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Muon Catalyzed Fusion Beam Window Mechanical Strength Testing and Analysis^a

A. G. Ware and J. M. Zabriskie
Idaho National Engineering Laboratory
EG&G Idaho, Inc.
Idaho Falls, ID 83415, USA

ABSTRACT

A thin aluminum window [0.127 mm (0.005-inch) thick x 146 mm (5 3/4-inch) diameter] of 2024-T6 alloy was modeled and analyzed using the ABAQUS non-linear finite element analysis code. A group of windows was fabricated, heat-treated and subsequently tested. Testing included both ultimate burst pressure and fatigue. Fatigue testing cycles involved "oil-canning" behavior representing vacuum purge and reversal to pressure. Test results are compared to predictions and the mode of failure is discussed. Operational requirements, based on the above analysis and correlational testing, for the actual beam windows are discussed.

INTRODUCTION

The beam windows discussed as the subject of this paper are used as part of a secondary containment for a muon catalyzed fusion experiment at the LAMPF facility at the Los Alamos National Laboratory. In this experiment, a target can with a very thin aluminized mylar window is filled with tritium. This resides inside a secondary containment containing deuterium. The pressures inside the target and the secondary containment are controlled to within 50 torr of each other to preserve the mylar window. Additionally, the absolute pressure inside the secondary containment is held to less than local atmospheric pressure, about 0.09 MPa (13 psia). In case of a leak in the containment, no deuterium or tritium would be released.

The beam windows are thin for two reasons. First, to allow the muon beam to get in to the experiment and interact with the tritium in the target can. Second, to allow the neutrons and electrons to get back out of the target can and containment to be detected. A competing requirement is to safely contain the hydrogen isotopes without failure regardless of any potential pressure excursion.

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DESIGN OF THE WINDOW

Particle physics calculations determined that an aluminum window of 0.127 mm (0.005-inch) thickness would be acceptable from a particle transmission standpoint. The challenge was to make it perform from a mechanical integrity and safety standpoint. Although the muon beam coming in to the secondary containment and target is less than 25.4 mm (1-inch) in diameter, the neutron and electron detectors are slightly less than 146 mm (5 3/4-inch) diameter and are positioned quite close to the secondary containment window to get maximum coverage angle. It is due to the detectors that the beam windows are so large.

The secondary containment is constructed from 25.4 mm (1-inch) thick 6061-T6 aluminum alloy plates welded together to form sides. The bottom plate is 6.4 mm (1/4-inch) stainless steel while the top plate is 19 mm (3/4-inch) acrylic. Figure 1 shows a cross-section of the flange, window and box interface. The final geometry used includes a 6.4 mm (1/4-inch) radius on the flange and a 3.2 mm (1/8-inch) radius on the secondary containment itself. Although the flange is 12.7 mm (1/2-inch) thick and quite rigid, we found that doubling the number of bolts to 32 eliminated window pullout at a bolt torque of 5 - 5.6 newton-meters (45 -50 inch-lbs). Standard Buna-N o-rings are used for sealing.

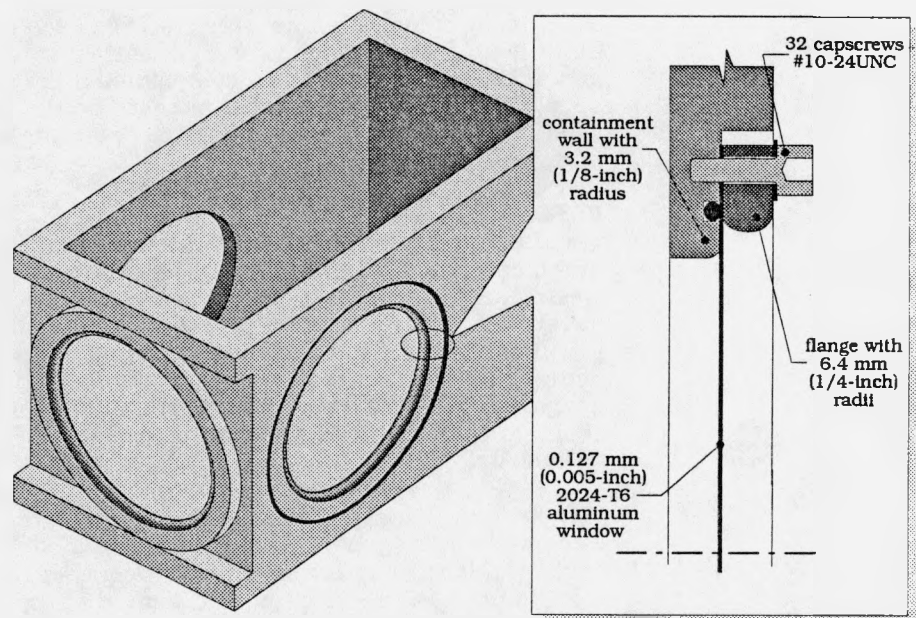


Figure 1. Cross-section detailing beam window geometry.

MATERIALS CONSIDERATIONS

2024-T6 aluminum alloy was chosen over other alloys and heat treats for several reasons. First, the 2024 sheet was on hand in the right thickness. Second, we felt that the T6 heat treatment gave a "tougher" material, high strength with a correspondingly high elongation value. The T6 treatment consisted of solution anneal at 499°C (930°F), a cold water quench, and aging at 190°C (375°F) for 12 hours.

FAILURE MODES

There are two potential modes of failure that could occur. One is bursting due to a high one time pressure load. This causes the stresses in the aluminum sheet to become so high that the sheet bulges, getting thinner and thinner, until it no longer has the strength to contain the pressure. The second potential failure mode is from metal fatigue. This can occur at much lower stresses than those required for bursting, but a number of stress cycles is required. In this case a crack is initiated in the metal. Subsequently the crack may be propagated through the thickness of the window at which time failure occurs. The higher the imposed stress, the fewer the cycles required for crack initiation.

In order to guard against these two potential failures, both computer analyses and testing of window specimens were conducted to find the burst pressure and fatigue life. Sixteen aluminum sheets were heat treated in each batch. Four windows were cut from each sheet. One was used for burst testing and one for fatigue testing, leaving two samples for use as actual beam windows. Upon completion of the tests and analyses, appropriate safety factors were imposed on the actual pressure and cycle conditions for failure to establish the operating conditions. The following paragraphs describe the results.

PRESSURE CAPACITY

The ultimate pressure capacity was determined experimentally by hydrotesting two windows from different sheets, but from the same heat treatment. Figure 2 is a graph of window deflection, radius of curvature, and membrane stress plotted vs pressure. Unfortunately, the maximum gage marking was 0.69 MPa (100 psi) [which is below the failure pressure], so the actual failure pressures are only estimates. Failures occurred at approximately 0.79 MPa (115 psi) and 0.90 MPa (130 psi) and exhibited classical center rupture with radial tearing. Figure 3 depicts the failed specimens.

The structural analysis was conducted using the ABAQUS nonlinear finite element computer code. The window was modeled as an axisymmetric thin shell, and large displacement theory was used. The exact boundary conditions at the outer edge were somewhat uncertain for the model, since the outer edge was restrained by a flange with a 6.4 mm (1/4-inch) radius in one direction and a flange with a 3.2 mm (1/8-inch) radius in the other direction. However, by bounding the possible conditions at the outer edge, it was determined that the exact assumption for the edge condition used made little difference on the final burst pressure.

the 19 mm (3/4-inch) diameter bar stock instead of thin sheet 2024-T6. However, the yield and tensile strengths and % elongation of the two alloys are similar.

Using the plastic strains computed for the fill case, the cycles to failure was estimated to be 900 cycles. It is interesting to note that the radius of curvature at the outer edge is important in preventing fatigue failure. Without this radius, i.e., with the outer edge clamped with sharp edges, the estimated cycles to failure would only be 260.

OPERATING CONDITIONS

Based on the tests and analyses described above, the operational limits were set at 0.17 MPa (25 psig) maximum pressure and 12 purge/fill cycles. This represents a safety factor of >4 on burst pressure and >40 on cycles. Further requirements were that the window must be changed after a pressure excursion >0.21 MPa (30 psig) or after 12 purge fill cycles, that the window must not have had pressure on them prior to installation, and they must be helium leak checked during the first purge pumpdown.

REFERENCES

Sessler, J., and Weiss, V. (1966). *Materials Data Handbook, Aluminum Alloy 2014*, Syracuse University, Syracuse, NY.

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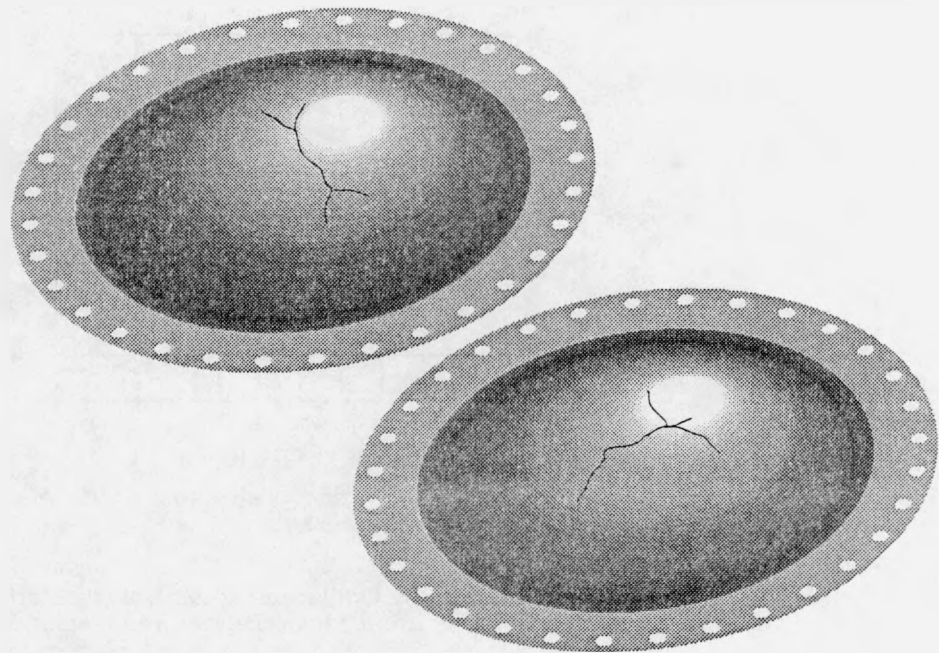


Figure 3. Sketch of the failed beam window specimens.

Further tests were conducted from vacuum to 0.25 MPa (37 psig). After 500 cycles with no failure, the test was stopped and the restraining flange interface area was examined. Inspection revealed essentially the same hairline scoring observed in the previous tests. The only difference was a somewhat thicker hairline.

As shown in Figure 1, the hole diameters of the flange [146 mm (5 3/4-inch)] and containment box [158 mm (6 1/4-inch)] are different, in addition to the corner radii. The reason is to increase fatigue life by eliminating reverse bendover in the same local region of the window. As the window experiences vacuum, for instance, it flexes and follows a 3.2 mm (1/8-inch) radius in a bend region of 146 mm (5 3/4-inch) diameter. As the pressure builds, the deflection reverses and the window now follows a 6.4 mm (1/8-inch) radius at a 158 mm (6 1/4-inch) diameter. This moves the bending in the reverse direction into a different region of the window.

The finite element model was used to determine the strain range associated with the fatigue tests. Since the window is a thin shell, it acts as a membrane and the bending stresses through the thickness need not be considered. For both vacuum and operating pressure the membrane stress in the wall is in tension; therefore, the maximum strain range was only from 0% strain (equilibrium position) to the strain at 0.24 MPa (35 psig). A cycles-to-failure curve constructed from fatigue data for 2014-T6 material was used to estimate the lifetime. (Sessler and Weiss, 1966). The curve is for

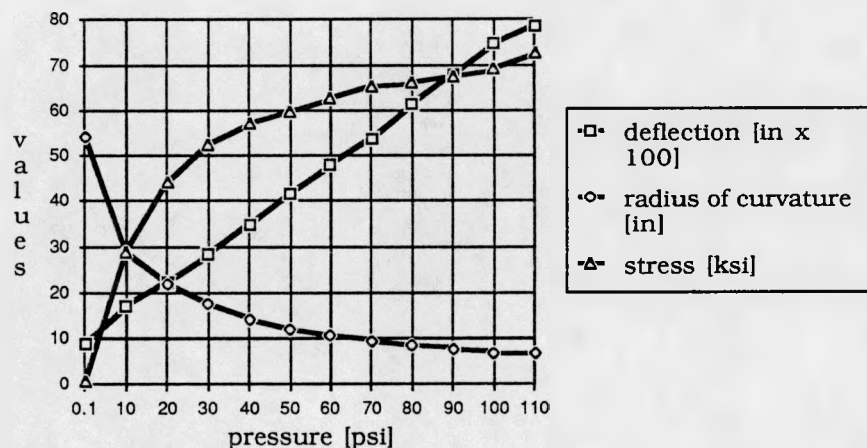


Figure 2. Plot of window deflection, radius of curvature, and stress vs. test pressure.

The model used a displacement-controlled algorithm, and computed the internal pressure to cause the required displacement. After the time of instability was reached, the required pressure for increasing displacements decreased. In the computer simulation, failure occurred when the wall started thinning faster than the pressure increased, resulting in an unstable condition. At this point in time the membrane started stretching to failure with no additional load, with separation occurring at the center. The central deflection was about 33 mm (1.3-inches) at this time, and the curvature of the membrane at its center was becoming increasingly larger.

The pressure at which the membrane became unstable was determined to be between 0.74 MPa (108 psi) and 0.78 MPa (114 psi), depending on the assumption made for the outer edge boundary condition. This corresponds relatively well with the burst test results.

FATIGUE LIFE

Two windows from different sheets, but from the same heat treat, were each tested to 60 cycles. A cycle consisted of 5 representative purges of 0.089 MPa (13 psig) vacuum and one fill to 0.24 MPa (35 psig). These tests were performed with nitrogen. Visual inspection showed what appeared to be a hairline crack in the region where the window was restrained by the 6.4 mm (1/4-inch) radius. Dye penetrant inspection revealed that this was only a region of high strain and had not cracked. The hairline marks were not circumferential, but were somewhat spiral, starting from the outside and curving towards the center. This corresponds exactly to the slight spiral surface finish of the contacting 6.4 mm (1/4-inch) radius surface. Our opinion is that these marks are from surface fretting, the slight rubbing action due to radial extension under pressure and contraction as pressure was reduced to vacuum.