DESIGN AND ANALYSIS OF SRF CAVITIES FOR PRESSURE VESSEL CODE COMPLIANCE*

C. Astefanous[1], J. Deacutis, D. Holmes, T. Schultheiss,
Advanced Energy Systems, Inc., Medford, NY 11763, U.S.A
I. Ben-Zvi, Physics and Astronomy Department, Stony Brook University, Stony Brook NY 11794,
Brookhaven National Laboratory, Upton, NY 11973, U.S.A.
Wencan Xu, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

Abstract

Advanced Energy Systems, Inc. is under contract to Stony Brook University to design and build a 704 MHz, high current, Superconducting RF (SRF) five cell cavity to be tested at Brookhaven National Laboratory. This cavity is being designed to the requirements of the SPL at CERN while also considering operation with electrons for a potential RHIC upgrade at Brookhaven. The β=1 cavity shape, developed by Brookhaven, is designed to accelerate 40 mA of protons at an accelerating field of 25 MV/m with a $Q_0 > 8E9$ at 2K while providing excellent HOM damping for potential electron applications. 10-CFR-851 states that all pressurized vessels on DOE sites must conform to applicable national consensus codes or, if they do not apply, provide an equivalent level of safety and protection. This paper presents how the 2007 ASME Boiler and Pressure Vessel Code Section VIII, Division 2 requirements can be used to satisfy the DOE pressure safety requirements for a non-code specified material (niobium) pressure vessel.

SRF CAVITIES AS PRESSURE VESSELS

Differential pressures above 15 psi put a vessel within the scope of the ASME Boiler & Pressure Vessel Code [1]. There are at least three events where the wall pressure of an SRF cavity can exceed 15 psi:

(1) *Cool down.* At minimum the supply pressure of the liquid helium is reached.
(2) *Backfill pressurization.* The implementation guide for DOE Order 440.1A, the order on which the pressure safety guidelines of 10-CFR-851 are based, states that there is a "…potential for catastrophic failure due to backfill pressurization".
(3) *Loss of insulating vacuum*. This results in rapid evaporation and expansion of the liquid helium.

The minimum required maximum allowed working pressure (MAWP) for the SPL cavity was selected to be 21.7 psi based on the aforementioned environmental considerations and available pressure relief devices. "Design by Analysis" (Section VIII, Div. 2, and Part 5)

addresses the safety of pressure vessel designs outside the design rules of Div. 1—in this case it is applied to the unique case of a niobium SRF cavity.

ACHIEVING CODE CONFORMANCE

SRF cavities cannot become ASME stamped pressure vessel until niobium is qualified per the code requirements [2]. To achieve that, an end user must make an official request to the ASME B&PV committee along with a request to the ASTM for an appropriate material specification. The required material data, at a minimum, is the mechanical properties of three heats of RRR niobium for each of these conditions: (1) -455.8 °F thru 70 °F in 100°F intervals, (2) Material thicknesses 1 mm thru 4 mm, (3) RRR values of 250, 325, and 400, and (4) Pre/Post heat treatment (Weld and Bakeout).

EQUIVALENT SAFETY CRITERIA

Due to the nested pressure vessel construction and pressure relief systems, there is no question of personnel safety. An equivalent level of safety to the ASME code requirements can be taken as ensuring the structural integrity of an SRF cavity throughout its operational life.

The design criteria of Div. 2 depend in part on the other criteria for materials, fabrication, inspection, and testing. Through the use of Div. 2 requirements and sound engineering judgement an equivalent level of safety to the ASME Boiler and Pressure Vessel Code can be achieved.

USER DESIGN SPECIFICATION

The user specification is the first step in assuring the safety of a pressure vessel and it is the absolute authority on all aspects of the vessel requirements. The specification must state clearly: the installation site, vessel identification, vessel configuration and controlling dimensions, design conditions, operating conditions, cyclic operating conditions, materials of construction, loads and load cases, and overpressure protection. All of these requirements must be addressed in the manufacturer's final report except for overpressure protection—which is the end user's responsibility. However, the end user may contract the manufacturer to design and fabricate the pressure relief system. The user specification can be a joint effort of the designer, manufacturer, and end user but the end user has the responsibility to certify the validity of the user specification. The manufacturer's design report is certified

by the manufacturer and must clearly correlate to each aspect of the user specification.

Reference [3] provides useful guidance on creating this specification

FABRICATION

Material Specifications

A suitable material specification must be created for RRR niobium by the end user. All material tests should include at least two samples for each heat used in cavity construction. Tensile testing (ASTM E8) should be performed at each applicable material state (as received, welded, and post bake-out). Testing and analysis can be simplified by ordering the material in a fully annealed state and returning it to that state after manufacturing.

The code imposes toughness testing for the determination of the minimum design material temperature (MDMT). For non-ferrous alloys Section 3.11.5 of Div. II, allows the MDMT to be based on material testing that convinces the user of sufficient ductility at its design temperature—such testing could include a Charpy V-notch impact test (ASTM E23), a fracture toughness test (ASTM E399) and/or a tensile test (ASTM E1450).

Welding Qualification

All weld joints and welders must be qualified according to the provisions in Section IX of the code. This requires qualifying welds and documenting the results in a Procedure Qualification Report(s) (PQR). Each PQR covers a small range of weld parameters. The PQRs in turn support a Welding Procedure Specification (WPS) that is associated with each weld. Weld design experience is of paramount importance to the successful construction of an SRF cavity—weld preparations affect the vessel integrity and internal RF volume.

INSPECTION AND TESTING

Inspection

Div. 2 imposes 100% inspection criteria upon the majority of welds. All electron beam welds are specified to be 100% ultrasonically inspected in addition to visual inspection (Div. 2, Part 7.4.3.3 (a)). However, inspection methods for SRF cavities may be limited by material thickness and geometry. The thin curved structure of an SRF cavity is a difficult geometry for ultrasonic inspection. Yet, a phased array ultrasonic system may be capable of sufficient clarity and resolution.

Ultrasonic and radiographic inspections are equally capable of detecting volumetric flaws. However, ultrasonic inspection is best suited for planar flaw detection [5]. It is reasoned that the code presumes that electron beam welding results in higher incidents of planar flaws, but that may not be true for niobium welds prepared and processed in clean room environments. A thorough characterization of niobium e-beam weld flaws

may demonstrate that UT is non-mandatory for RRR niobium e-beam welds.

Pressure Testing Requirements

SRF cavities do not use the test requirements for a vacuum vessel because they must have a MAWP above 14.7 psi. Div. 2, Part 8.1.1(b) allows selecting pneumatic testing over hydrostatic testing if the hydrostatic test could cause permanent visible distortion in the SRF cavity. The cavity design must ensure that testing does not result in a permanent geometry change.

ANALYSIS PARAMETERS

Material Mechanical Properties

The literature shows a wide range of RRR niobium mechanical properties [6,7]. Analysis should use minimum values based on the purchasing material specification. All analysis results should be checked against the actual material mechanical test results.

It is possible that the external surface of the cavity receives a flaw during fabrication. It is suggested that a fracture mechanics evaluation is used to calculate the allowable stress at ≤ 4.22 K using a conservative flaw size.

Pressure Loads

The chosen MAWP must have margin above actual operating conditions in order to prevent accidental triggering of pressure relief devices. Pressure relief has to coincide with the highest MAWP of the cavity. Therefore, the cavity must be designed for the most severe conditions of concurrent loads and temperature.

Manufacturing Complications

SRF cavities go through a number of manufacturing processes. Analyses must take into account: (1) thickness reduction due to buffered chemical polishing (BCP) and/or electro-polishing, (2) Plastic strain induced by initial tuning, (3) Annealing due to bake-out temperatures, (4) Heat affected zones at welds, and (5) Tuner preload.

DESIGN BY ANALYSIS

The design by analysis requirements of Div. 2, Part 5 requires demonstrating protection against five failure mechanisms: plastic collapse, local plastic failure, buckling, fatigue, and ratcheting. For each failure mechanism, there is a choice to use at least one of three different material models: elastic, elastic-perfectly plastic, and elastic-plastic. The vessel needs to meet code criteria for only one material model. It should be noted there are cases were a vessel will not pass under all three models.

Plastic Collapse and Buckling

Plastic collapse and buckling are highly related failure mechanisms. In both cases, the goal is to determine sufficient margin against structural instability. Buckling only applies under compressive stress conditions, whereas

Accelerator Technology

Tech 21: Reliability and Operability

plastic collapse can occur under tension or compression. These analyses, for an SRF cavity, must consider both stress stiffening (coupling of in plane displacements to out of plane displacements) and applied tuner displacement.

Fatigue and Ratcheting

Fatigue cycles result from temperature excursions (2 K to 293 K) and tuner travel. The active tuner displacement over the mean stress imposed by tuner preload is not significant for continuous wave operation but could have an effect over the cavity life in pulsed configurations.

The allowable number of cycles for integral construction, which exempts a vessel from fatigue analysis, is 1000. The code addresses cyclic loads due to pressure variations as well as both local and global temperature changes. Additionally, displacement induced stress cycles, such as from tuner travel, are not specifically addressed and must be considered.

A ratcheting analysis should always be performed when yielding occurs due to cyclic loads. Plastic strains are typically developed during temperature transitions by material CTE mismatch—such as a cavity constrained in a vertical test fixture and at stainless steel flanges.

Local Plastic Failure

The code requires evaluation for local plastic failure at 1.7*MAWP. However, plastic strain accumulates in the cavity mostly due to initial forming and tuning. If the manufacturing bakeout temperature is $\geq 800^{\circ}$C for ≥ 2 hours it can be assumed that all forming and tuning strains are relieved. However, this means a reduction in strength for parts that did not begin annealed. The code recommends using an elastic-plastic model instead of the elastic evaluation. The use of an elastic-perfectly plastic model is conservative for this analysis.

The strain limit criterion against plastic rupture is based upon the triaxiality of stress, material crystal structure, uniaxial strain limit, and the strain hardening exponent. The triaxiality of stress is presented as a simple equation; however, the other variables require some discrimination in their selection. The basis for the uniaxial strain limit in order of accuracy is: percent area reduction at failure, percent elongation at failure, strain hardening exponent [8]. An evaluation of the uniaxial strain limit equations shows that reduction of area specified is the same formulation for all material. If another uniaxial strain limit formulation is used the BCC crystal structure of niobium suggests using ones for aluminum or copper. The strain hardening exponent (slope of the plastic stress-strain curve) as calculated from available data at room temperature is ~0.2 (welded+formed) and ~0.3 (annealed). Those values should be used as a guideline since the material data does not meet ASME requirements. There is not adequate data for estimating the strain hardening exponent for ≤ 4.22 K.

The code provides a formulation for determining forming strains but it does not account for a reversal in curvature—such as in the forming of the iris. If peak strains occur near the curvature of the iris, it is suggested to perform a rigorous evaluation of the forming strains.

OPERATIONAL CONSIDERATIONS

Cavities may require a procedure for warm-up that limits the coarse tuner displacement so that the niobium is not yielded during transitions from ≤ 4.22 K to 293 K. Additionally, cool-down must occur slowly in order to maintain a $\Delta T \leq 28^{\circ}$C across the cavity surface because the code allows temperature variations below 28°C to be ignored as a load contributing to a fatigue failure.

CONCLUSION

The requirements of the ASME Boiler and Pressure Vessel code provide a framework for designing safe and reliable equipment. Due to the uniqueness of addressing SRF cavities as pressure vessels, an SRF community committee could be formed to qualify niobium and clearly address the unique aspects of SRF cavity pressure safety within the code.

As of the publishing of this paper, the analyses were completed which demonstrate that the SPL cavity design meets the Div. II, Section VIII "Design by Analysis" requirements during vertical testing.

REFERENCES

[1] ASME, 2007, 2008 & 2009 addenda, *ASME Boiler and Pressure Vessel Code, Section VIII – Div. 2*, ASME, New York, NY

[2] ASME, 2010, ASME Boiler and Pressure Vessel Code, Appendix 5 of Section II, Part D, Mandatory Appendix 5, "Guideline on the Approval of New Materials under the ASME Boiler and Pressure Vessel Code," ASME, New York, NY.

[3] T. Seipp and S. George, "User's Design Specification Recommendations for ASME Section VIII, Div. 2," ASME Conf. Proc.,(2010).

[4] D. Osage and M. Prager, "Technical Basis of Material Toughness Requirements in the ASME B&PV Code, Section VIII, Div. 2," ASME Conf. Proc. (2010)

[5] Jack Spanner, "Effectiveness of Substituting Ultrasonic Testing for Radiographic Testing for Repair/Replacement" ASME Conf. Proc. 2005, 33 (2005)

[6] T.J. Peterson, H.F. Carter, M.H. Foley, et. al., "Pure Niobium as a Pressure Vessel Material," Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference, Vol. 55 (2010)

[7] Walsh, R.P. et al., "Low Temperature Tensile and Fracture Toughness Properties of SCRF Cavity Structural Material", SCRF'99, Santa Fe, 1999.

[8] Wolf Reinhardt, "Investigation of the Elastic-Plastic Design Method in Section VIII Div. 2" ASME Conf. Proc. 2009, 41 (2009)