shell at the circumferential groove that captures the rods used to compress the coil's preload spring system to around .04 inches. This reduces the simplistic pressure rating of the axial fibers in the inner shell to just over 100 psi.
E. The Clip experiences bending loading. The head's arching at the pivot of the seal weld also pushes the outside end of the clip radially outward. This deflection is enough to bring the clip's side tack welds (originally meant to not be loaded) to yield stress values in small zones of fibers. The motion imposes a local distortion on the clip shelf portion of the shell on the inner shell that imposes high outer fiber tensile stresses in bending in the thinned, rod capture portion of the shell mentioned above.

We used the characteristics of stainless steel at 80 K (4 K not available) of 71,650 psi yield and 226,500 psi ultimate strength in an ANSYS inelastic analysis of the worst-case joint (downstream, inner shell (after several repair cycles) at 30 psia. with an increase to 120 psia. The analysis (Appendix 5) shows that even at the low pressure, the joint weld experiences bending with compressive and tensile stress such that inner fibers would be stressed to beyond 78,000 psi. (Von

Mises Stress). These small portions of the joint undergo yield stress but no failure occurs. The increase to 120 psi in the analysis shows that this same pattern of high inner fiber stress and with even higher yielding stresses (to 95,000 psi) continues but no failure occurs (with ultimate stress at 226,000psi). Actual rupture pressure (for a limited number of cycles) is thus beyond the 120 psi analysis pressure which is 4 times the MAWP.

Very important is that if there is a rupture at these weld joints, the clips take on the load and help prevent further rip opening of the joint.

Even at 30 psi, some work hardening of the joint and subsequent increase in the strain hardening advances as a function of number of pressure cycles. It is prudent to limit the number of pressure cycles to the MAWP.

The piping joints are generally welded with butt or fillet welds. Piping connections that need to be taken apart were converted from welded connections to CF flanges. These size flanges have Design Pressures in the hundreds of psi as shown in Appendix 1, Conflat Flange Calculations Tab.

Additional exceptions to higher rating: An exception to the robust characteristics of the helium piping is the thin wall, 3/8 inch OD flexible metal hose, without reinforcing braid, used in the helium supply circuit. Original rating is not known, but present day literature (See the Docushare Engineering/Manufacturer's Rating's folder) for similar bellows-like tubes gives a rating of 70 psia. Welded bellows, with CF Flange connections and anti squirm covers are used in the Chimney connection region to connect the two-inch coil return tubes to the Cryo Can Tubes. The bellows are qualified for a 30 psia working pressure by a hydraulic proof test of one bellows from the batch of three where no failure was observed at 120 psi.

The 30 psia MAWP can be supported because rupture is beyond 120 psi.(4 times the MAWP). But the analysis uses plastic flow analysis and use of a thin part in bending that are not part of ASME design practice.

Off Normal Operations:
A small probability exists that a higher pressure to the 75-psi range could be generated in coil 1 and 40 psia in others during a Loss of Insulating Vacuum (LIV) incident. This condition can be made highly improbable but is still possible. A tens of seconds pressure spike in the helium vessels beyond 30 psia is anticipated in these cases until the vent systems sufficiently discharge the cryogen inventories.

For the loss of insulating vacuum accident that condenses air (or nitrogen from a shield failure), the literature (V. Lehmann & G Zahn – see Docushare: Engineering/Reference Material) shows that heat transfer rate on a super insulated helium vessel does not exceed 6000 watts/ m^2. Our calculations (See Appendix 4 – Helium Venting Calculations) show that only Coil 1 has the large surface area and helium inventory where the 2-inch vent tubes restrict flow such that pressure spikes to 75-psi. With the same heat transfer rate, the other three, lower volume coils peak at 40 psia. The coil vessels will have to be at liquid helium temperature so their material will be in the "strong" state. Again the vessel is “safe” but does not conform to ASME’s factor of four or more between pressure experienced and rupture pressure required. Our analysis didn’t find a “rupture” pressure.

Two additional macro failure modes that create a pressure burst are remotely possible: (1) a full quench of the magnet and (2) an undefined, catastrophic electrical failure causing an arc in the coil with similar release of energy into the liquid helium inventory.

A quench is highly improbable. In its history, the magnet has never quenched. A full quench is precluded in these magnet coils in the presence of a full level of liquid helium because the conductor is cryo-stable. In a quenched zone, heat transfer to helium exceeds resistive heat generated and the conductor returns to superconducting state. Helium should always be full. Our interlock system starts a fast magnet dump sequence when low helium in the service unit (several meters above the magnet) is detected (We also added double redundant sensors and circuits). Also the quench detector detects abnormal voltages (indicating a potential transition from superconducting to resistive state) and shuts off the power supply and performs a fast energy dump into an external resistor.

If we could even get Coil 1 (the worst example) to fully quench, it generates 32 kW at 1500 A while the conductor remains at less than 10 K (low resistivity state) because of cooling by the helium. Comparing the heat input from LIV, 125 kW deposits into Coil 1. Thus the LIV is almost 4 times more severe. If we impose another case with the extremely remote possibility that a low level of helium in the vessel allows a quench, the low helium inventory leads to a much lower pressure spike. Because in all cases, severity is less than LIV, I conclude that quench failure mode may be ignored.

The catastrophic burnout is an undefined failure. Worst case, a conductor is severed when at full current, a low resistance plasma arc will complete the circuit as the magnet current dumps its energy through the arc and through the dump resistor. It is unlikely that the coil dumps energy to the helium at a rate greater than the LIV accident because a burn-out, at worst case, looks like a quench (above) in series with a the power lost in a low resistance Plasma Arc. A burnout of the Dump Resistor is precluded by a hard wired temperature switch interlock that precludes Power Supply turn-on if the resistor is still at too high a temperature. Current leads burning out will be an extremely low probability as well. Engineered design of the burn out resistant leads and the thorough checkout for the test will uncover weak electrical connections and fabrication defects.

A possibility of a burn-through breach of the helium vessel to the insulating vacuum volume is possible. Helium, a non-condensing gas, increases heat transfer rates across the vacuum space but less than condensing air systems. I conclude that this highly improbable event has less pressure effect than the LIV event.

Note that the current leads have been “oversized” in two ways to minimize the possibility that they become the burnout postulated above. They are rated for 2000 A with our maximum current is 1500 A and they have been designed as “burn-out resistant”, allowing them to survive low cooling flow.

Note that just a helium leak within the vacuum volume, with no condensation heat transfer, has a lower pressure spike than the condensing gasses case and can be ignored.

Legacy System

The Jefferson Lab effort to refurbish and use these coils started in 2001 and is a Registered Legacy Pressure System # PS-007-00-024, before the 10CFR851 based, formal rules for pressure systems were propagated in ES& H Manual's Chapter 6151. The system is given a new number (PS-PHY-08-005) to fit into the existing database for contemporary record keeping (this document and others)

The significant difference of this Legacy System from new systems is that it does not have the extensive documentation package of design, material certifications, Charpy impact testing of materials at cold temperatures, welding certifications & inspection and repair records. Our assumption is that we have to rely on the capability of the system's original builders and repairers. A data point in this reliance is that these coils operated successfully at two DOE institutions for a total of 14 years with no pressure based failures.

Before receipt by JLab, the Coil Vacuum vessels and some Helium vessels were fully opened and repaired at SLAC and at Los Alamos. The Nitrogen Shield piping was cut, re-welded and in some instances, re-configured. Documentation of some initial and repair welding by ASME qualified welders per qualified welding procedures is not available. These coils have cycled through a repair process since their receipt by JLab in 2003. Repairs included repair of the leaks in the shield tubing at the sites of pitting corrosion caused by residual chloride fluxes. (There is no concern that corrosion allowance is used up because this corrosion is in the form of isolated 0. 03-inch dia or less pits where strength of the base tube is not compromised.) Other, electrical repairs to the coils required cutting open the vacuum vessel's chimney and cutting all helium and nitrogen tubes as well as grinding open the upstream head of Coils 1, 2 and 3. CF Flange based connections for all piping was added. The two, 2-inch diameter helium return tubes were reattached in the chimney jog by welding CF flanges to the tubes and bolting the flanges together upon re-assembly. Other tube repairs were made with couplings, butt joints, and fillet joints. CF flanges were attached to all tubes in the chimney outlet to substitute for the exclusively welded joints used in the original installations. Additional tubing assemblies are made to transition from the coil flanges to the fewer flanges of the Service Unit. Much of this repair work was done before the JLab implementation of 10CFR851. Materials were uncharacterized and welders and their procedures were not ASME Qualified. We consider all of this work to be Legacy Work.

In recognition of the use of best practice, all welding at JLab and at Indiana University Cyclotron Operations after 2008 was by ASME Qualified Welders per Qualified Weld Procedures. All records of the welds at JLab are in Docushare.

Any new tube materials and bolts for CF flanges used were not Charpy impact tested because of the inability to extract a sample from the thin tube or bolt material. We may use CF Flanges without Charpy characterization because we do not have to add the high bolt load stress to the low stress caused by pressure operations in our calculation of flange stress. At our low pressures, Flange stresses are much lower than the 35% threshold of the allowable stress for stainless steel for no Charpy characterization allowed by ESH&Q 6151.

Risk Assignment and Conformance to 10CFR851

As Design Authority, I rely on the policy of the Laboratory that the Pressure Systems (Legacy Equipment) registered before the formal implementation of 10CFR851 may be accepted for use, as is, if they reflect safe engineering design and manufacturing. The subject systems were manufactured using the non-code manufacturing practice of the earlier time and have the deficiencies, as described above, principally the head to vessel joint.

JLab must still fulfill the mandate of 10CFR851 "*When national consensus codes are not applicable (because of pressure range, vessel geometry, use of special materials, **etc.**), contractors must implement measures to provide equivalent protection and ensure a level of safety greater than or equal to the level of protection afforded by the ASME or applicable state or local code.*

In the remainder of the analysis I argue that I provide the "equivalent protection" required to bring these systems to the high level of safety required. I use the guidance of ESH&Q Manual 3210 T3 (**Risk Assignment**) in dealing with the probabilities of Off-Normal, higher-pressure spikes and the consequences of any failures. I judge, without mitigation, the Probability of these modes of failure is L (Low) and that the Consequence is H (High). **This combination in the matrix equates to an unacceptable Assigned Risk Code of 3.** I argue below that mitigations bring this Assigned Risk Code to an "N" (Negligible). I argue that Negligible Risk implies I have achieved protection "equal" to "Code".

I mitigate Off Normal Events by reducing both their Probability and I mitigate Consequence Level of normal operation and off normal events.

The first mitigations address Probability. Mitigation works at reducing the probability of an LIV incident, the generator of a possible overpressure event.

The vacuum vessel is puncture proof ½ inch wall stainless steel. A puncture can only happen at thin or weak points. I consider a hammer blow to be the model of what could cause a puncture. Mitigation is to "armor" these thin zones. The first thin zones are the two bellows where walls are 0.015 inches thick. The vacuum pump's bellows has stainless steel braid to act as its armor. We added 1/16-inch aluminum covers over the Chimney Bellows.

The ceramic disk insulators in feed-throughs are the second potential weakness. When looked at in detail, however, all such feed-throughs are covered with screw-on, metallic plugs and are defended by their flange and local piping and bayonets/u-tubes on the Cryo Can/box when the coil is full of cryogens. I judge that no additional armoring of feed throughs is necessary.

The valve that seals off the Insulation Vacuum Volume from its vacuum pump is a potential path for Loss of Insulation Vacuum through human error. Opening is allowed in the presence of a good vacuum between pump and valve. Ideally, the system will have no leaks into the insulation vacuum and we can close this valve. In this case, we will administratively lock out this valve so that only the Hall D Coordinator can open it. In the case helium system leak, where the valve is required to be open, we use the vacuum gauging on each side of the valve to establish an interlock such that a good vacuum on the pump side is required to open. It is wired to fail closed with a loss of power.

In the four-coil configuration of Hall D, the vacuum volumes are separated by vacuum breaks built into the Cryo Box. The influence of a loss of vacuum is reduced to about a fifth of the non-isolated design.

The result of Incident Probability mitigation is that the Probability of failure of the helium vessel due to over-pressurization reduces from Low to Extremely Low.

The second mitigation works on Consequence Levels. If there is a failure, no one should get hurt.

Both the helium system and nitrogen system are captured within a robust, stainless steel vacuum vessel system. The copper and three hundred series stainless steel materials of the helium and nitrogen systems are ductile down to 4 K such that any failure is going to be a tear that immediately relieves pressure, venting into the insulation vacuum volume. The clips on the helium vessel joints assure that a tear is going to stop when pressure is relieved. Failure will be "leak before break". This Vacuum Vessel containment will catch any minor projectiles from a tear/rupture of the inner vessel and tubes.

I am able to re-look at my ability to mitigate consequences when I re-define the pressure boundary from the Helium Vessel and Piping and the Liquid Nitrogen Shield System to the Vacuum Vessel System. This redefinition recognizes that we are dealing with a double wall system. A bonus of this re-definition is that questionable joints and differences from Code manufacturing practice of the inner systems are less important. This re-definition has precedence in the way the SNS qualified the vacuum vessels of the Cavity Cryostats as the Pressure System Boundary. (SNS Document 104100000-PN0001-R00, Plan for Achieving 10CFR851 Requirements With New SRF Cryomodules – See Docushare Engineering folder) They assumed, as I do, that their inner vessels could fail. A demonstration that this redefinition is valid is the JLab experience with a superconducting magnet is Hall C where a LIV accident resulted in a helium vessel rupture that was fully contained by vented vacuum vessel. (SC-ORO--SURA-TJNAF-1998-0004 – See Docushare Engineering Folder)

The follow-on mitigation to this re-definition is to make sure that the Vacuum Vessel is robust. This is shown earlier in summary Table 3 and Appendix 3. Of vital importance is that any cryogen burst from the inner systems is fully vented such that the vacuum vessel is never pressurized above 15 psig. This characteristic is demonstrated in the venting of the vacuum vessel calculations of Appendix 4.

Existing Relief - Each Coil Vacuum Vessel is designed to be relieved by a parallel plate relief valve, at less than 1 psig through the vacuum pump-out's 5-inch pipe. There is potential obstruction in this system that we have removed. The pump-out pipe, at the vacuum vessel end, faces the shield panel. Actual gas flow area into the pipe at the shield is limited to a 9/16-inch high annular space between shield and vacuum vessel, about 60 % of the flow area of the pipe. If the passive shield panels flex toward the pipe opening during the gas rush of an overpressure event, a check valve like condition could result, making the annular gap smaller or even closing it. We cut out the passive panel shield material on coils 1, 2 and 3 at these port points to eliminate this check valve possibility and substituted thin copper tape applied in a spaced pattern. These copper tapes are designed to rip out if there is a large flow. This condition actually increases the available annular space to more than the flow area of the pipe by adding the annular gap from shield to the helium vessel to the flow area. Any venting plume has to be ducted away from personnel. This is accomplished with a stainless steel pipe installed from the relief valve to above the height of personnel on the platform above the coils.

We augment this original relief system to make absolutely sure that the vacuum vessel is relieved adequately and the consequence level can be reduced. The augmentation consists of parallel plate, 6-inch diameter reliefs. Coil 1 has four such secondary reliefs and Coil 3 and Coil 4 have a single secondary relief. The reliefs for Coil 1, 3 & 4 are mounted in the original, 6-inch diameter ports used to access the Radial Heim Columns. Unlike the somewhat restricted flow channel to the primary relief, these reliefs directly face the vacuum volume upstream of the axial Heim columns where a circumferential void is formed by the step in the outer shell of the helium vessel. This void, coupled with existing cutouts in the shield and slits in the super insulation allows unrestricted cryogen relief flow. Coil Two's secondary relief taps the Chimney's vacuum volume with similar characteristics. Cryogen flow from these reliefs is to be channeled such that personnel can't be harmed by the relief blast. We will cover the gap between the upstream yoke ring and the coil's yoke for coil 1, 3 & 4. This will force the second stream of venting helium to inside the yoke bore which will be off limits to personnel during magnet operations. Any venting helium will drain up and out the ends and around the platform above the bore, toward the ceiling,

If these mitigation conditions are in place, we qualify this legacy Coil Pressure System for use under the latest directives for a Class II Vacuum Vessel defined in EH&S 6151 T5. Having a working pressure below 15 psi allows the Vacuum Vessel to not be built per Consensus Codes. Simple code calculations qualify the material shapes and bolting for use as shown below. Materials do not have to have pedigree and welds do not have to be full penetration.

Using this pressure boundary redefinition along with relieved vacuum vessel mitigation and the vacuum vessel qualification, I reduce Consequence Level for this failure to (L) Low for harm to personnel (the mandate of 10CFR851). Property loss from a failure may still be damage to the coils and possible detector damage.

CONCLUSION

With the above mitigations, Risk Code Assignment is N for Negligible Risk from Table 3 of ESH&Q 3210 T3. As argued earlier, Negligible Risk indicates we reached: "equivalent protection and ensure a level of safety greater than or equal to the level of protection afforded by the ASME or applicable state or local codes." The coils can be used with the mitigations.

Summary of the Analysis:

For ease of comprehension, I summarize the design analysis results of all components of the helium system, nitrogen system, vacuum vessel and venting system in the tables below. I utilize the Code nomenclature and formulas as a reference to benchmark the design where possible. When applicable, ASME Code calculations are performed in accordance with B31.3-2008 or BPV Section VIII, Division 1-2007. Actual calculations are recorded in Appendices 1 through 4. The stresses or design pressure revealed by these calculations lead to the judgment of "Safe" when their value is better than the acceptable stress for the Code Material.

The exception to the above calculations is the analysis of the finite element calculations using both plastic analysis of the Inner Joint of the downstream flange of all coils. These calculations are in Appendix 5. These calculations show that breaking strength is not approached after a cycle to 86 psi.

Appendix 6 is the list of drawings

Table 1 Helium Analysis Summary

Vessel Feature	**Analysis Location:**	**Design Pressure, Maximum Allowable Stress**	**Max Service Pressure (piping), MAWP (vessels), Calculated Stress at MAWP**	**Conclusion**
Outer Shell circumferential stress	Appendix 1, Helium Vessel Tab, Calculation #1	164 psi pressure	30 psia pressure	Safe
Inner Shell compressive stress	Appendix 1, Helium Vessel Tab, Calculation #2	132.7 psi pressure	30 psia pressure	Safe
Down Stream End Heads of Vessel (Upstream is smaller hence less stressed)	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5
Clip stress	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5
Weld stress at seal weld	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5	See finite element analysis, Appendix 5
2 inch tube nozzle, circumferential stress	Appendix I, Helium Piping Tab, Calculation #4	6616 psi pressure	30 psia pressure	Safe
Joint of 2 inch tube to End Plate	Appendix I, Helium Vessel Tab, Calculation #5	12000 psi stress	250 psi stress	Safe
0.5 inch flex hose tube, circumferential stress	Appendix I, Helium Piping Tab, Calculation #6	20000 psi stress	648 psi stress	Safe
Joint of .5 inch tube to End Plate	Appendix I, Helium Vessel Tab, Calculation #7	12000 psi stress	62.4 psi stress	Safe
Material replacement for	Appendix I, Helium	Takes effect at 2-3/8	2 or ½ inch dia	May be

shell associated with nozzles	Vessel Tab, Item #8	inch dia min		ignored per UG 39(a)
Welds of shell to Mounting Flange Face	Appendix I, Helium Vessel Tab, Calculation #9	Shear stress in web welds: 6000 psi shear	264 psi shear stress	Safe
Welds of shell to Mounting Flange Face	Appendix I, Helium Vessel Tab, Calculation #9	Tensile stress in web flanges: 12000 psi shear	4856 psi tensile stress	Safe
Coil 1 LHe Fill Chimney Adapter. Coils 2, 3 and 4 have tubing length differences – no additional analysis necessary	Appendix I, BOM Justification Tab	100 psig	30 psia	Safe
Coil 1 LHe Vent Repair Assy. Coil 2 vent repair identical.	Appendix I, BOM Justification Tab	100 psig	30 psia	Safe
LHe 2" Vent Sensor Bellows Weldment	Appendix I, Welded Bellows tab	51 psig	30 psia	Safe

Table 2 Nitrogen Analysis Summary

Vessel Feature	**Analysis** is located in: **Location**	**Design Pressure, Maximum Allowable Stress**	**Max Service Pressure (piping), MAWP (vessels), Calculated Stress at MAWP**	**Conclusion**
Coil 1 LN2 Fill Chimney Adapter. Coils 2, 3 &4 have tubing length differences – no additional analysis necessary.	Appendix 2, Nitrogen System Calculations, BOM Justification – Nitrogen SystemTab	100 psi	75 psia	Safe
Coil 1 LN2 Vent Chimney Adapter. Coils 2, 3 & 4 have tubing length differences – no additional analysis necessary.	Appendix 2, Nitrogen System Calculations, BOM Justification – Nitrogen SystemTab	300 psi	75 psia	Safe
LN2 Vent Sub-Assy Coil 3L	Appendix 2, Nitrogen System Calculations, BOM Justification – Nitrogen SystemTab	100 psi	75 psia	Safe
LN2 Vent Sub-Assy Coil 3R	Appendix 2, Nitrogen System Calculations, BOM Justification – Nitrogen SystemTab	100 psi	75 psia	Safe
LN2 Fill Sub-Assy Coil 3	Appendix 2, Nitrogen System Calculations, BOM Justification –	100 psi	75 psia	Safe

	Nitrogen SystemTab			
Coil 3 Outer LN2 Shield	Manufacturer rated – see TP16842 Rev C	100 psi	75 psia	Safe
Coil 3 Inner LN2 Shield	Manufacturer rated – see TP16842 Rev C	100 psi	75 psia	Safe
Coils 1, 2 & 4 Outer LN2 Shield	No formal analysis – panels formed under many hundreds of psi internal pressure	100 psi	75 psia	Safe
Coils 1, 2 & 4 Inner LN2 Shield	No formal analysis – panels formed under many hundreds of psi internal pressure	100 psi	75 psia	Safe
Nitrogen Relief Valve Venting Under Loss of Vacuum Condition	Appendix 2, Nitrogen System Calculations, Nitrogen Venting Tab	1828 kg/hr capacity	1479 kg/hr required flow	Safe
Nitrogen Relief Valve Venting Under Stuck Open JT Valve	Appendix 2, Nitrogen System Calculations, Nitrogen Venting Tab	1828 kg/hr capacity	566 kg/hr required flow	Safe
Nitrogen Rupture Disc Venting Under Loss of Vacuum Condition	Appendix 2, Nitrogen System Calculations, Nitrogen Venting Tab	2767 kg/hr capacity	1479 kg/hr required flow	Safe
Nitrogen Rupture Disc Venting Under Stuck Open JT Valve	Appendix 2, Nitrogen System Calculations, Nitrogen Venting Tab	2767 kg/hr capacity	566 kg/hr required flow	Safe

Table 3 Vacuum Vessel Analysis Summary

Vessel Feature	**Analysis** is located in **Location:**	**Design Pressure, Maximum Allowable Stress**	**Max Service Pressure (piping), MAWP (vessels), Calculated Stress at MAWP**	**Conclusion**
Vacuum Vessel Outer Shell Internal Pressure	Appendix 3, Calculation Tab,	103.3 psi pressure	15 psi pressure	Safe
Vacuum Vessel Inner Shell External Pressure	Appendix 3, Calculation Tab,	69.6 psi pressure	15 psi pressure	Safe
Vacuum Vessel End Plate Stress	Appendix 3, Calculation Tab,	16700 psi tensile stress	15354 psi von Mises stress	Safe
Vacuum Vessel End Plate Weld Shear Stress	Appendix 3, Calculation Tab,	8350 psi shear stress	976.7 psi shear stress	Safe
Vacuum Vessel OD Bolt Stress	Appendix 3, Calculation Tab,	80000 psi tensile yield stress	18992 psi tensile stress	Safe
Vacuum Vessel ID Bolt Stress	Appendix 3, Calculation Tab,	80000 psi tensile yield stress	23216 psi tensile stress	Safe

_____________________________________ Date______________________
George Biallas

Design Authority Reviewer:

_____________________________________ Date______________________