Conformal Window for the AirBorne Laser Aircraft

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ABSTRACT

The Airborne Laser (ABL) program requires a large aperture, highly transparent window to allow the high energy laser beam to be focused on targets. This window presents many challenges as it is thin (2.2 cm), large in diameter (1.71 m) and very highly curved (r = 1.31 m). Additionally, the window must be made from a material highly transparent at 1.315 micrometers, the chemical oxygen-iodine laser (COIL) wavelength, have good transmission from the visible through 3 micrometers and be able to withstand the rigors of operations on a tactical aircraft. To manufacture this window, a unique partnership between two companies, Heraeus and Corning, was forged to demonstrate the process and manufacture the window blanks. Infrasil 302, a Heraeus product, is the only material with low absorption at 1.31 micrometers that can be produced in large enough quantities to make a window blank of the required size. Corning has developed the technology to flow-out and sag glass products to make highly curved optics without the need to machine them out of a cylindrical block. Using their experience and a common desire to support the ABL program, the two companies worked together to develop the processes that produce the window blanks. Each company was presented with unique challenges, requiring process changes and improvements to produce the windows. Contraves Brashear Systems of Pittsburgh will polish the blank into its final form, with coatings applied by Optical Coating Laboratories, Inc. of Santa Rosa to maximize transmission.

Keywords: COIL window, COIL transmission, Infrasil, conformal window

1. INTRODUCTION

The AirBorne Laser (ABL) program requires a window to transmit the Chemical Oxygen-Iodine Laser (COIL) energy from the laser device through the aircraft skin to the target. This window presented a number of significant challenges to the manufacturers, as the then-current technology was insufficient to meet the minimum performance requirements. The design of the ABL turret assembly incorporates a common optical system for the optical tracker, the beacon and track illuminator lasers and the COIL system. This results in a requirement for transmission from 1 to 3 μm with superb transmission at the high energy COIL wavelength (1.315 μm).

Although ABL was in the planning stages for several years, Heraeus' and Corning's involvement began with idea discussions in 1996. At that time, several proposals were presented for a large aperture near infrared (NIR) window of different designs. All proposals involved the manufacture of a 1 meter plus optical blank requiring high NIR transmission and size and mass properties that were beyond the capability of Heraeus at the time. As a material candidate, some of Heraeus' fused quartz products had the potential to meet the optical properties, but the large mass that was required to be formed into a window blank seemed to be an insurmountable hurdle. Over the course of many months of discussion, several innovative ideas were generated that led to a plan to produce the optical blanks required for final 1.8 meters window design. The starting point for these discussions was an approach to generate synergy among the three companies, using the unique capabilities of each. This enabled the window to be produced without significant new capital expenditure. In this case, Heraeus has the material, Corning has the large blank fabrication technology and Contraves Brashear has the task of consolidating the effort and optically finishing the window. Several hurdles had to be overcome to make a 1.8 meter steeply curved meniscus window. Two companies with commercially competitive materials had to work together, Heraeus manufacturing the raw material in a large, monolithic boule and Corning processing it through several challenging steps into a final window blank. In addition, independent technical review, assistance and inspection of the in-process and final boule materials is being provided by Logicon RDA. Lockheed Martin has overall responsibility for the ABL turret assembly and provided overall project leadership and support.

A project of this size and complexity using capabilities of two companies with competing materials cannot happen without cooperation, coordination and planning. A diligent respect was maintained for each of the participating company's

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technology and contributions. All participating companies agreed beforehand to sign non-disclosure statements and share technical assistance in their areas of expertise.

The window must conform to the ABL turret ball shape and have a clear aperture of 1.55 meters. Figure 1. shows the conformal window and its relationship to the turret assembly. To meet the structural requirements and conform to the shape of the ball, the window must have an outside radius of curvature of 1.31 meters and a chord diameter of 1.71 meters. After structural analysis, and a review of likely process yields, it was determined that a thickness of 2.2 cm could be achieved and provide adequate safety margins for the system.

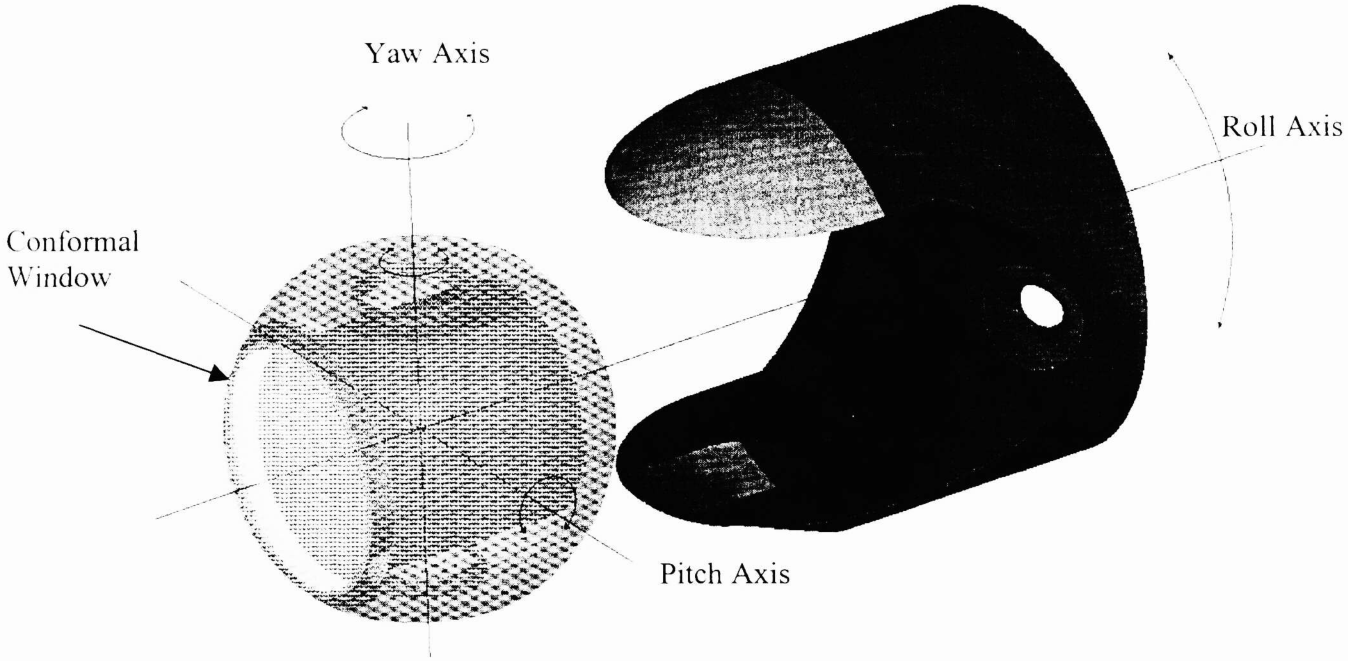

Figure 1. ABL Turret Assembly with Conformal Window

2. SELECTION OF INFRASIL 302 AS WINDOW MATERIAL

2.1 Survey of Available Material

When the available fused silica and fused quartz products were reviewed for suitability for the ABL conformal window, most were eliminated for their inability to meet the minimum requirements for transmission discussed above. Of the candidates, most were only available in small quantities (< 50 kg) or possessed a high OH^- content. OH^- content is critical as the COIL wavelength of 1.315 µm is close to an OH^- absorption band centered at 1.35 µm. Infrasil 302, manufactured by Heraeus Quarzglas in Hanau, Germany was the only product that could be produced in the required quantities and simultaneously meet the optical requirements. The Infrasil has low OH^- content (< 10 ppm) and simultaneously possesses good index homogeneity across the large volume of the window material.

2.2 Infrasil Raw Material Characteristics

For near-infrared (NIR) optical applications (out to about 3 microns), Infrasil has always been a good candidate material. Made from the electrical fusion of natural quartz crystal, it can be produced with residual OH^- of less than 8 ppm. This is important for avoiding the OH^- absorption lines at 1.3 µm, 2.2 µm and 2.8 µm (See Figure 2. Infrasil 302 transmission). After the material is formed, it is further annealed and refined to produce the desired optical specifications for residual strain, index homogeneity and low bubble class.

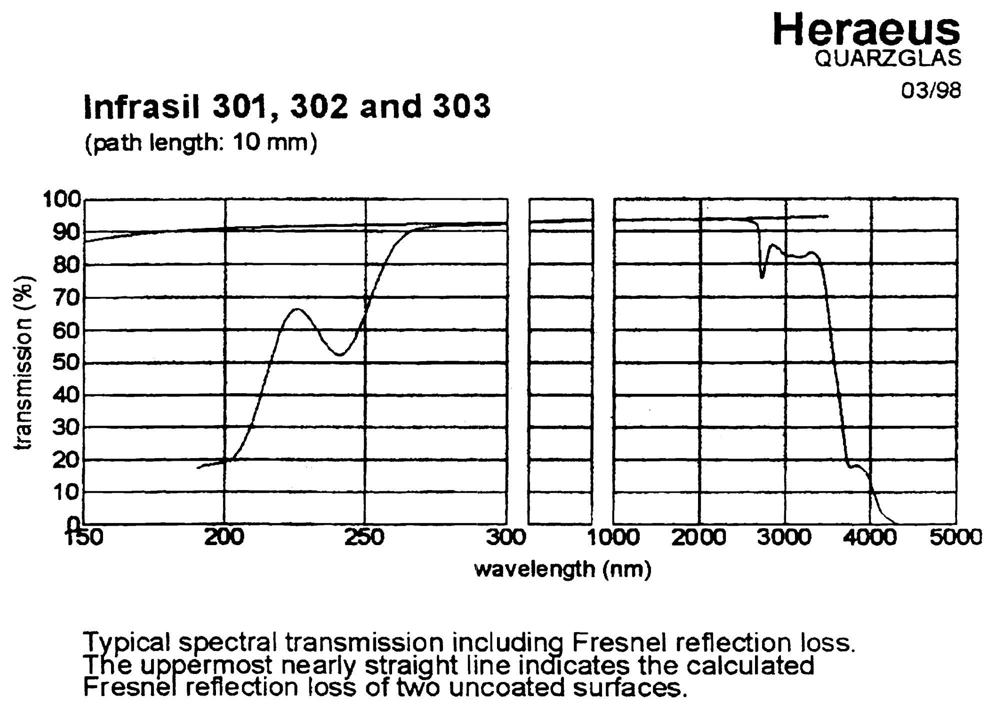

Figure 2. Infrasil 302 Spectral Transmission

3. MANUFACTURING PLAN

In order to determine the amount of Infrasil 302 required, a manufacturing plan was developed by Heraeus Quarzglas, Heraeus-Amersil, Corning, Contraves Brashear, Lockheed Martin and US Air Force representatives. A number of concepts were discussed, with the following processes developed.

Corning has the equipment and experience in re-forming glass into curved blanks through flow-out and sag processes. These processes have been demonstrated numerous times in support of large mirror blank production. Corning calculated the mass of glass required for a reasonable probability of manufacturing the window blank. Heraeus and Heraeus Amersil have the existing equipment to manufacture a boule of Infrasil a maximum of 1.1 meters in diameter with a mass of up to 450 kg. This required modifications and extensions to some of their current processes (described below) but no new capital equipment. To improve the manufacturing margins, Heraeus agreed to ship the boules to Corning as molded. Forming the required plano-plano blank to the 1.8 meter size requires several reforming steps at Corning. Here another cost saving idea was realized. Since material will be lost during subsequent forming and machining steps, it was proposed that a lower grade "expendable" material be used to sandwich the optical blank, a practice often used at Corning. This glass, Heraeus' HOQ 310SV, is used as a "cap glass" to increase the mass sufficiently to meet the flow-out and sag requirements. The HOQ 310SV is similar to Infrasil 302, but is of lower optical quality. (See Figure 3 below.)

Hence, the idea was formed to accomplish a stack seal using two HOQ-310SV slabs for the top and bottom expendable layers. In addition to forming the 1.1 meter Infrasil 302 blank, a parallel effort produced an HOQ-310SV blank. The SV designation indicates that the HOQ 310 was processed to the same low OH^- content as the Infrasil 302 to minimize the likelihood of OH^- migration from the cap glass into the Infrasil and to minimize mechanical stresses at the seal planes.

The Corning facility in Canton, New York has many years of experience in flowing out 1.5-meter diameter fused silica and ULE™ boules[†] to produce optics and optical components up to 2.5 meters in diameter.[1] The subsequent sagging process used to slump plano-parallel pieces to near-net shape contoured parts has also been used for optics under 0.5 meter up to the recent 8-meter class mirrors for ground-based telescopes.[2] Demonstration of the flowout and sagging processes using the Heraeus low-water Infrasil material was necessary for the ABL program and presented new challenges.

† ULE is a trademark of Corning Incorporated

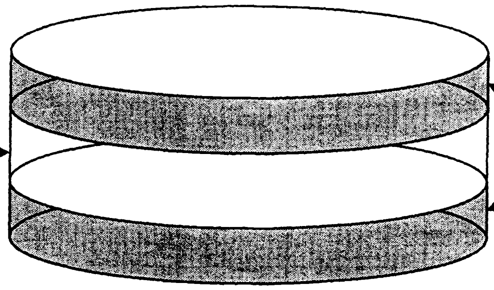

Figure 3. Stack Sealing of HOQ 310SV (top and bottom) with Infrasil 302

3.1 Process Steps

3.1.1 Manufacture/refinement of raw material at Heraeus and subsequent processing at Corning

The following steps were followed in manufacturing the conformal window blank (details in Section 4. below):

a) Reforming Infrasil and cap glass to 1.1 meter diameter
b) Transfer of glass to Corning
c) Stack seal of HOQ 310SV and Infrasil
d) Flow-out to 1.8 meter diameter
e) Sag to proper radius
f) Grind away cap glass and seal planes to provide final window blank

3.1.2 Process development required

These process steps are the result of the consideration of numerous suggestions and alternatives. The resulting process required the minimum amount of Infrasil 302, keeping costs to a minimum. Both Heraeus and Corning were required to develop new processes to support the unique aspects of this program, and performed several risk reduction trials to maximize the likelihood of success.

3.2 Program Requirements

The ABL program team elected to produce two windows, a primary and a spare, to avoid long delays in the event the conformal window is damaged in production or during use. With the total production time for a window (from glass manufacturing through figuring and coating) approaching three years, this was considered essential to minimize risk to the program.

4. PROCESS DETAILS

4.1 Infrasil 302 and HOQ 310 SV Production at Heraeus

An important key to success was accomplishing both the political diplomacy and technical coordination of resources between two (in this case, competing) companies. This seems to best occur when the coordinating organization is a neutral customer who can participate in technical discussions on both sides without compromising the intellectual property of either company.

From the onset, it was determined that the most cost effective process to produce the desired window would require the fabrication of meter sized plano-plano boules with subsequent hot forming to increase the diameter and create the curvature, then final machining to net shape. The total mass required, considering estimated yield losses throughout, was beyond existing capability at the time. Standard production techniques could produce blanks up to 690 mm in diameter and 80 kg mass. Heraeus had the material technology to produce the optical quality plano-plano blanks but with limited mass and diameter.

Additionally, forming and machining equipment beyond a 1 meter size was not available at Heraeus without considerable investment. Fortunately, Corning's capability to hot form and machine large diameter (several meters) optical blanks was well known. With a joint effort from both companies, the job could be done with a considerable reduction of time, effort and money.

4.1.1 Production and formation of required mass

To produce the required larger mass of material, several ingots must be fused together and reformed to larger sizes while maintaining optical quality. A risk reduction effort was required to determine if several optical ingots could be fused together, while maintaining specified optical properties. Heraeus accomplished this through a multi-step process (See Figure 4). First, several 140 mm diameter ingots were manufactured to create the starting raw material. The ingots were then refined and reformed to an intermediate size, and finally, fused together and re-formed to 650 mm diameter to achieve a total target mass of over 450 kg.

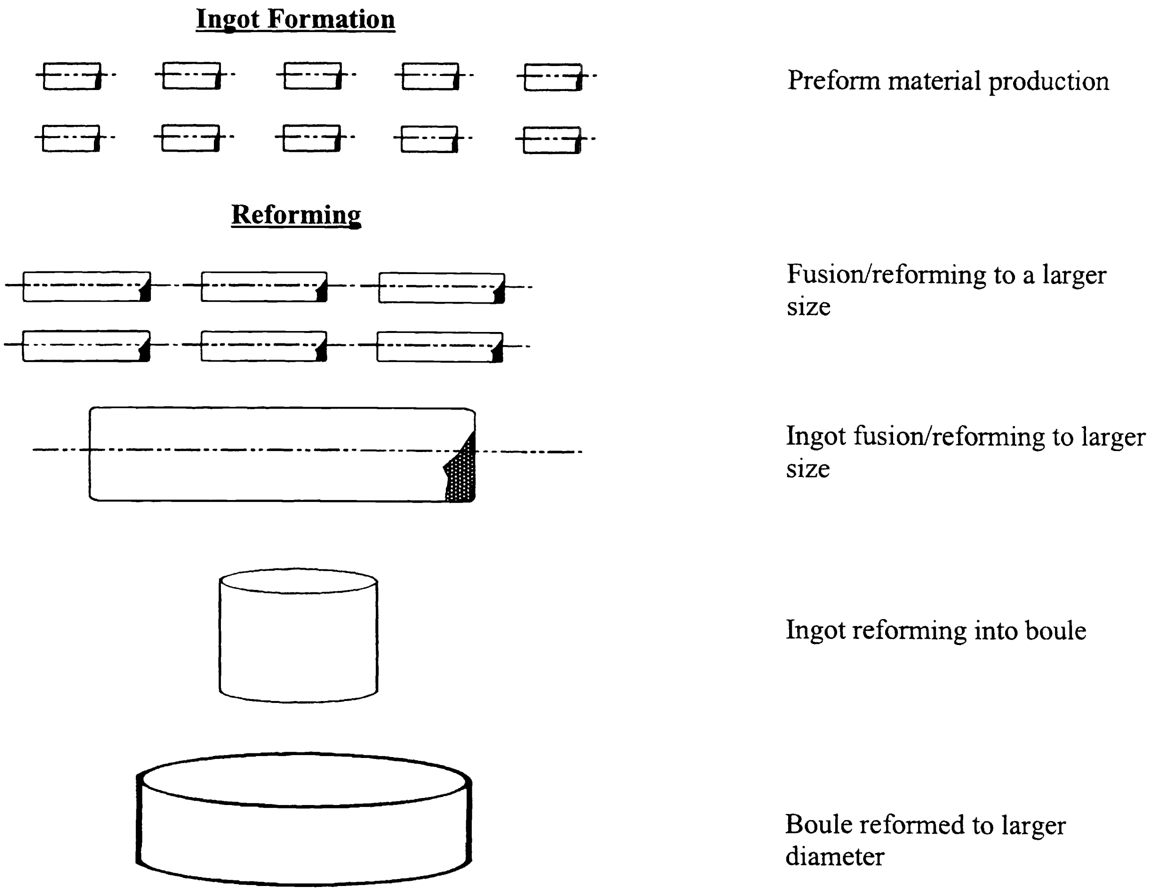

Figure 4. Forming Process to Produce 1.1 meter Boule of Infrasil

4.1.2 Challenges in making a large enough 1 meter monolithic SiO_2 blank

The key concerns for forming the large 1 meter optical blanks were to conserve the mass of the material through all the processing steps, minimizing the yield losses at each step and the control of bubble migration. Bubbles can be induced into the glass at several different steps in the process. To achieve the large mass required to manufacture the window blank, it was essential to be able to fuse together ingots of bubble free Infrasil 302 without allowing bubbles to be introduced at the seal planes.

4.1.3 Risk reduction efforts - ingot fusion

The large mass of optical glass formed in long ingot was not suitable for forming directly into 1.8 meter blanks. To produce a larger diameter, the 650 mm ingot required a horizontal flow out in the Oyster furnace. (The Oyster furnace is a vacuum electric furnace at Heraeus Amersil with a capability to process glass to a 1.1 meter diameter.) This was accomplished using the Oyster furnace with a controlled environment and specially designed molds. Molds were designed to maximize the available mass and to prevent the formation and migration of larger bubbles that typically form between the lower glass surface and the mold. The final Infrasil 302 hot forming step used at Heraeus resulted in a plano-plano boule, 1.1 meter diameter, with a mass greater than 450 kg as formed, a critical process milestone.

4.1.4 Use of German and US resources

Throughout this program, use of existing global equipment and personnel resources helped reduce cost by removing the need for new capital equipment or staff members. Heraeus made effective use of glass fusing, refining, metrology and reforming equipment at its parent facilities in Germany, as well as larger forming equipment at its US facility in Georgia. Special key technical personnel followed the path of the glass through every production step. This assured extended quality control and process verification for all operations.

4.1.5 Key factors leading to success

The technical keys to success at Heraeus were the accomplishment of activities that led to the desired goal in the following steps:

a) ingot fusion and refining to produce a 400 kg mass of optical grade Infrasil 302

b) multi-step re-forming processes that minimized loss in each step to achieve 1meter (See Figure 4.)

This was accomplished through careful project management of specific tasks, each with its own risks and goals that must be achieved to move forward.

4.2 Corning Processing of ABL Conformal Window

Corning Incorporated has extended proven glass technology by successfully demonstrating a process to produce the 1.7-meter conformal windows for the ABL program. The processing of the first prime piece is well underway, with scheduled completion anticipated in May 1999.

4.2.1 Material considerations

Heraeus' Infrasil fused quartz is very similar in most ways to Corning Fused Silica Code 7940/7980. The viscosity curves are similar, but available data indicated the viscosity of Infrasil 302 is slightly lower than fused silica, so the flow point temperature of the Infrasil 302 is approximately 25°C to 50°C higher. Thus, furnace heating capacity and refractory tests were performed to confirm the process capability for flowing and sagging the hotter glass with Corning's process technology.

To assist with these tests, Heraeus provided viscosity data and the fine annealing schedule for Infrasil, needed since flowout and sagging take the glass well above the anneal point.

An additional concern was that Corning's standard process utilizes gas-oxygen fired furnaces for the thermal processing steps. Thus, there existed the potential for water (OH^-) migration into the low-water content Infrasil 302. Prior experience led Heraeus engineers to predict minimal OH^- migration, with only a few millimeters penetration depth. Tests were conducted to quantify any change in water content resulting from Corning processing and to verify it would not affect the final product, the ABL conformal window.

4.2.2 Thermal processing

Corning's standard flowout and sag processes can be summarized as follows:

- Select prime glass and appropriate cap glass
- Grind and clean surfaces to be sealed
- Load pieces into furnace in oversized refractory cup (Figure 5.)

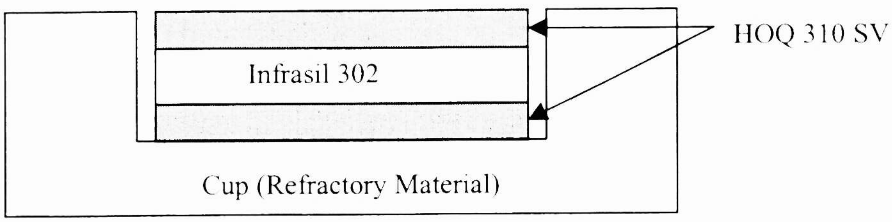

Figure 5. Refractory Cup Used for Stack Seal at Corning

- Preheat and soak glass to stabilize temperature
- High fire above melting point to seal and flow glass
- Remove glass from furnace
- Grind surfaces to remove embedded refractory material
- Clean and inspect the surfaces
- Load onto a convex refractory sag form mold (Figure 6.)
- High fire above softening point to sag glass to approximate contour
- Fine anneal (controlled cool down)
- Grind and generate final window blank to specification

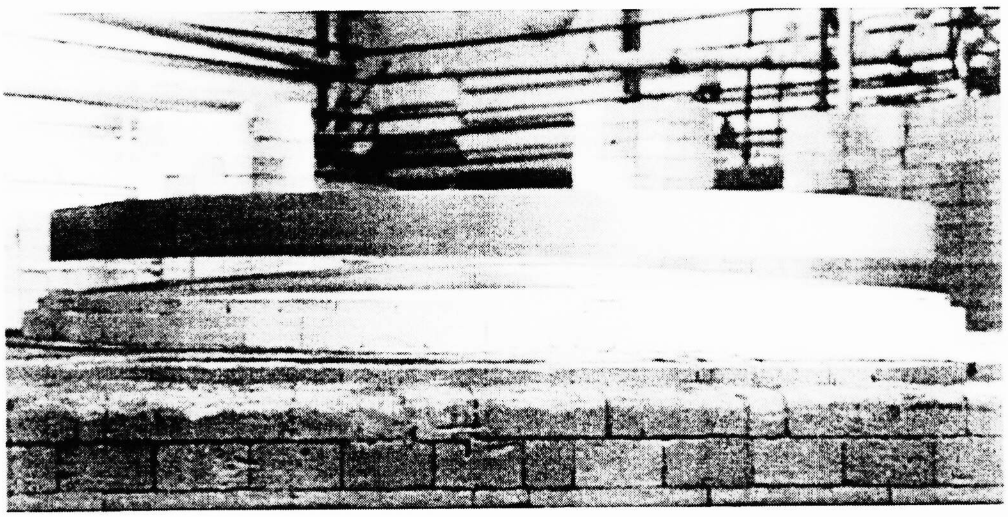

Figure 6. Convex Refractory Sag Form with Similar 2 meter Class Blank

Corning has performed these thermal processes on its fused silica and ULE™ for many years. The key concerns for processing the Infrasil 302 are:

- Achieving proper viscosity for adequate and predictable flow

- Minimizing OH^- migration into the low-water glass
- Ensuring furnace refractory materials perform at higher temperatures without negative impact on overall process
- Achieving proper fine anneal of sagged window blank

4.2.3 Risk reduction efforts conducted

4.2.3.1 Sub-scale process development and qualification

The sub-scale process screening tests were conducted using six-inch diameter pieces of Infrasil 302 in a small Corning furnace. The furnace was fired until effective flowout of the glass was observed. Due to the higher flow point temperature of the Infrasil glass, correspondingly higher furnace temperatures were required to achieve the flowout, as expected. The required temperatures were within Corning process technology, with some modifications to refractory design as was anticipated.

Next, fusion sealing of high-water HOQ-310 cap glass to the low-water Infrasil 302 was performed. Lower cost cap glass was used to provide additional mass to obtain the necessary hydraulics during flowout, as well as to act as sacrificial glass on the outside of the prime Infrasil material. The differential CTE between the cap glass and the prime glass was confirmed to be within process guidelines, so excessive stresses were not generated at the fusion seams. The OH^- migration was also confirmed to be within expectations, at a low enough level not to impact the glass in the final window blank. Measured OH^- penetration characteristics for the sub-scale stack seal tests are shown in Figure 7.

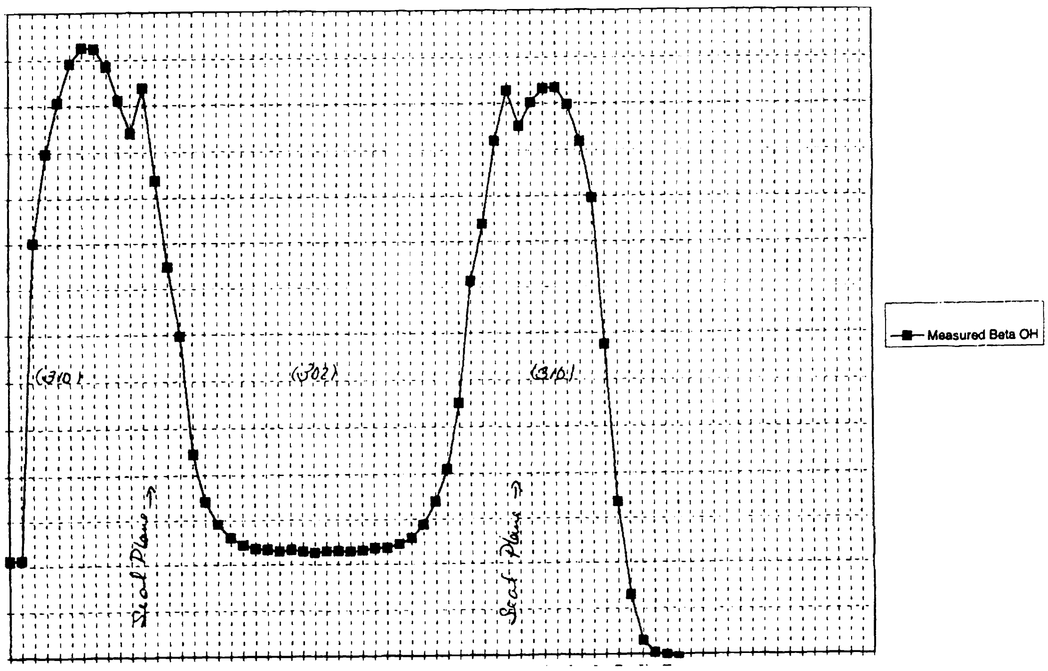

Figure 7. Beta OH^- vs. Distance for 6" Stack Seal of HOQ 310 and Infrasil 302

Concurrent with these tests, Heraeus suggested that a low OH^- version of HOQ 310 (HOQ 310SV) be used to eliminate this concern. For subsequent processing of the prime window material, the SV, low OH^- cap glass was used.

The final sub-scale risk reduction effort was to flowout an 11-inch diameter piece of Infrasil to just over 20 inches in diameter, simulate a sag firing thermal cycle, and then verify the OH^- content and optical homogeneity of the final blank. Again, the OH^- content of the final blank was determined to be within specification. The optical homogeneity of the flowed out part was compared to that of the incoming 11-inch part. The thinner, 20-inch part homogeneity data were affected by the aspect ratio of the part, but it was concluded that the thermal processing had not negatively impacted the homogeneity. Results of the optical homogeneity measurements on this part are shown in Figure 8.

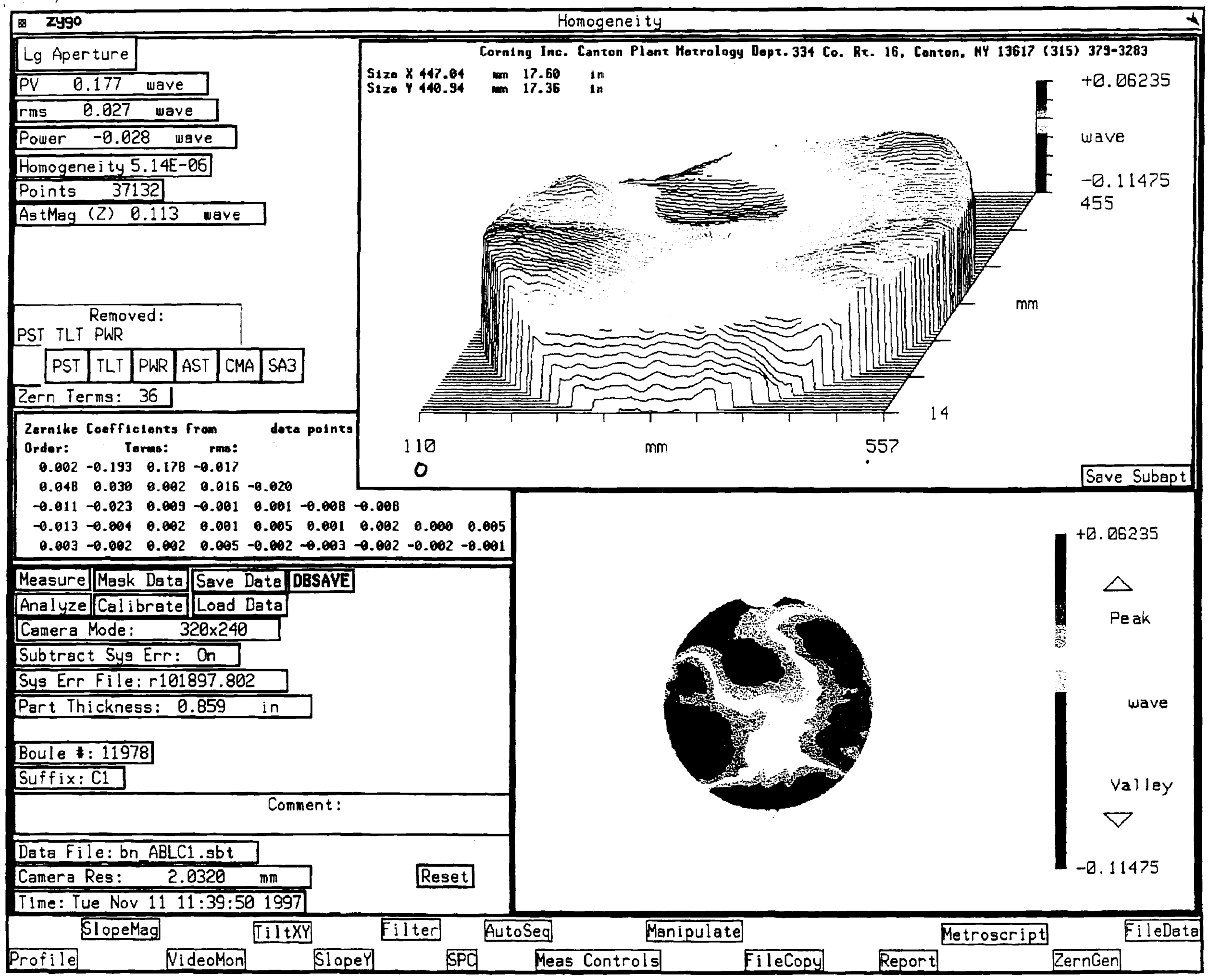

Figure 8. Index Homogeneity Measurements on Sub-scale Infrasil Part

4.2.3.2 Full-scale process risk reduction

The physical characteristics of the first 1.1 meter Infrasil 302 boule delivered to Corning offered additional challenges for Corning's successful subsequent processing into the final window blank. Incoming inspection of the boule included visual inspection and dimensional, stress birefringence, and optical homogeneity measurements. The total volume of useable glass was lower for the first boule than expected due to surface anomalies. The bottom surface had several large bubbles protruding into the thickness, and the top surface was not flat. The outside portion of the top surface exhibited substantial roll-off. (See Figure 9.) These two anomalies combined to effectively reduce the mass of prime Infrasil 302 that will become the final window blank. As a result, Corning invested in additional risk reduction efforts to try to conserve the mass of the prime glass and overcome these difficulties.

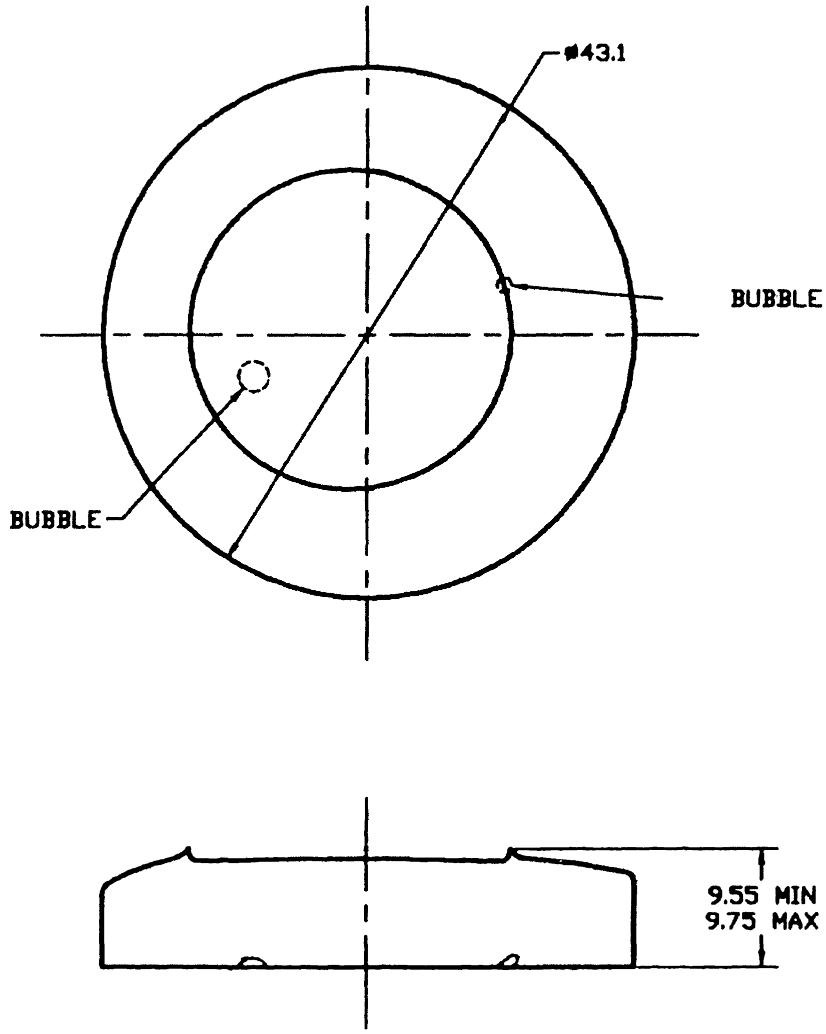

Figure 9. Infrasil 302 Boule #1 as Produced by Heraeus

While risk reduction efforts were being planned, Corning flatted the incoming glass and measured its optical homogeneity using phase shifting interferometry. Thermal control of the Oyster furnace at Heraeus Amersil is not sufficient for a fine anneal of the glass. Therefore, the contribution of the residual stress was noted in the homogeneity measurements. Even so, the boule was deemed acceptable and further processing was approved and initiated.

In attempts to address the top surface roll-off, Corning planned slight changes in the firing process. Several alternate refractory materials were evaluated for use at the higher temperatures required for processing the Infrasil material. Full-scale firing tests were conducted to evaluate the modified firing approach. Corning 7940/7980 glass was used for these tests, with the surfaces ground to simulate the incoming Infrasil boule's geometry. The modified process was run at the higher temperatures planned for the Infrasil firing. Results were used to again modify the refractory design, with the goal of maximizing the usable diameter of the glass after firing. The second full-scale firing was more successful, and the final process parameters to be used with the prime Infrasil glass were chosen.

The flowout of the first blank has been completed at Corning, and the sagging will be completed in April 1999. Although some risk remains in achieving the desired conformal window thickness from the first Heraeus blank, the second Heraeus ingot contains a much larger useable volume of glass. (See Figure 10.) This occurred in part because of a process developed by Heraeus to minimize large bubbles in the boule bottom surface. This process was proven in the production of the second boule. As such, the processing of the second blank is expected to be well within allowable process margins.

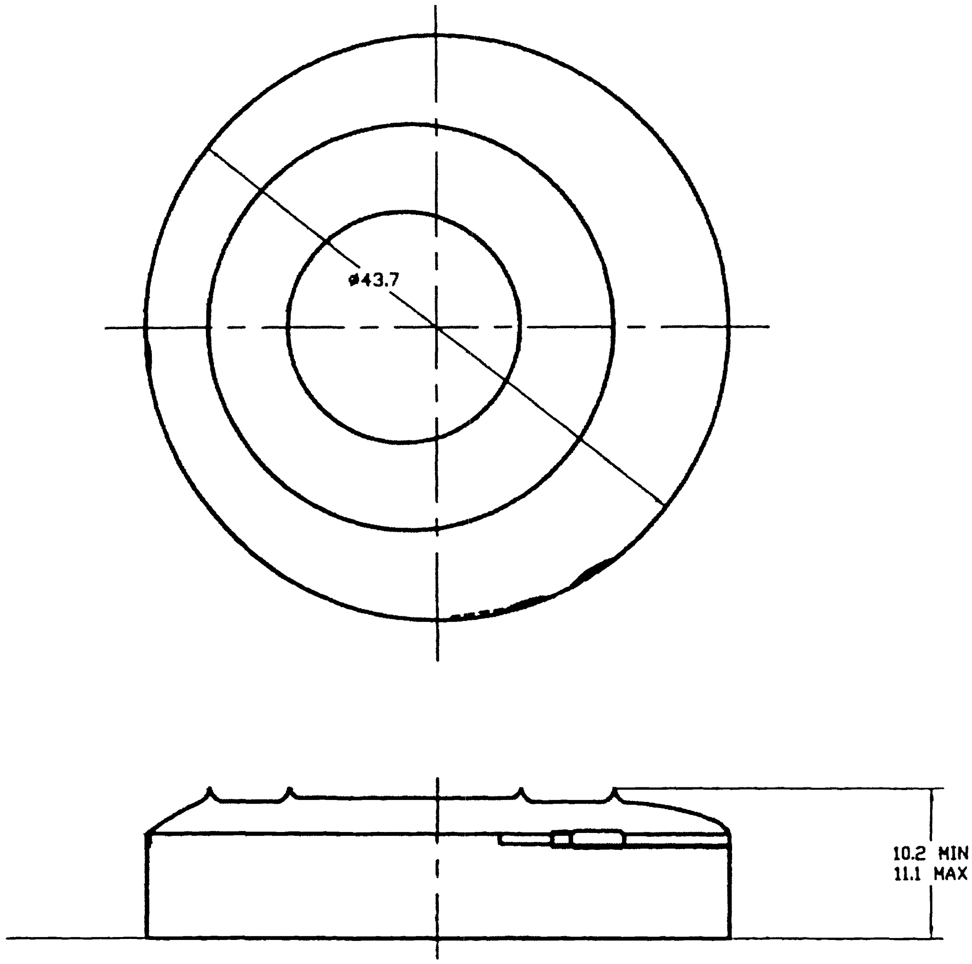

Figure 10. Infrasil 302 Boule #2 as Produced by Heraeus

4.2.4 Summary of Corning conformal window processing efforts

The work performed to date at Corning indicates that the standard Corning thermal processes of flowout and sagging can be used for the prime ABL conformal windows, with the major differences being:

- Higher temperature refractory materials and modified refractory designs
- Higher furnace temperatures based on Infrasil viscosity curves
- Standard Infrasil fine anneal cycle, as provided by Heraeus

Corning processes, modified by what was learned from risk reduction efforts and combined with the improved 1.1 meter boule mass and geometry developed by Heraeus, result in a low risk, production-ready technique to produce the ABL conformal windows. To support the blanks during grinding and generation at Corning, blocking bodies have been manufactured and machined of ULE™. The generation of the convex blocking body is shown in Figure 11 and the steepness of this window design is clearly apparent in both Figures 11 and 12. The remaining challenge for Corning will be handling and support of the high aspect ratio (74:1), high value glass blanks themselves. Corning will generate the blanks to near final specifications, requiring only figuring and polishing at Contraves-Brashear Systems.

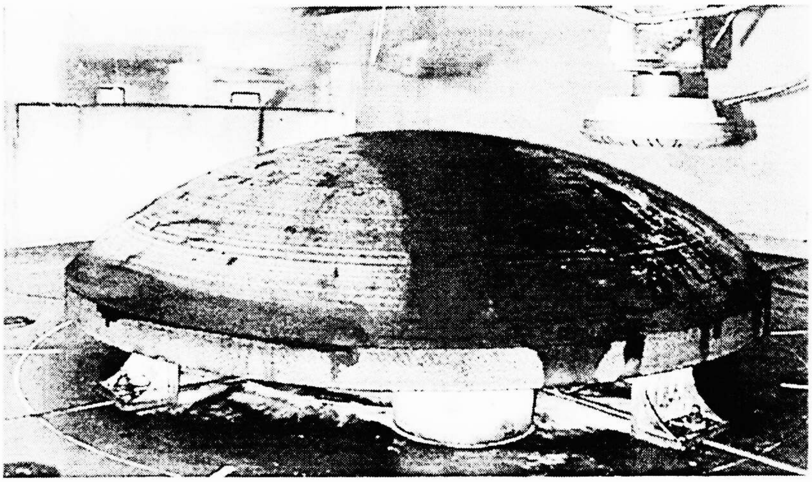

Figure 11. Convex Window Blocking Body on Corning Grinder

Figure 12. Concave Blocking Body for Conformal Window after Generation

5. SUMMARY

A unique, international team of glass experts from the government and industry jointly developed a process to produce the largest fused quartz window ever made. Each member provided key contributions, enhancing and improving techniques for producing the highest quality optical components to make the blanks for the ABL conformal windows. This was done with no requirements for capital investments on the part of Heraeus or Corning and with a constant consideration of meeting ABL program goals while keeping program costs to a minimum. The window is in its final stages of processing at Corning and will be polished and figured at Contraves Brashear for the first ABL aircraft.

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