Manufacture of Mirror Glass Substrates for The NUSTAR Mission

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Abstract

The NuSTAR (Nuclear Spectroscopy Telescope Array) observatory (Harrison et al. 2009), expected to be launched into an equatorial low earth orbit in 2011, will have two mirror assemblies capable of imaging X-rays in the hard X-ray band between 5 keV and 80 keV. It will be the first X-ray observatory using multilayer coatings to significantly expand the bandwidth of the typical X-ray telescope of 0.1 keV to 10 keV. The mirror assemblies use a segmented design to simplify the construction process, as such they require 4,680 mirror substrates coated with appropriately designed multilayers to enhance reflectivity for hard X-rays. These substrates are produced by slumping commercially available thin glass sheets. In this paper we report on our work of manufacturing these substrates at NASA Goddard Space Flight Center.

Key Words: X-ray optics, lightweight optics, NuSTAR, Glass Slumping

1 Optical Design and Requirements for Substrates

The NuSTAR mirror assemblies have their heritage in the previously flown balloon payload HEFT (High Energy Focusing Telescope) (Koglin et al. 2005). They use the conical approximation to the traditional Wolter-I optical design. The conical approximation is implemented in two steps: (1) starting with cylindrically-shaped mirror segments whose radii of curvature are within 1 mm of their respective design values; (2) the alignment and integration process bends the cylindrical mirror segments into the required conical shapes and attaches them to the mirror assemblies under the monitoring of real-time metrology. As such the first step of making these mirror assemblies is the manufacture of cylindrically shaped glass substrates.

The NuSTAR substrate production is based on a glass slumping technique developed for the International X-ray Observatory (IXO mission, formerly known as the Constellation-X (Zhang et al, 2006) mission. It uses commercially available thin borosilicate glass sheets and slump them on precisely polished and figured fused quartz mandrels. As a result, the finished curved glass is a replica of the mandrel. It takes up the overall shape of the mandrel while preserving the excellent microroughness of the glass sheets.

Table 1 lists the relevant parameters that specify the substrates.

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Table 1. Key parameters specifying the mirror assemblies and substrates.

Parameter	Quantity	Comment
Mirror assembly focal length	10,150 mm	Determined by the mast that connects the focal plane detectors and the mirror assembly; Realized by bending the cylindrically shaped mirror substrates into conical shapes
Number of flight mirror assemblies	2	Determined by the mission level effective area requirement
Number of concentric shells per mirror assembly	130	Determined by optical design
Number of shells segmented into 60-degree sectors	Inner 65 shells	The division between the inner and outer rings is determined by a compromise between the desire to constrain each mirror as much as possible and the desire to minimize blockage by mechanical structures
Number of shells segmented into 30-degree sectors	Outer 65 shells	
Diameter of the innermost shell	110 mm	Determined by a compromise between having as many shells as possible without breaking the mass budget
Diameter of the outermost shell	382 mm	Determined by the size of the launch vehicle fairing
Axial height of either the primary or secondary segment	225 mm	Determined by a compromise between the desire to have as large a height as possible and desire to minimize the error caused by conical approximation
Total number of mirror substrates per mirror assembly	2340	=65*6*2 + 65*12*2
Substrate thickness	0.21 mm	Determined by the mass budget allocation and availability of glass sheets
Glass type	Schott D263	Determined by its easy and economic availability
Dimensions of the smallest substrate	225 mm (axial direction) by 56 mm (azimuthal direction)	Determined by optical and mechanical designs
Dimensions of the largest substrate	225 mm (axial direction) by 100 mm (azimuthal direction)	

2 Production Facility

The NuSTAR substrate production facility, shown in Figure 1, is located in Building 22 at the Goddard Space Flight Center. It occupies a high-bay laboratory with a ~2,000 sq ft floor area. It has 8 ovens enclosed in Class 100,000 clean tents that are specially constructed and fitted. The HEPA units of the clean tents are fitted with cooling coils that chilled water flows through to cool the inside of the clean tents when necessary. The chilled water flow rate is controlled by a manual valve that can be turned to the appropriate setting determined by the need.

The ovens are industrial ovens manufactured by L&L Special Furnace, Inc. of Aston, PA. They are steel frames insulated with firebricks and fiberglass wools and heated with electric heaters. They can sustain a high temperature of 1,100° C. They use standard industrial and fully programmable Honeywell PID controllers. In addition there is an over-temperature controller that turns off the oven in case the programmable controllers malfunction and the oven temperatures run away. These ovens also have an interlock switches that turn off the heaters whenever the oven doors are open. These ovens use multi-zone controls and, when no load is present, can achieve a temperature gradient less than 1° C with little convection.

In addition, the facility has a flat glass sheet cutting and cleaning system, including a state of the art glass cutter, an ultrasonic cleaning station, and custom-designed and –built glass drying station. The facility is also protected by a state of the art aspirated fire protection system. It regularly samples the air of the laboratory and reports the results to the central console of the Goddard Space Flight Center.

Figure 1. Photo of the mirror substrate manufacture facility: eight ovens in Class 100,000 clean tents, four of which are visible from this perspective and the other four are to the right of this scene.

3 Production Process

The production of each NuSTAR substrate is accomplished in five steps, detailed in Sections 3.1 through 3.5.

3.1 Forming Mandrels and Their Preparation

Forming mandrels are fused quartz cylinders. A total of seventy-five blanks were ordered from Technical Glass Products, Inc. of Painesville, OH. They range in outer diameter from 100mm to 396mm, one cylinder every 4mm increment: 100, 104, 108, …. 396mm.

These blanks were further polished by Rodriguez Precision Optics, Inc. of Gonzales, LA to meet NuSTAR requirements. Of the 75 blanks, 73 were sent to Rodriguez for processing, 3 (256, 292, and 396) of which were damaged during the polishing process or during shipping. The axial figures of the remaining 70 were measured using a 24-inch aperture Zygo interferoemeter at four different meridians: 0°, 90°, 180°, and 270°. If they meet clear aperture (middle 225mm) requirements, they are cut in half along the symmetry axis so that there are two mandrels to use for slumping that double the mirror substrate production rate.

The polished fused quartz mandrel surface is coated with a layer of boron nitride as a release layer. The boron nitride performs two functions. First it prevents the glass sheet from adhering to the mandrel surface. Second it provides a lubricious interfacial layer between mandrel and glass sheets so that the glass sheet can slide freely. This is especially necessary because of the large CTE (coefficient of thermal expansion) mismatch between fused quartz and the D263 glass sheets. After the boron nitride layer is applied, it is gradually smoothed by buffing to achieve a semi-specular surface on which the glass sheet will slump.

3.2 Preparation of Flat glass sheets

Flat glass sheets are procured from Schott. They come 50 sheets to a packet. Each sheet is 17 inches by 14 inches and 0.21mm thick. They are first cut to appropriate sizes and then washed in a standard process: (1) soap and hand-rub, then (2) ultrasonic cleaner with detergent, and then (3) dried under HEPA units. The amounts of detergent and soak time in the ultrasonic solution are minimized to prevent any degradation of microroughness that can be caused by the detergent.

3.3 Slumping

The slumping process is illustrated in Figure 2. The flat glass sheet is placed atop a forming mandrel. As the temperature is ramped up from room temperature to about 600° C, the glass sheet becomes soft and gradually wraps itself around the mandrel, taking the precise shape of the mandrel. The temperature is then ramped down slowly to ensure that the glass sheet is adequately annealed to minimize any frozen stresses that can degrade the figure at room temperature.

Figure 2. Illustration of the slumping process: a sheet of glass is placed atop of the cylindrical mandrel in an oven. When the temperature is gradually ramped up from room temperature to about 600°C, the glass sheet softens and conforms itself to the mandrel.

After the slumping, each glass replica is designated with a unique label identifying the mandrel off which it is slumped and the telescope shell it is meant to be part of and a unique serial number. Fiducial marks are also placed on the glass replica to serve as guides for the cutting step.

Figure 3 shows several mandrels with their replicas just coming out of an oven.

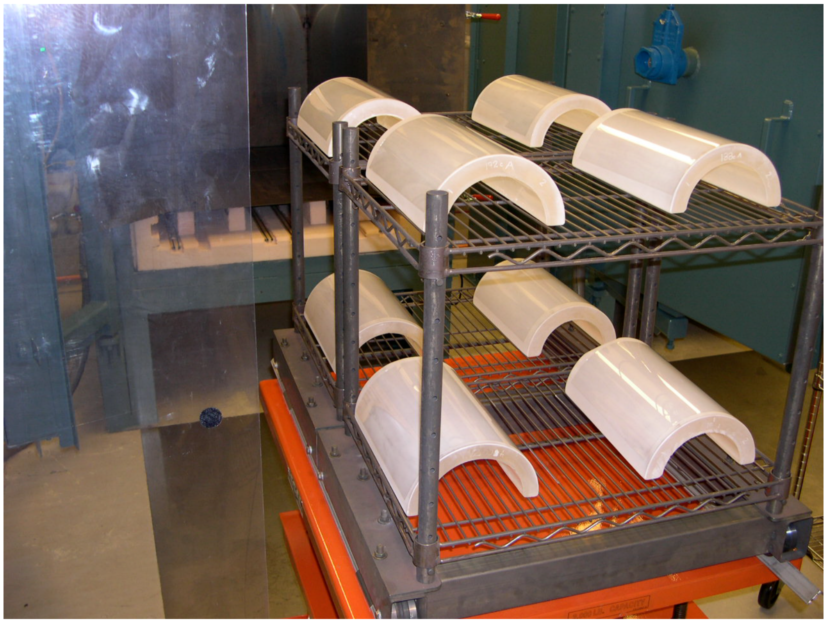

Figure 3. Eight mandrels with formed substrates on them are brought out of the oven. Each whole cylinder mandrel has been cut into two so it can be used as two mandrels, speeding up the production.

3.4 Post-Slumping Cutting

The formed replicas taken off the forming mandrels are much larger than needed. They need to be cut to required dimensions for mounting into mirror assemblies. A Mylar template is made according to engineering drawings for each of the 130 mirror shells: 130 primaries and 130 secondaries. These templates are used to mark each replica for its specific shell designation using the fiducial marks placed on the replicas while they were still on the forming mandrels. A hot-wire cutting technique is used to cut the replica along the markings, resulting in the final substrate. The cutting is to ensure that each substrate have the correct dimension for the assembly and that the edges are free of micro-fractures that could propagate to cause the loss of the mirror substrate. Figure 4 shows the cutting process and Figure 5 shows the resulting cutting edge in comparison with the edges from other techniques.

Figure 4. Post-slumping cutting of the substrate using a hot-wire. The glass cracks under thermal stress. The crack trails the Nichrom hot-wire which is heated with an electric current. There is no material loss. It leaves a very smooth and fracture-free edge as shown in Figure 5.

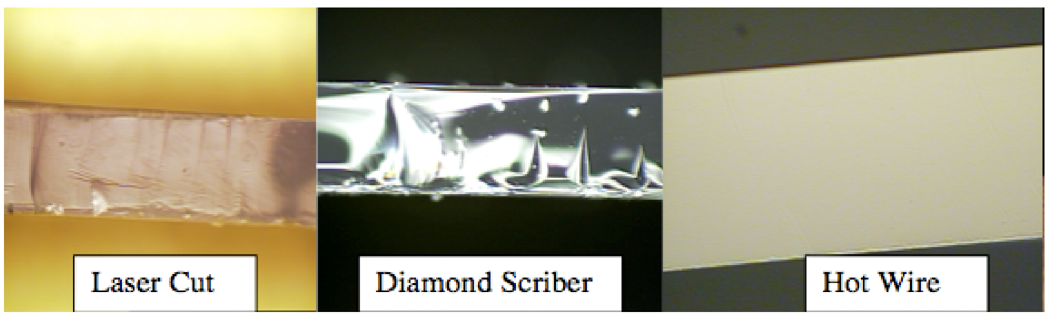

Figure 5. A comparison of glass edges resulting from the three different cutting techniques.

3.5 Metrology

The optical surface quality is measured using two instruments. The first instrument, a Zygo Newview 5000 surface profiler, is capable of measuring the microroughness covering the length scale from about 1 μm to about 1 mm. In general the slumping process does not change the excellent microroughness of the glass sheets. This has been demonstrated by both measurement using the Zygo Newview 500 profiler and X-ray scattering measurement. In particular, numerous X-ray measurements indicate the microroughness of finished mirror substrates is about 4 Angstroms, fully meeting NuSTAR requirements.

As part of the quality control process, one substrate from each oven is randomly sampled every slumping cycle for measurement on an interferometer. The measurement equipment is shown in Figure 6 (Lehan et al., 2007). For a mirror substrate to be measured with the equipment, it is sputtered with ~2 nm of Ir which is sufficiently reflective but is not thick enough to distort the figure of the substrate.

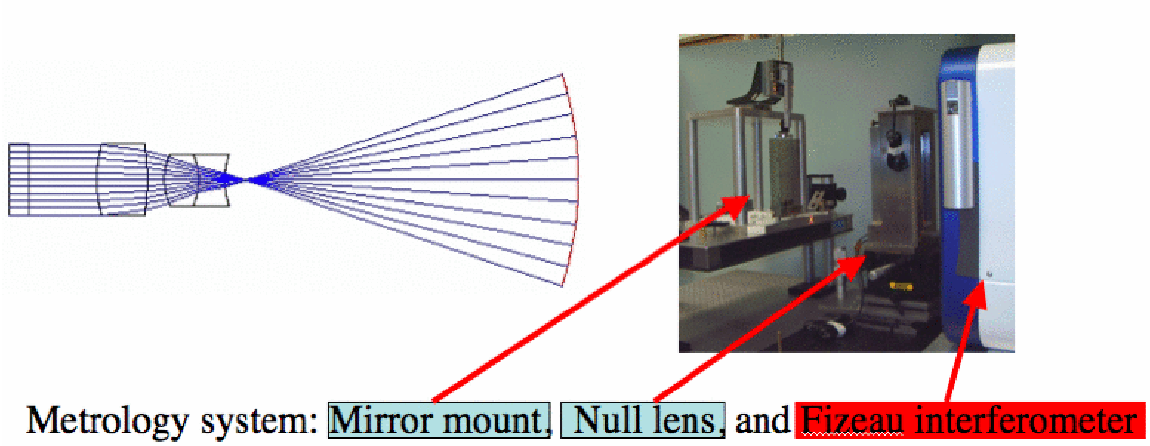

Figure 6. Fast and accurate measurement of a mirror substrate is done using a Fizeau interferometer and a lens that converts a plane wave to a cylindrical wave. The cylindrical wave front is compared with the mirror substrate surface to determine its figure error.

Figure 7 displays the measurement results of three typical substrates. Each substrate is completely characterized by the following equation (in the usual cylindrical coordinate system whose Z-axis coincides with the optical axis of the substrate):

$$\rho(z,\phi) = \rho_0 + z \cdot \tan\theta(\phi) - \left(\frac{z}{2L}\right)^2 \cdot s(\theta) + R(z,\phi), \qquad (1)$$

where ρ_0 is the average radius of the substrate; $\theta(\phi) = \theta_0 + \Delta\theta(\phi)$ is the cone angle which decomposes into an azimuth-independent part (average cone angle) and an azimuth-dependent part (cone angle variation); L is the axial length of the mirror substrate, i.e., 225mm for NuSTAR; $s(\phi) = s_0 + \Delta s(\phi)$ is the sag which decomposes into an azimuth-independent (average sag) and an azimuth-dependent part (sag variation); and $R(z,\phi)$ represents the remainder. Figure 7 shows the measurement results of three typical mirror substrates.

The multi-layer coating process and the mirror assembly process affect and indeed correct errors in average radius, cone angle, and sag (Koglin et al. 2005). The most important term that the substrate manufacture process has to adequately control is the remainder. The requirement imposed on the substrate is that the contribution by the remainder term to the 2-reflection image quality must be, on average, less than 30 arcsec half-power diameter (HPD).

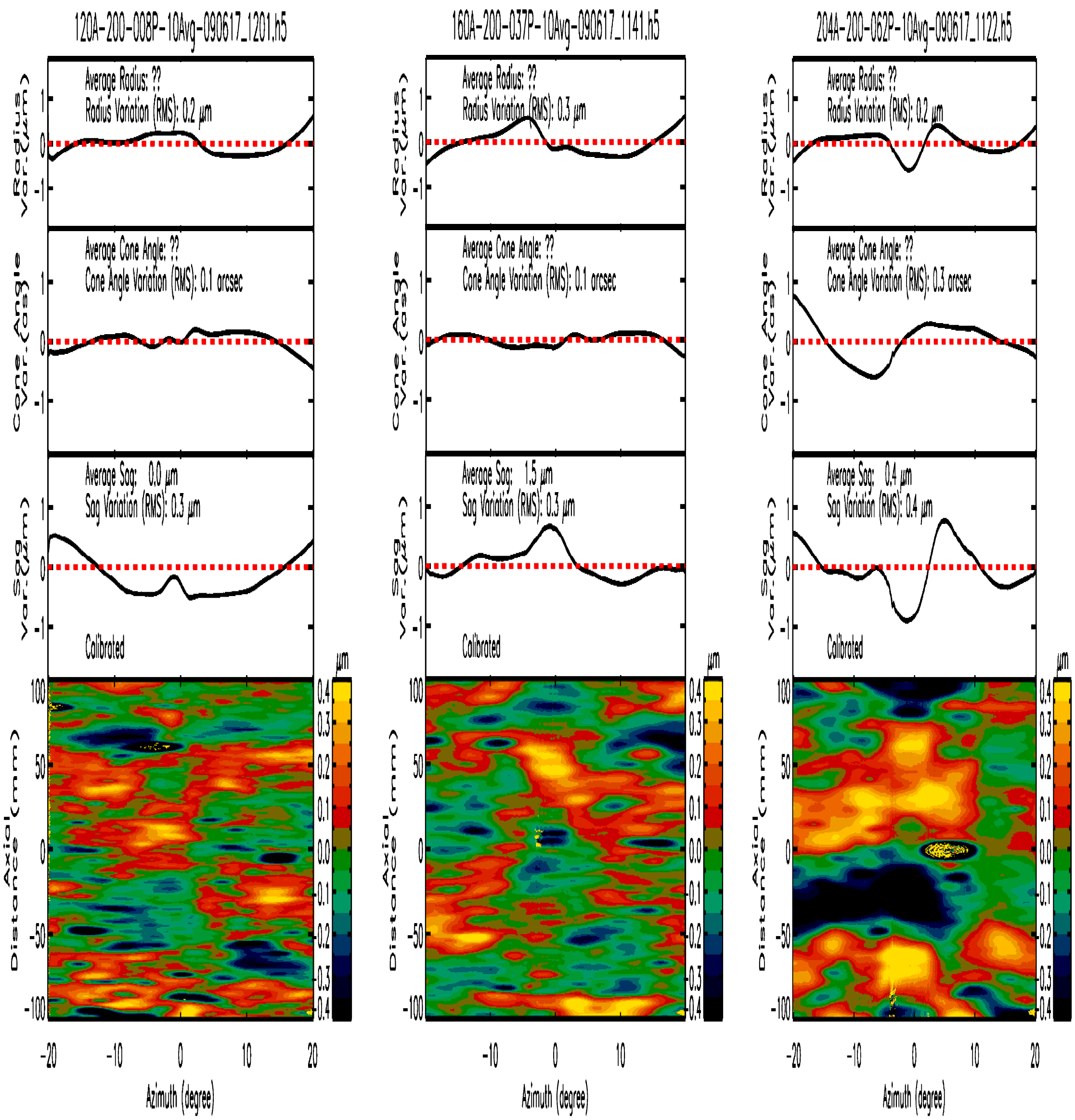

Figure 7. Three typical substrates as measured by the interferometric system. For each substrate the data is decomposed into four panels (from top): radius variation vs. azimuth, cone angle variation vs. azimuth, sag (or second order axial figure) variation vs. azimuth, and the residual errors. The question marks in place of the average radius and average cone angle show that these parameters are not measured as part of this process. They are not required for these substrates as they will be affected by the multilayer-coating process and eventually determined by the assembly process.

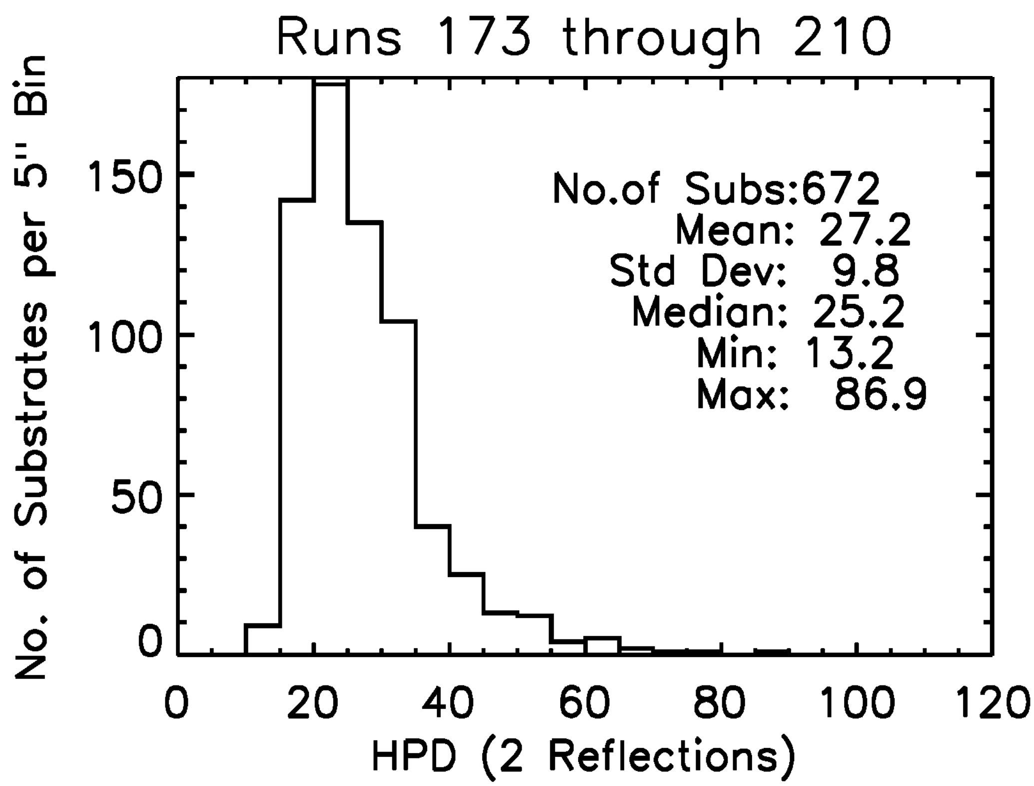

Figure 8. Two-reflection HPD of all mirror substrates that have been measured as part of the manufcature quality control process. All statistical information of this distribution is printed.

As of the writing of this paper, a total of 672 mirror substrates have been coated with 2-nm Ir and measured. The 2-reflection HPD distribution of these substrates is shown in Figure 8. Overall the median HPD is 25.2 arcsecs and the average HPD is 27.2 arcsecs, fully meeting the 30 arcsec average HPD requirement. We note that approximately 10% of substrates (64 out of 672) having HPD larger than 40 arcsecs. They will be screened out later in the inventory control process at Columbia University where each substrate after coating will be measured and selected. The substrate production process will make sufficient spares to account for the removal of 10% for this reason and other losses as part of the coating and handling process.

3.6 Shipping, Receiving, and Inventory Control

All substrates are packed and shipped to the Nevis Laboratory of Columbia University, where each substrate is received and stored. The receiving process includes an independent measurement of each substrate's dimensions to ensure that it fit into the final assembly. The integrity of each mirror's cut edges is also visually inspected before it is sorted according to its shell designation and placed in storage for multilayer coating.

4 Summary

The production of mirror substrates for the NuSTAR mission is taking place at the Goddard Space Flight Center. The facility construction began on February 1, 2008 and was completed and certified on August 31, 2008. Between September 2008 and February 2009 a number of pre-production runs were conducted and production parameters were optimized. The flight substrate production began on March 20, 2009. The production has been proceeding as expected, producing substrates better than NuSTAR baseline requirements. The production will continue through March 31, 2010 when sufficient numbers of substrates will have been produced to make two flight mirror assemblies and a calibration and test mirror assembly. The calibration and test mirror assembly, being identical to the flight mirror assemblies by design and construction, will be used to perform a number of measurements to facilitate a complete understanding of the two flight assemblies.

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