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DESIGN ALTERNATIVES FOR CRYOGENIC BERYLLIUM WINDOWS IN AN ICF CRYOSTAT

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IN AN ICF CRYOSTAT

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Summary

We propose three backup design options for the cryogenic beryllium windows in a cryostat. The first, a beryllium flange option, reduces peak tensile stresses to 1/3 of that in the original design. The second, a fiberglass flange option, reduces peak tensile stresses to 1/2 of that in the original design and is also low cost. A third option, replacing the beryllium windows with spherical Mylar caps, would require a development program. Even though Mylar has been used previously at cryogenic temperature, this option is still considered unreliable.

The near-zero ductility of beryllium at cryogenic temperature makes the reduction of peak tensile stresses particularly desirable. The original window design did function satisfactorily and the backup options were not needed. However, these options remain open for possible incorporation in future cryostat designs.

Introduction

The cryostat discussed here was designed, built and tested by a vendor under contract to the Lawrence Livermore National Laboratory. Specifications

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required that a steady, uniform temperature be maintained in a cylinder 220 mm in diameter and 300 mm long. The temperature inside the cylinder was to be maintained between 17 and 40 K in a helium atmosphere at pressures ranging from vacuum to 1 bar (100 kPa). A key feature of the cryostat was the inclusion of tandem beryllium windows in parallel, with the inner beryllium windows operating at cryogenic temperature in a compression mode (curved toward the pressure side), and the outer beryllium windows operating at ambient temperature in a tension mode.

The cryostat was completed on a particularly tight time schedule and the windows did operate satisfactorily. However, our interest in alternative designs for the cryogenic beryllium windows stemmed from our concern that, because 100-MPa tensile stresses were present at cryogenic temperature where beryllium has essentially zero ductility, the cryogenic windows might fail. The stresses occurring in the cryostat resulted mainly from differential thermal contraction between the beryllium windows and the dissimilar metal attachments as the cryostat was cooled below ambient temperature. At the time we proposed the alternatives, we did not know if the cryostat could be successfully manufactured. Even today, we feel that reducing the stresses would still improve the design because an initial flaw in the beryllium could propagate under stress conditions leading to window failure. Hence, our pursuit of options.

We document herein three alternate designs for the cryogenic beryllium windows. These alternate designs vary from the original design by: 1) incorporating a large beryllium flange, 2) using a fiberglass flange, and 3) using thin Mylar for the windows instead of beryllium. We include stress

calculations of the original design and of the three alternatives. We also include results of an experiment where we found that thermal contraction of fiberglass was larger than expected and we discuss the reason for this divergence.

Original Design

The original design contained cryogenic beryllium windows attached to the cryostat in two fashions as shown in Fig. 1. Because beryllium cannot be bonded directly to stainless steel, the beryllium was electron-beam butter welded to an aluminum transition piece that had been previously roll-bonded to type 304 stainless steel. The roll-bonded stainless steel was machined and then shaped into the form of a thin, compliant curved ring welded at its outer radius location to a rigid stainless steel flange. The flange design shown at the left, in turn, was welded to a stainless steel cylinder that formed the inner wall of the cryostat. The flange design shown on the right was glued to a fiberglass conical frustum. As the cryostat was cooled below ambient temperature, the compliant curved ring flexed so that bending stresses in the beryllium windows were kept as low as possible. The weld joint between the compliant curved ring and the rigid flange acted as a seal.

Buckling

We used Blake's method for the response of shallow spherical caps¹ to estimate the pressure difference across the inner beryllium window that would

Beryllium at 4K has a tensile strength of about 450MPa but only 0.16% elongation

Figure 1. Details of two cryogenic beryllium window attachments.

cause buckling. First, we checked how the buckling would occur by calculating:

$$\lambda_0 = 2.57\sqrt{H/T} \quad (\text{Blake's Eq. 36.40})$$

where H is the maximum height of the cap and T is the thickness of the cap. For the original design, the window diameter, D , is 240 mm and the radius of curvature, R , is 610 mm; therefore H is 12 mm. Using a thickness, $T = 1.4$ mm gives $\lambda_0 = 7.5$. According to Blake, any buckling failure would be local and independent of the method of support if $\lambda_0 > 6$, which it is.

Next, we calculated critical buckling pressure using

$$P_{cr} = 0.075E n_0^{-4} \lambda_0^{4.15} e^{-0.095\lambda_0} \quad (\text{Blake's Eq. 36.42})$$

where E is Young's modulus equal to 280 GPa and $n_0 = D/2T = 86$. The calculated value of $P_{cr} = 800$ MPa, well above the maximum value of 1 bar (100 kPa) required. Hence, no buckling is anticipated.

Stress Calculation and Beryllium Properties

Peak tensile stresses, calculated using NIKE2D (Ref. 2), are about 100 MPa at the locations shown in Fig. 2. Measured tensile strength and elongation of beryllium on 2-mm-thick specimens at 4 K were about 450 MPa and 0.16%, respectively.³ Although the strength is adequate, the elongation is essentially zero. Room temperature strength is somewhat

lower, ~300 MPa, but ductility is the same as at cryogenic temperature. Normal ductility at room temperature for the type SR-200-E beryllium used in manufacturing the cryostat is 10% or greater.⁴ The reason for the divergence of the experimental data is unknown, but it could be caused by differences in the material or by machine damage of the test specimens. Hauber⁵ ran tests on 6.5-mm-diam beryllium samples in the late 1960s and found that elongation both at room temperature and at cryogenic temperature was low, less than 0.6% for the material studied. We know of no fracture toughness data for beryllium at cryogenic temperature, but based on his test results, Hauber anticipates that the fracture toughness, K_{IC} , at cryogenic temperatures, is equal or slightly higher than the room temperature value of 11 MPa $\sqrt{m}$. His logic is as follows: 1) his fracture strength data had little scatter for the samples tested at the same temperature, which suggests that the distribution and length of the initial cracks are constant throughout the beryllium material; 2) the fracture strength for beryllium increases as the temperature is reduced; 3) $K_{IC} = \sigma_f \sqrt{a}$, where σ_f is the fracture strength and a is the crack length. Hence, for constant "a" and for a " σ_f " that varies inversely with temperature, K_{IC} also varies inversely with temperature.

If the as-yet-unknown fracture toughness at cryogenic temperature is small, then flaws in the beryllium windows could propagate to failure. Any defect changes the stress state in the window and tends to increase the peak tensile stress present. Hence, what might seem to be an adequate factor of safety is diminished if a defect is present. On the

other hand, cracks present in Hauber's tensile specimens⁵ were generally not connected, which suggests that small flaws do not join together to form larger flaws. Regardless, the importance of the project suggested that adequate design backup be established.

Design Alternatives for the Cryogenic End Windows

Beryllium Flange Backup Option

Our first attempt to reduce the peak tensile stress was to thicken the inner steel wall associated with the design shown on the left in Fig. 1, thereby giving the beryllium window a more rigid support. A comparison of our designs and of the calculated peak tensile stresses are shown in Fig. 2. In each case, the beryllium window (or flange in the lower right hand corner) was electron-beam butter welded to a piece of aluminum that had previously been roll-bonded to a piece of 304 stainless steel. We started with a 0.77-mm-thick window attached to a 1.5-mm-thick wall but tensile stresses in the window exceeded the strength of the beryllium material. Increasing the window thickness reduced the peak tensile stress by a factor of 2. When we increased the wall thickness to 3-mm, peak tensile stress decreased to 130 MPa. Further increases in wall thickness increased the peak tensile strength because the wall was too rigid to permit flexing in the region of window attachment. The lowest peak tensile stress (30 MPa with a 10 KPa pressure difference) was achieved with a nearly square cross-section beryllium flange where the window was attached close to the centroid (lower right hand corner of

Figure 2. Summary of NIKE2D elastic-plastic stress calculations for the beryllium flange option.

Fig. 2). In each case, we modeled the flange using elastic-plastic stress analysis with NIKE2D (Ref. 2).

A similar beryllium flange glued to the fiberglass-composite conical frustum (design shown on the right in Fig. 2) was designed but not optimized. Peak tensile stresses associated with this non-optimized design were 76 MPa. We expect a reduction to around 30 MPa for the right side should the design be optimized.

The beryllium flange design has the advantages of a low peak tensile stress and of reliability, but the cost of the beryllium and of its fabrication is expensive. The most reliable method of manufacturing the beryllium window-flange unit is to machine it as a single integral part. This eliminates any brazing of the window to the flange, but it must be machined from a large and expensive block of beryllium.

Fiberglass Flange Backup Option

With the next option, we attempted to eliminate thermal forces by matching the thermal contraction between the beryllium window and the connecting components. We proposed replacing the stainless steel flange and aluminum transition piece of the original design with a fiberglass-composite flange because the thermal contraction of fiberglass (in the direction parallel to the fibers) was reported⁶ to be the same as that of beryllium between room temperature and 20 K. Fibers would be wrapped circumferentially to form a tube with a winding angle measured from the axis of the tube as close to 90° as feasible (see Fig. 3). A winding angle of exactly 90° was not feasible because the fibers must be

Cylinder with fibers wound nearly parallel around the circumference (winding angles, θ , close to 90°)

Thermal contraction (293 K to 77 K)

Fiberglass (from literature)

fibers	-0.11%
⊥ fibers	-0.52%

Fiberglass cylinder (measured radial contraction)

$\theta = 86^\circ$	-0.20%
$\theta = 77^\circ$	-0.21%

Beryllium

From literature	-0.13%
Measured	-0.12%

The biaxial thermal contraction characteristics of fiberglass shows a radial contraction that is between published values parallel and perpendicular to the fibers

Figure 3. The biaxial thermal contraction characteristics of fiberglass results in a radial contraction that is between published values parallel and perpendicular to the fibers.

wound along the complete length of the tube. Because peak thermal stresses in the window were caused mainly by differential thermal contraction, and because differential thermal contraction was minimized by the beryllium/fiberglass combination, NIKE2D calculations predicted peak tensile stress values of only 7 MPa. A further advantage of using fiberglass is that it costs much less than beryllium.

We proposed making the flange and cylinder (or conical frustum) as an integral piece of fiberglass manufactured from a thick-walled cylinder that was the length of the cryostat. The beryllium window would then be glued to the fiberglass. We had fiberglass tubes manufactured with 86° and 77° winding angles so that we could experimentally verify the thermal contraction and, therefore, the low stress values predicted by NIKE2D.

Thermal Contraction Experiment. We conducted a thermal contraction experiment (see Fig. 4) where two, 300-mm o.d. fiberglass rings, one with each of the two winding angles, and a beryllium ring were cooled to liquid nitrogen temperature (77 K). The rings were positioned on edge as shown with linear displacement transducers placed to measure radial contraction. Thermocouples were installed at the bottom and top of each ring. Finally, foam insulation was positioned across the entire top of the test Dewar flask, which minimized heat loss and temperature gradients.

After calibrating and zeroing the displacement transducers, liquid nitrogen was passed from an external Dewar flask through a copper fill tube into the test Dewar flask. At first, all nitrogen passing into the test cryostat was gas, but as the system cooled, liquid nitrogen entered the test cryostat until the three test rings were completely submerged.

Figure 4. Experimental apparatus used to measure thermal contraction of fiberglass and beryllium from 293 K to 77 K.

The cool down was accomplished slowly--over a period of about 2 to 3 hours.

Three tests were performed on three consecutive days with the results summarized in Table 1. Also shown in Table 1 are published values of thermal contraction from the literature.⁷ Contraction of fiberglass was about double the reported value measured parallel to the fibers, and 40% of the reported value measured perpendicular to the fibers. Measured beryllium contraction compared favorably to the published value (within 6%!!), which gave added confidence in the test results.

The reason why the fiberglass test results were double the published value parallel to the fibers, was first suggested by Kriz⁷ and is best explained by referring to Fig. 3. The fibers are oriented nearly circumferentially and the circumferential contraction wants to be that of the documented value parallel to the fibers. If the cylinder has a large radius, a section of its circumference approximates a flat plate and the circumferential contraction is nearly unrestrained by the curvature of the circumference. Hence, the radial contraction ($\Delta R/R$) would be close to the circumferential contraction ($\Delta C/C$). However, as the radius becomes smaller, the curvature of the circumference becomes greater and the contraction perpendicular to the fibers (in the radial direction) has more influence. Our cylinder is thick-walled with a radius less than three times the thickness, hence, we should expect that the contraction would be between the published values for parallel and perpendicular to the fibers. An analytical approach⁸ to predict the magnitude of contraction is complex but feasible.

Table 1. Comparison of Published Values with Experimental Data for Thermal Contraction

Published Data⁷ - $\Delta L/L$ (293 K to 77 K)

<u>Contraction (dimensionless)</u>	
Fiberglass (fibers)	-0.00111
Fiberglass ($\perp$ fibers)	-0.00528
Beryllium	-0.00132

Experimental Data - $\Delta L/L$ (293 K to 77 K)

<u>Run #</u>	<u>Contraction (dimensionless)</u>		
	<u>Fiberglass</u> <u>(77° winding angle)</u>	<u>Fiberglass</u> <u>(86° winding angle)</u>	<u>Beryllium</u> <u>(SR-200-E)</u>
1	-0.00218	-0.00210	-0.00136
2	-0.00209	-0.00198	-0.00121
3	-0.00209	-0.00193	-0.00115
Average	-0.00212	-0.00200	-0.00124

We ran a NIKE2D problem using experimental values of contraction to complete our evaluation of the fiberglass flange option. Predicted results show a maximum tensile stress of 50 MPa at the edge of the beryllium window--about half of that in the original design but still higher than the 30-MPa value for the beryllium flange option. The big advantage of the fiberglass option is its low cost.

Mylar Window Option

A final option uses thin Mylar sheet material formed into a spherical cap and held at its periphery with a polyurethane (or equivalent) flange. The Mylar is also brittle at cryogenic temperature, but if a pressure difference is always maintained across the window, there is little if any flexing of the Mylar. A development program would be required to assure that a reliable design could be made, because even a slight crease in the Mylar causes stress concentrations that reduce the allowable pressure difference to a negligible value. Mylar windows have been successfully made and operated at cryogenic temperature but specific care was taken to assure that a nearly constant pressure difference existed during cool down and during operation. A constant pressure difference reduces the chance of creasing the Mylar and increases the probability of successful operation.

We calculated the tensile stress in a spherical cap made of Mylar using the equation

$$\sigma = PR/2T$$

where P is the differential pressure, R is the radius of curvature, and T

is the Mylar thickness. The thickness was chosen as 0.18 mm, the maximum thickness readily available from suppliers; R was set from geometrical considerations equal to 1 m, and P was set equal to 10 kPa (0.1 bar). The resulting hoop stress (28 MPa) is at least a factor of 8 below the tensile stress of Mylar⁹ at cryogenic temperature.

Reliability remains a problem with the Mylar option because creasing most likely would cause failure at cryogenic temperature where the ductility of Mylar is very low. Further, maintaining a constant differential pressure requires incorporation of a control system and associated instrumentation.

Souers¹⁰ estimated the diffusion coefficient for helium through Mylar. Although no data at cryogenic temperature exist, his estimate suggests that a Mylar barrier is nearly impermeable to helium at cryogenic temperature. From this standpoint, Mylar appears to be satisfactory.

Conclusion

Three backup design options are suggested for the cryogenic beryllium windows in a cryostat. If a beryllium flange is used instead of the original steel flange and aluminum transition piece, peak tensile stresses in the beryllium window can be reduced from 100 MPa to 30 MPa. A low-tensile stress is important because beryllium has only 0.16% elongation at cryogenic temperature.

We also examined the case where an integral fiberglass flange-cryostat wall is glued directly to the cryogenic beryllium windows. Initially, we thought the peak tensile stresses would be even lower than with the beryllium flange option because the thermal contraction of beryllium was the same as fiberglass in the direction parallel to the fibers. A test showed that for our geometry, the thermal contraction did not match as well as initially anticipated. The peak tensile stress in the cryogenic beryllium windows (using experimental values of contraction) was calculated with the NIKE2D code to be 50 MPa. However, fiberglass has the advantage of low cost when compared to the beryllium flange option.

A third option was to replace the beryllium window with a Mylar sheet shaped as a spherical cap. Although a factor-of-safety of at least 8 on the tensile strength could be obtained with Mylar, at cryogenic temperature it has close to zero ductility, as does beryllium. Non-uniform loading or a small crease in the Mylar would result in window failure. Although Mylar has previously worked successfully at cryogenic temperature, this option was considered unreliable, would require a development program, and would require a control system to maintain a nearly constant differential pressure across the Mylar during cool down and operation.

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