PRESSURE SAFETY OF JLAB 12GEV UPGRADE CRYOMODULE*

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Abstract

This paper reviews pressure safety considerations, per the US Department of Energy (DOE) 10CFR851 Final Rule [1], which are being implemented during construction of the 100 Megavolt Cryomodule (C100 CM) for Jefferson Lab's 12 GeV Upgrade Project. The C100 CM contains several essential subsystems that require pressure safety measures: piping in the supply and return end cans, piping in the thermal shield and the helium headers, the helium vessel assembly which includes high RRR niobium cavities, the end cans, and the vacuum vessel. Due to the vessel sizes and pressure ranges, applicable national consensus code rules are applied. When national consensus codes are not applicable, equivalent design and fabrication approaches are identified and implemented. Considerations for design, material qualification, fabrication, inspection and examination are summarized. In addition, JLAB's methodologies for implementation of the 10 CFR 851 requirements are described.

PRESSURE SYSTEMS IN C100 CM

The C100 CM design is based on other cryomodules that JLAB has designed/fabricated/tested in the past, such as the original CEBAF cryomodule, the Renascence cryomodule, etc. To abide by the DOE 10CFR851 Final Rule, JLAB established a counterpart chapter in the ES&H manual on pressure systems safety [2]. The ES&H manual requires design authorities to identify pressure systems and apply national consensus codes in design/fabrication/testing of such systems. In the C100 CM, it is determined that the following piping systems are pressure piping covered by ASME B31.3 code [3]: 1) piping in the copper thermal shield assembly, 2) piping in the primary and secondary (or shield) circuits of end cans, and 3) supply and return headers. The helium vessel assembly consisting of a 316L stainless steel outer pressure boundary and a high RRR niobium inner pressure boundary is considered to be a pressure vessel that is covered by ASME Boiler & Pressure Vessel Code (BPVC), Section VIII rules [4]. The vacuum boundaries of the end cans and vacuum vessel are pressure systems that are not covered by ASME codes due to pressure range. A series of JLAB Technical Notes (TN) have been written to document the design analyses that were done on the above-mentioned pressure systems per the applicable ASME codes. Statements of Work (SOWs) for these systems have been prepared for manufacturers to abide by during the fabrication and testing to ensure compliance with ASME code requirements. All subsystems of the C100 CM are currently in the procurement process. The following paragraphs summarize the design efforts on them.

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END CAN PIPING

Detailed ASME B31.3 design of the C100 CM end can piping is presented in JLAB-TN-07-056 [5]. Four piping subsystems, the primary and shielding circuits in the supply and return end cans, are examined per ASME B31.3 rules on five aspects: (1) straight pipe minimum wall thickness, (2) strength of branch connections, (3) pipe fittings pressure design, (4) pressure relieving, and (5) piping system flexibility, stress, and support. The primary and shielding circuits have internal design pressures of 5 atm and 10 atm, respectively. Gaseous and liquid helium of nominal 2K temperature is flowing in the primary circuit and 35K-50K helium gas is flowing in the shielding circuit. Due to the pressure and temperature range, both types of circuits are performing normal fluid service per B31.3 definition. Fabrication and assembly of these piping systems are also analyzed; in particular, the weld throat sizes are checked to assure their meeting pertinent B31.3 requirements.

B31.3 paragraph 304.1.2(a) equation (3a) is employed to calculate the minimum required wall thickness for straight pipes under internal pressure. All straight pipes in the end can piping are found to have more than sufficient wall thicknesses. The ratios (or safety factors) of actual pipe wall thicknesses versus required thicknesses are mostly greater than 10, with only four such ratios falling between 2.7 and 9. According to B31.3 paragraph 304.3.2, branch connection strength verification is waived since the run pipe wall thicknesses are sufficiently in excess of that required to sustain pressure. ASME B16.9 compliant pipe fittings are generally used in these circuits. Pressure relief devices are installed in the piping systems with conservative pressure settings. ASME B31.3 paragraph 319.4.1 equation (16) is used repetitively to evaluate each subsystem to see if a formal system flexibility analysis is required. It is found that none of these systems demands such analysis. In conclusion, all of the piping in the end cans meets the design requirements of B31.3, with most having generous factors of safety.

THERMAL SHIELD CIRCUIT PIPING

The thermal shield circuit piping B31.3 analysis is summarized in JLAB-TN-07-079 [6]. The thermal shield circuit designs of the original CEBAF and upgrade cryomodules are very similar. The shield circuit cools the nominal 50K thermal shield. The design pressure for the shield circuit is 10 atm. The operating temperature range is between 35K and 50K. Hence, this circuit performs normal fluid service. The B31.3 design procedure for this circuit is similar to that applied to end can piping systems. The wall thicknesses of the copper and stainless steel tubes are found to be at least 8 times thicker than what B31.3 code requires. Bellows and braided flex hoses are used to strain-relieve the thermal shield circuit piping. The thermal shield circuit piping design is considered to be conservative.

SUPPLY AND RETURN HEADERS

Two JLAB technical notes [7-8] address the design of C100 CM supply and return headers (also called cryogenic circuit) per ASME B31.3. An earlier design [7] adopts B16.9 compliant tees to transition from headers to the helium vessel. Initially, there was an intention to use SCH 5S pipes to reduce material cost. Subsequent investigations revealed that B16.9 tees reduce the margin between headers and helium vessel too much and SCH 5S piping is not easy to procure. Then the later JLAB TN [8] analyzed the updated design that uses straight piping branches in lieu of B16.9 tees and SCH 10 pipes. The design pressure and temperature for supply and return headers are 5 atm and 2K, respectively.

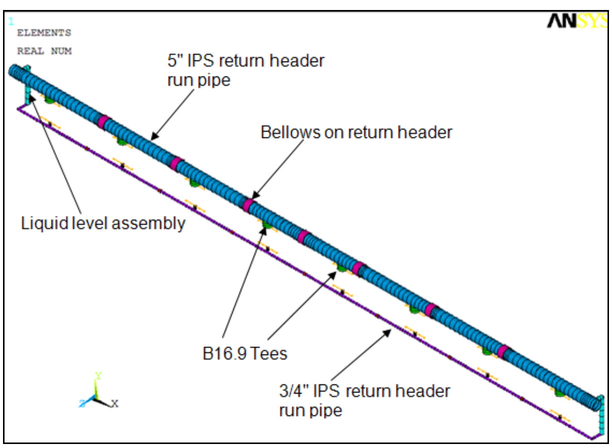

Figure 1: Finite element model of the cryogenic circuit.

Compared to the end can and thermal shield piping design analyses, two issues are specially emphasized in the headers' B31.3 design: a formal system flexibility analysis (see B31.3 paragraph 319.4) taking into account the thrust forces generated in the bellows, and bellows design per ASME BPVC Section VIII, Division 1, mandatory Appendix 26.

For the system flexibility analysis, the main purpose is to evaluate stresses in the piping system. The B31.3 code differentiates stresses caused by thermal load from those resulting from pressure and gravity loads. The former is termed "displacement stress" and the latter "sustained load stress." Both types of stresses shall be quantified and compared to their corresponding allowable values per B31.3. The supply/return headers, liquid level assembly pipes, and helium vessel are all made of the same type of stainless steel. Therefore, a negligible amount of thermal stress will exist in the pipe line; i.e., the displacement stresses due to differential thermal contractions are close to nil.

There are seven 5.63" OD bellows in the return header and seven 1.36" OD bellows in the supply header. Once pressurized, these bellows will produce "thrust forces," which will induce bending moments in the cryogenic circuit that is anchored to the helium vessel. It is clear that such sustained load-induced stresses in the supply and return headers must be evaluated. A finite element model, as shown in Figure 1, is created in ANSYS® to facilitate the stress analysis in the cryogenic circuit. Note that although the finite element code yields all kinds of stress results, such as von Mises stress, principal stresses and normal stresses, B31.3 actually has its unique definitions (refer to B31.3 paragraph 319.4.4 and Appendix P) of bending stress, S_b; torsional stress, S_t; and the manner to combine stresses due to axial load, bending, and torsion. Stress intensification factors are introduced in these definitions, and the code allows adjustment of allowable stress (refer to B31.3 paragraph 302.3.5) in consideration of stress range factor *f*, allowable stress at minimum metal temperature S_c, allowable stress at maximum metal temperature S_h, and longitudinal stress S_L. For the C100 CM cryogenic circuit, the combined load stress per B31.3 definition is found to be much lower than [8] the adjusted allowable stress permitted by B31.3: for the supply header, the calculated stress is 6% of the adjusted allowable stress; for the return header, the calculated stress is 15% of the adjusted allowable.

One important conclusion that can be drawn from such a low stress state is that the Charpy impact tests can be waived: B31.3 Table 323.2.2 Note (3) gives conditions when impact testing can be waived, but the temperature range given in this note does not cover the extremely low 2K temperature that the C100 CM cryogenic circuit operates at. DOE 10CFR851, Appendix A, Section 4(c) requires protection equivalent to or greater than that afforded by ASME or applicable state or local codes. In the spirit of this, the ASME BPVC Section VIII, Division 1, UHA-51(g) "Exemption From Impact Testing Because of Low Stress" rule is applied and Charpy impact tests are waived for the C100 CM cryogenic circuit.

For the bellows design, ASME B31.3 Appendices F and X outline the basic requirements of expansion joint design and manufacturing. The designer's main responsibilities, as summarized from paragraph F304.7.4 and paragraph X301, that are applicable to the supply and return headers include: specifying loading conditions, design of main anchors, bellows stress verification, and bellows instability check. Bellows stress and instability verifications were carried out per the 2007 ASME Boiler and Pressure Vessel Code Section VIII, Division I, Appendix 26. The applicable formulas are cited from chapter 26-6 "Design of U-Shaped Unreinforced Bellows." Pressure induced circumferential and meridional membrane, bending, membrane plus bending stresses, as well as instability were all examined. It was found that both the 5.63" OD and 1.36" OD bellows are safe while subjected to 5 atm internal pressure. The cryomodule does not undergo many thermal cycles during its lifetime. Typically, the cryomodule is predicted to operate for 40 years with one thermal cycle per year. Allowing for certain safety margins, a conservative estimation of the maximum number of cycles is 100. The bellows fatigue design is thus not deemed to be critical. Nevertheless, bellows fatigue design is addressed in JLAB-TN-07-051.

VACUUM VESSEL DESIGN

Strictly speaking, the C100 CM vacuum vessel is not covered by ASME BPVC code due to the fact that the external pressure is 14.7 psi. However, per 10CFR851 [1] and JLAB ES&H [2], it was decided to design it in accordance with ASME BPVC Section VIII Division 1 rules. Three JLAB TNs [9-11] are written on the vacuum vessel design per BPVC. From a structural point of view, the vacuum vessel is subjected to a combination of pressure and structural loads. Pressure loads include either internal or external pressure. Structual loads include weight from the end cans, weight of the spaceframe assembly including components attached to the spaceframe, its own weight, and the weight of accessories such as waveguides. The vessel has multiple openings, such as waveguide ports, instrumentation ports, an access port, a tuner port, etc. The design pressures on the vacuum vessel are 1 atm external and 2 atm internal. The BPVC code design of the vacuum vessel includes the following major steps: 1) determination of the required minimum thickness of the vacuum vessel shell subjected to internal/external pressure, 2) determination of whether reinforcement areas are needed at interfaces of major openings for internal and external pressure loading cases, 3) verification of the reinforcing rings' required moment of inertia per UG-29 and weld sizing, and 4) lockdown studs' strength verification. The lockdown studs are used to join the spaceframe assembly and the vacuum vessel. During transportation, it is assumed that there may be 4g vertical or 2g axial accelerations to the vacuum vessel. The strength of the vessel and studs under such g-forces needs to be verified.

The first step was accomplished by creating a finite element model as illustrated in Figure 2. ASME BPVC Section VIII Division 1 UG-23(c) requires evaluation of the maximum general primary membrane stress, P_m, and the combined maximum primary membrane stress plus primary bending stress, $P_m + P_b$. The definitions of such stresses from Division 2 are adopted in JLAB-TN-09-029 [11] and the stress linearization procedure as stated in Division 2, Part 5, Annex 5.A.4.1.2, is implemented to calculate the required P_m and $P_m + P_b$. In fact, the minimum vessel thickness enforced by Division 1 UG-16(b), i.e., 1/16", is selected as an initial guess of the required minimum vessel thickness. Stress results show that with 1/16" wall thickness, either the P_m or the $P_m + P_b$ does not exceed 10,000 psi for both internal and external pressure loadings. Therefore, the required vacuum vessel minimum thickness is 1/16". The actual vacuum vessel shell thickness is 0.25". The P_m and $P_m + P_b$ are found to be less than 2,100 psi for 0.25" vacuum vessel shell and thus the shell thickness is sufficient.

The reinforcement area determination for all openings is done by following the procedure set forth in BPVC Section VIII, Division 1, UG-37. This code analysis triggers the determination of the required thickness of a seamless nozzle wall, t_{rn},which is dictated by rules in UG-16(b), UG-45(a), (b), and (c). For the C100 CM vacuum vessel openings, a systematic procedure is set up in a Microsoft Excel® worksheet, and it is found that no openings require additional reinforcement.

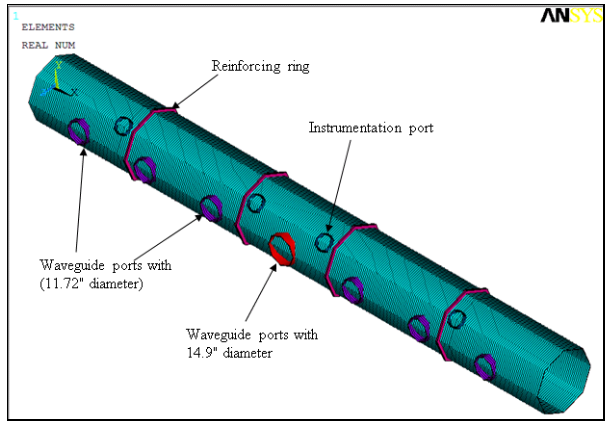

Figure 2: Finite element model of vacuum vessel.

For reinforcing ring weld sizing, nodal forces from the finite element model are used as inputs. Weld strength verification was done by observing the distortion energy failure theory. Determination of the appropriate weld size for reinforcing rings needed a few iterations. In the end, all welds were determined to have a safety factor that is greater than 2.

The lockdown studs were analyzed for the transportation loads as described and found to be adequate. There is also a special demand for lockdown studs during assembly of the CM: to lift the spaceframe assembly with two studs and allow alignment activities. It is found that the thread stress is the driving factor in sizing these two studs. The robustness of welds between the stud caps and washers and between the washers and vacuum vessel shell was also verified.

HELIUM VESSEL DESIGN

The design pressures for the helium vessel (HV) are 5 atm internal and 2 atm external. Pressure loading only exists when the CM is in normal operation, which means the HV is at 2K temperature. Figure 3 shows the design of C100 CM helium vessel assembly. Item 1 is a high RRR niobium cavity and the rest of the components are all made of 316L stainless steel.

Niobium is not currently included in ASME BPVC. An investigation [12] on the use of niobium in the construction of pressure vessels is conducted. It is found that the niobium's thermal and mechanical properties may change from batch to batch. Heat treatment significantly affects niobium's properties. JLAB's specification for

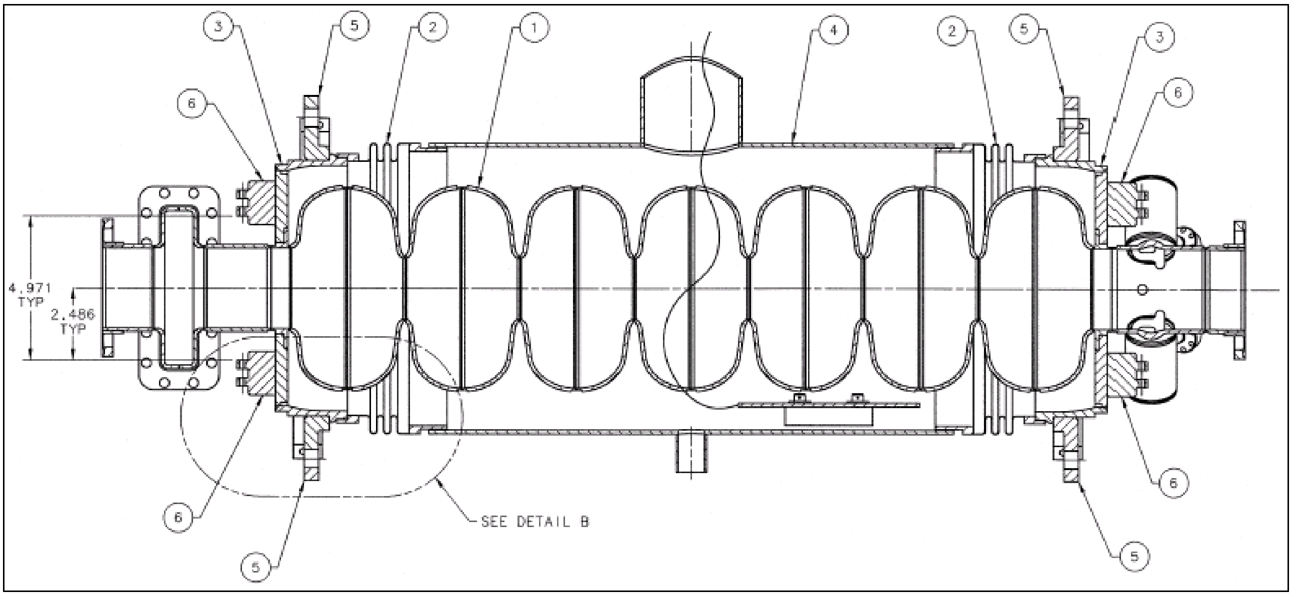

Figure 3: C100 CM helium vessel assembly containing high RRR cavity.

high RRR niobium requires a minimum of 7,000 psi yield and 14,000 psi ultimate strengths, respectively. To confirm that the niobium material used to build C100 cavities meets these specifications, it is necessary to measure the important thermal and mechanical properties. Observing the requirements set forth in the ASME BPVC Section II's "Guideline on the Approval of New Materials under the ASME Boiler and Pressure Vessel Code," ASTM E8/E8M "Standard Test Methods for Tension Testing of Metallic Materials" and ASTM E1450 "Standard Test Method for Tension Testing of Structural Alloys in Liquid Helium" shall be performed for at least three heats of each niobium product form.

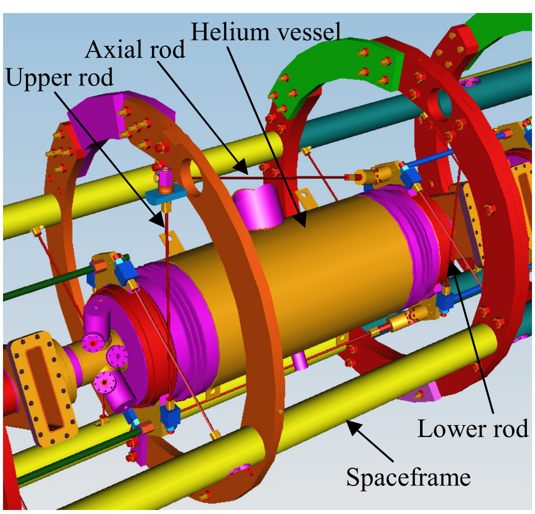

Figure 4: Spaceframe, HV, and Nitronic rods.

The 316L stainless steel pressure boundary of the HV consists of HV head assembly (item 3), bellows (item 2), and HV shell assembly (item 4). The BPVC-required minimum wall thicknesses for stainless steel HV components are calculated and compared with actual design values in JLAB-TN-07-037 [13]. All wall thicknesses are found to be adequate. The requirement for reinforcement areas at the two HV-to-headers transition pipe openings is also analyzed, and it is found that no additional reinforcement is needed for either opening.

The stress in the C100 CM HV is analyzed and results are documented in JLAB-TN-09-049 [14]. The HV head assembly is identified to withstand the primary portion of the mechanical loads transferred from upper, lower, and axial Nitronic rods [14-15]. Figure 4 illustrates the layout of the spaceframe (with one tube omitted for clarity), helium vessel, and Nitronic rods. The HV bellows is guided by tuners so that there is no concern of bellows squirming instability and it will absorb axial displacement without causing noticeable stress. The shell and transition pipes are mainly subjected to pressure loading. On each HV head assembly, there are two preloaded upper Nitronic rods and two lower rods. During normal operation, these Nitronic rods will contract and hence apply additional thermal contraction loads to the HV head. The two centering HV heads have two axial Nitronic rods: one at the top of the head assembly and the other at the bottom. These two axial rods will also contract and result in additional loads to the HV head assembly. Stresses in one HV head assembly are analysed by a 3-D finite element model. Both internal and external pressures are considered in two separate case studies. Figure 5 shows the von Mises stress in the head assembly when 5 atm internal pressure and loads from all Nitronic rods are applied to the head structure. The stress in the main body of the head assembly is below 20,000 psi. At some sharp corners, stress singularities [16] occurred. Stresses at these corners are not reliable and it is impossible for a finite element analysis to overcome the stress singularity problem in a rational manner. The peak stress from the external pressure loading case turns out to be even lower. It is deduced that such a low stress condition allows the C100 CM HV stainless steel components to be exempt from Charpy impact tests , per ASME BPVC Section VIII, Division 1, UHA-51(g).

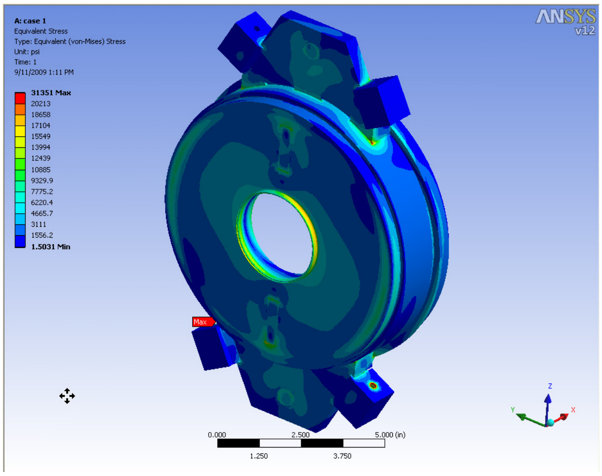

Figure 5: Von Mises stress in HV head assembly.

FABRICATION

The vendors are required to abide by specifically developed SOWs in fabrication of all C100 CM components and subsystems. Weld Procedure Specifications (WPS), Welder Performance Qualifications (WPQ), and Procedure Qualification Records (PQR) per ASME BPVC Section IX are required to be submitted prior to fabrication. All vendors are required to observe either ASME B31.3 or BPVC rules during their fabrication activities. Quality control plans from vendors are reviewed to ensure compliance with ASME code requirements. Currently, receiving inspection travellers are being developed.

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REFERENCES

[1] Department of Energy, “10 CFR Parts 850 and 851 Chronic Beryllium Disease Prevention Program; Worker Safety and Health Program; Final Rule,” Federal Register Part II, Thursday, February 9, 2006.

[2] W. Oren and D. Kausch, “Jefferson Lab ES&H Manual, 6151 Pressure Systems,” issued by JLAB ES&H Division, June 24, 2008.

[3] ASME Code for Pressure Piping, B31, “ASME B31.3-2006 Process Piping,” The American Society of Mechanical Engineers.

[4] 2007 ASME Boiler & Pressure Vessel Code, Section VIII, Divisions 1 & 2, The American Society of Mechanical Engineers.

[5] G. Cheng and E. Daly, “C100 Cryomodule End Can Piping Design per ASME B31.3,” JLAB-TN-07-056, Jefferson Lab, Newport News, VA.

[6] E. Daly, G. Cheng, and J. Hogan, “JLab Cryomodule Thermal Shield Circuit Piping Design per ASME B31.3,” JLAB-TN-07-079, Jefferson Lab, Newport News, VA.

[7] G. Cheng and E. Daly, “C100 Cryomodule Supply/Return Header Desgin per ASME B31.3,” JLAB-TN-07-051, Jefferson Lab, Newport News, VA.

[8] G. Cheng, W. Hicks, and E. Daly, “C100 Cryomodule Supply/Return Header Design per ASME B31.3-An Addendum to JLAB-TN-07-051,” JLAB-TN-08-006, Jefferson Lab, Newport News, VA.

[9] G. Cheng, W. Hicks, and E. Daly, “C100 Cryomodule Vacuum Vessel Structural Analysis,” JLAB-TN-07-081, Jefferson Lab, Newport News, VA.

[10] G. Cheng and E. Daly, “C100 Cryomodule Vacuum Vessel Structural Analysis-An Addendum to JLAB-TN-07-081,” JLAB-TN-09-007, Jefferson Lab, Newport News, VA.

[11] G. Cheng, E. Daly, and M. Wiseman, “C100 Cryomodule Vacuum Vessel Structural Analysis-Addendum II to JLAB-TN-07-081,” JLAB-TN-09-029, Jefferson Lab, Newport News, VA.

[12] G. Cheng and E. Daly, “On Niobium in Construction of Cryogenic Pressure Vessel Systems,” JLAB-TN-09-002, Jefferson Lab, Newport News, VA.

[13] W. Hicks and E. Daly, “C100 Helium Vessel, Boiler & Pressure Vessel Code Documentation,” JLAB-TN-07-037, Jefferson Lab, Newport News, VA.

[14] G. Cheng and M. Wiseman, “C100 Cryomodule Helium Vessel Stress Analysis,” JLAB-TN-09-049, Jefferson Lab, Newport News, VA.

[15] G. Cheng and M. Wiseman, “C100 Cryomodule Spaceframe Structural Analysis,” JLAB-TN-09-048, Jefferson Lab, Newport News, VA.

[16] P. Kurowski, “Easily Made Errors Mar FEA Results,” Machine Design, September 13, 2001, p. 69.