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USE OF POLYCARBONATE VACUUM VESSELS IN HIGH-TEMPERATURE FUSION-PLASMA RESEARCH

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Magnetic fusion energy (MFE) research requires ultrahigh-vacuum (UHV) conditions, primarily to reduce plasma contamination by impurities. For radiofrequency (RF)-heated plasmas, a great benefit may accrue from a non-conducting vacuum vessel, allowing external RF antennas which avoids the complications and cost of internal antennas and high-voltage high-current feedthroughs. In this paper we describe these and other criteria, e.g., safety, availability, design flexibility, structural integrity, access, outgassing, transparency, and fabrication techniques that led to the selection and use of 25.4-cm OD, 1.6-cm wall polycarbonate pipe as the main vacuum vessel for an MFE research device whose plasmas are expected to reach keV energies for durations exceeding 0.1 s.

I. INTRODUCTION

MFE plasmas must be of high purity to reduce depletion of fuel ions and radiation losses. The maximum tolerable level of impurities decreases strongly with increasing atomic number, Z, ranging from a few percent for fusion products like α particles, to 1% for oxygen, 0.1% for molybdenum, and below 0.01 % for tungsten.[1] A way to reduce low-Z impurities from carbon- and oxygen-bearing molecules is by ultra-high-vacuum (UHV) techniques. Commonly, this is accomplished by use of treated stainless-steel vacuum vessels with "hard-seals," an approach that removes hydrocarbons, water, and carboxides from both the gas phase and as lightly bound surface molecules. It also provides a mechanically robust structure. As a vacuum vessel material, few drawbacks can be identified for stainless steel: a potential one is shielding of electromagnetic radiation, including radiofrequency and optical wavelengths. We restrict our attention to cases where these are of prime importance.

For over six decades, field-reversed-configuration plasma devices (FRCs)[2] have used insulating vacuum vessels. The first FRC plasmas were short (10 μs) pulses, formed in theta pinch devices.[3] Theta pinches need vacuum vessels that permit the rapid penetration of pulsed magnetic fields. Large bakeable quartz or alumina cylinders were and remain the standard for the vacuum vessels of theta-pinch-based FRCs. Quartz allows unobstructed views of the plasma but, because of the difficulty in fabricating holes in the brittle material, few penetrations for diagnostic access.

In the 1960s the rotating-magnetic-field (RMF) method was invented[4] to provide continuous generation of plasma current in an FRC, an improvement over the pulsed theta-pinch method. Glass vessels with protruding ports, the standard for over 40 years of RMF/FRC experiments,[5] permitted RMF antennas external to the vacuum vessel, a boon in terms of antenna deign, installation, operation, and repair. The Princeton RMF/FRC experimental program, begun in 2000, followed the lead of the early RMF experimentalists and used, with great success, multi-port Pyrex vessels for its first FRC device, the PFRC-1.[6] Concern over the brittleness of Pyrex vessels and their awkward, access-limiting protruding ports, led to consideration of other transparent insulating materials for the vacuum vessel of the successor device, the PFRC-2.

Polycarbonate, see Figure 1, quickly became the leading candidate because of its well-known toughness, impact resistance, machineability, and optical and RF transmissivity. (Moreover, we had positive experiences with small polycarbonate port covers on the PFRC-1.) Additional properties are necessary for a material to serve as the UHV vessel in the harsh MFE environment. In the following sections we describe the mechanical, vacuum, and electrical properties of a polycarbonate vessel we fabricated that has allowed the PFRC-2 to attain a base pressure below 10^{-7} T while providing 87 zero-length penetrations for improved diagnostic access and numerous electrical and cryogenic feedthroughs.

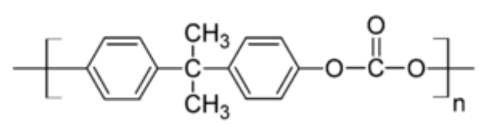

Figure 1. Repeating chemical structural unit[7] of polycarbonate. Two water molecules are released for each unit added.

II. MECHANICAL PROPERTIES

Many of the mechanical properties must be matched against the vessel dimensions required. For the PFRC-2, the maximum desired plasma radius was 8 cm. Eight internal superconducting coils[8] of 2-cm radial width surround the plasma column and require 1-cm separation from the cylinder's inner wall for thermal insulation. Thus the minimum required ID of the polycarbonate cylinder was 22 cm. The cylinder's wall thickness was set by two criteria: structural rigidity under vacuum forces and sufficient thickness for blind-tapped screw holes for securing Viton-seal port covers over the penetrations.

Using ANSYS,[9] several models of the vessel with wall thicknesses and penetrations of varying dimensions, were analyzed for their stress and buckling response to vacuum loading. Guided[10] by basic equations for the compression of cylinders, radial deflection ~ $(\text{radius})^2/\text{thickness}$,[11] we refined the dimensions by ANSYS simulations until we achieved radial deflections less than 0.015" everywhere and less than 0.005" locally around each penetration, a criterion set by Viton-seal requirements for the port covers. Figure 2 shows the predicted radial deformation under 1 ATM loading of a 33"-long, 10"-OD, 5/8"-thick polycarbonate vessel, with 87 penetrations, each sealed with a port cover. The greatest outward radial deflection occurs on the top, near the series of penetrations needed for cryogenic feedthroughs for cooling the superconducting inner coils (flux conservers). The greatest inward deflection occurs near the two thin penetrations reserved for viewing the plasma midplane.

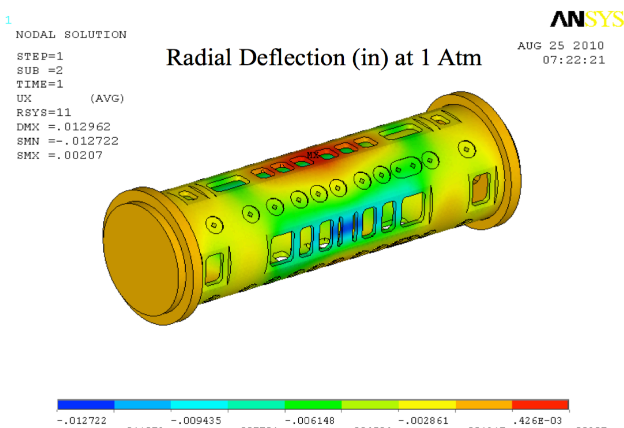

Figure 2. ANSYS prediction for the radial deflection of the PFRC-2 polycarbonate vessel under 1 ATM pressure. Dimensions are in inches. The cylindrical pipe is 33" long, 10" OD with 5/8" wall.

ANSYS simulations were run to pressures above 5 ATM, to ensure that stress limits were not exceeded. As evident in Figure 2, bridging ribs have been retained to fix the axial length of any penetration below ~ 6 cm, to reduce distortions, deflections and stresses. We note that the ANSYS simulations did not assume stiffening provided by the port covers, not shown in Figure 2.

Further observe, in Figure 2, the flat surfaces machined unto the outer surface of the cylinder, for mating with the Viton seals on flat port covers.

Obtaining a 25.4-cm-OD, 1.6-cm-wall, 84-cm-long polycarbonate cylinder proved difficult. Common commercial sources were only able to provide 3/8"-wall pipes of the diameter needed. The Plastics Manufacturing Center at the Pennsylvania College of Technology, an affiliate of the Penn State University system, was able to provide the cylinder, though not by the originally intended rotomolding method. Instead a solid boule was formed, bored out, and then firepolished.

At PPPL, penetrations and sealing surfaces were machined into the polycarbonate cylinder using a CNC milling machine. Felt-covered aluminum discs were pre-inserted inside the cylinder and at its ends, to avoid distortion during milling and to provide indexing for machining on different faces. To avoid heating above 115° C, the work point was air-cooled and the tool speed set to 15"/s while a feed rate of 2.5"/min or less was maintained. Air-cooling also avoided potential water uptake, possibly detrimental to vacuum. Penetrations varied in size and shape from ~2"x2" rectangular to ~1/2" diameter circular. There are 48 of the latter, arranged in four groups of 12, 45° above and below the horizontal midplane of the cylinder. One group is visible in Figure 2. Also machined in were 12 meters of linear O-ring seal surface and 578 blind holes, drilled and tapped for 8-32 nylon screws. Testing showed that nylon screws in the tapped polycarbonate (32-in-oz torque) were rugged and provided sufficient force on the port covers that metal Helicoils inserts were not needed, following our prescription to keep metal away from the RF antennas.

After the polycarbonate vessel was machined, reentrant end flanges, as illustrated in Figure 2, were attached. The Viton seal to the end flanges is placed in a groove in a circumferential surface of the flange which presses on the inner surface of the polycarbonate cylinder. This promotes plastic-to-plastic transmission of axial forces between the cylinder and end flanges. The port covers were then installed and the vessel evacuated. The measured deflections matched the predicted ones to better than 10%, including a growth in the length of the cylinder by 0.006".

The change in the polycarbonate cylinder length due to a change in ambient temperature is 0.001"/10°F, a consideration because room temperature varies from 55° to 95° F. For mechanical reasons, polycarbonate should stay well below its glassy transition temperature, 147° C.

Some port covers required penetrations and attachments. We used vacuum-compatible Locktite Hysol epoxy rather than the more commonly used solvents for polycarbonate. The transparency of polycarbonate aids the construction of a good vacuum seal by epoxy.

III. Vacuum properties

At important steps in the fabrication and assembly schedule we measured the outgassing of the polycarbonate cylinder using a turbopump "cart" equipped with a quadrupole mass spectrometer (SRS RGA100). The first test was before any machining, soon after the cylinder arrived from PMC/PCT/PSU. With end flanges only, the cylinder was pumped down with a 50 l/s turbo pump and the outgassing monitored with a the RGA directly attached to one end flange. Over ten days, the total pressure fell to ~6 x 10^{-6} T, with a dependence of $(\text{time})^{-1/2}$, indicative of mobility-limited diffusive outgassing from a semi-infinite slab. At this point the outgassing rate was 2 x 10^{-8} T l s^{-1} cm^{-2}, comparable to untreated stainless steel. The primary species in the RGA spectra were: water-85%, nitrogen-6%, hydrogen-4%, carbon-monoxide-3%; and oxygen-1%. The presence of water is not surprising considering that polymerization of bisphenol-A releases two water molecules *per* unit polymerized. Polycarbonate has been shown to contain up to 0.4% water *per* unit mass.[12,13]

Machining required six weeks. Following this lengthy period, we assembled the vessel with Viton-sealed polycarbonate port covers over each of the 87 penetrations, see Figure 3, and mounted the assembly on the pump cart for retesting. Similar pressure behavior, that

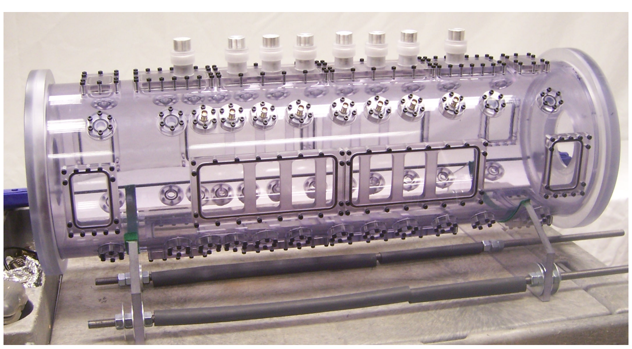

Figure 3. Assembled vacuum vessel. Note the polycarbonate end flanges, the black nylon screws, the black Viton seals for each port cover, and the eight polycarbonate quick disconnects epoxied to the top port covers.

is, $P \sim t^{-1/2}$, was observed over a 30-day period. We accelerated the pump-down by gentle heating, to 140° F for 12-hour periods, eventually attaining a pressure below 4 x 10^{-6} T on the pump cart. Leak checking showed small leaks on two Viton seals, partially causes of the air peaks in the RGA. These were fixed; smaller air peaks persisted.

The internal components of the PFRC-2 were then installed in the vessel. These included six diamagnetic loops and eight boron-nitride-clad high-temperature-superconductor flux conservers. The flux conservers could be cooled with liquid nitrogen (LN2), introduced through ¼" refrigeration tubing centered in ferules mounted in "quick disconnects" epoxied to port covers. The vessel was then installed on the PFRC-2 facility and pumped down by a system with a net pumping speed for water of 200 l/s. Within a few months of operations, the base pressure had fallen to the lows 7. Cooling the room reduced the pressure to the 10^{-8} T range, see Figure 4. The temperature dependence is exponential, with a 15,000 K (1.3 eV) characteristic. Cooling the flux conservers to 77 K reduced the base pressure, to below 10^{-8} T.

Figure 5 shows RGA spectra in the PFRC-2 for four cases on the same day, June 1, 2012: **Case a) 10:33 AM,** before the run. The base pressure was 4.7 e-7 T. Water is seen to be the predominant residual gas. Components of air, N_2 and O_2, and H_2 and CO_2 are present at ~ 20x lower

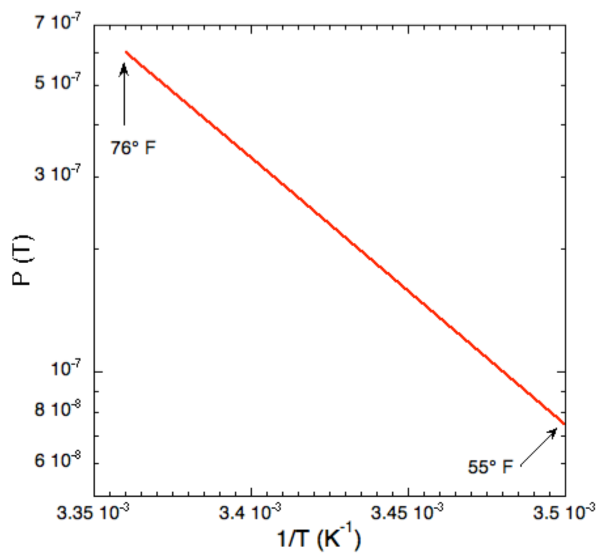

Figure 4. Dependence of vessel pressure on room temperature.

levels. **Case b) 10:54 AM,** with the flux conservers cooled to LN2. The water level has dropped an order of magnitude while the H_2, N_2, O_2 and CO_2 levels have dropped a factor of 2 to 3. The water behavior is consistent with cryo-pumping on cold surfaces. The H_2 behavior implies that the source of H_2 in the RGA spectrum in not simply molecular hydrogen. **Case c)**

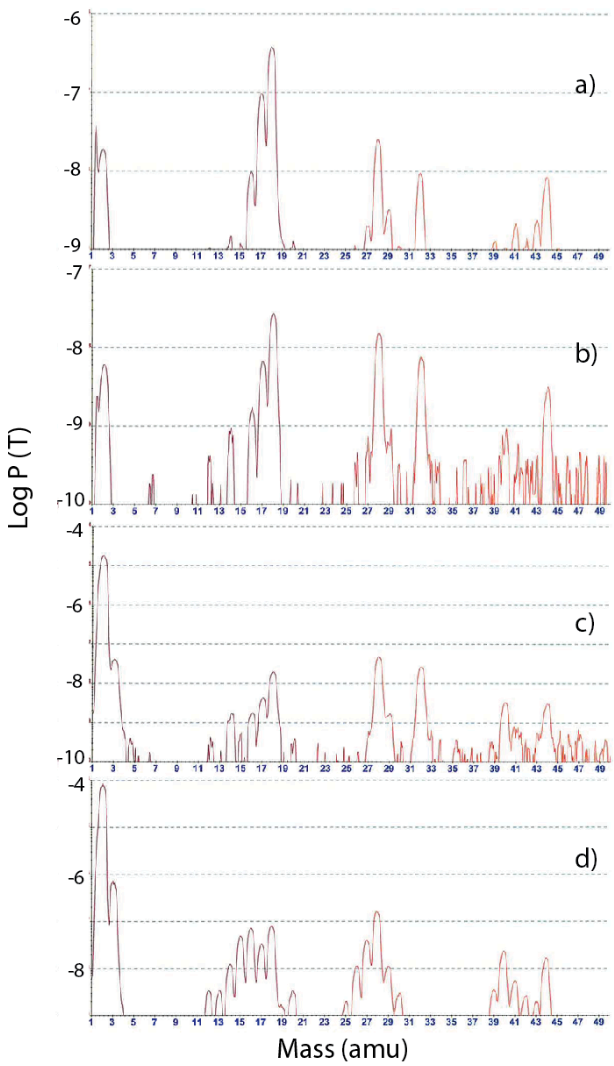

Figure 5. RGA spectra in the PFRC-2 for 4 cases on the same day, the first day the high-temperature superconducting flux conservers were cooled to LN2 temperature and the plasma pulse extended to 100 ms.

11:06 AM, with the H_2 feed gas being fed into the PFRC-2. The H_2 signal rises a factor of 3000. The water level continues to drop. The air and CO_2 peaks have risen slightly. **Case d) 11:49 AM,** with 13-ms duration plasma pulses (½% duty factor) at 10 kW of RMF heating power. The H_2 peak has risen slightly as H_2 gas is ionized and expelled from the polycarbonate vessel into the divertor chamber in which the RGA is mounted. The mass-32 peak, O_2, has disappeared, an effect we have seen before, with room-temperature flux conservers and which we attribute to dissociation by the plasma and pumping by activated wall surfaces. Swarms of peaks have appeared in three mass ranges, 12-20 amu, 25-30 amu, and 38-43 amu, commonly viewed as being caused by pump oil. These swarms grew less abundant as the run proceeded, that is, their 0.1% abundance in Figure 5 d) was the largest of the day, even though the RMF power and the pulse length were increased, the latter to 100 ms. The source for the (reputed) pump oil may be plasma bombardment of the BN cladding on the flux conservers or of the polycarbonate walls. Future experiments aim to resolve this question.

Spectroscopic measurements of impurities in the plasma support O and C levels below 0.1%.

IV. Electrical properties

The electrical properties of polycarbonate have been tabulated elsewhere.[13] As expected, polycarbonate has high surface and volume resistivities, 10^{15} Ohms and 10^{17} Ohm-cm, respectively, and a dielectric strength of 378 V/mil. At RF frequencies (1 MHz), the dielectric constant is 2.96 and the dissipation factor is 0.01. Polycarbonate has good transmission properties in the IR but poor in the UV, microwave, and THz regions. In the visible wavelength range, the index of refraction is 1.59 and the transmittance is 88%. Optical properties can be changed by additives which impart color, opacity, UV stabilization, and strength (*e.g.*, by glass fibers).

V. Summary

We have designed, constructed, and tested a 33"-long, 10"-OD, 5//8"-thick-wall cylindrical polycarbonate vacuum vessel for a long-pulse MFE experiment. The insulating and optical transmitting properties are a great boon to RF heating because they allow external RF antenna and excellent viewing of the plasma in the visible (optical) wavelength range. The mechanical rigidity of the vessel is adequate for the load, which is primarily due to vacuum forces. The thick-walled vessel allows "zero-length" ports which improves diagnostic viewing angle from ±45° to ±78° maximum.

The main concern was achieving a low base pressure. The achieved values ranged from 6 x 10^{-7} T at a room temperature of 76°F to 8 x 10^{-8} T at 55° F without LN2-cooled surfaces in the vessel, to below 2 x 10^{-8} T with internal LN2-cooled superconducting coils. The outgassing rate of polycarbonate at 76°F is about 3 times lower than for untreated stainless steel. Without LN2 cooling, the main residual gas is water, likely a product of the polymerization process. To date, the residual gasses are at such low levels as to not effect the plasma performance. When ion-heating experiments begin in the PFRC-2, charge exchange (CX) sputtering may occur and increase the impurity generation rate. Whether the neutral density – hence CX – in the polycarbonate chamber can be maintained at a low level by carefully orchestrated operation methods, remains to be seen.

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