# CESR-TYPE SRF CAVITY - MEETING THE ASME PRESSURE VESSEL CRITERIA BY ANALYSIS *

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*Abstract*

Over a dozen CESR-B Type SRF cryomodules have been implemented in advanced accelerators around the world. The cryomodule incorporates a niobium cavity operating in liquid helium at approximately 1.2 bar and at 4.5 K, and therefore, is subjected to a differential pressure of 1.2 bar to the beam vacuum. Over the past few decades niobium RRR values have increased, as manufacturing processes have improved, resulting in higher purity niobium and improved thermal properties. Along with these increases may come a decrease of yield strength, therefore, prior designs such as CESR-B, must be evaluated at the newer strength levels when using the newer high purity niobium. In addition to this the DOE has directed the U.S. National Laboratories to evaluate structure based on the ASME code, DOE directive 10CFR851. The goal of this work was to analyze the CESR-B Type cavity and compare the results to ASME pressure vessel criteria and where necessary modify the design to meet the code criteria.

## ANALYSIS REQUIREMENTS

The ASME Division 2 rules [1] call out the required procedures and define the allowable yield strength, ultimate strength, strain limit, buckling load, and collapse load, that must be satisfied. These procedures are based on protection against failure modes. They are; protection against Plastic Collapse, protection against Local Failure, protection against Collapse from Buckling and protection against Failure From Cyclic Loading. The procedures called out may only be used if the allowable stress evaluated at the design temperature is governed by time-independent properties unless the specific design procedure allows it. The CESR-B cavity was analyzed following these step by step requirements, the analysis and results of the analysis procedures is presented here. At the time of this analysis BNL set the pressure limits in their cryostat liquid helium system to 1.49 bar. This pressure is the maximum allowable working pressure, MAWP, for all analyses. Load factors account for differences in material properties and variations in loading and provide safety margin to the design. The load factors are given in tables, 5.4 and 5.5 of the 2007 Section VIII, Division 2 code.

## PROTECTION FROM PLASTIC COLLAPSE

Three alternative analysis methods are acceptable for evaluating the structure for protection against plastic collapse. The first is the elastic stress analysis method, the second is the Limit-Load Method and the third is the Elastic-Plastic Stress Analysis Method. Preliminary analysis has shown that the structure undergoes plastic deformation, therefore we are limited to the second or third procedure. The limit-load method is performed to determine a lower bound to the limit load of a component. In this procedure bilinear elastic-perfectly plastic material properties are used where the tangent modulus is set to zero for stresses above the yield point of the material. The final method, elastic-plastic stress analysis was not used in the analysis.

## LIMIT-LOAD ANALYSIS

This analysis addresses failure modes of ductile rupture and the onset of gross plastic deformation (plastic collapse) of a structure. Small displacement theory and equilibrium must be satisfied up to the point of collapse.

The finite element code ANSYS was used for all of the analyses. The model shown in figure 1 was received from BNL in CAD format and translated to ANSYS. The flanges are made from reactor grade niobium, the fluted beam pipe, cavity, beam pipe, and waveguide are made from RRR grade niobium. The thickness of the waveguide is 4 mm, the beam pipe and cavity are 3 mm thick. The fluted beam pipe is 3.2 mm thick in the cylindrical section and 2 mm thick in the knuckle and top of the flute to account for thinning during forming. The thickness transitions from 2 to 3.2 mm in the flat of the flute, shown in the figure.

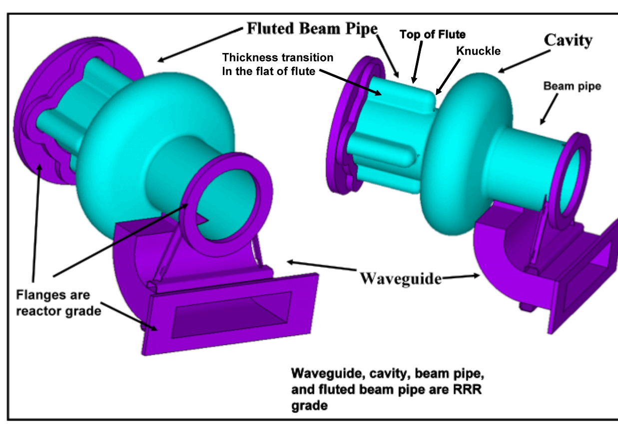


Figure 1: Model of CESR-B cavity.

The material properties used are from the BNL specifications to the material fabricator. They define minimum yield and minimum tensile strength.

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The model is constrained at the three flange locations. The flange in the back and to the left of Figure 1 is attached to the helium vessel through a bellows. Stiffness is provided to the flange by a frequency tuner, this tuner is also connected to both the helium vessel and the flange. Load factor requirements are given in ASME table 5.4 of the ASME code for limit load analysis.

Within the analysis code a procedure known as the arc-length procedure is employed where loads are gradually applied. This procedure looks at the change of pressure, step to step, and compares it to the change in structure displacement. As the structure displacement gets large the increase in pressure for the next step is decreased. At the point of collapse the pressure will be decreased from the previous load step. On a pressure vs. displacement curve the slope will be zero at the point of collapse which corresponds to the ASME definition of collapse as the inability to achieve an equilibrium solution for a small increase in load.

Gravity loading is set at 1.5 times and is kept constant in the analysis. The pressure loading is increased to show that the structure does not collapse at 1.5 times maximum allowable working pressure, 2.235 bar. Figure 2 shows the results of the limit load analysis. The loading was stopped at 2.6 bar and the component had not collapsed.

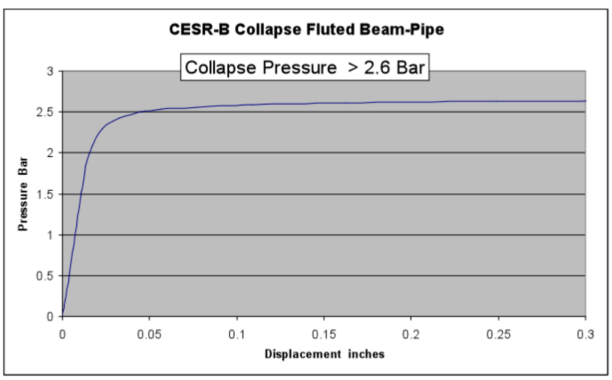


Figure 2: Limit-load analysis showing collapse is greater than 2.6 bar.

Limit load analysis was also completed for a pressure only case as well as for a gravity only case.

The gravity only case was run with a load of 1.5 times gravity. The resulting maximum von Mises stress of 429 psi (2.96) MPa is far below the yield strength of RRR niobium, 7000 psi (48.3 MPa), and far below the elastic allowable of 2/3 of yield which is 4666 psi.

Protection against plastic collapse is satisfied. The geometry does not collapse under 1.5 times gravity and pressure loading. Furthermore, it does not collapse for either case of pressure or gravity acting alone.

## LOCAL FAILURE

Section 5.3 of the ASME code describes the requirements for protection against local failure. The chosen method uses elastic-plastic analysis and compares the total equivalent plastic strain to a limiting strain. The material model requires that the effects of non-linear geometry be included. Since we did not have a full stress-strain curve for niobium we used the same material model as in the limit-load analysis, a bi-linear kinematic elastic-perfectly plastic model. However, the local failure procedure requires that non-linear geometry is used with a load factor of 1.7, therefore this procedure is more stringent than the limit load procedure. The arc-length procedure and gradually applied pressure was also used for local criteria so that non-linear geometry and plastic effects would be properly accounted for. Figure 3 shows the criteria that must be met for protection against local failure.

Elastic-Plastic Analysis (2007, Sec VIII, Div2, 5.3.3)

<u>Analysis Procedure</u>

For a location in the component subject to evaluation-determine the principal stresses ($\sigma_1$, $\sigma_3$ and $\sigma_3$), the equivalent stress ($\sigma_e$) and the total equivalent plastic strain ($\varepsilon_{peq}$)

<u>Acceptance Criteria</u>

For a location in the component subject to evaluation:

$$\varepsilon_{peq} + \varepsilon_{cf} \leq \varepsilon_L$$

where $\varepsilon_L$ = Limiting triaxial strain

$= \varepsilon_{Lu}.\exp[-(\alpha sl/1+m2)[\{(\sigma_1 + \sigma_2 + \sigma_3)/3\ \sigma_e)\}\ -1/3]$

$\varepsilon_{cf}$ = Forming Strain

Figure 3: Requirements for meeting local failure by strain limits.

For all locations of the model the principal stresses, total equivalent plastic strain and the forming strain were determined. The uni-axial strain limit was then combined with other constants from ASME table 5.7 and the local principal and equivalent stress to determine the multi-axial strain limit. Of note is that niobium is not included in the list of materials. Therefore, we used the expressions for copper which is the listed material that behaves most closely to niobium. The forming strain is calculated from ASME table 6.1, equations for forming strain [2]. A limiting tri-axial strain is calculated and compared to the sum of the plastic and forming strains. When principal strains are negative the limiting tri-axial strain can become much larger than the uni-axial strain limit determined from tensile tests. All locations in the model passed the criteria.

## COLLAPSE FROM BUCKLING

The ASME code requires that in addition to evaluating protection against plastic collapse a design for protection against collapse from buckling shall be satisfied to avoid buckling of components with a compressive stress field under applied design loads. The bifurcation buckling analysis method was chosen here. On the left side of Figure 4 the design factor and pre-stress load conditions are shown. $\beta_{cr}$ for a spherical or elliptical head is .124 resulting in a required design factor of 16.1. The pre-stress load condition is the maximum allowable working pressure, 1.49 bar plus gravity loading. On the right of the figure the result for the first buckling mode shape is shown. The model was a full representation of the geometry so that no modes were excluded. The first buckling mode has a load factor of 19.9 and is significantly above the required minimum load factor of 16.1. The design meets the requirements for protection against collapse from buckling.

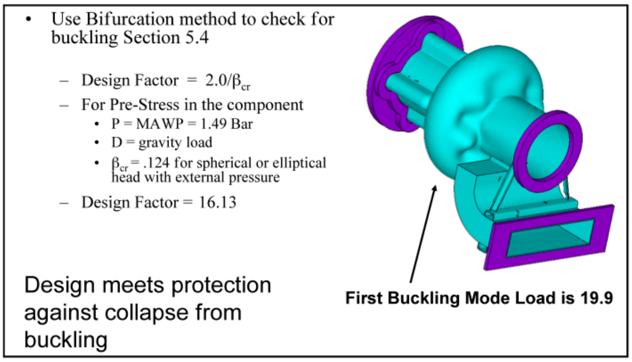


Figure 4: Collapse from buckling is satisfied.

## COLLAPSE FROM CYCLIC LOADING

Section 5.5 of the ASME code describes the requirements for protection against failure from cyclic loading. A fatigue evaluation is needed if the component is subject to cyclic operation. The evaluation is based upon the number of cycles of a stress or strain range at a point in the component. Screening criteria are provided to determine if a fatigue analysis is required as part of the design. Method A [4] can be used for materials with a specified minimum tensile strength that is less than or equal to 80,000 psi. This is the case for niobium at room temperature.

### *Screening Criteria for Fatigue Analysis 5.5.2*

The expected number of cycles satisfy the criterion in ASME Table 5.9: Components that do not contain a flaw and the total number of cycles is ≤ 1000 do not require a fatigue analysis. The following steps identify the number of cycles to be counted in the screening.

The number of full pressure cycles including startup and shutdown. There are 2 full range pressure cycles per year for 30 years = 60 cycles = $N_{\Delta FP}$

Determine the number of operating pressure cycles in which the range of pressure variation exceeds 20% of the design pressure for integral construction or 15% for non-integral construction. There are 2 pressure cycles that exceed 20% of the design pressure range per year for 30 years = 60 cycles = $N_{\Delta PO}$

Based on the load history determine the number of changes in metal temperature difference between any two adjacent points and designate this value as $N_{\Delta TE}$. The effective number of changes is determined by multiplying the number of changes in metal temperature difference of a certain magnitude by the factor given in Table 5.8 of the ASME code. Thermal analysis showed that all temperature differences at adjacent points throughout the transient are less than 26ºC. Therefore, this factor is zero for all pressure cycles. $N_{\Delta TE} = 0$

The next step looks at welds between materials of differing CTE, coefficient of thermal expansion. All materials of this component are niobium and have the same CTE. $N_{\Delta Ta} = 0$

Total number of cycles= $N_{\Delta FP} + N_{\Delta PO} + N_{\Delta TE} + N_{\Delta Ta} = 60 + 60 + 0 + 0 = 120$. The number of cycles ≤ 1000 therefore, no fatigue analysis is required.

### *Ratcheting Assessment – Elastic-Plastic Stress Analysis*

By applying, removing and re-applying the loads an assessment of protection against ratcheting can be made. The objective is to show that the stress-strain hysteresis loop along the strain axis will stabilize after a finite number of cycles. An elastic-perfectly plastic material model using the von Mises yield criteria was used with non-linear geometry. The loading events considered here begin with the pressure defined by pneumatic testing, 1.15 times the maximum allowable working pressure (MAWP), followed by removal of this load and three additional cycles where the pressure is increased to MAWP and then the load is removed. Figure 5, shows a table of the maximum von Mises stress and maximum displacement of the model at the end of each load step beginning with load step 2. Convergence of the results after cycling indicates the criteria is satisfied.

| End of Load Case | Max von Mises Stress Psi | Max* Displacement In |
|---|---|---|
| 2 | 6900 | .00104 |
| | | |
| 4 | 6910 | .00104 |
| | | |
| 6 | 6910 | .00104 |
| | | |

* Vector sum of displacements

Analysis shows that there is no change in dimension between the last and next to last cycles demonstrating convergence. This indicates that the structure has an elastic core.

Protection Against Cyclic Loading-Ratcheting has been met

Figure 5: Table of stress and displacement at end of load cases.

## CONCLUSIONS

Analysis shows that by incorporating wall thicknesses given in this paper the CESR-B type cavity meets ASME criteria for a MAWP of 1.49 bar. BNL subsequently performed independent analysis and is currently considering increasing the helium pressure limits and therefore, MAWP, to 1.55 bar based on recent BNL results.

## REFERENCES

[1] ASME Boiler and Pressure Vessel Code 2007 Section VIII, Division 2, Part 5 Design by Analysis Requirements.

[2] ASME Boiler and Pressure Vessel Code 2007 Section VIII, Division 2, Part 6 Fabrication Requirements.

[3] M. C. Lin et al., "Elastoplastic Buckling of the Bent Waveguide of the CESR-Type SRF Cavity," IEEE Transactions on Applied Superconductivity 17(2) June 2007.

[4] ASME Boiler and Pressure Vessel Code 2007 Section VIII, Division 2, Part 5.5.2.3.