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APPLICATION OF THE ASME BOILER AND PRESSURE VESSEL CODE IN THE DESIGN OF SRF CAVITIES AT FERMILAB*

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Abstract

Jacketed Superconducting Radio Frequency (SRF) cavities structurally comprise of an inner niobium vessel surrounded by a liquid helium containment vessels. The pressure of the helium bath and/or its volume might be such that a jacketed SRF cavity shall be considered a system of pressure vessels. Thus, methods described in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) should be used to analyze the structural soundness of jacketed SRF cavities. This paper will report the use of the set of rules developed at Fermilab for the design of SRF cavities, such as jacketed 1.3 GHz cavities for LCLS-II HE and jacketed Single Spoke Resonator type 2 (SSR2) for PIP-II, to ensure a similar level of safety as prescribed by the ASME BPVC.

INTRODUCTION

Jacketed Superconductiong Radio Frequency (SRF) Cavities are designed, manufactured, and used at Fermi National Accelerator Laboratory for a variety of research purposes. SRF cavities have multiple pressure retaining volumes that bring them within the scope of the Boiler and Pressure Vessel Code (The Code) [1]. There are multiple issues inherent in the design of SRF Cavities that prevent an acceptable Code design such as using materials not accepted into The Code. As required by the Department of Energy (DOE) directive 10 CFR 851, an equivalent level of safety is required for the vessels as the The Code, so to ensure an equivalent level of safety, internal documentation has been defined [2]. Additional documentation needed for acceptance is defined in the Guidelines for Design, Fabrication, Testing and Installation of SRF Nb Cavities (SRF Guidelines) [3].

The SRF guidelines provides additional requirements to The Code such as material properties, allowable weld documentation, and analysis methods. Details of these processes will be discussed as they relate to the LCLS-II HE [4] and SSR2 Cavities [5] [6].

The LCLS-II HE and SSR2 cavities serve as an intermediary point between design methods at Fermilab. Starting with the SSR1 Cavities [7], the elastic-plastic method of analysis has been used to verify the safety of the cavities. Cavities previously designed at Fermilab have been analyzed using primarily design by rule and elastic material methods. The LCLS-II HE, SSR1, SSR2 are the beginning of cavities designed using primarily elastic-plastic material methods. The successful design of cavities using the elastic-plastic material methods may lead to more optimized cavity designs in the future.

CAVITY DESIGNS

There are two general designs for SRF cavities made at Fermilab, Elliptical Cavities and Spoke Cavities.

Elliptical cavities are generally designed as a two part structure comprised of a Cavity and Jacket. The cavity is a convoluted niobium structure. The Jacket is a cylindrical helium vessel, usually made of Titanium, and joined to the cavity through conical transition rings. The frequency of each cavity is controlled with a tuner. The tuner serves as a way to finely tune the frequency of the cavity during operation. Details of the effects of the tuner on their cavities can be seen in their respective engineering notes [8]. One example of a dressed cavity designed at Fermilab is the LCLS-II HE 1.3 GHz Cavity seen in Figure 1.

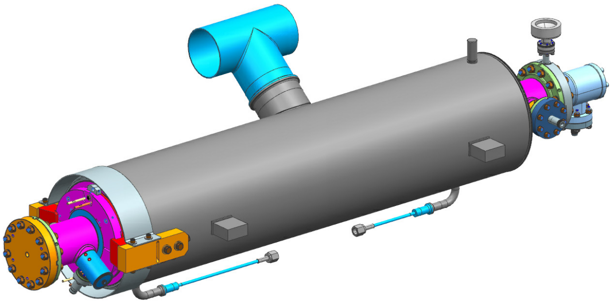

Figure 1: LCLS-II HE Cavity Assembly.

Spoke cavities are designed as a niobium cylindrical shell surrounded by the metallic jacket. The cavity addressed in this report is the SSR2 cavity for use in the PIP-II project and can be seen in Figure 2.

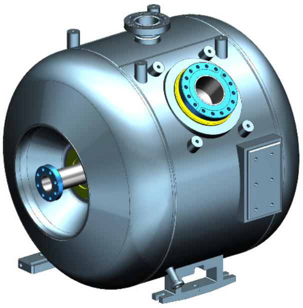

Figure 2: SSR2 Cavity Assembly.

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MATERIALS

A combination of three types of materials were used for components used in the LCLS-II HE and SSR2 cavities; ultra-pure niobium, Niobium Titanium, and Titanium. Whenever possible, material properties supplied by The Code were used, however not all of the materials used for SRF cavities are allowed by The Code to be used. When materials properties were not provided for use in the design of pressure vessels, values from other ASME codes or internal testing reports were used.

When allowable strengths are not available for the materials, the values are created using the methods described in Mandatory Appendix 1 in Section II-D of The Code [1].For the development of the stress strain curves using the methods described in Annex 3-D of Section VIII Div 2 of The Code [1].

For materials properties at cryogenic temperatures, either the values proscribed by the SRF Guidelines [3] or obtained through material testing. If testing data is not available at the time of writing a report, the cryogenic strength values will be assumed to be identical to their room temperature strength.

Titanium Alloys

The properties of Titanium alloys used in the analysis primarily come from ASTM B265/B348 from Section II-B of The Code [1].The properties of Niobium Titanium were taken from the SRF Guidlines [3]. The strength properties can be seen in Table 1. The elastic modulus is defined by he SRF Guidelines as 62 GPa.

Niobium

In the design of the LCLS-II HE cavity, the values proscribed by the SRF Guidelines were used. For the SSR2 Cavities, material testing was performed to determine the strength values for both the sheet and tube form of the material. The general strength properties in the SRF Guidelines and the SSR2 analysis can be seen in Table 1. The elastic modulus is defined by the SRF Guidelines as 104.8 GPa.

Table 1: Nonstandard Material Properties [3] [9]

Material/Form	T(K)	S_y (MPa)	S_u (MPa)
Nb, Min. Properties	293	38	114
	2	317	600
Nb, SSR2 Spec.	293	65	150
	2	317	600
NbTi, Min. Properties	293	45	114.5
	2	317	600

WELD DOCUMENTATION AND EXAMINATION

The SRF Guidelines requires the use of Division 1 due to the degree of Non Destructive Examination (NDE) required. For welds made in a Division 1 Vessel, it is possible to avoid performing NDE if a joint efficiency is applied in the design process. For Division 2 vessels, NDE is always required. Due to the complex shape of the vessels the assembly methods, it is not always possible to perform NDE on each of the welds. This is the primary motivation for using Division 1 for the design of SRF cavities at Fermilab. As the geometry at some locations of the cavities are thin, it is not always possible to accept the joint efficiency decrease in the design process. When it is also not possible to perform NDE on each weld, nor is it possible reduce the thickness of the part, the SRF Guidelines provide an alternative acceptance process for Electron-Beam (EB) and and Gas Tungsten Arc Welding (GTAW).

The exact requirements of the alternative qualification process can be seen in the SRF Guidelines [3], but the general procedure is to create alternative documents showing that a safe weld is possible. This is done by creating a Welding Procedure Specification (WPS) for each unique joint in the vessel. Each joint is then verified with a Procedure Qualification Record (PQR) which includes multiple mechanical tests and inspection of the quality of the welds with a microscope, metallograph, or Scanning Electron Microscope (SEM). To ensure consistent design, the EB welding equipment is required to be calibrated biannually and welding performance qualifications are required for the GTAW welding. In addition to the stringent requirements during the development of the weld joints, the cavities undergo extensive leak checks along the assembly process. The vessels also undergo pressure testing according to the Code requirements [1].

DESIGN AND ANALYSIS METHODS

There are two methods for the design of pressure vessels, Design by Rule methods and Design by Analysis Methods. Design by rule methods use a combination of simple calculations, tables, and charts for the design process. These methods are well established and are used in the Division 1 of The Code and Part 4 of Division 2 of The Code. Calculations provided for the design of bellows by the Expansion Joint Manufacturers Association (EJMA) have been used [10]. While Design by Rule methods are reliable, they are only applicable for some geometry. For complex geometry, such as for Dressed SRF Cavities, Design by Analysis Methods are preferred.

Section VIII, Division 1 of The Code generally uses design by rule methods, however as per U-2(g), alternative methods may be used. To be able to design the complex shapes of cavities, design by analysis methods are used as per Part 5 of Division 2 of The Code.

To provide an initial check on the safety of the cavities, design by rule methods are used to perform calculations for the simpler components. These include aspects such as the wall thickness of the outer vessels, bellows calculations, and external pressure calculations. Details of the calculations used can be seen in the documents for each cavity [8] [9].

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The design by analysis methods prescribed in Section VIII Part 5 is used to verify the complex connections and shapes of the cavities. The design by analysis process can be generally broken down into four steps:

- Protection Against Plastic Collapse
- Protection Against Local Failure
- Protection Against Collapse from Buckling
- Protection Against Failure from Cyclic Loading

Finite Element Analysis (FEA) is performed to show acceptance for each of the four steps. Each step is required to be examined for each loading condition of the cavity. Each loading condition considered factors such as the pressure of the liquid helium, the temperature of the cavity, the extension of the tuner, and the dead weight of the assembly. Six loading conditions were created for the LCLS-II HE cavities while five load cases were developed for the SSR2 Cavities.

The details of each of the analysis steps are controlled by the material model, either elastic or elastic-plastic. In general, elastic material model generally compares the stresses generated to an allowable stress value while an elastic-plastic model is generally constrained by the amount of strain and deformation that occurs from applied loads. Details of each analysis process can be seen in The Code [1]. The relatively low yield strength of Niobium could lead to some overly conservative designs if it was used as a limit to the thickness of cavities. As the cyclic loads of cavities are relatively small compared to other pressure vessels, accounting for the plasticity in the material can be done to optimize the thickness of some vessels. Both the LCLS-II HE Elliptical Cavities and SSR2 Spoke cavities were examined using a combination of elastic and elastic-plastic methods. Examples from both cavities will be used to demonstrate the analysis process.

Protection Against Plastic Collapse

Assessing the protection against plastic collapse can be performed using elastic, limit load, or elastic plastic methods, the details of which can be seen in Section VIII Division 2, chapter 5.2 of The Code [1]. The SSR2 and LCLS-II HE cavities were assessed using the elastic-plastic methods. The elastic-plastic method uses a material model with stress-strain curves with perfectly plastic behavior occurring outside of the allowable ranges. To determine what loads will create stresses outside of the allowable ranges, the applied loads are scaled by a value, β. A minimum β is defined by The Code.

The required β is determined by the vessel class and defined in Section VIII Div 2 of The Code in Table 4.1.3. Successful cavity designs have been made using the parameters of a class 2 vessel, which has a β factor of 2.4. In addition to the Code defined factor, an the factor is required to be increased by 25 percent as required by the SRF Guidelines [3] leading to a total effective β factor of 3.0.

As the welds joints are designed to the Division 1 requirements, some weld joints will have a joint efficiency, E. The joint efficiency of a weld joint is determined as per UW-12 in The Code [1]. To account of the joint efficiencies, when using the elastic plastic model, the factor β is required by the SRF Guidlines to be increased by a similar value [3]. As an alternative to increasing the loads, if the welds are manually modeled, it is also acceptable to reduce the weld area by the joint efficiency instead of adjusting the load or allowable strength. Reducing the weld area is recommended when a few welds have a lower joint efficiency than the others which could potentially overly constrain the design of the vessel and was used on both the LCLS-II HE and SSR2 Cavities.

For the SSR2 Cavities, the weld joints were physically modeled for the FEA simulation and the joint area was reduced by the joint efficiency. The loads on the five load cases were scaled up until the model failed to reach convergence. The values were then reduced by the required β factor. The results of this process can be seen in Table 2.

Table 2: SSR2, Protection Against Plastic Collapse Analysis Results

Load Case	MAWP (bar)	Requirement (Bar)
LC1	2.24	2.05
LC2	2.56	2.05
LC3	8.91	4.1
LC4	8.91	4.1
LC5	2.33	2.05

Protection Against Local Failure

Both the elastic and elastic-plastic methods were used to show the LCLS-II HE and SSR2 Cavities met the protection against local failure requirements. The elastic method is performed for each loading condition with the nominal loads applied. Each loading condition was solved using an elastic material model and the principal stresses were found. The peak principal stresses were compared to the allowable limit of four times the allowable safety factors. The details of the requirements can be seen in 5.3.2 of The Code [1].

The elastic plastic process is done using a similar method as the Protection against Plastic Collapse Requirements. The models are solved using the same process, but a β factor of 1.7 is applied instead of 2.4. The load is also increased by 25 percent and a joint efficiency is applied. The β for local failure and plastic collapse requirements can be seen in Table 3.

Table 3: SRF Cavity Elastic-Plastic β Factors

Purpose	β
Local Failure	2.125*E
Plastic Collapse	3.0*E

On the converged model, the forming strain, and the stress and strain as a result of the mechanical loads are combined to determine if the cavity is at risk of failing locally. As the cavities are heat treated, the forming strain is reduced to zero. Combining equations 5.6 and 5.7 in 5.3.3 of The Code [1], the resulting function can be checked at each point in the model for each material:

$$\frac{\epsilon_{peq}}{\epsilon_{Lu} * exp[-(\frac{\alpha_{sl}}{1+m_2})(\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e} - \frac{1}{3})]} \leq 1 \qquad (1)$$

Both the elastic and elastic plastic methods were used to determine if the LCLS-II HE cavity would fail locally. Solving the cavity elastically gave the maximum combined principal stresses. While the cavity was shown to meet the local failure requirements for most load conditions, the combined principal stresses in the niobium section were shown to be above the allowable limits in load cases 1 and 3. To verify that the cavity is safe, an elastic-plastic assessment was performed by using an elastic-plastic material model, scaling the load by the appropriate β, and accounting for the joint efficiencies. The results of the assessment, seen in Table 4 showed that the cavity met the local failure requirements.

Table 4: LCLS-II HE Cavity Elastic-Plastic Local Failure Assessment

Material	**LC1**	**LC3**
Nb	0.16	0.61
Ti Gr. 2	0.14	0.014
TiNb	2.5e-12	2.7e-12

Protection Against Collapse from Buckling

The requirements for protection against Collapse from Buckling are given in chapter 5.4 in Section VIII, Div 2 of The Code. Three types of approaches are provided, one using an elastic material model, and two using an elastic-perfectly plastic material model. The SSR2 and LCLS-II HE Cavities were examined using the elastic material model methods. To show that the cavities meet the Protection against Collapse from Buckling requirements, bifurcation buckling assessment is ran for each of the load cases. The results of each of the simulations are then compared to the minimum design factor given by 5.4.1.2(a). The minimum design factor is given by the equation:

$$\Phi = \frac{2}{\beta_{cr}} \qquad (2)$$

The value β_{cr} is based on what type of buckling mode that occurs. In the LCLS-II HE and SSR2 cavities the most common forms of buckling which occur in the analysis are either due to a collapse in the cavity cells, a collapse a spherical surface, or in the collapse of the helium vessels. The design factors can be seen in chapter 5.4.1.3 of The Code [1]. In addition to The Code required design factor, as required by the SRF Guidelines, the design factor will need to be increased by 25 percent.

The buckling process was similar for both the SSR2 Cavities and the LCLS-II HE Cavities and can be seen in the individual reports in detail [8] [9]. The summary of the resulting multipliers and the required load factor for the SSR2 cavity can be seen in Table 5.

Table 5: SSR2 Cavity Protection Against Collapse from Buckling Results

Load Case	**Load Multiplier**	Φ_B
LC1	27.6	3.125
LC2	27.8	3.125
LC3	15.6	3.125
LC4	15.6	3.125
LC5	9.5	*

Protection Against Failure from Cyclic Loading, Screening Criteria

To show protection against failure from cyclic loading, a fatigue screening analysis and a ratcheting assessment is needed.

The fatigue screening analysis is performed to check if additional fatigue analysis is needed. Two methods are provided in section 5.5.2.3 of The Code, Method A and Method B. Both methods involve creating a load histogram for all load combinations, but Method A limits the number based on a fixed fatigue screening criteria while Method B bases the limit of cycles on the result of factoring in the stress amplitude, material properties, and criteria factors. Due to the limited operational lifetime of cavities, Method A has been used for both the LCLS-II HE cavities and the SSR2 Cavities. Details of a Method A can be seen in 5.5.2.3 of The Code [1]. The number of cycles in Method A are limited based on the criteria given in Table 5.9 of The Code. In addition to the required limit, the fatigue created due to tuning the cavity during operation will also be considered. Modifying the criteria provided in Table 5.9 of The Code [1] to account for the contribution of the tuner cycles, the criteria becomes:

$$N_{\Delta FP} + N_{\Delta PO} + N_{\Delta TE} + N_{\Delta T\alpha} + N_{\Delta tuner} \leq 1000 \qquad (3)$$

The results of Method A fatigue screening analysis, shown in Table 6 show that both the LCLS-II HE cavity and SSR2 Cavity have less cycles than the screening criteria, therefore meeting the Method A requirements.

Table 6: Method A Fatigue Screening

Variable	**LCLS-II**	**SSR2**
$N_{\Delta FP}$	42	28
$N_{\Delta PO}$	0	0
$N_{\Delta TE}$	84	56
$N_{\Delta T\alpha}$	42	28
$N_{\Delta tuner}$	480	300
Total	684	412

Protection Against Failure From Cyclic Loading, Ratcheting Assessment

The ratcheting assessment requirements are defined for elastic material model in 5.5.6 while the elastic-plastic model

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[*] Bellows buckled, addressed by using EJMA methods [10]

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methods are defined in 5.5.7 of The Code. The evaluation of both the SSR2 Cavities and LCLS-II HE cavities have been performed using the elastic-plastic method. In the elastic plastic ratcheting assessment, an elastic perfectly plastic material model is used with the plastic limit defined as the minimum yield strength of the materials. The ratcheting assessment is modeled as a repeated series of loading events. Each load is applied to the model and cycled a minimum of three times. The model is considered to have meet the requirements if at least one of three criteria is met:

- There is zero plastic strain the the assembly
- There is an elastic core in the primary load bearing boundary of the component
- There is no permanent change in deformation in the component between cycles

The loading process of both the SSR2 cavities and the LCLS-II HE cavities was similar. As seen in Figure 3, the LCLS-II HE ratcheting begins unloaded and the pressure, tuner displacement and temperature increased to their peak value then reduced back to the original values.

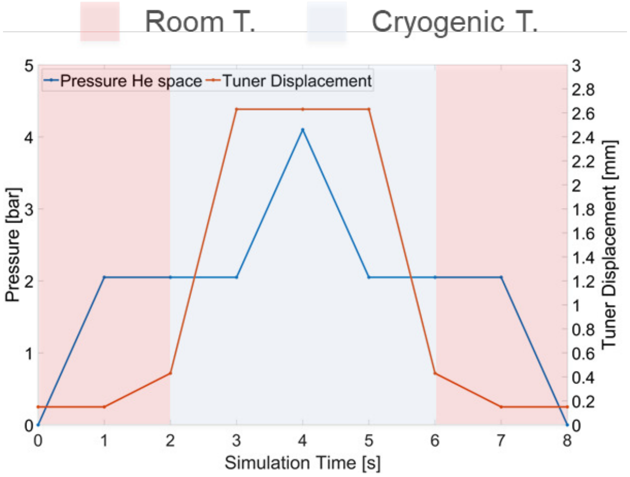

Figure 3: LCLS-II HE Cavity Ratcheting Load Cycle.

As seen in Figure 4, applying the load cycle multiple times did not create any permanent deformation in the system. Additionally, while there is some plastic strain in the assembly, there is a large elastic core in all of the load bearing surfaces. Both of the conditions show that the ratcheting is not occurring in the jacketed cavity.

CONCLUSIONS

Using a combination of elastic and elastic-plastic material methods, FEA analysis of the LCLS-II HE and SSR2 Cavities have been performed. The results of the local failure analysis show that the elastic plastic methods can be used to resolve issues of high localized stresses without compromising the safety of the vessel. Further refinement of the methods discussed is still needed, but the elastic-plastic material model has been shown to be able to lead to cavity designs to an equivalent level of safety as the pressure vessel code.

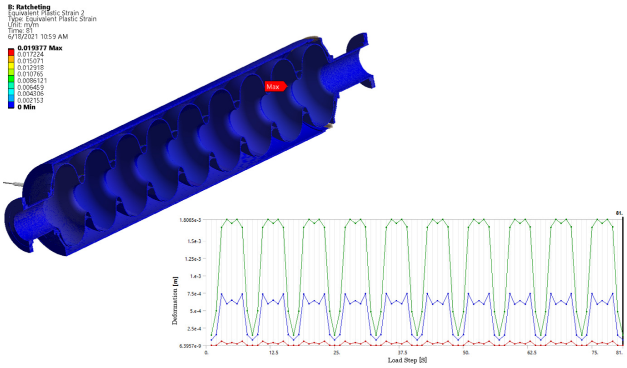

Figure 4: LCLS-II HE Cavity, Ratcheting Results.

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