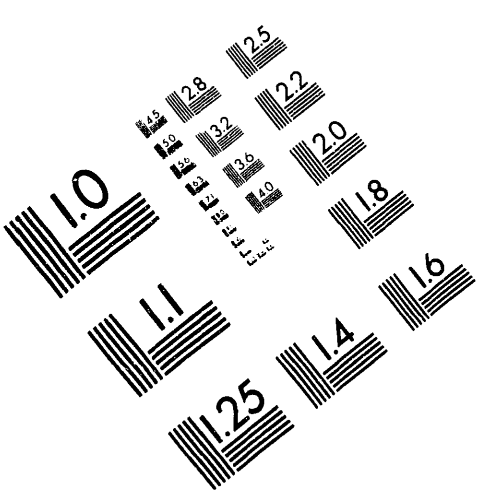

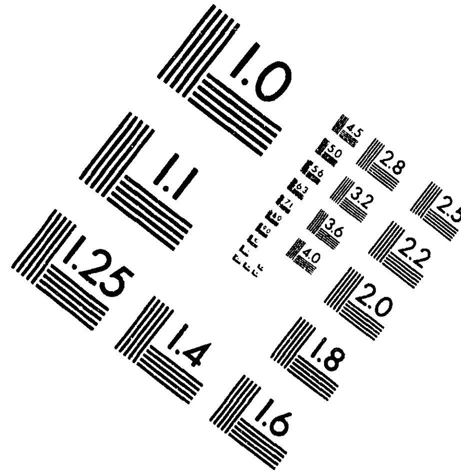

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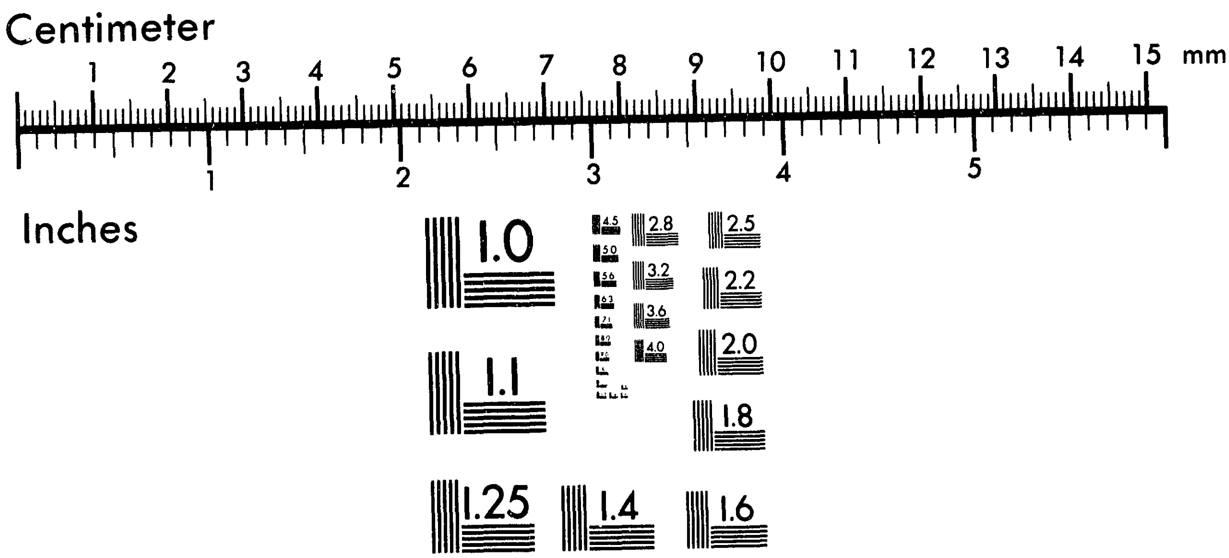

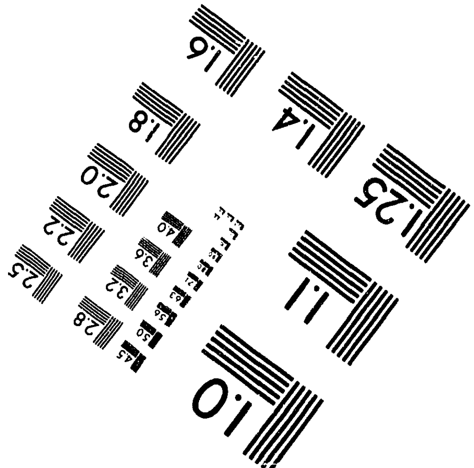

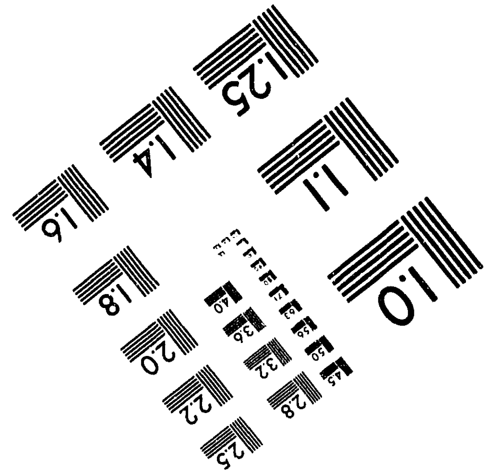

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Design and Analysis of the Collider SPXA/SPRA Spool Piece Vacuum Barrier*

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DESIGN AND ANALYSIS OF THE COLLIDER SPXA/SPRA SPOOL PIECE VACUUM BARRIER

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ABSTRACT

A design for the Collider SPXA/SPRA spool piece vacuum barrier was developed to meet a variety of thermal and structural performance requirements. Both composite and stainless steel alternatives were investigated using detailed finite-element analysis before selecting an optimized version of the ASST SPR spool vacuum barrier design. This design meets the structural requirements and will be able to meet the thermal performance requirements by using some newer thermal strapping configurations.

INTRODUCTION

Collider Accelerator Arc Sections of the Superconducting Super Collider (SSC) have specific requirements[1] for an insulating vacuum system, one of which is for a vacuum barrier to provide separate vacuum domains per half cell, a 90-m section. There are several other requirements that govern the design of the vacuum barrier,[2] most of which are directly or indirectly generated from the 3B specification. The normal operating loads for the vacuum barrier are the thermal loads imposed from the cryogenic lines that penetrate it. These include the cold mass pipe and the liquid helium (LHe) and gaseous helium (GHe) return lines, all of which operate at approximately 4 K; the 20-K shield helium supply line; and the 80-K shield nitrogen supply and return lines. The vacuum barrier must also withstand a 0.1-MPa pressure at room temperature seen during vacuum pump down. Additionally, the vacuum barrier must be designed for an emergency pressure load of 0.2 MPa at cryogenic temperatures, since the relief valves for the outer cryostat are required to vent at less than 0.2 MPa. The design of the vacuum barrier should also decouple the cold mass axial motion from the vacuum barrier. This should relieve the vacuum barrier from the load resulting from the thermal shrinkage of the cold mass and remove the pressure load on the vacuum barrier from being carried by the fixed post. Overall, the vacuum barrier design should meet a safety factor of 1.5 against yield and 3.0 against critical buckling pressure to insure the safe and successful operation of this component.

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In addition to the structural requirements, the vacuum barrier has some thermal constraints on its design. It is required that the heat leaks into the 4-K, 20-K, and 80-K regions for the vacuum barrier must fit within the overall heat budget for the SPXA/SPRA spool pieces. To meet the overall requirements, the goals for the vacuum barrier heat leaks were defined as follows: 130 mW into the 4-K lines, 10.31 W into the 20-K line, and 27.43 W into the 80-K lines

DESIGN CONCEPTS

Several different design ideas for the vacuum barrier were looked at to meet the performance criteria. These included a flat composite bulkhead overlaid with metal, a standard concentric shell design similar to the ASST vacuum barrier (except made out of composite and overlaid with metal), and a stainless steel vacuum barrier that was an optimized version of the ASST design.

Composite Bulkhead Design

This design utilized a 0.125-in.-thick flat composite plate of G-10 with a 2-mil coating of 304 stainless steel. This coating is necessary for the barrier to be helium leak-tight. The 20-K and 80-K thermal shields were integrated into this bulkhead plate, limiting the cryostat to cold mass radiation. Other benefits of this design included space savings in the spool piece as well as simplification in manufacturing. Also, all of the cryogenic lines penetrate this barrier without any bends.

However, there were several shortcomings in this design that removed it from consideration. Foremost were the extremely high stresses in the stainless steel coating and rather high stresses in the composite itself. The stainless steel stresses arise from cooling from 300 K to 4 K with the boundaries restrained, while the pressure loads caused high bending stresses in the composite. Additionally, the heat leak into the 4-K lines was more that six times the goal, as might be expected with such a short conduction path.

Composite Concentric Shell (ASST) Design

This design used the geometry from the ASST vacuum barrier (4-K, 20-K and 80-K plates, each connected by a concentric shell pair) but was made of G-10 composite overlaid by 304 stainless steel. One of the advantages of this design idea was that the use of composites allowed the vacuum barrier to be shortened to about 4 in. and still easily meet the heat-leak budget. Also, geometrically it had more flexibility in allowing the thermal contractions from 300 K down to 4 K. Additionally, it was hoped that this complex geometric piece could be molded as a single composite piece, greatly simplifying the manufacturing process.

High stresses also overshadowed any benefits this design might offer. Although the stresses generated from thermal cooldown were manageable, the stresses from the pressure loading were exceedingly high, especially in the thin stainless steel coating. The highest stresses generally were located in the return end bends of the concentric shell pairs. Other concerns were raised about the radiation resistance of the composites, as well as the ability to make the composite-to-stainless steel connections helium leak-tight. Therefore, it was decided to pursue an optimization of the ASST vacuum barrier design for the final configuration of the collider arc spools.

Optimized SS304 Concentric Shell (ASST) Design

The optimization of the ASST vacuum barrier design into a Collider configuration was begun with goals of decreasing the amount of space the vacuum barrier occupied and simplifying the design from a manufacturing standpoint while still meeting the design requirements. The new Collider vacuum barrier design replaced the three plates and three shell pairs of the ASST design with two plates connected to each other with one concentric shell pair and connected to the outer cryostat with another. (The actual cryostat connection is made through a weld ring.) The inner plate in this design is penetrated by the three 4-K lines: the cold mass pipe, and the LHe and GHe return lines. Additionally, pipe sleeves were added to connect the LHe and GHe lines to the vacuum barrier front plate, increasing the conduction path to the 4-K region and thus decreasing its heat leak. A bellows connection between the cold mass pipe and this front plate also was added, which increased the conduction path, while structurally the connection decoupled the motion of the cold mass pipe from the vacuum barrier, especially in the axial direction.

The outer plate is penetrated by the 20-K and 80-K lines. A pipe sleeve connection between the 20-K line and this plate was needed to keep the 20-K and 80-K regions thermally separated. To keep the heat leak under control, the thermal strapping to the 80-K and 20-K lines was improved. One of the changes was to add copper straps from the 20-K line to a thin copper strip that ran around the circumference of the outer face of the inner shell pair. A similar strapping mechanism was also added between the 80-K lines and the inner face of the outer shell pair. Then the 20-K and 80-K lines intercept more heat than before from the opposite side of the vacuum barrier, reducing the heat into the 4-K region. This allowed the length of the vacuum barrier to be reduced to about 8 in.

Due to high bending stresses at the connection between the front plates and the thin shell pairs, a reinforcing ring was added at these connections, giving a thicker, stronger connection that gradually tapers down to the thin shell.

ANALYSIS

A thermal and structural finite-element analysis was performed on the final design using an established code, ANSYS, version 4.4A. The vacuum barrier is made of 304 stainless steel, and the thermal straps utilize OFHC copper. Temperature-dependent elastic, thermal, and mechanical properties for these materials were used in this analysis. These properties were obtained primarily from "LNG Materials and Fluids"[3] and "Materials at Low Temperatures."[4]

Thermal Analysis

The thermal model of the vacuum barrier (Figure 1) was built almost entirely using ANSYS STIF57 elements, an isoparametric quadrilateral thermal shell element with four nodes in 3D space. The copper thermal strap connections were made using the STIF33 element, a thermal bar with two nodes in 3D space. The weld ring used to connect the concentric shell pairs at the return end was also modelled with the STIF33 element. The bellows connection between the cold mass and the front plate of the vacuum barrier was made using the STIF14 element, a 1D spring-damper element with temperature as its only degree of freedom. The equivalent thermal "spring rate" for the bellows was input as kA/L, where k, A, and L are thermal conductivity, cross-sectional area, and length. The model geometry was defined through the use of parameters for most of the dimensions on the vacuum barrier. This allowed for a more efficient optimization of the design, since new configurations could be quickly implemented and analyzed by changing only a few parameters and real constants.

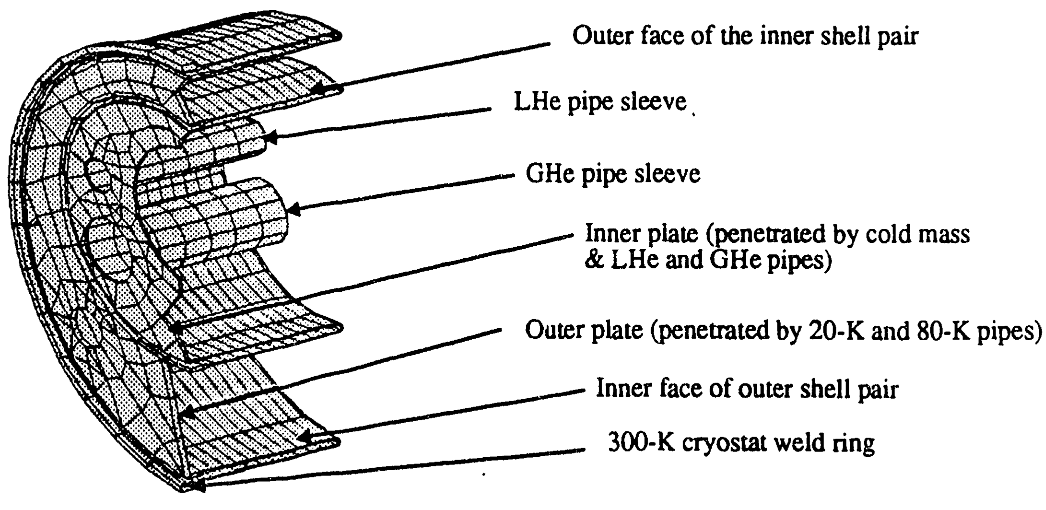

Figure 1. Finite element model of collider vacuum barrier concept. Cryogenic pipes not shown for clarity.

The boundary conditions for the thermal analysis included convection boundaries on the inner surfaces of all of the pipes. These boundaries were given temperature-dependent convection film coefficients and bulk temperatures of 4.25 K for the cold mass, LHe, and GHe lines, 20 K for the 20-K shield helium supply line, and 80 K for the 80-K shield nitrogen supply and return lines. The outer surface of the cryostat had natural convection with a bulk temperature of 317 K. Due to limitations within ANSYS, radiation was not included in this analysis.

Structural Analysis

After the thermal analysis, the modal was resumed and prepared for a linear static analysis. The STIF57 thermal elements were replaced with STIF63 elastic quadrilateral shell elements, and the STIF33 elements of the weld ring became STIF4 3-D elastic beams. The STIF33 elements that modelled the copper straps were removed, since these were not load-bearing members.

The boundary conditions used both fixed nodes and spring elements. The nodes on the outer cryostat were fixed at a location corresponding to the location of the fixed post, while the lead ends of the 4-K lines were connected to STIF14 longitudinal spring elements that simulated the stiffness of the fixed post. The lead ends of the 20-K and 80-K lines were connected to STIF14 longitudinal and torsional spring elements to simulate the stiffness of the 20-K and 80-K shield connections at the fixed post. The return ends of the cryogenic pipes and cryostat were left free and unconstrained.

This vacuum barrier model was subjected to three loading conditions: thermal loads at operating temperatures, 0.1 MPa pressure at room temperature, and 0.2 MPa pressure at operating temperatures. Additionally, a linear eigenvalue buckling analysis was done on this model to determine the critical buckling pressure. These results were then compared with theoretical calculations.

RESULTS

The results of the thermal analysis show that the final design has a heat leak of 0.131 W into the 4-K region, 12.08 W into the 20-K region, and 36.27 W into the 80-K region. These results are 1%, 17%, and 32% over the previously stated goals, respectively.

The results of the static structural analysis show safety factors with respect to yield of at least 3.7 for the thermal loads, 2.4 for the 0.1 MPa pressure loads, and 1.5 for the 0.2 MPa loads at operating temperatures. For all three load cases the safety factor was greater than 5.0 against ultimate tensile strength. Additionally, the buckling safety factor was 3.07.

CONCLUSION

This proposed design for the collider SPXA/SPRA spool piece vacuum barrier meets or exceeds all of the structural requirements of the applicable specifications, using less space and simpler manufacturing requirements than previous designs. Although the thermal performance of this design is less than the stated goals, this should improve by utilizing newer thermal strapping configurations presently being developed in the design of the vacuum barrier for the High Energy Booster of the Superconducting Super Collider.

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