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THE DEVELOPMENT OF 6061-ALUMINUM WINDOWS FOR THE MICE LIQUID ABSORBER

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ABSTRACT

The thin windows for the Muon Ionization Cooling Experiment (MICE) liquid Absorber will be fabricated from 6061-T6-aluminum. The absorber and vacuum vessel thin windows are 300-mm in diameter and are 180 μm thick at the center. The windows are designed for an internal burst pressure of 0.68 MPa (100 psig) when warm. The MICE experiment design calls for changeable windows on the absorber, so a bolted window design was adopted. Welded windows offer some potential advantages over bolted windows when they are on the absorber itself. This report describes the bolted window and its seal. This report also describes an alternate window that is welded directly to the absorber body. The welded window design presented permits the weld to be ground off and re-welded. This report presents a thermal FEA analysis of the window seal-weld, while the window is being welded. Finally, the results of a test of a welded-window are presented.

KEYWORDS: Thin Aluminum Window, Seals, Welds, LH_2, and Hydrogen Safety
PACS: 07.20Mc, 27.30+t, 06.60Wa

INTRODUCTION TO THE MICE ABSORBER

MICE demonstrates muon ionization cooling by measuring the change in longitudinal and transverse momentum of the muons in a beam, one muon at a time [1]. The MICE channel consists of two detector (or tracker) modules at either end of a muon-cooling channel. The tracker modules measure the muon beam emittance before and after cooling. The MICE cooling channel between the tracker modules consists of three absorber-focus coil modules (AFC modules) interposed with two RF coupling coil modules (RFCC modules).

The absorber (liquid or solid) is a central part of the AFC module. The liquid absorber consists of 20.4 liters of liquid hydrogen or helium separated from the world by thin aluminum windows [2]. This report discusses the thin aluminum windows on the MICE liquid absorbers. FIGURE 1 shows a cross-sectional view of the MICE liquid absorber in the center of a two-coil superconducting solenoid that is the heart of the AFC module. The thin absorber windows and safety windows are clearly designated in FIGURE 1.

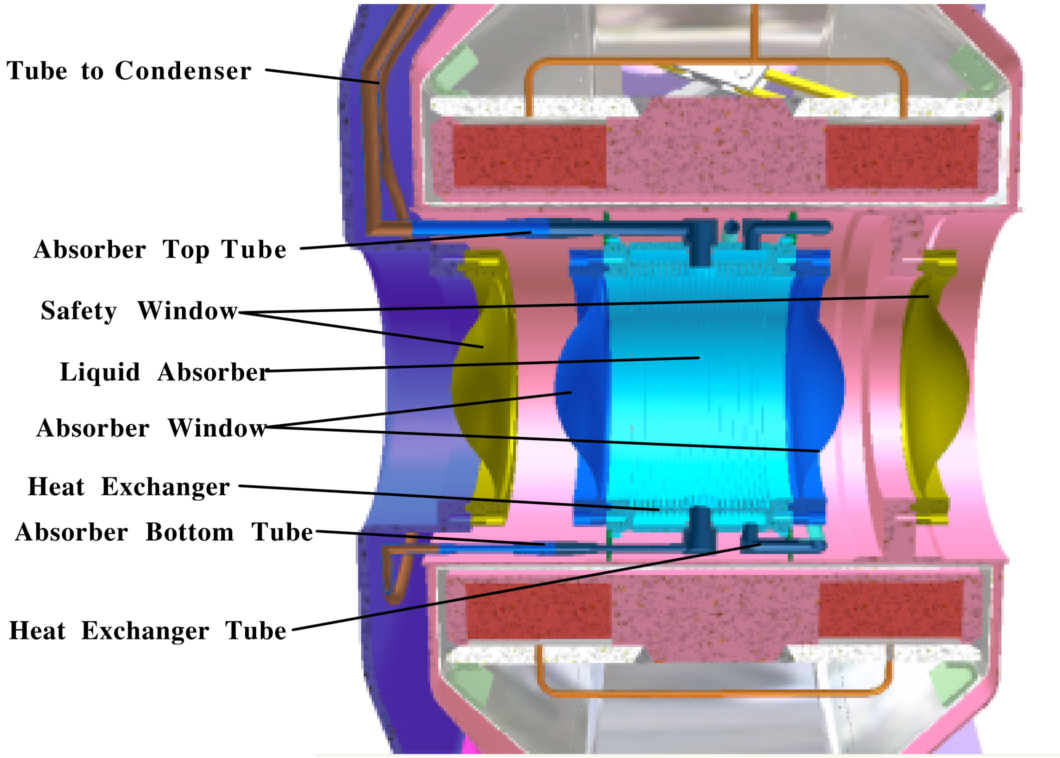

FIGURE 1. A three dimensional cross section of the MICE liquid absorber showing the absorber liquid volume, the absorber body, the body heat exchanger, the thin absorber windows, the thin safety windows and the hydrogen feed tubes.

The purpose of the MICE absorber is to reduce the momentum of a muon beam in both the longitudinal direction and the transverse direction through ionization cooling. The RF cavities in the RFCC modules between the absorbers restore the longitudinal momentum to the muon beam. If there is a net reduction of transverse momentum of the muon beam, it is said that beam has been cooled.

THE THIN ALUMINUM WINDOW DESIGN

The MICE absorbers have two types of windows. The first type of window is the hydrogen (helium) containment window on the absorber. The diameter of the hydrogen window is dictated by the maximum beam size at a point that is 175 mm from the center of the AFC module. From the various experimental configurations of MICE, a maximum beam diameter of 290 mm was calculated. The absorber window diameter was set at 300 mm. The second type of window for the MICE absorber is the safety window. The purpose of the safety window is to contain the fluid in the MICE absorber vacuum vessel in the event of an absorber window failure. The center of the safety window is approximately 325 mm from the center of the AFC module. The maximum beam diameter at this location (when the beam β is very low at the center of the AFC module) is very close to 300 mm.

The first of two factors important for the design of absorber windows is the selection of the window material. The window material selection factors include the following; 1) The material must have a low Z [3]. 2) The window material must not be subject to hydrogen embrittlement. 3) The material must be strong and ductile at cryogenic temperatures. The following types of materials were considered beryllium (Z = 4), strengthened Mylar (Z ~ 4), magnesium alloys (Z = 12), and aluminum alloys (Z = 13). Hydrogen embrittlement eliminated beryllium and magnesium. Lack of ductility at cryogenic temperatures eliminated Mylar. 6061-T6-aluminum was selected for the thin windows, because this material is easy to machine and weld. Other aluminum alloys, such as the 7000 series, may be attractive, but more development would be required.

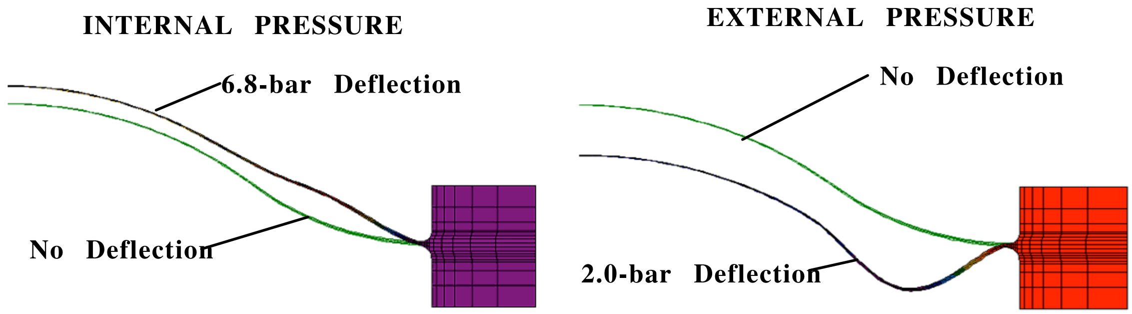

FIGURE 2. A magnified view of the deflection of the MICE thin windows under internal pressure and external pressure. One the left, the MICE absorber thin window deflection at an internal pressure 0.68 MPa is shown. The window stress when the internal pressure is 0.68 MPa ranges from 270 to 311 MPa. On the right, the deflection at 0.2 MPa external pressure is shown. There is no buckling. The window yields just before it starts to buckle. At 0.17 MPa external pressure there is no yielding in the window.

The second key design factor is the shape of the thin window. The initial thin window design was a torispherical window. For a window that is 300 mm in diameter, with a burst pressure of 0.68 MPa, the window thickness had to be about 285 μm. Four 210 mm diameter torispherical windows were burst and compared to an FEA model. The measured burst pressure was within 5 % of the calculated burst pressure. The window design subsequently evolved to a bellows window design with a double bend. The bellows window is thin in the center and thicker at the edges. The bellows type of window adopted for the MICE has a heavy flange as shown in the windows in FIGURE 2. The absorber window diameter is 300 mm. The edge thickness is 1 mm. The window becomes thin rapidly as one moves inward from the flange. The window thickness at the center is about 180 μm.

The final design requirements for both the absorber and safety windows are as follows: 1) The absorber and safety windows shall be 300-mm in diameter. 2) The minimum burst pressure of both types of windows at room temperature shall be > 0.68 MPa. 3) There shall be no yield in the window material at an internal pressure of 0.206 MPa. 4) The minimum window external buckling pressure shall be > 0.17 MPa. The final MICE thin window design that meets the design criteria is illustrated by the window deflections shown in FIGURE 2. The absorber and safety windows have the same shape, and the same diameter so that only one window type has to be qualified by the burst test. The thick window flange shown in FIGURE 2 permits the window to be attached to the absorber without distortion. The seal for the absorber window is designed to be vacuum leak tight to a helium leak rate of < 10^{-9} Pa m^3 s^{-1} (<10^{-8} atm cm^3 s^{-1}) at 0.1 MPa.

THE ABSORBER AND SAFETY WINDOW SEAL

In 2004, the current absorber design was adopted. The liquid absorber with its piping became removable from the magnet warm bore. This permits the AFC magnet and absorber to be manufactured and tested separately. The windows are installed on the absorber and the whole assembly is tested on the bench. It is unlikely that either the absorber windows or the safety windows have to be changed more than once. One safety window is in the AFC magnet warm bore. The other safety window is installed on the stainless steel absorber vacuum door, which allows the absorber assembly to be changed.

The bolted windows were developed in Japan. There were many discussions as to whether the bolted window with its seal should be replaced with a welded window. The advantages of the bolted window are: 1) The bolted flange and indium seal design was demonstrated in late 2003, and this design has been used in the MUCOOL hydrogen absorber at Fermi National Laboratory. 2) The bolted window is attractive when the aluminum safety window is attached to a 304 stainless steel absorber vacuum vessel. There has been experience using indium seals between dissimilar materials in liquid hydrogen bubble chambers built over 40 years ago, so rapid changes in temperature should not be a problem.

The advantages of welded windows are: 1) Welds in aluminum are strong and don't leak, if the welds are done correctly by qualified welders. There is a history of using welds to close high vacuum systems in physics. Reliable aluminum cryogenic vessels are welded. Cold seals are rarely used on the vessels themselves. 2) Welded absorber windows might take up less radial space, if the weld and flange are properly designed. The downside of welding the safety windows is the aluminum-to-stainless transition piece that is needed to permit the aluminum windows to be welded to stainless steel.

After discussion within the collaboration, the bolted windows with indium seals were adopted. The welded absorber windows were left as a backup option. For the safety windows, the bolted windows were preferred because of the dissimilar metal problem. FEA models were made of both types of window seals to see if the flange and seal design would have an effect on the window burst pressure and buckling pressure. The FEA study showed that the type of window seal made no difference on the burst pressure of the windows.

THE BOLTED WINDOW AND ITS SEAL

The bolted seal consists of a pair of indium seals that are on the corners of an exposed ring that goes into a slot machined into the surface that the window will be attached to. The indium seals are compressed by a ring of bolts that are outside of the seal. The pressure from the bolts causes the indium seal to flow so that the seal becomes vacuum tight, even with liquid helium or liquid hydrogen on the absorber side of the seal. The bolted seal for the MICE absorber is shown in FIGURE 3. The seal shown in FIGURE 3 is similar to the seals used for the windows of the 72-inch bubble chamber built at LBNL in the early 1960s.

The seal shown in FIGURE 3 was tested with a thick window. It is felt that such a test is valid because the thin window has no effect on the seal flange and the seal flange has no effect on the window. The tests included a pressure test and a vacuum leak check before and after window pressurization to 0.68 MPa. One cold test had a portion of the window seal at liquid nitrogen temperature while the rest of the seal was warmer. There was considerable temperature variation around the seal during this test. The bolted seal passed all of the tests. The seal appears to be robust and vacuum leak tight over a range of temperature from room temperature to 77 K. The MUCOOL test at Fermi Lab showed that the seal design works well at 20 K. There is little doubt that a bolted seal can be used for a 300 mm diameter window at liquid hydrogen or liquid helium temperatures. The safety window seals should be tight as well even if there is a hydrogen or helium spill into the absorber vacuum [4, 5].

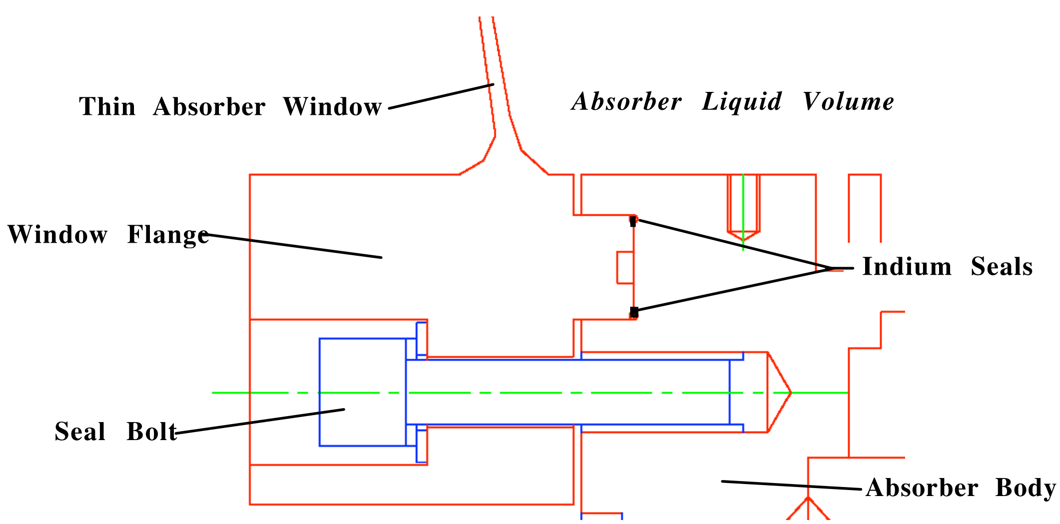

FIGURE 3. The MICE bolted window design with two indium seals. The space between the seals can be pumped. The gas between the seals can be analyzed to see if there is a leak in the inner seal.

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THE DESIGN OF A WELDED SEAL FOR THE MICE ABSORBER

The design criteria for a welded seal for the MICE absorber are as follows: 1) The welded seal must not take up more radial space than the bolted seal. 2) One must be able demonstrate the ability to grind off the seal weld and re-weld the seal several times. 3) One must be able to demonstrate that welding the seal does not damage the thin windows. 4) The welded seal must be vacuum leak tight after pressurization to 0.68 MPa. 5) The seal must be vacuum, tight after being pressurized to 0.68 MPa once the seal has been ground off and re-welded. 6) The seal must withstand large temperature changes and it must be vacuum tight when part of the seal is at liquid nitrogen temperature. The definition of being vacuum leak tight is that the leak rate shall be $< 10^{-9}$ Pa m^3 s^{-1}.

FIGURE 4 shows the proposed welded window for the MICE absorber. The window absorber body shown in FIGURE 4 has a bayonet so that 70 kN force on the window (when pressurized to 0.68 MPa) is not carried by the weld. With the bayonet engaged, the weld carries only a fraction of the pressure force.

When the window is installed in the absorber body, it is rotated 10 degrees to engage a number of bayonets around the circumference of the window. This locks the window into position. The weld nib shown in FIGURE 4 is about 4-mm long. The short weld nib shown permits the weld to be ground off and re-welded at least once. To grind-off and re-weld five-times the weld nib length should be about 8 mm. The absorber body portion of the weld nib is about 2 mm thick. The window portion of the weld nib is also about 2-mm thick. The nib on both sides is tapered permitting one to lay in the weld with the axis of the window perpendicular to the table supporting the absorber. When the weld is finished, it is about 3-mm wide. Even at the low yield stress for a 6061-aluminum weld, the finished weld should be capable of carrying the full 70 kN pressure force without the bayonets being engaged.

FIGURE 5 shows that even if the weld nib is at 1200 C (during the short time that it takes to make the weld) the flange at the base of the weld nib will still be very close to 20 C. The FEA model shows that distance from the 1200 C zone to the zone at or near 20 C is about 5 mm. It takes more energy than is put into the weld to raise the flange temperature above much above 20 C. Therefore, it was concluded from the study that distortion of the window flange should not be a factor when a 4-mm wide seal weld is made.

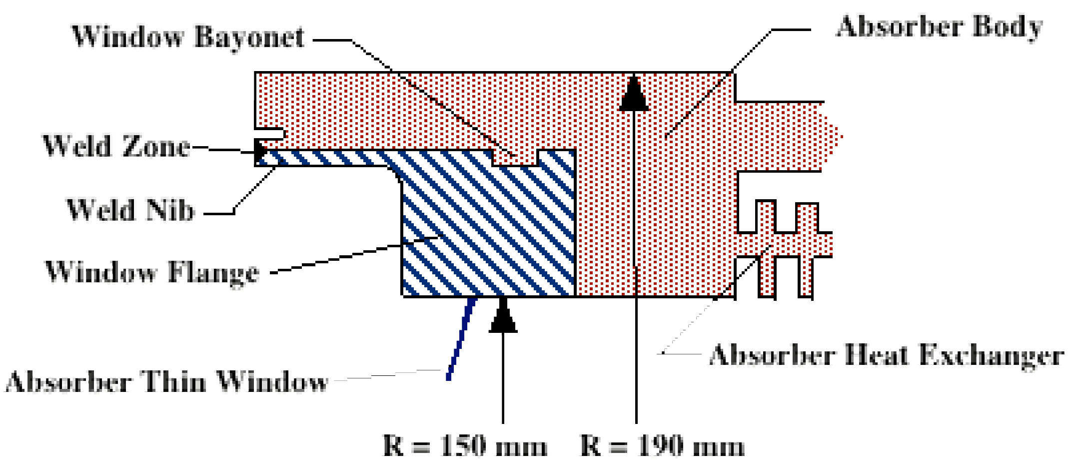

FIGURE 4. The Oxford welded seal for the MICE absorber. Note: the window flange size is the same size as the flange for the bolted window shown in FIG. 3. The window bayonet carries the pressure force when the window is pressurized to the burst pressure of the window. The weld shown is over 2 mm wide for a short weld nib (about 3-mm long). This permits the weld to be removed and re-welded at least once.

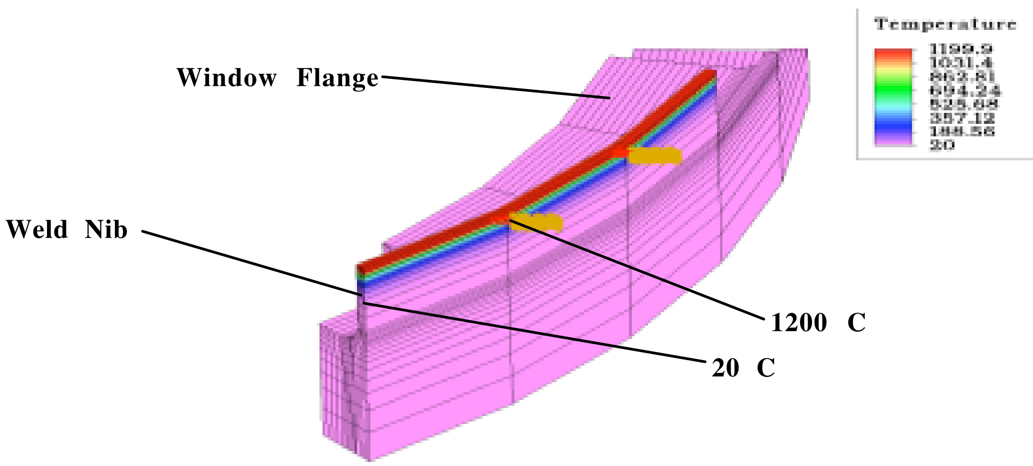

FIGURE 5. An FEA analysis of the temperature in the window flange while the weld nib end is at 1200 C.

We know from the FEA simulations of 20 K hydrogen splashing on room temperature thin windows that the window itself deforms where the cold is applied [5]. During this deformation, the stress in the thin window is well below the 6061-T6-aluminum yield stress, even when a temperature change of 280 K has occurred in the window. It is therefore reasonable to expect that a change of temperature in the window flange of 50 K should not have much effect on the thin window. The conclusion drawn from the simulation is that welding the window onto the absorber will not damage the thin window or the flange. This conclusion was later verified during the weld window test at the Rutherford Appleton Laboratory (RAL).

A TEST OF A WELDED SEAL FOR AN ABSORBER WINDOW

A window test fixture was fabricated in the RAL shops. The test fixture permits a dummy window that is 10-mm thick to be welded to a dummy absorber, which can be pressurized to 0.68 MPa. The whole assembly is designed to be cold-shocked down to 77 K using liquid nitrogen. The window diameter in the test fixture was 300 mm. The overall diameter of the fixture, which simulates the absorber body, was about 380 mm. Since the welded window seal was a back up for the bolted seal, there was no attempt to reduce the thickness of the window flange to a diameter that was less than that of the bolted window

The test fixture and test window are shown in FIGURE 6. The window flange is about 30-mm thick in the radial direction and about 36-mm thick in the longitudinal direction. The 12-mm wide bayonet slots were machined in the window in the middle of the window flange. The bayonets themselves are part of the base-plate part of the welded window assembly.

The weld nib on the window is 20 mm long (in the longitudinal direction) and 2 mm thick (in the radial direction). The weld nib on the base plate is only about 4-mm long and two-mm thick. The total distance from the seal weld to the window edge is about 50 mm as shown in FIGURE 6. FIGURE 6 shows a pair of thermocouples that are attached to the window flange. The thermocouples shown in the cross section in FIGURE 6 were attached at four places (about 90 degrees apart) around the circumference of the weld window experiment. The thermocouples allow one to measure the temperature of the window flange during the process of making the seal weld.

The space between the window and the base plate is pressurized with helium gas through a fitting that is mounted on the base plate (see FIG. 6). The fitting is welded to the base plate assembly in accordance with the British pressure-vessel code. In fact, the whole test fixture is designed in accordance with the pressure-vessel code. The window experiment was designed to be pressurized to 0.68 MPa using helium gas.

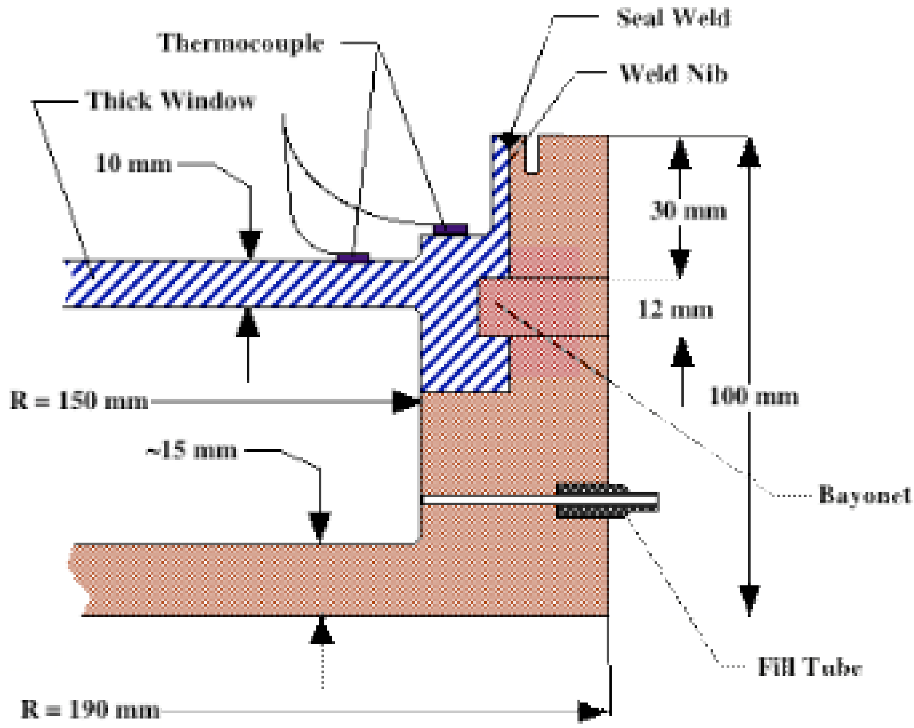

FIGURE 6. The window test fixture for testing welded window seals at pressures up 0.68 MPa. The test fixture is shown with a bayonet to support the pressure force when the window is pressurized.

During the first test of the window seal, the window was installed in the base assembly and it was twisted about 10 degrees in order to engage the bayonet fully. Most of the pressure force was to be transmitted to the base plate through the bayonets around the window circumference. Once the bayonets were engaged, the window seal was made by welding around the weld nib. The weld produced was about 4 mm wide and 4 mm deep. After the weld was made, the welded window and base plate assembly were cold shocked five-times in a bath of liquid nitrogen. The weld assembly was pressurized to 0.68 MPa and the leak rate was measured. The seal weld was found to be helium leak tight to $<10^{-9}$ Pa m^3 s^{-1}.

The second part of the test was to test the seal weld without the bayonets. The seal weld is quite large. Even at a pressure of 0.68 MPa, the weld should carry the window pressure force even if there are no bayonets. The following equation can be used to calculate the average stress in the weld when the window is pressurized;

$$\sigma_{ave} = \frac{D_{seal}P}{4t} \tag{1}$$

where σ_{ave} is the average stress in the weld. D_{seal} is the seal diameter (0.36 m); P is the design pressure (0.68 MPa); and t is the thickness of the weld (0.004 m). Using the nominal values for the dimensions and pressure, one gets an average weld stress of 15.3 MPa (2230 psi). The calculated stress for a 4 mm thick weld is a factor of six lower than the yield stress for the weld material in the 6061-aluminum weld (~100 MPa). Even if the weld thickness is half of the nib thickness (~2 mm), the average weld stress is still well below the yield stress for 6061-aluminum. This suggests that the weld can support the pressure force.

In the second part of the experiment, the seal weld was ground off and the window was disassembled from the base plate. The window support bayonets were ground off. The window and base plate were reassembled. The seal was re-welded on the ground nib. After the assembly was completed the weld was inspected for cracks. The window assembly was cold shocked five times in liquid nitrogen and the pressure test was repeated. The weld was able to support the 69.2 kN force. The second weld was helium leak tight to $<10^{-9}$ Pa m^3 s^{-1}.

CONCLUDING COMMENTS

The thin absorber windows and safety windows are a key part of the MICE absorbers and their safety systems. The absorber and safety windows must be thin and they must be made from a low *Z* material in order to eliminate scattering of the muons during cooling. The thin windows for the MICE absorbers will be made from 6061-T6 aluminum. The diameter of both types of windows has been set at 300 mm. As a result, the windows are interchangeable. The window thickness varies from ~1 mm at the edge to about 180-μm thick at its center. Over 95 percent of the window area, the window thickness is < 200 μm.

The MICE absorber design team studied two types of window seals. A bolted window with indium seals was adopted by the collaboration. A welded seal was adopted as a backup. The bolted window seals are well suited for the room temperature seals between aluminum windows and the stainless steel vacuum vessel. The bolted seals on an aluminum absorber were cold shocked to liquid nitrogen temperature and were pressurized to 0.68 MPa. The bolted indium seal was vacuum leak tight after cold shocking and pressurization. The bolted indium seal was used for the MUCOOL hydrogen absorber test at Fermilab. FEA studies of both seals showed that neither type of seal limits the burst pressure of the window.

The welded seal was modeled using FEA to see whether welding the seal would affect the thin window. The temperature of the window flange only rises a few degrees during welding. This was verified by temperature measurements taken while welding the seals of the test windows. The welded window was designed with a bayonet that allows the window to be installed and rotated so that the pressure force on the window is carried by the bayonet rather than seal weld. The welded window was installed, welded, and cold shocked to liquid nitrogen temperature. The window was then pressurized to 0.68 MPa. The window was vacuum leak tight after cold shocking and the pressurization. The seal weld was ground off, and the bayonets were ground off so that the seal weld would have to carry the pressure force, during the second test. The window was re-welded and the test was repeated. The window seal weld supported the 69.2-kN pressure force.

Both types of window seals were successfully tested. Either type of seal can be used on the AFC module and its absorber.

ACKNOWLEDGEMENTS

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REFERENCES

1. Gregoire, G. Ryckewaert, G., Chevalier, L., *et al.*, "MICE and International Muon Ionization Cooling Experiment Technical Reference Document," http://hep04.phys.itt.edu/cooldemo ,(October 2004).
2. Baynham, D. E., Bradshaw, T. W., Cummings, M. A., *et al.*, "A. Liquid Cryogen Absorber for MICE," *Advances in Cryogenic Engineering* **51**, AIP Press, Melville NY, (This publication) (2005).
3. Kaplan, D. M., "MuSat and MICE Experimental Verification of Ionization Cooling Techniques," presented at the First International Neutrino Factory Summer Institute, Abingdon UK 29 June 2003.
4. Yang, S. Q., and Green, M. A., "The Effect of a Hydrogen Spill inside of a 300 K Vacuum Vessel on MICE Absorber Hydrogen Safety," Oxford University Physics Department Engineering Note 1, MICE Note 100, http://hep04.phys.itt.edu/cooldemo, (March 2004)
5. Green, M. A., "Safety Issues for an Absorber that is designed for Liquid Helium Operation as well as Liquid Hydrogen Operation." Oxford University Physics Department Engineering Note 14, MICE Note 113, http://hep04.phys.itt.edu/cooldemo, (January 2005)