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1. INTRODUCTION

The ZT-40 Toroidal Reverse Field Pinch Fusion Experiment uses an all-ceramic, 99.5% alumina, toroidal plasma-containment vessel. This torus is a 400-mm-diam bore, 3.2-mm-OD vessel that has eighty 57.2-mm-diam sapphire windows, eighteen 57.2-mm-diam instrumentation ports, and four 76.2-mm-diam evacuation ports.

The torus was fabricated by joining four 6° alumina segments with specially formulated ceramic sealants to form 24° torus sections. Special segments, those with windows and/or ports, were inserted between the 24° sections using rectangular cross-section Viton O-rings. The total length of ceramic-to-ceramic seals for this torus exceeds 66 meters. A schematic drawing of the torus is shown in Fig. 1.

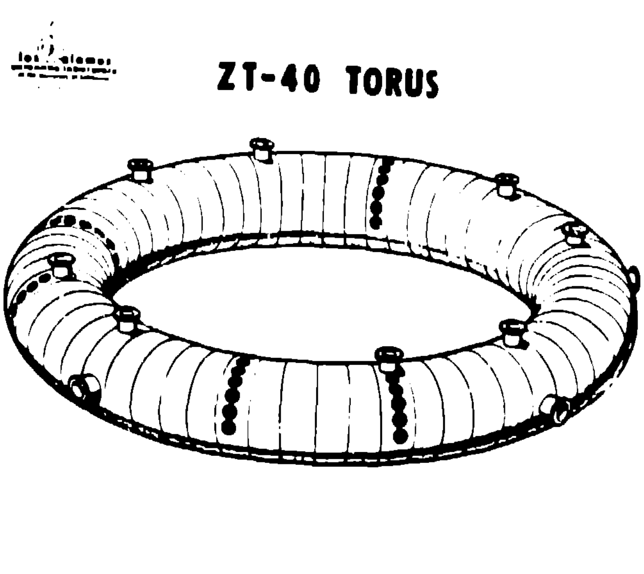

Fig. 1. Schematic drawing of ZT-40 torus.

*This work was performed under the auspices of the USDOE.

A program was undertaken to develop the materials, joint designs, and the technology necessary for the required ceramic-to-ceramic seals. This program resulted in the modification of two commercially available sealants and the development of five new sealants for alumina-to-alumina and alumina-to-sapphire seals. Fabrication of the ZT-40 torus has been accomplished using these sealants, which can also be used to repair and/or modify seals previously formed.

The successful hermetic ceramic-to-ceramic seals made using these vitreous and recrystallizing ceramics as a "brazing" material, demonstrate the usefulness of this technology. This provides a new approach for the fabrication of other large ceramic parts such as insulators for Tokamak machines.

2. DISCUSSION

2.1. Approach

The fabrication of the ZT-40 torus can be divided into four stages: (1) development of a series of sealants to join alumina-to-alumina and alumina-to-sapphire, (2) sealing of the 6° torus segments to form 24° sections, (3) fabrication of the all-ceramic special segments containing sapphire windows, diagnostic and vacuum pump-out ports, and (4) final assembly of the torus.

3. SEALING GLASS DEVELOPMENT

Five materials for sealing of high purity alumina and sapphire shapes, with maturing temperatures ranging from 500 to 1300°C, developed for the ZT-40 program, have been described by Hauth, et al. [1]. These sealants have uses and advantages as follows:

i. These sealants can be used to join large alumina ceramic shapes.

ii. They can be used to join alumina to sapphire.

iii. The sealing glasses, raw or fritted, can be used to repair joints made with other glasses in the series having equal or higher melting temperatures. Refiring the glasses to their original maturing temperature has no apparent

effects on the joints.

iv. Sequential sealing operations using successively lower melting glasses allow very complex parts to be fabricated without damaging previously made joints.

v. The glasses can be applied by conventional methods such as spraying, brushing, dipping, or buttering, using water as the vehicle.

vi. The glasses are stronger in tension than alumina when tested using joints of the type shown in Fig. 2.

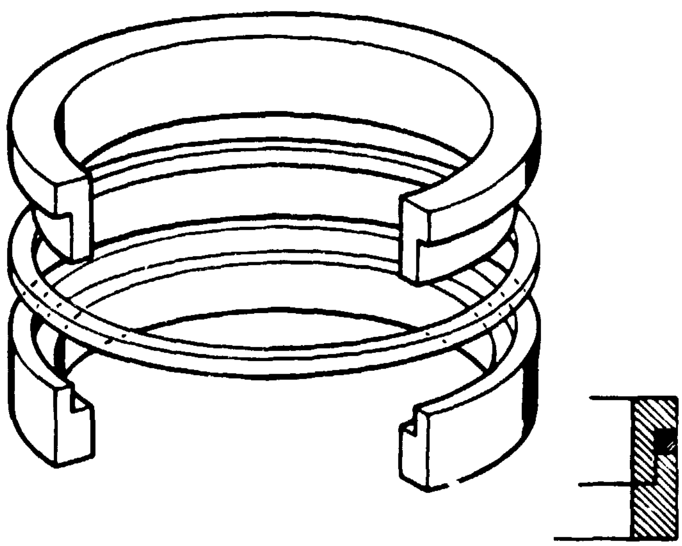

Fig. 2. Design of joint used between torus segments.

4. ZT-40 SEGMENT SEALING

The sealing glasses and joint design for joining 6° segments of the ZT-40 were evaluated using small 76-mm-diam alumina tubing. The process was then scaled up in size. Before joining the ZT-40 segments we successfully joined 150-, 200-, and 300-mm-diam torus segments using these glass compositions.

In addition to strength and vacuum tightness requirements, the joint had to be designed to minimize the possibility of contaminating the plasma with impurities from the sealant glasses. The joint design accepted, as shown in Fig. 2, permits no line-of-sight contact between the plasma and the glass sealant. Joints of this design can also be sealed with an 'O'-ring -- an important factor, since the final assembly requires that some 'O'-rings be employed.

The 1300°C maturing glass was selected for segment joining to increase the temperature range available for subsequent operations, modifications, and repairs, if needed, to the torus. Close tolerances ± 0.070 mm, on the joints were required to allow good vacuum seals to be formed, to prevent any glass runthrough to the inside of the torus, and to insure that the completed assembly would meet design specifications with regard to cumulative tolerances, etc.

The 6° torus sections for the ZT-40 were made by Western Gold and Platinum Company (WESGO) using a 99.5% alumina ceramic. WESGO sealed the 400-mm-diam segments together in groups of four to form 24° torus sections using the technology and materials developed by the Materials Technology Group of the Los Alamos Scientific Laboratory (LASL). The glass was applied by a buttering technique, and the parts fired at 1260°C for 1 h, using a heating and cooling rate of 50°C/h. One of these is shown in Fig. 3. Twelve such segments were required.

Fig. 3. Four 6° torus segments glass sealed to form a 24° torus section.

4.1. Special segment fabrication

4.1.1. Sapphire window-to-alumina sealing.

The fabrication of the special segments was the most difficult part of the ZT-40 torus construction. Twelve of these sections having very different appearances were required and are described in Table I.

A window assembly, shown in Fig. 4, containing a retaining ring of alumina was developed for the ZT-40. The retaining ring prevented excessive flow of sealing glass, and held the window firmly in place during the sealing operation, which was done with the windows in a vertical position. Tolerances of less than 0.050 mm between the window, ring, and window seat were required. In addition, the window seat was flat and square to within 0.025 mm to prevent unwanted glass flow or window misalignment. A small rounded annular groove was ground in the window seat, as shown in Fig. 4, to prevent glass flow to the inside of the torus.

TABLE I

DESCRIPTION OF THE SPECIAL SEGMENTS OF THE ZT-40 TORUS

Segments Required	Number of Windows & Ports Per Segment: 57-mm-diam Sapphire Windows	57-mm-diam Diagnostic Ports	76-mm-diam Evacuation Ports
2	--	3	--
4	--	2	1
2	9	2	--
2	14	--	--
2	17	--	--

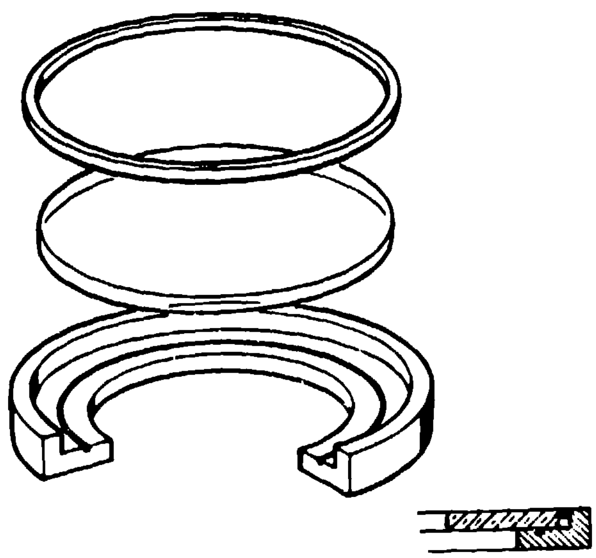

Fig. 4. ZT-40 window assembly design.

During the development of the special segment fabrication techniques, sapphire windows were sealed into 300-mm-diam torus segments using several of the sealing glasses. Some distortion occurred in the windows and it was dependent upon the coefficient of thermal expansion mismatch between the sealant, alumina, and sapphire. Using the 850°C sealing glass we were able to keep the distortion to less than 2λ.

Before making the actual ZT-40 window segments we sealed twelve windows into a 300-mm-diam torus segment in a single operation. The segment was vacuum tight and satisfactory from the glass flow requirements.

Figure 5 shows a 17-window segment with the sapphire windows and retaining rings ready for assembly and Fig. 6 a segment containing two diagnostic ports and nine windows.

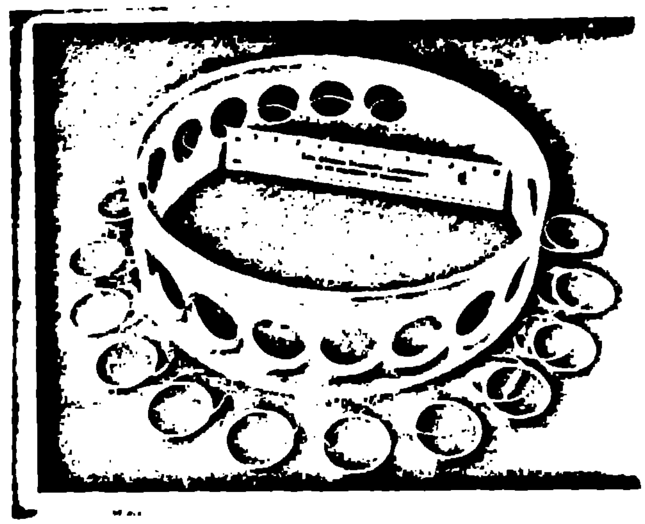

Fig. 5. A 17-window torus segment ready for assembly.

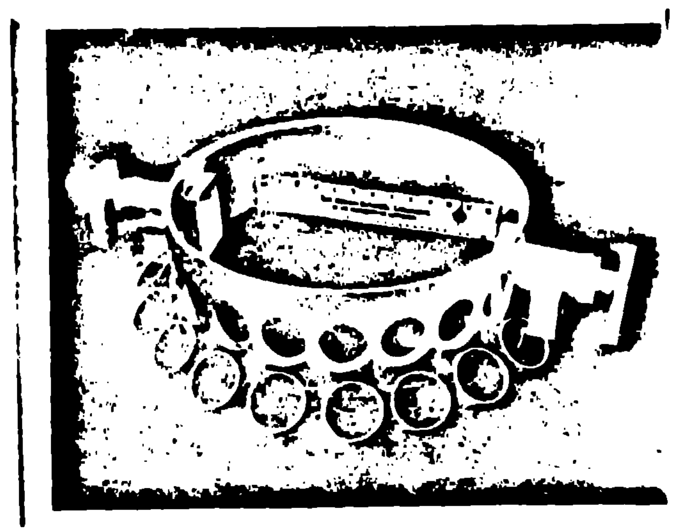

Fig. 6. A 9-window torus segment with two diagnostic ports ready for assembly.

4.1.2. Joining pump-out and diagnostic ports to torus segments.

The 57-mm-diam diagnostic port segments were assembled in much the same way as the window segments. The only change was the addition of alumina fixtures to support the port tubes during firing. Figure 7 shows a partially assembled segment with two 57-mm-diam ports and one 76-mm-diam port. The retaining ring which slides over the tube and fits between the OD of the seat and OD of the tube is shown balanced on part of the support fixtures. The port is pushed into position, glass is brushed into the seat, the retaining ring is pressed into place and a little extra glass brushed over the retaining ring. Final assembly of this segment is shown taking place in the furnace in Fig. 8.

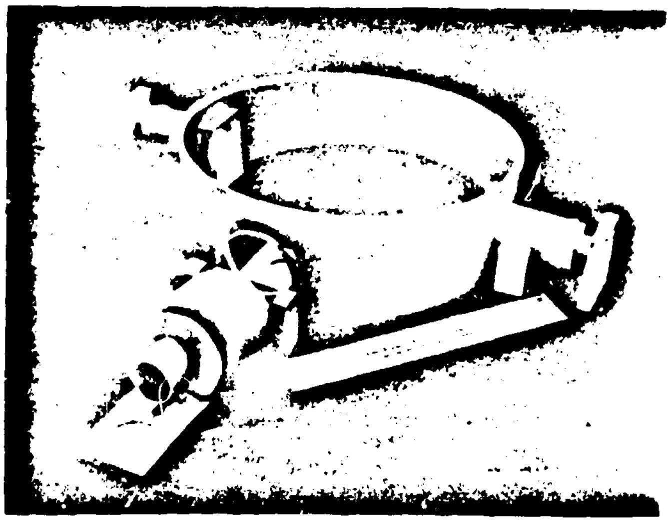

Fig. 7. A three-port, two diagnostic, one vacuum segment of the ZT-40 torus partially assembled.

The large pump-out port, also shown in Figs. 7 and 8, was somewhat more complex. Because of its larger diameter a seat could not be ground in the torus wall. Instead a sealing groove was ground on the tube. This entailed very complex contours ground to match the curvature of the torus. These tubes were sealed using a contour-ground retaining ring in much the same way as the smaller ports. Figure 7 shows the pump-out ports in an exploded view and the finished three-port segment of the ZT-40 is shown in Fig. 9.

4.2. Final assembly

The special segments are to be joined to the 24° torus sections using square cross-section 'O'-rings. The only clamping pressure will be supplied by the vacuum, which is specified as less than 1 μPa. Plasma cleanliness requirements dictate that organic material usage be minimized; consequently, vacuum grease on the 'O'-rings has been prohibited. This puts severe requirements on the uniformity, hardness, and surface finish of the square section 'O'-rings. They are being compression molded in a special steel die set from Viton B compound without a carbon black filler to a Durometer hardness of 55.

Fig. 8. Final assembly of a ZT-40 special segment showing the firing furnace.

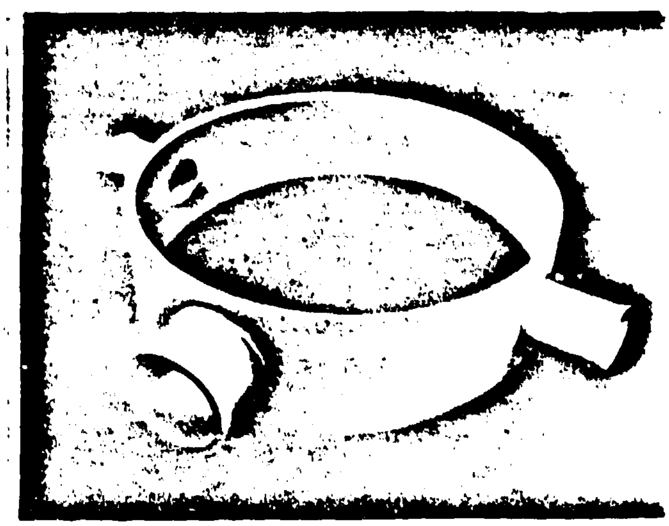

Fig. 9. Completed three-port ZT-40 special segment.

5. CONCLUSIONS

The technology developed during this program has made possible the fabrication of the large, 400-mm-bore, 3.2-m-OD ceramic ZT-40 torus. The torus is joined with specially developed glass sealants and the number of 'O'rings required is minimized. This ceramic-to-ceramic joining technology makes it a practical operation to fabricate large complex ceramic parts by furnace "brazing" (glass sealing) together several simpler shapes.

ACKNOWLEDGEMENTS

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REFERENCE

1. Willard E. Hauth and Stephen D. Stoddard, "Large Ceramics for Fusion Applications," presented at the First Topical Meeting on Fusion Reactor Materials, Miami Beach, Florida, January 31, 1979.