How Beryllium Proved Successful on the Space Shuttle Orbiter

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The paper discusses the design and material property requirements that led to selection of premium structural grades of beryllium for three primary areas of the Space Shuttle Orbiter: the crew module windshield retainers, spacers, and beams; the navigation base in the crew module; and the umbilical external tank doors in the aft fuselage. Beryllium was used for two primary reasons: it is light and stiff. There are 22 mechanically attached beryllium parts and 15 adhesive-bonded beryllium parts in each Orbiter. Special tooling and fabrication processes were developed. Fabrication of detailed components required special cutting and etching parameters to eliminate cutter-induced twinning of the grain structure. These methods and processes, as well as some of the problems encountered, are discussed in detail. The windshield components, which were fabricated from premium structural grades of hot-pressed beryllium, are the first structural applications successfully used in a man-rated, pressurized spacecraft.

Background

WHEN the Shuttle Orbiter design phase began, there was no plan to use beryllium in either the structure or system components. As the design of the horizontal flight test Orbiter (Enterprise, OV-101) was completed, an analysis indicated that the Orbiter was overweight. This triggered a series of weight reduction studies, which included consideration of beryllium in areas where its high stiffness-to-density ratio, in particular, could be utilized.

The first weight trade study to recommend beryllium was completed and approved in March 1975. It recommended replacement of six crew module windshield 2124 Al alloy spacers and six A286 iron-base superalloy inner retainers, as well as four external A286 windshield beams, with parts produced from hot-pressed beryllium block. The design concept is shown in Figs. 1 and 2. It was estimated that the weight saved was 128 lb at a cost of $2268/pound of weight saved. This price was very cost effective since the target upper limit was $5000/pound.

In the fall of 1975, a series of inertial guidance system design studies resulted in a decision to design and fabricate an adhesive-bonded honeycomb sandwich structure with beryllium edge members and facings to produce a high stiffness-to-density ratio, thermally stable navigation base for Columbia (OV-102). These studies consisted of defining the critical design constraints, structural design requirements, ground support equipment, alignment, and mounting techniques. This was followed by a complete stress and environmental analysis and qualification test plan. Results indicated that a bonded beryllium, tapered honeycomb box structure was the most feasible approach to satisfy the critical engineering requirements for the stable navigation base. The base is required for mounting three inertial measurement units and two electro-optical star trackers as sensors for navigation of the Orbiter in Earth orbit. An aluminum star tracker boom is attached to the navigation base and two beryllium adapters are attached between the boom and two star trackers. The navigation base design concept is shown in Fig. 3, the star tracker boom in Fig. 4, and the installation concept in Figs. 5 and 6.

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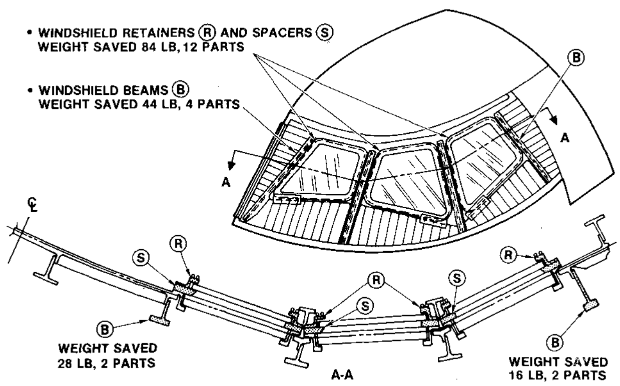

Fig. 1 Crew module beryllium applications.

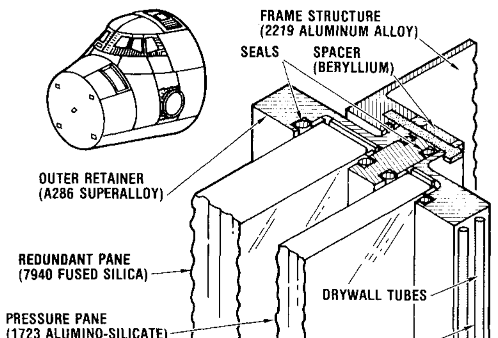

Fig. 2 Current design of crew module windshield.

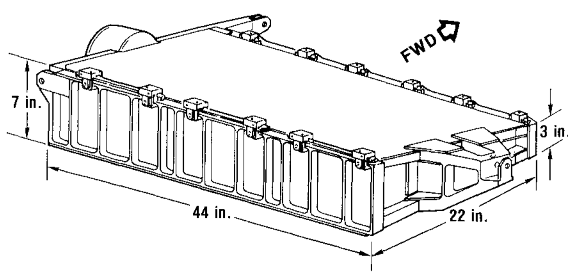

Fig. 3 Adhesive-bonded navigation base assembly.

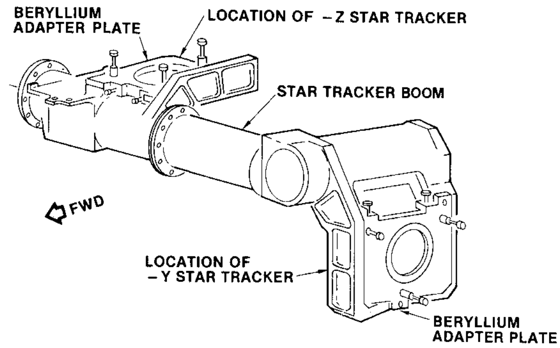

Fig. 4 Star tracker boom portion of navigation base.

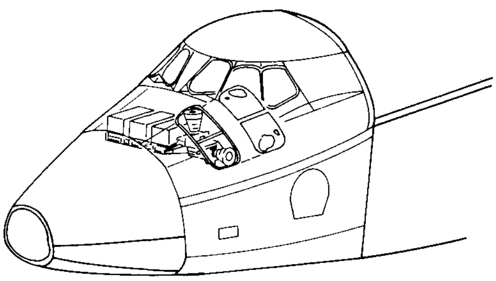

Fig. 5 IMU, star tracker, and navigation base installation.

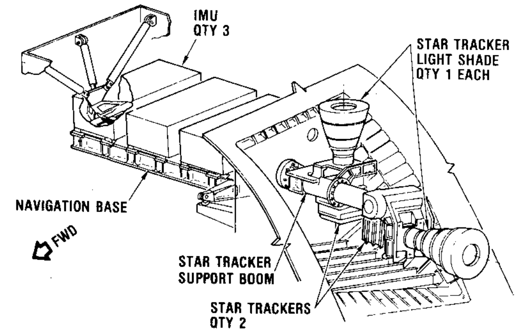

Fig. 6 Location of IMUs and star trackers in crew compartment.

In May 1976, a third design study was completed on the two external tank (ET) umbilical doors. This study compared several concepts for the door structure: a double-skin aluminum, two aluminum waffles and a tapered-plate beryllium. After an engineering stress, thermal, and operation design analysis was completed, the tapered-plate beryllium door was selected. Again, beryllium was selected primarily because it had the lowest weight for the required stiffness. The overall cost increase per pound of weight saved was estimated to be only $1350.

Design Requirements and Considerations

All of the previously mentioned structural designs needed beryllium to satisfy the high stiffness-to-density requirement and size limitations, even though beryllium had serious drawbacks. It was well known that beryllium was expensive, had limited ductility, was notch sensitive, and was difficult to machine without surface damage. It also had a toxicity hazard. Therefore, many design considerations and ground rules were established to ensure success:

1) Select the most ductile types of beryllium for structural applications. A minimum of 3% elongation in all directions is required.

2) Use conservative design allowables, resulting in $f/s = 2.0$ in tension and 1.5 in compression.

3) Require acid-etch stress relief for all machined parts to obtain twin-free surfaces. Qualify the machine tools and parameters to limit the depth of twinning.

4) Prohibit metal removal on assembly or installation.

5) Specify liberal fillet radii and a 125 μin. or better surface finish.

6) Avoid tapped holes and pressed-in bushings or inserts on structurally loaded applications.

7) Ensure that all holes are match drilled at the detail level.

8) Provide adequate corrosion protection between dissimilar materials.

9) Assemble by mechanical fastening or adhesive bonding.

Windshield Retainer and Post Beam Design Requirements

Since the windshield frame structure had already been designed and fabricated for the Enterprise, the beryllium retainer and spacer had to be designed so that each new windshield assembly was interchangeable with the original windshield assemblies. Also, there was to be no loss in vision or change in glass trim. The six inner beryllium retainers were required to have 304L stainless steel tubes attached by aluminum plasma spray to provide thermal conductivity and eliminate condensation (Fig. 2).

Interchangeability of the beryllium windshield post beams with the A286 required that bearing strength allowances be determined for ratios of the edge distance to the hole diameter of less than 1.5. The most important design requirement was that the beams and windshield retainer assemblies be stiff enough to prevent excessive deflection. Large deflections could induce bending loads in the glass panes when the crew module windshields have a maximum pressure differential of up to 16 psi in space.

Navigation Base Design Requirements

A primary design requirement was that the navigation base be as stiff and dimensionally stable as possible because of the critical alignments needed for accurate navigation in space. This meant that the navigation base had to be stable in an environment of inertial, vibroacoustic, and thermal conditions. Also, the location available for installation limited the thickness of the base. Using beryllium, with its high modulus of elasticity and its excellent thermal properties, along with a tapered honeycomb sandwich platform, avoided any avionic impact risk. To satisfy the thermal conductivity requirements, all adhesive bond thicknesses were 0.005 in. or less. In addition, each inertial measurement unit (IMU) attachment to the navigation base was to be thermally isolated from the base (the IMUs are aircooled). This required assembling 6AL-4V titanium isolators and 304L stainless steel pads to the navigation base (Figs. 3 and 5).

In order to meet the avionic alignment requirements, each IMU four-pad set had to be machined to within a maximum of ± 500 arc-seconds per axis with respect to each other pad set. For each of the three IMU stations, all four-pad alignment surfaces were machined flat and parallel within 0.0005 in. (After assembly of the navigation base, the IMU and star tracker pad sets are measured optically to support the vehicle navigation and payload pointing.[1])

The star tracker boom assembly, which attaches to the navigation base, has two mechanically fastened beryllium adapter plates with precision flat surfaces for mounting the two star trackers (Fig. 4). Beryllium was chosen for its high modulus and thermal stability. The critical alignment surfaces were nickel plated and lapped within 0.000044 in. over three coplanar surfaces.

External Tank Umbilical Door Design Requirements

The ET umbilical door design requirements are unique because these are the only doors that must be open during launch and closed prior to re-entry. During ascent, there is a nominal clearance of only 0.80 in. between the tiles on the doors and those on the lower surface of the aft fuselage. This means that the doors must be very stiff to withstand the dynamic and static deflection loads, as well as the vibro-acoustic and thermal conditions during launch. With use of a simple beryllium plate, machined from hot-pressed block, 1.29×50×50.25 in., an analysis revealed that the 0.80-in. deflection clearance could be met. Beryllium provided other advantages, too. Its high heat resistance, high specific heat, good thermal conductivity, and low thermal growth ensured that there was no need for internal insulation during launch.

The only critical requirement for fabrication was to maintain the external and internal attachment surfaces flat and parallel within 0.010 in. with a surface finish of 125 μin. or better after etching.

Suitability of Beryllium

In applying beryllium to the Shuttle Orbiter, the designers took advantage of its unique combination of properties. The modulus-to-density ratio (Fig. 7) of beryllium is 6.4 times greater than that of aluminum at room temperature. This advantage was significant in the design of the navigation base. At 500°F, considered acceptable for noninsulated beryllium ET doors and comparable to insulated aluminum doors at 350°F, the modulus-to-density ratio of beryllium is 7.7 times that of aluminum. In addition, beryllium's high strength-to-density ratio, high specific heat, and high thermal conductivity proved to be the best choice for the Orbiter applications discussed. For comparison, the densities, moduli, and thermal properties of several materials are shown in Figs. 8-10 and Table 1.

Selection of Beryllium Grades

A premium high-purity grade of isostatic press block was selected originally for the windshield beams. This beryllium block, known commercially as CIP-HIP 1, was produced by the cold/hot isostatic consolidation process. It had the highest minimum tensile yield properties (35,000 psi), combined with a minimum elongation of 3%.[2] After CIP-HIP 1 was used on Columbia and Challenger, the supplier discontinued production of this beryllium grade. As a result, the beams for the remaining two Orbiters were made from the S65 premium structural grade, which has a minimum tensile yield strength of 30,000 psi and a minimum elongation of 3%. Since the conservative design allowable tensile yield of 28,000 psi had been used, only a minor design increase in the cross section was required. Typical F_{ty} values taken from S65 certification test specimens were 33.3-36.1 ksi with elongations of 3.4-5.9%, the transverse properties being slightly higher than the longitudinal values, particularly in elongation. Minimum guaranteed tensile properties for all grades selected for the various parts are shown in Table 2. In order to retain these properties, no inclusions were allowed.[3]

Tooling

All of the matched-hole drilling, boring, and reaming of the detail parts was done on conventional steel drill fixtures produced from master drill plates or interface control tools. All other metal-removal operations were accomplished by programmed numerical control (NC) tape milling machines. All NC tapes were tested on aluminum prior to machining beryllium. All the cutting tools were either solid carbide or had carbide inserts. The adhesive bond fixtures for the navigation base were especially designed for accurately positioning all the parts and maintaining that accuracy at bond temperatures up to 250°F with autoclave pressures up to 50 psi. Achieving this accuracy meant that the tooling material had to have almost the same coefficient of expansion as beryllium. Therefore, PH 17-4 steel was selected. The finished bond fixture, with all parts in place for vacuum bagging, is shown in Fig. 11.

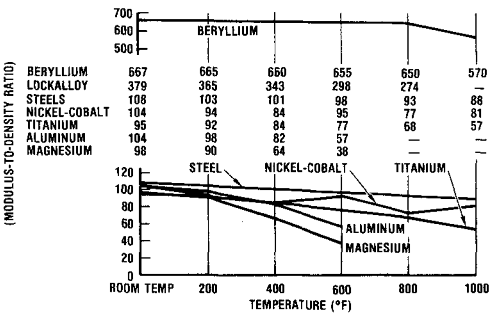

Fig. 7 Modulus-to-density ratio of various metals.

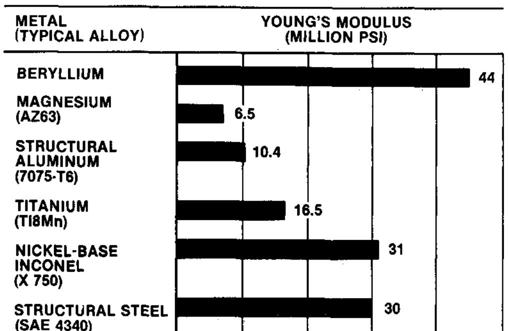

Fig. 8 Modulus of various metals.

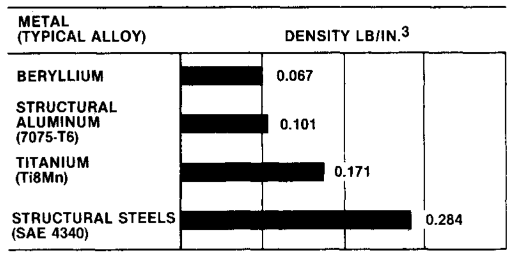

Fig. 9 Density comparison of various metals.

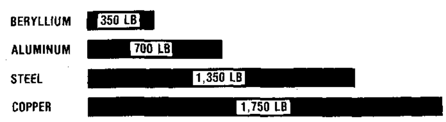

Fig. 10 Heat absorption efficiency of beryllium.

Table 1 Comparative thermal properties of materials

Material	Specific heat, Btu/lb·°F	Melting point, °F	Thermal conductivity, Btu ft/ft²·h·°F	Coefficient of linear expansion, ×10⁻⁶in./in./°F
Beryllium	0.46	2,345	104	5.4
Aluminum	0.22	1,220	128	13.1
Steel	0.12	2,800	27	8.3
Copper	0.09	1,980	226	9.8

Table 2 Selection of beryllium grades

Part description	Grade	Minimum guaranteed values F_{tu}, psi	Minimum guaranteed values F_{ty}, psi	Elongation, %
Windshield post beams (first two Orbiters)	CIP-HIP I block	50,000	35,000	3.0
Windshield spacers, retainers, and post beams, navigation base fittings, ET doors	S65 block	42,000	30,000	3.0
Navigation base facesheets and splices	SR-200E sheet[a]	70,000	50,000	10.0
Forward windshield heat sinks	S-200E block	40,000	30,000	1.0

[a]0.020-0.249 in. thick.

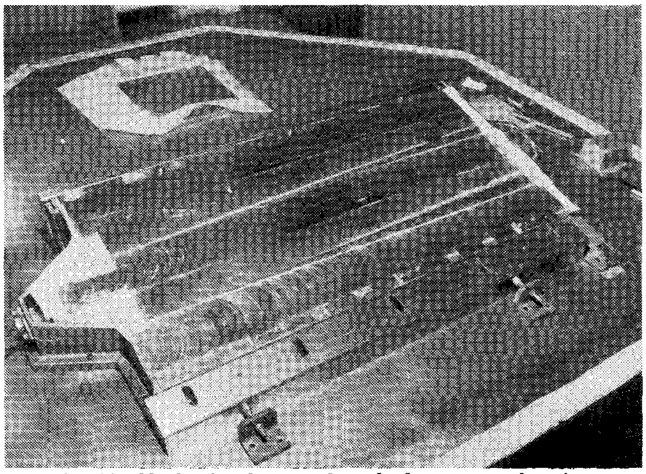

Fig. 11 Navigation base tool ready for vacuum bagging.

Machining

Early in the process development phase of fabricating beryllium parts (from literature surveys and prior experience), it was recognized that beryllium surfaces had to have all evidence of machine damage eliminated to be successful in structural applications on the Shuttle Orbiter. It has long been known that, because of its hexagonal close-packed atomic structure, beryllium is extremely susceptible to surface damage from machining. This damage is manifested in the form of "twinning" of the crystallographic grain structure to varying depths in the beryllium surface. Twinning can ultimately lead to surface microcracks at the intersecting twins, which later travel along the matrix twin surface until complete fracture occurs. Historical observations reveal that premature failure of beryllium is initiated at twinned surfaces.[4]

Precautions were taken during all machining and etching operations to eliminate any possibility of beryllium toxicity that could cause a health hazard. All machining was performed with vacuum collection ducts mounted over all the cutting tools, in controlled areas in compliance with OSHA requirements.

Machining and Etching Requirements

To preclude the possibility of premature failure, stringent requirements were imposed on the machining of all the beryllium components for Space Shuttle applications. The most stringent was that, after machining and etching (to remove twinning), no twinning was to be present in metallographically prepared in-process control specimens. To satisfy this requirement, it was first necessary to qualify the metal removal and acid-etch process used by each fabricator and approve it prior to fabrication of any production parts. This required documented evidence that all processes and all parts were in compliance with all of the Rockwell Shuttle Orbiter Division engineering requirements. For further control of the metal removal process, in-process control specimens were fabricated from the same material at the same time as the production parts and were metallographically examined for verification of twinning removal.

The amount of acid-etch metal removal finally required to eliminate twinning is now a minimum of 0.006 in. This was not determined overnight. Prior industry practice was typically 0.003-0.004 in. with 0.005 in. considered maximum. The studies conducted covered a range of 0.005-0.010 in. of acid etching following the various machining parameters of depth of cut, cutter speed, and feed rate. Since the machining parameters were established on unetched specimens with twinning depths less than 0.006 in., it was determined that a removal of a minimum of 0.006 in. by etching eliminated all evidence of twinning.

Machining Procedure

Two experienced beryllium machining sources were initially unsuccessful in qualifying to the "twin-free" requirement after etching on test specimens. Qualification to the fabrication specification was subsequently accomplished by first improving the machining procedure and then improving the specimen polishing procedure. While the detail procedure varied slightly between the two sources, all test specimens were at last free of twinning.

Generally for milling operations, the cut depths were 0.025-0.030 in. for roughing, 0.010 in. for semifinishing, and 0.005 in. for finishing, so that the machine damage from each pass would be removed by each succeeding pass. In most cases, it was found desirable to make two semifinishing passes, followed by only one finish pass.[5]

Rough cuts were milled at carbide cutter speeds of 157-357 surface ft/min (sfm) at a feed rate of approximately 0.003 in./turn (ipt). Finish cuts to minimize surface roughness and maintain critical dimensions required speeds as low as 131 sfm at a feed of 0.00075 ipt. Hole drilling, boring, and reaming used speeds of 50-80 sfm at feed rates of 0.0005-0.00083 ipt.

Fabrication of Beryllium Structures

External Tank Umbilical Doors

The ET umbilical doors are machined from plates of S65 beryllium block cut from a 72-in.-diam hot pressing. The as-received 50.00×50.25 in. slabs are 1.190 in. thick and are required to be flat within 0.030 in. total indication reading (TIR) and have a 63 μ-in. finish. The finished machined and etched doors are 1.100 in. thick in the center, tapering to 0.507 in. toward the edges; the entire edge perimeter is 0.900 in. thick. The outer surface is machined flat within 0.010 in. TIR. The finished width is 49.230 in. and the length is 49.353 in. A row of holes is drilled, reamed, and etched in the 0.900-in.-thick periphery of each door. Etching 0.006 in. (0.012 in. diam) from all the hole surfaces presented a problem, since a "bell-mouth" condition occurs in thick sections because of non-uniform etch rates. Tests produced a bellmouth diametrical difference of only 0.0016 in. This was within the ± 0.002-in. design tolerance, so it caused no problem. The completed pair of doors is shown in Fig. 12. The doors are protected against corrosion with a conversion coat and primer. The doors, following assembly operations, are then installed on the underside of the aft fuselage of the orbiter.

The first two ship sets of doors were fabricated without defects or problems, but the third set had a slight out-of-flat warpage condition. One was discovered to be 0.020 in. convex, while the other was 0.052 in. concave during machining. Fortunately, the doors 0.052 in. out of flat had not been final machined and 0.025 in. remained prior to etching. By turning the door over and taking a light cut and then turning it over a second time to complete the finish machining, both doors were corrected and were accepted through material review action. Another problem arose when they were to be assembled: one hole was undersized. However, this was readily corrected by manual swab acid etching and repriming.

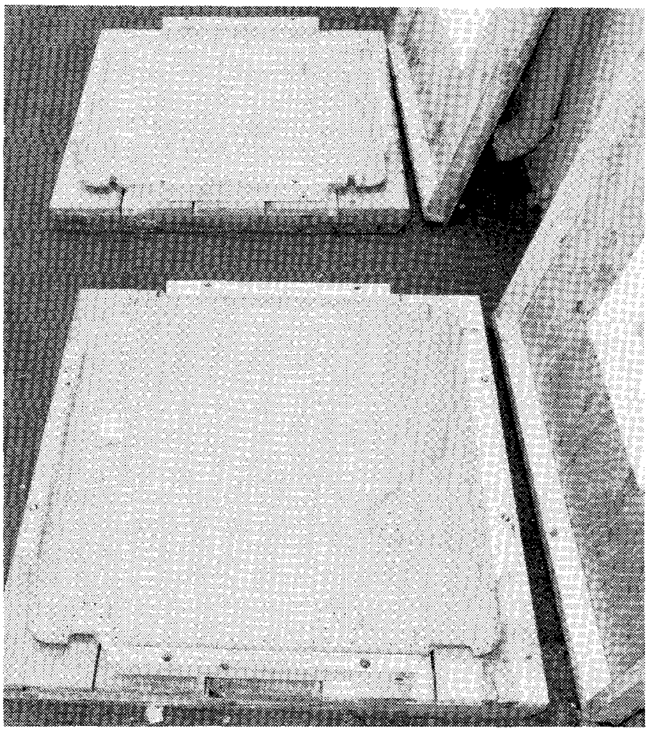

Fig. 12 External tank umbilical doors.

Windshield Retainers and Beams

Once all of the tooling for the match holes was approved and the machining and etching parameters established, there were few fabrication problems. The etching of the 0.700-in.-thick beryllium windshield spacers caused bellmouthing of the holes; the diametrical difference was almost 0.002 in. There was concern that the bolted retainer assembly might move enough to affect the bending stiffness of the assembly adversely. However, the 0.002 in. bellmouthing was accepted after evaluation of the condition and tests on windshield test articles.

The only other problem was the attachment of the dry-wall stainless steel tubes to the beryllium inner retainer by an aluminum plasma spray process. This process involved considerable development and testing. The aluminum plasma spray was used to obtain good heat transfer from the warm water tubes to prevent condensation inside the window in the cold environment of space. A test program was established to verify the design and process and to qualify a source. The results were successful. The thermal shock test was twice the temperature range expected in flight. The test consisted of three cycles of heating the specimens to 216°F and then quenching into an alcohol and ice bath at 10°F. To date, these tubes, plasma sprayed to beryllium windshield re-

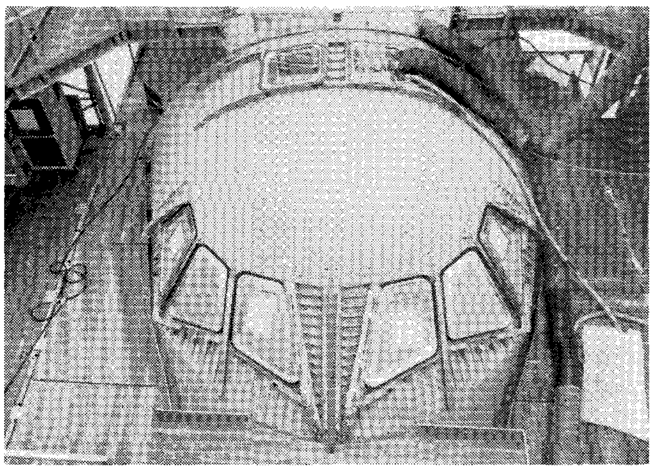

Fig. 14 Orbiter 103 crew module (Oct. 18, 1982).

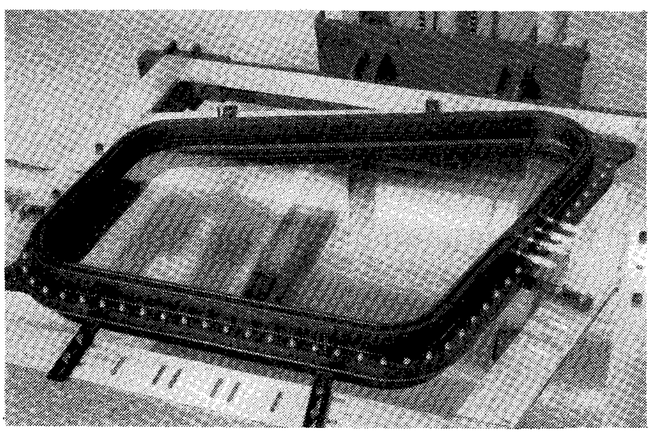

Fig. 13 Assembled crew module windshield.

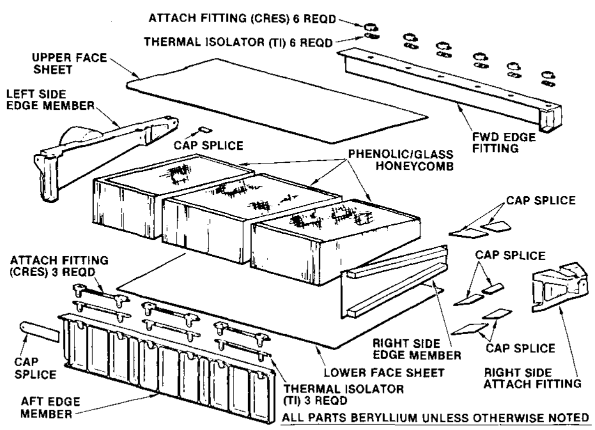

Fig. 15 Navigation base detail parts (exploded view).

Table 3 Seven-stage bonding of navigation base

Stage	Adhesive	Type of joint	Cure temp, °F	Time,h	Pressure, psi
1	Epoxy-phenolic HT 424	Beryllium splices to fitting, right-hand end	340±10	1-1.5	≥10
2	Nitrile epoxy FM 123 and FM 37	Beryllium honeycomb panel	250±10	60-90	45±5
3	FM 123	3 beryllium splices to Be panel	190±10	6-7	10-15
4	Epoxy 206	1 beryllium splice to Be edge member	RT or 180±10	72 1-2	1-10 1-10
5	EA 934	Fill small tool holes and gaps	RT or 115-180	24 6	Contact Contact
6	Epoxy 206	Titanium and CRES fittings to Be upper surface	RT or 180±10	72 or 1-2	1-10 1-10
7	Epoxy 206	Six CRES bushings and six Vespel guards	RT or 180±10	72 or 1-1	1-10 1-10

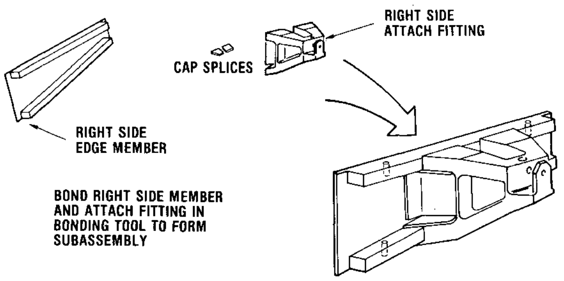

Fig. 16 Navigation base adhesive-bonded subassembly.

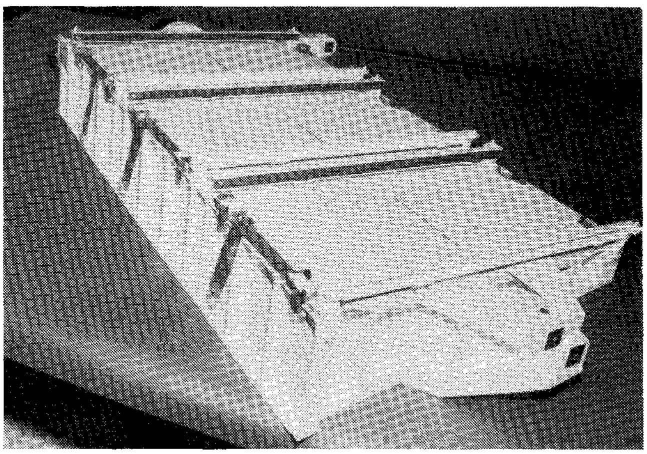

Fig. 17 Navigation base with IMU guide rails attached and painted.

tainers, have been assembled on four ship sets of double-pane glass windshields (Fig. 13).

The retainers and spacers are complete surrounds diagonally measuring roughly 40 in. Each set contains 164 match-drilled holes, of which half are 0.193±0.001 in. and half 0.195±0.001 in. One style of beam is a "T" 51 in. long and the other is roughly an "L" 42 in. long. They have 41-49 holes (0.190+0.0017, −0.0005 in.) in one flange and two 0.025-in. holes (same tolerance) in the other.

All six windshield assemblies and the four beryllium beams are shown in Fig. 14 after being installed in the crew module

Table 4 Room temperature mechanical property test requirements

Adhesive	Type/test	Minimum strength required
HT 424	Lap shear	2,500 psi
FM 123	Lap shear	3,500 psi
FM 123	Honeycomb peel	55 part/in.
EA 934	Hardness	75 Shore D
Epoxy 206		
Grade A	Lap shear	3,500 psi
Grade A	90 deg peel	40 lb/in.
Grade B	Hardness	70 Shore

of the third Orbiter. It should be noted that all windshield spacers and inner retainers inside the crew module were given an added corrosion protection coating of black polyurethane paint over anodized beryllium to protect the crew from any potential toxicity.

Navigation Base

Of all the beryllium applications, fabrication of the adhesive-bonded honeycomb sandwich navigation base is by far the most complex and precise. The size is shown in Fig. 3. Figure 15 is an exploded view of the 36 detail parts that are subsequently bonded in 7 stages. Five different adhesives are used, including the foaming type (FM37) that splices the HFT 1/8-5.5 glass fabric honeycomb core, which is impregnated with a heat-resistant phenolic resin. The honeycomb core assembly required splicing and precision machining to a thickness tolerance of ±0.005 in. between the top and bottom surfaces as well as between the step cuts. All of the beryllium details were machined, etched, and primed with BR127 primer. The seven-stage bond cycles are described in Table 3, the subassembly bonded in the first stage in Fig. 16, and the mechanical property test requirements in Table 4. Figure 17 shows the base with IMU guide rails attached and painted, ready for the star tracker boom to be added for bench check alignment.

Conclusions

All of the beryllium applications discussed met or exceeded the design requirements, as demonstrated by the successful Earth orbital fights of Columbia, Challenger, and Discovery. The beryllium windshield applications were the most critical structurally, since they prevented any excessive deflection of the glass windshield panes when pressurized. This is the first successful structural application of hot-pressed beryllium on a pressurized manned spacecraft. From a fabrication viewpoint, the navigation base was probably the most difficult adhesive-bonded honeycomb sandwich structure ever undertaken. It required several tooling, design, and fabrication improvements before a quality, stable platform was attained. It was also learned that damaged areas of beryllium can be reworked in most cases. To date, after fabrication of four ship sets of beryllium details and assemblies, only three details have been scrapped. One resulted from improper clamping during a machining operation, which caused the part of fracture. Operator error caused the other two.

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