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HELIUM PRESSURE VESSEL JACKETING OF THE FERMILAB SSR1 SINGLE SPOKE SC CAVITIES

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Abstract

Meyer Tool recently completed the welding of the liquid helium pressure vessel jackets around ten (10) superconducting single spoke niobium cavities for Fermilab. The SSR1 cavities are intended for use in the PIP-II Injector Experiment Cryomodule. Meyer Tool's scope of supply included review of the Fermilab Pressure Rating Analysis Document, the development of fabrication details and a fabrication sequence, and the actual jacketing of the cavities. This paper will focus on the development of the sequence and how the sequence evolved over the course of welding of the ten (10) jackets. As the frequency of these cavities is critical, the fabrication sequence accommodated numerous in-process frequency checks, a frequency tuning step prior to the final weld, the use of thermal cameras to monitor weld heat input into the cavity, and post welding final machining of critical features. Lessons learned from this fabrication will be discussed.

PRESSURE RATING ANALYSIS

Fermilab provided Meyer Tool with a pressure rating analysis document which " is a partial report on the extensive campaign of calculations and finite element analysis performed with the intent of verifying compliance to the 2010 ASME Boiler and Pressure Vessel Code Section VIII for the dressed SSR1 resonator of 3rd generation (SSR1 G3)."[1] Prior to fabrication Meyer Tool reviewed this document for Code compliance and possible stamping.

The Fermilab report utilized a mix of requirements from Division 1 and 2 of the ASME BPV Code Section VIII in developing the analysis. Our opinion was that while the mix of Division 1 and 2 analysis and fabrication details did not compromise the pressure safety of the helium jacket, the design did not fully meet the requirements of either Division 1 or 2 of Section VIII. Without changes to weld design details and the addition of the NDE requirements that would have added significant cost and unnecessary fabrication risk, the helium jackets could not be stamped. Fermilab elected not to make these changes and the helium jackets were not Code stamped.

JACKET COMPONENTS

The helium jacket was constructed of eight main components. These main components were fit and welded together to form the pressure vessel that surrounds the SSR1 cavity. Figure 1 identifies these main components in the vessel assembly.

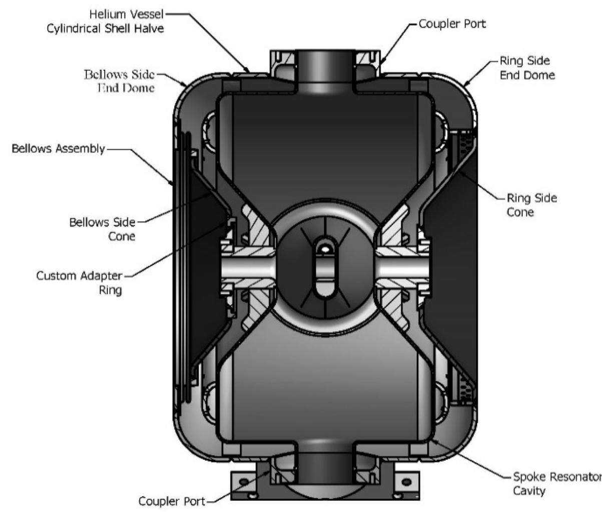

Figure 1: Helium jacket components.

These components consisted of: (1) A single rolled cylinder, made from 316LSS 0.25" plate and split into halves. (2) Two spun formed end domes, constructed of 316LSS 0.25" plate. These end domes were custom machined to fit each cavity and bellows. (3) Two spun formed conical heads, again constructed from 316LSS 0.25" plate. These conical heads also had to be custom machined to each cavity and bellows. (4) A single bellows assembly provided by Fermilab. (5) A 316LSS adapter ring. The adapter ring was added during fabrication of the first SSR1 cavity helium jacket to adjust for the variations in cavities and weld shrinkage and distortion. The bellows, bellows side cone, and custom adapter ring were welded as a subassembly prior to fit up to the cavity. The counterbore detail on the backside of the adapter ring, which interfaced with the beam tube flange on the cavity, was left unmachined until all other welding was complete. This allowed customization of adapter ring in final fit up to eliminate undue stress on either the cavity or the bellows.

INITIAL WELD DESIGN

Eleven welds were necessary to complete the helium jacket after fit up. They are identified in Figure 2. Backing strips, either integral to mating stainless steel components on the cavity or consisting of 316L sheet install behind weld seams, were used behind all the welds made on the helium jacket components assembled around the cavity.

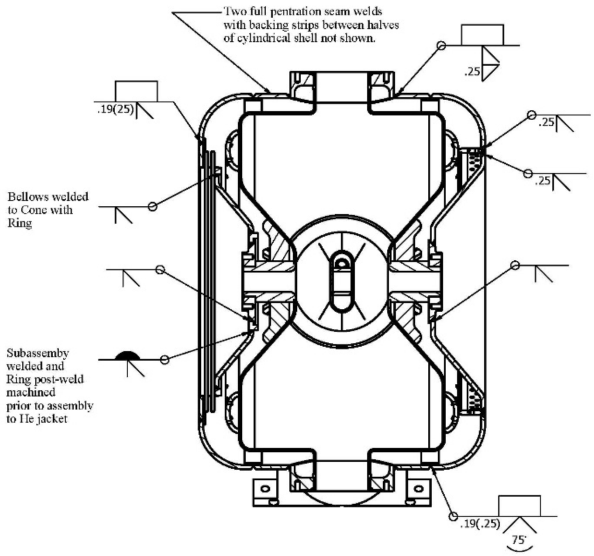

Figure 2: Helium jacket welds.

Initially we estimated our weld shrinkages based on the thickness of members, the number of welds, and their configuration. We enlarged the penetrations in the cylindrical shell halves for the coupler ports to account for the expected shrinkage. Locations of exterior features welded to the cylindrical shell halves prior to fit up to the cavity were adjusted. This was all based on our experiences welding half and quarter wave cavities assemblies made with a similar number of components and welds.

A weld sequence was developed identifying the welds in the order in which they were to be completed. The sequence was based on performing welds in a manner to leave the cavity uncoupled from the helium jacket for the longest amount of time. This sequence was never used as we quickly realized after fit up of the first helium jacket and the welding of the shell seam and girth welds that we had underestimated the weld shrinkages for this configuration.

FERMILAB REMOTE MONITORING

During the welding of the first SSR1 helium jacket Fermilab engineers were in attendance at Meyer Tool. They monitored the temperature of the cavity using a thermal camera and performed multiple frequency measurements during the welding process. For subsequent units the camera output was displayed on a lap top computer which was remotely viewed from Fermilab. The Meyer Tool welder adjusted the camera as needed and performed the frequency tests at the specified points in the weld sequence. Thus the Fermilab engineers could view real time temperature data and review frequency test results from their offices at the laboratory. With the thermal camera mounted on the cavity, the Meyer Tool welder had data on the cavity temperature to guide him in halting a welding pass or when welding could resume.

LESSONS FROM THE FIRST UNIT

Our experience with the helium jacketing of the first spoke cavity forced us to revaluate our shrinkage and distortion estimates. We found our initial estimates were much smaller, by a factor of ~2 times the actual shrinkages.

The change in our shrinkage estimates also caused us to reconsider the weld sequence order. A new sequence, in consultation with the Fermilab engineers, was developed. With minor adjustments this new weld sequence was used on all the SRR1 helium jackets.

The main cause of the discrepancy in our weld shrinkage estimate also made the jacketing of each SSR1 cavity unique. The variation in the dimensional compliance of the cavities themselves, especially in regards the position of the beam line flanges to the coupler ports, caused us to not only customize jacket components to each cavity, but also led to fit up issues requiring best fit adjustments of the jacket components on the cavity. A typical fit up compromise is such as shown in Figure 3.

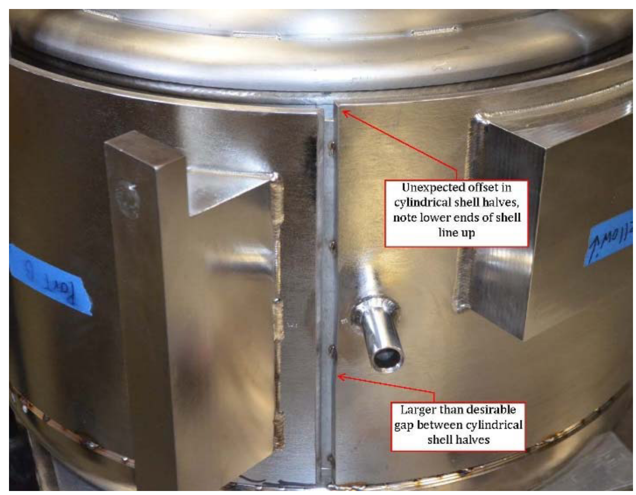

Figure 3: Typical helium jacket fit up to cavity.

The fit up compromises led to larger than desired gaps at weld joints and thus more weld metal having to be put into the seams. More weld metal means more heat thus more shrinkage. Adding to the larger than expected welds was the unexpected consequence of real time feedback on temperature and a very cautious approach to cavity temperature limits. This approach lead to smaller weld beads and more passes to fill the larger gaps. This approach lead to more shrinkage.

To compensate for the greater weld shrinkage the penetrations in the helium jacket shell had to be enlarged to accommodate the movement of the shell and end domes without causing an interference with the still free cavity coupler ports. This enlargement of the penetrations increased the amount of weld needed in those areas and thus to an additional increase in shrinkage of the jacket on the cavity. The amount of shrinkage experienced precipitated the addition of the custom adapter ring.

EVOLUTION OF THE SEQUENCE

The experience of fit up of the helium jacket to the first SSR1 cavity led to immediate changes in our weld sequence and to some of our pre-fit up fabrication details.

The weld sequence was changed to add a number of customization steps during fit up. Each cone and head was custom fit to each cavity. After fitting and tacking the ring side cone, the two end domes, and the shell halves, the assembly were purged. The weld sequence was then as follows: Weld the two cavity ring to cone and end dome welds. Jumping between welds. Weld the shell seam and girth welds. Jumping between welds. Weld the two coupler port welds. Jumping between welds. Weld ring side cone to cavity beam tube flange. Take measurements to determine adjustments to the adapter ring. Machine the adapter ring. Fit the bellow assembly. Weld the bellows assembly adapter ring the cavity beam tube flange. Weld the bellows assembly to the end dome. The above sequence also included in-process frequency checks and points where Fermilab might choose to perform an inelastic tuning operation.

This sequence while still experiencing increased weld shrinkage and distortion over the initial estimates worked well when the cavity variations were similar to the first SSR1 cavity jacketed. There were however some cavities where the variations were more extreme and additional measures such as added shell strips were needed.

FABRICATION CHALLENGES

The challenges to the fabrication of the helium pressure jackets around the SSR1 cavities can be summarized. (1) Account for the variations in the dimensional conformance of the cavities, especially the positional locations of the beam tube flanges and coupler ports to one another. (2) Keep the cavity temperature below the limits specified by Fermilab during the welding process. (3) Execute a weld sequence that decouples or minimizes stresses induced by jacket welding on the cavity. (4) Execute a weld sequence that minimizes distortion to the shell allowing for final post weld machining of critical features within tolerance. (5) Meet the above criteria while achieving fabrication cost goals.

SOLUTIONS

The solutions utilized during the fabrication of helium jackets around the ten SSR1 cavities were implemented with success for the four technical challenges, but not for the fifth business goal. The technical solutions worked, but resulted in increased fabrication costs over estimate.

Technical solutions utilized included. (1) Custom sizing of jacket components to adjust for variations in cavities. (2) The use of the thermal camera to give real-time feedback on cavity temperature during welding. (3) The use of new weld shrinkage and distortion estimates to account for larger welds and more passes to make adjustments to pre-positioned component locations. An offset oval penetration (Figure 4) was used for each coupler port as a compromise to keep weld size to minimum, while allowing the cavity to stay decoupled from the helium jacket shell during welding.

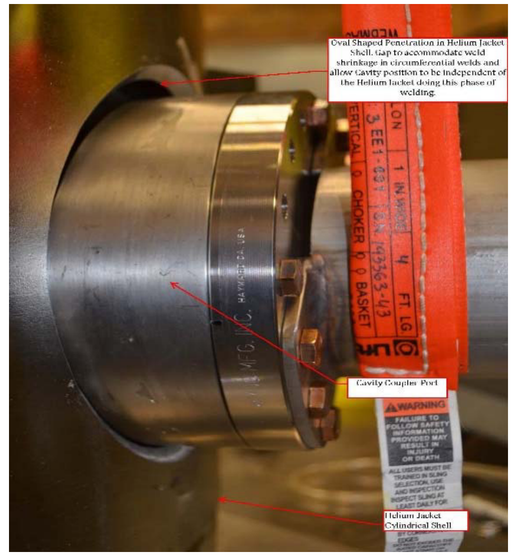

Figure 4: Coupler port penetration detail.

(4) Changing the weld sequence and design to incorporate an adapter ring to allow for variation in weld shrinkage. Incorporating in the weld sequence the moving from weld to weld to minimize distortion by delocalizing shrinkage. Changing the order of the welds to ensure the cavities sees the least amount of stress from jacket welding.

Solutions not incorporated that we would like to implement on a future helium jacket fabrication include. (1) In the low volume environment these cavities are presently being produced under it is naïve to think that the variations experienced in future low volume orders will not be repeated. This expectation has to be fully taken into account in future planning. (2) Add additional stock to exterior features that are post-weld machined to simplify final machining set up. (3) Review the value added of the in-process frequency measurements to find a balance between the fabrication cost of performing the measurement and the value of the information at a given point in the weld sequence. (4) Review the cavity temperature restrictions to balance the fabrication cost of halting welding versus the actual risk to the cavity.

REFERENCES

[1] D. Passarelli, "*Fermilab Pressure Rating Design Analysis SSR1 Helium Jackets*", unpublished.