# The Current and Future State-of-the-art Glass Optics for Space-based Astronomical Observatories

## *Abstract*

*Recent technology advancements show significant promise in the ability to reduce the cost, schedule and risk associated with producing segmented Primary Mirrors (PMs) as well as monolithic optics larger than Hubble Space Telescope (HST) scale to the surface figure and smoothness required of current and future astronomical systems. This paper describes the present state-of-the art technology for glass mirrors at ITT and a path to next generation technology for use in a wide range of applications. In-process development activities will be discussed as well as the areas in which future investments can further enhance glass PM technologies. Active, passive, monolithic, and segmented mirror technologies will be discussed along with some basic descriptions of the different ways by which light-weighted glass mirror blanks are fabricated. There will be an emphasis on Corning's Ultra Low Expansion (ULE®) and borosilicate optics, with some discussion of glass ceramics and other material substrates. The paper closes with a table that summarizes potential areas of investment that will continue to advance the state of the art for the use of glass and other materials in optical systems.*

**Robert Egerman**
ITT Corporation
585-269-6148
robert.egerman@itt.com

**Co-Authors (from ITT)**

Gary Matthews
Jeff Wynn*
Charles Kirk
Keith Havey

*ITT Retiree

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## 1.0 Introduction

Glass and glass ceramics have always been the primary candidate optical materials for space based reflective telescope systems that study electromagnetic radiation in the cosmos in wavelengths ranging from x-rays to the near infrared. ULE® is perhaps the best known, since it was the material of choice for the Hubble Space Telescope Primary Mirror (HST PM). ULE® has many favorable characteristics; the most notable of which is its extremely low coefficient of thermal expansion (CTE) around room temperature (<30ppb/°K from 5-35°C). Schott Zerodur®, a glass ceramic, has material characteristics comparable to ULE® and was the material substrate of choice for the optics in the Chandra X-ray Observatory and the segmented Hobby-Eberly telescope mirrors finished by ITT. Borosilicate and fused silica are two other generic glasses that have been used for flight and ground based systems. For telescopes that require extremely stable optics, these two materials are preferable for optical systems operating at temperatures of ~40K and ~100K respectively. Since the completion of the fabrication of the HST PM in 1981, significant advancements have been made in glass optic fabrication technologies to reduce mirror areal density (see Figure 1), enabling increased PM aperture sizes, while reducing risk, cost and schedule. Through these activities, telescope architectures that utilize segmented primary mirrors with active figure control have been developed and demonstrated. The James Webb Space Telescope (JWST) PM is the most prominent example of this, comprised as it is of 18 hexagonal beryllium mirror segments, each with a force actuator to control radius of curvature, and displacement actuators to control each segments' rigid body location. Comparable architectures of varying complexities have been designed and demonstrated using glass as the PM segment substrate. The ITT Advanced Optical System Demonstration (AOSD) testbed, shown in Figure 2, has a passive center segment and active outer petal segments (only 1 outer petal is shown). This testbed has been used to demonstrate several critical PM technologies over the years including ultra light-weight optics fabrication, active figure control and phasing of segments,

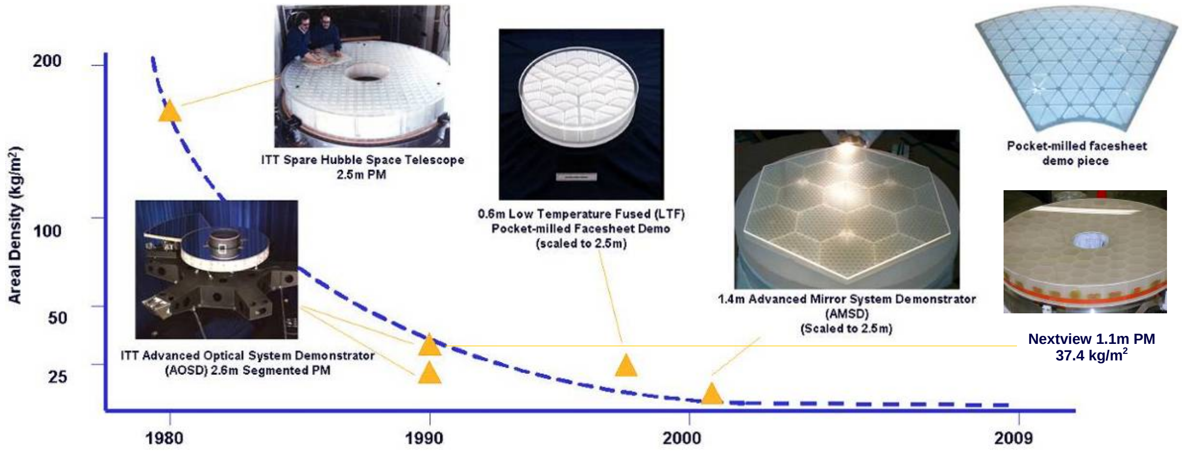


*Figure 1: History of ULE® Mirror Areal Density of ITT PM designs*

*Figure 2: ITT started the development of segmented PMs in the 1980's*

wavefront sensing and control, dynamic disturbance isolation, and petal deployment with precision mechanisms and latches.

This paper serves to describe the current and future state-of-the art technology for glass mirrors at ITT for use in a wide range of observatories from medium sized missions such as Joint Dark Energy Mission (JDEM) to future large sized missions such as Terrestrial Planet Finder (TPF) or Life Finder. In-process development activities will be discussed as well as the areas in which future investments can further enhance glass PM technologies. Active, passive, monolithic, and segmented mirror technologies will be discussed together with some basic descriptions of the different ways by which light-weighted glass mirror blanks are fabricated. There will be an emphasis on ULE® and borosilicate optics, with some discussion on glass ceramics and other material substrates as well. Recent technology advancements show significant promise in the ability to reduce the cost, schedule and risk associated in producing segmented and monolithic PMs even larger than HST to the surface figure and smoothness required of current and future systems.

## **2.0** Mirror Material Overview

### **2.1.1** ULE® Material: Current State-of-the-Art Fabrication Processes

ULE® optics are optimal for reflective telescopes designed to operate at or near room temperature because the material CTE is near zero in this temperature range. Corning does have the ability to vary the temperature (by 5-15K) at which the CTE is minimized by tuning process parameters during the manufacturing of the material. ULE® is fabricated using a flame soot deposition process that currently yields monolithic boules that have a 1.4m (56" usable diameter) in thicknesses up to ~150mm (6"). Larger pieces of ULE® (both diameter and thickness) can be fabricated utilizing one of two approaches, or a combination of both. The first process, involves stacking multiple standard-sized boules together in a furnace and heating them to a temperature at which the boules fuse together. If desired the boules are allowed to flow out to some larger specified diameter. In the second process, known as edge sealing, boules are cut into hexagons and then tightly packed together in a furnace where heat is used to fuse the individual pieces together into a monolithic piece of glass.

These two processes yield solid, flat (plano) ULE® that are that contains horizontal striations (also known as striae) due to the slight variation in titania content that is inherent to the ULE® fabrication process. To maximize the thermal stability and to maximize the achievable surface smoothness during polishing (particularly in the spatial frequency range of ~10microns to 10mm) it is typically required that the striation layers to be parallel to the optical surface being polished. For curved optics, this is accomplished through another high temperature furnace cycle in which the ULE® is slumped over a curved mandrel that has a radius close to the radius of the mirror being fabricated. The monolithic and solid PM blank for the ground based 4.2m Discovery Channel Telescope (http://www.lowell.edu/dct/index.php) was fabricated using the edge seal and high temperature slumping process described above. It should be noted that whenever ULE® is subject to a high temperature operation, the part is annealed during cool down to remove residual stress and to maintain the materials CTE as initially fabricated.

### **2.1.2** ULE® Material: Opportunities for Technology Investment

The costs and schedule associated with the high temperature sealing and flow processes used in ULE® production, are significant. Corning has already invested in research to minimize ULE® striae to support the needs of the lithography industry. Corning has had some success in this area, but the current refined process only minimizes striae within small region of the standard sized ULE® boule. Future systems, such as those that may be developed to image and characterize exoplanets, could have increased optical performance if additional research and investment is made to minimize striae over an entire ULE® boule.

One of the driving reasons that the Advanced Mirror System Demonstrator (AMSD) optic (shown in Figures 1 and 7) was designed to be a 1.4m hexagon was to take advantage of the standard size ULE® boule. The development of a qualified manufacturing process that would yield a larger diameter boule would enable the fabrication of larger mirrors without the need for the costly and time-consuming high-temperature boule flow out process. Similarly, technology investment that yields thicker boules would reduce the number of high temperature sealing and flow-out processes needed to fabricate the glass needed for large monolith optics that have light-weight cores that are >~10 cm (4") deep.

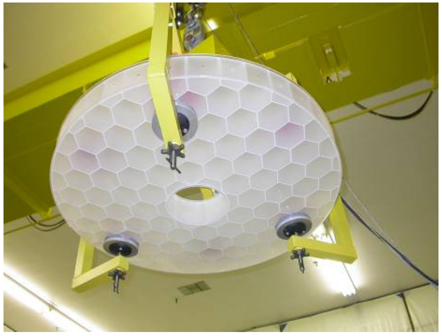


*Figure 3: ITT's NextView 1.1m ULE® frit PM is the heart of the Geo-Eye 1 Nextview Telescope*

In addition to its low CTE, one of the benefits of ULE® is that it can be joined together via several flight-qualified methods to form closed-back mirror blanks. This enables light-weight mirrors that have continuous monolithic front and back facesheets. Facesheets are fused to Abrasive Water-Jet (AWJ) cut light-weight cores to form mirrors that have an excellent strength and stiffness-to-weight ratio. The HST PM (the backup mirror for which was processed by ITT) is a closed-back design produced using the now obsolete high-temperature fusing process that requires relatively thick facesheets joined to smaller core cells with thicker webs to withstand the distortions of the high-temperature fusion process. While state-of-the art in its day, the HST PM had an areal density of over 160 kg/m$^2$.

To reduce the areal density of ULE® mirrors, alternatives to the high-temperature fusing process have been developed since HST. There are now two flight-qualified technologies that can be used to join the components of a closed-back ULE® mirror together. The first technology utilizes a Corning proprietary frit material (a ground glass powder with other chemical components that when sintered joins faceplates to a lightweight core) that allows a lower temperature joining process. ITT's recently launched GeoEye-1 1.1m aperture high resolution NextView Electro-Optical payload PM (shown in Figure 3) was fabricated using the frit process. Additional information on this system can be found at: http://www.ssd.itt.com/heritage/nextview.shtml. The second technology (developed by ITT and transferred to Corning) is the Low Temperature Fusion (LTF) process, where ULE® components can be joined together under pressure (without a filler material like frit), at a relatively low temperature such that thin and light components are not distorted. The resulting part is 100% ULE®. The LTF process can be used to fabricate plano mirror blanks that can then be Low Temperature Slumped (LTS) to form a near net shape (75 microns P-V) curved aspheric optic. This was the process that was used to fabricate ITT's AMSD blank to less than 12.5kg/m$^2$. The LTF process can also be used to join curved components together, eliminating the need for the LTS furnace cycle. It is also worth noting that the LTF process has also been demonstrated with fused silica and borosilicate glasses (ITT has used low and high temperature fusing processes with borosilicate, the latter being described in Section 3).

There are several other potential light-weight mirror substrate development areas that are more tailored towards the needs of some innovative mirror designs as discussed in Section 3.

### **2.1.3** Schott Zerodur®**:** Current State-of-the-art Fabrication Processes

*Figure 4: The Zerodur® Magellan M2 blank*

Zerodur® and a Russian-fabricated equivalent called Astrosital are glass ceramics that have material properties very similar to ULE®. Zerodur® is widely used for ground-based telescopes. The manufacturing process and crystalline structure of Zerodur® is significantly different than that of ULE®. ULE® can be used to make very large primary mirrors, like the 8.3 meter Subaru Telescope, by stacking boules of glass in multiple furnace operations, however, the process is expensive and time consuming. Zerodur® has the benefit that it can be cast in larger sizes in different shapes in fewer furnace operations. Schott has made 8m class mirror blanks in the past, but has not used this capability recently due to lack of market demand. One drawback of the crystalline structure of Zerodur® is that there are no flight-proven processes that can be used to join Zerodur® parts together to form completely closed-back mirrors as can be done with ULE®. As a result, it is not possible to achieve the same amount of light-weighting and corresponding high stiffness-to-weight ratio in Zerodur optics as it is with ULE® optics. 1.5m class ULE® mirrors with areal densities of <10kg/m$^2$ have been flight qualified in contrast to Zerodur® optics for flight systems at about 45kg/m$^2$.

### **2.1.4** Zerodur® Material: Potential Opportunities for Technology Investment

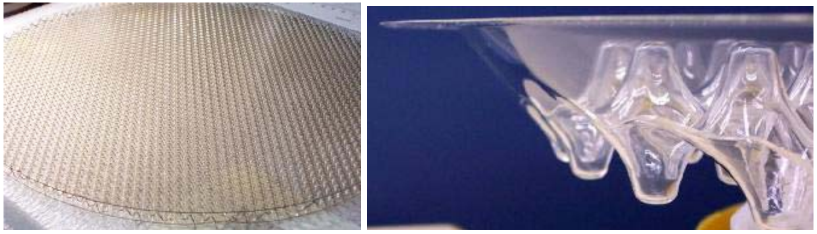
Earlier in this decade, Schott developed a low-temperature bonding process (LTB). The LTB technology involves the use of an aqueous, inorganic bonding agent to chemically join two or more Zerodur® surfaces and form a bonded component that has similar properties to that of monolithic Zerodur®. See http://optics.nasa.gov/tech_days/tech_days_2004/docs/18%20Aug%202004/23%20Schott%20Low%20Temperature%20Bonding.pdf for additional detail. However, this technology has not been developed to the point where it is a proven technology for flight optics and Schott has not invested in it further over the last 5 years.

### **2.1.5** Borosilicate Glasses: Current State-of-the-Art Fabrication Processes

Borosilicate is a term that refers to a general class of glasses that are comprised primarily of silica and boron oxide. In addition to its use in kitchen and laboratory glassware (under the Corning owned, and now licensed brand name of Pyrex), borosilicate has a long history in the field of optics as well. The 5.1m ground based Palomar Observatory PM was fabricated from borosilicate in the 1930's. In comparison to ULE® and Zerodur®, borosilicate has a relatively high CTE at room temperature. However, certain telescope systems, such as those used in LIDAR applications, can tolerate this higher CTE. The CTE of borosilicate glass approaches zero at ~40K, making it well suited for cryo temperature applications. As a result, the lightweight auto-collimating flats (ACFs) that will be used for the ground testing of JWST are being fabricated out of borosilicate glass by Hextek under subcontract to ITT.

Today, the largest market for borosilicate glasses is the flat panel television market. This market has driven borosilicate manufacturers such as Corning and Schott to develop material manufacturing processes that yield large, thin (<1mm) and polished glass straight off the manufacturing line. For large LCD and plasma displays, Schott has a Borofloat® glass that is 0.7mm thick and fabricated in a continuous strip 2.3m wide. This strip is laser cut in half and then laser cut again to a length of ~2m. Schott has stated that with minimal investment in handling equipment they could fabricate sheets of 0.7mm thick polished Borofloat® that is 2.3x2.3m in size. The flat panel display market will undoubtedly drive borosilicate material manufacturers to develop factory lines that will yield even larger pieces of glass in the future.

The availability of thin borosilicate glass has enabled the development of new mirror designs and manufacturing processes at ITT. ITT has patented these approaches and refers to the resulting optics as corrugated optics (in the past, these optics have also been referred to as multi-core mirrors or waffle mirrors, but these terms are now considered obsolete). This technology is discussed in detail in the following section.



*3 layer micro-corrugation facesheet Layer 4 Macro Corrugation*

*Finished plano 0.6m mirror blank*

*Figure 5: ITT has finished a plano 0.6m Corrugated Borosilicate mirror to 380 nm-rms. After one ion figuring run, the error is expected to drop to ~75 nm-rms, and in ultimately ~20nm-rms*

## **3.0** Borosilicate Corrugated Mirrors: Current State of Technology

ITT has developed a mirror design (U.S. Patent 7,429,114 B2) which leverages commercially available thin sheets of Borofloat® glass to dramatically reduce mirror fabrication times and costs. Utilizing 0.7mm and 2mm sheets of Borofloat®, ITT has developed novel mirror designs and manufacturing processes that yield plano mirror blanks in 5 working days and curved, f/2 spherical mirror blanks in six days. An example of a corrugated mirror is shown in Figure 5.

The "front facesheet assembly" is comprised of 3 pieces of glass: a solid facesheet (layer 1), a micro corrugation (layer 2), and a middle facesheet which tapers up and is fused to layer 1. This facesheet assembly is then placed upon a macro core (layer 4) and a back facesheet (layer 5), both of which have upward tapers at the perimeter. During final assembly, the front facesheet assembly is fused to the macro core (layer 4) and the back facesheet (layer 5) in a furnace at high temperature. The finished mirrors are 0.6m in diameter and have an areal density of <10kg/m$^2$. As of this writing, ITT has only polished the plano optics. Curved optics will be polished in the coming months. The curved optics have been measured post assembly and they match the mandrel to <2 microns-rms. This technology is currently at a TRL of 5, in part due to work that was performed jointly by NASA Goddard Industrial Partnership Program funding and ITT IR&D funding. Unlike the LTF/LTS process that is used in fabricating curved ULE® mirror blanks, the corrugated mirror blank manufacturing processes occurs at relatively high temperatures (compared to the material softening temperature). The final assembly furnace cycle utilizes proprietary tooling and a process which precisely controls all of the surfaces (front, back, and sides) of the finished part. The process is more akin to a forming process (rather than a slumping process where gravity and static loads are used to bend the part over a mandrel).

## **3.1** Borosilicate Corrugated Mirrors: Current Developments and Future State of Technology

ITT has been awarded an Advanced Component Technology (ACT) contract under the NASA ROSES 2008 Solicitation NNH08ZDA001N-ACT and is also supporting the Hybrid Doppler Wind Lidar Transceiver ACT contract awarded to NASA Goddard. With additional IR&D funding and the ACT funding, ITT plans to further mature borosilicate mirror technologies. Ongoing and future development plans include: 1) developing stress modeling techniques that are correlated to empirical test data, 2) fabricating an f/1.3 on-axis 0.5m diameter parabolic optic with a center hole, 3) improving the matching between the mirror blank and the mandrel to reduce mirror finishing schedule and 4) increasing the TRL of the technology, including developing cryogenic and room-temperature mounts.


*Figure 6: A ULE® corrugated macro core*

Ultimately, with further investments, ITT could advance this precision forming technology to the point where optics are replicated to a precision mandrel during final assembly, completely avoiding the need for any grinding after the part comes out of the furnace. It is anticipated that some short duration conventional polishing may be needed followed by ion figuring to meet final surface performance requirements. This process could enable aggressively light-weighted, high quality finished mirrors to be fabricated in 4-8 weeks starting from raw material stock.

### **3.2** Leveraging Borosilicate Corrugated Mirror Process to ULE®, Current and Future State

Aside from material availability, one of the main reasons why ITT began its investment in corrugated optics with borosilicate instead of ULE® lay in the fact that ULE® must be worked at higher temperatures than borosilicate glass and it is a highly reactive material while at temperature and can be easily contaminated. However, ITT has completed some preliminary work in extending its corrugated mirror manufacturing processes to ULE. A handful of small 3-layer ULE® corrugated optics and components have been fabricated (see Figure 6). Furthermore, ITT has identified a coating for use on furnace tooling and mandrels that acts as barrier layer (eliminating contamination) and as release layer (preventing the optic from sticking to the tooling). We have also investigated a fire polishing and stretching method for efficiently generating thin polished sheets of ULE® to eliminate the costly process of grinding and polishing the material to ready it for the corrugation processes. ITT has a vision, requiring additional investment from internal and external sources, to leverage the borosilicate forming processes starting with conventional AWJ AMSD-style ULE® blanks, with the ultimate goal of precision replication over mandrels. Additional explanation as to why this is a good direction to bring the technology is discussed in Section 4.1.

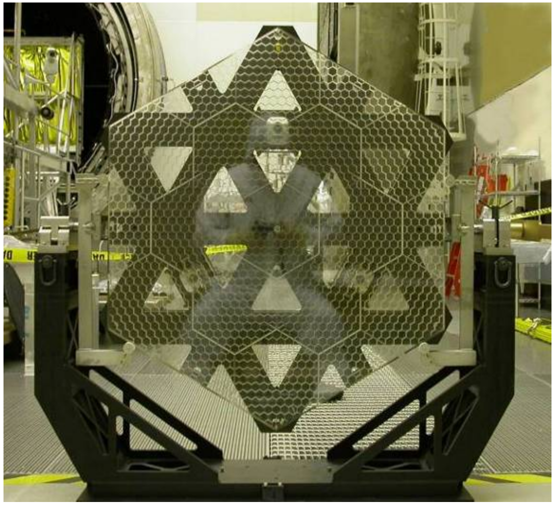


*Figure 7: ITTs 1.4m AMSD in its testing gantry at XRCF*

## **4.0** ULE® Mirrors

### **4.1** AMSD-style Segmented PMs: Current and Future-state-of the Art

ITT developed its 1.4m ULE® AMSD off-axis active primary mirror segment under government funding in the late 1990's, leveraging the

LTF/LTS/AWJ blank manufacturing technology it had previously developed. The optic was designed to have 16 force actuators for figure control, but due to budget constraints in the AMSD project office, only one force actuator, which could be used to change the radius of curvature of the segment, was integrated. The AMSD was successfully optically tested at cryogenic temperatures in the X-Ray Calibration Facility (XRCF) at the NASA Marshall Space Flight Center. ITT's AMSD optic and composite reaction structure are shown in Figure 7. One of the noteworthy features of the AMSD technology is the mirror's segmented core. By utilizing 19 individual core segments (13 hexes and 6 trapezoids) low-temperature fused between two monolithic facesheets, the mirror blank fabrication schedule and risk are significantly reduced. The segmented core enables core segments to be cut in parallel. As a result, if one is damaged there is minimal cost and schedule impact due to the size of the core segment and the ability to fabricate segments in parallel. ITT has continued to develop AMSD-related technologies for the past decade. Several of the most significant efforts have been in AWJ technology, mirror finishing technology, actuator technology, and the flight qualification of AMSD type mirrors. ITT has worked with Flow International Corporation, one of the pioneers in AWJ, to leverage its latest technologies into the cutting of glass. These new advances have enabled AWJ cutting speeds to increase by nearly a factor of 2X. ITT anticipates that the advances in AWJ, when used in conjunction with advances in wire sawing (by Corning) of glass to thickness and in double-sided planetary polishing, will enable the production of AMSD-style plano blanks on 4-5 week centers and the production of off-axis parabolic blanks on 6-8 week centers without any additional investment in capital equipment. Given the potential to fabricate AMSD-style blanks on four week centers, if we are successful in applying the forming and replication technologies that have been/are being developed for borosilicate, the potential return in investment would be tremendous. There is the potential to bring the cycle time to fabricate a single segment from 12-18 months to less than three months.

It should be noted that ITT has mounted an AMSD-type optic with a room-temperature mount design and subjected it a full array of environmental tests (sine vibe, random vibe, acoustic, and shock), fully qualifying the mirror and mirror mount design bringing the design to TRL-6.

Through the work ITT has done related to AMSD, force actuators that have a flight design (yet to be qualified) have been developed and integrated to an AMSD style optic. This optic was polished using fairly conventional techniques and optically tested in gravity with the force actuators in place. In this highly successful test, ITT demonstrated that an operational wavefront error of <25-nm wavefront could be maintained in a space operational environment for a large fully assembled actuated segment.

Prior to this successful demo, ITT developed a full tool active lap (FTAL), shown in Figure 8, which is extremely efficient at smoothing off-axis optical surfaces. The lap bends to conform to the aspheric shape of an off-axis optic as the lap is stroked across the part. The development FTAL was disassembled so that some of its parts could be re-used on the Technology Planet Finder Technology Demonstration Mirror (TDM), which was to be a fast 1.8m off-axis f/2.11 optic (f/0.86 parent). Unfortunately due to budget cuts, the TDM optic was never built and the larger FTAL it required was never assembled. Finishing the TDM contract would be a worthwhile investment to demonstrate the capability to process off-axis optics to the requirements needed for planet finder missions employing visible imaging coronagraph technology and

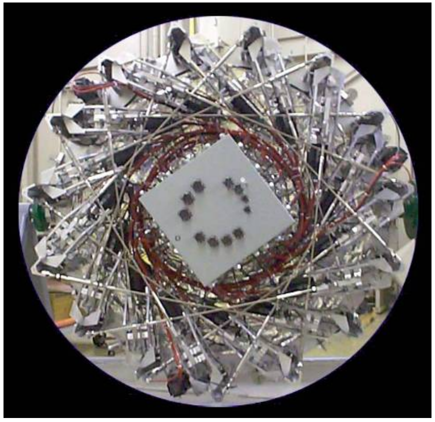


*Figure 8: ITT's Full tool active Lap*

possibly fly the PM on a future mission. The technology demonstrations performed with the FTAL prior to its disassembly indicate that the technology can significantly reduce mirror polishing times for off-axis segments that are ~1.5m in size. Active lap technology can also be applied with on-axis aspheric optics. The University of Arizona (UofA) has successfully utilized a sub-aperture active lap in grinding and polishing several 8m ground based mirror segments, both on- and off-axis. ITT's FTAL has more degrees of freedom than the UofA lap, and should be able to perform as or more efficiently than the UofA lap on a large optic that is very light-weight in comparison. ITT and the UofA would likely collaborate to optimize mirror finishing processes for a large monolithic mirror such as those being considered for THEIA, TPF-C, or the TPF-now missions.

### **4.2** ULE® Light-weight Monolithic PMs: Current and Future State of the Art

As previously discussed, monolithic light-weighted PMs can be manufactured using a frit process, an LTF process, or a combined LTF/LTS process. The LTF/LTS process has only been demonstrated on relatively compliant mirrors such as AMSD. The TDM mirror would have been the first relatively stiff mirror to have been manufactured this way. Analyses were performed during the TDM program which indicated that the LTS should be successful, but it has yet to be demonstrated.

ITT has developed another technology that can be used to light-weight relatively stiff mirrors by removing more mass from the facesheet through a process known as pocket milling. There are two approaches by which a facesheet can be light-weighted. In both cases, after the milling operation, wide ribs that are hexagonal in shape remain that can be fused to hexagonal cores. Within these hexagonal landings, 3 or 6 additional and narrower ribs increase the local stiffness of the facesheet, minimizing the uncertainty in the gravity release of the part and making it easier to finish to the required optical tolerances. Figure 1 includes an image of a 0.6m small scale pocket-milled facesheet optic along with a pocket-milled facesheet demonstration. Another example which shows this more clearly is depicted in Figure 9 is a 2m-class ULE® finished optic that has an areal density of ~25kg/$m^2$ that has pocket-milled facesheets that were low-temperature fused to a segmented AWJ core.

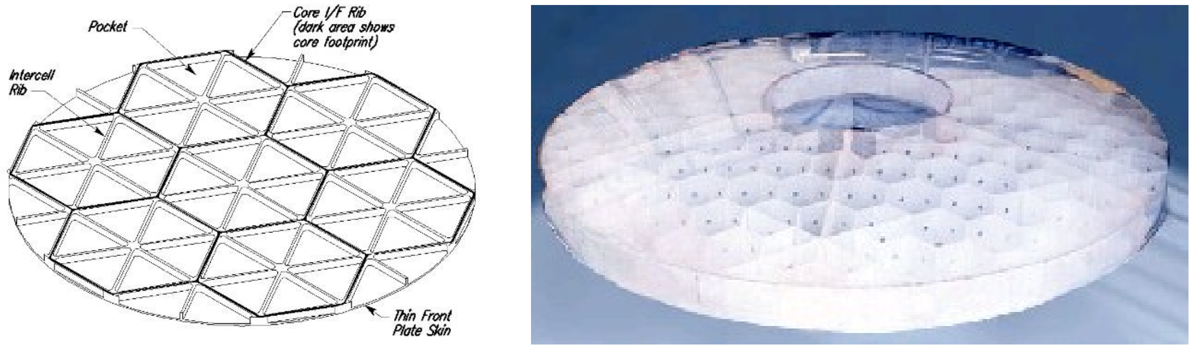


*Figure 9: Schematic of a Pocket-milled facesheet with 6 reinforcing ribs per hexagonal cell (left)*
*Bottom view of 2m class 25kg/$m^2$ ULE® mirror with three reinforcing ribs per hex cell on the back facesheet (right)*

The technology required to fabricate large monolithic mirrors for proposed future missions exists today. With some modest investments in technology subscale demonstrations it could be shown to be ready for flight. The missions which require large optics such as these could benefit from having larger raw material boules to start from, as discussed in Section 2.1.2, but it is certainly not required. A different technology investment area was identified by ITT during the TPF-C funded Large Monolithic Mirror (LMM) program that if successful, could reduce fabrication time and risk for these large optics. The technology is ULE® welding, and the premise behind it is that a large optic could be built up from smaller segments and then welded together to form the full scale mirror blank. The blank would then be finished using conventional polishing processes and sub-aperture active laps. Should the large optic be damaged, ULE® welding could be used to repair the damaged area by replacing it with a section of new pristine glass. During phase 2 of the LMM study, Corning, under subcontract to ITT developed two proof-of-concept pieces on a very tight schedule and budget. ITT feels that results of these demo parts successfully demonstrate proof of concept, and that with continued investment to refine process controls, ULE® welding could become a viable technology for fabricating large, stiff monolithic mirrors.

It is also worth noting that the recent advancements in AWJ cutting of glass have only addressed the needs of more rapidly fabricating relatively shallow (<50mm deep) cores. There is also an opportunity to apply these developments to increase the AWJ cutting speed while making cores of larger depths ranging from 5cm to >30cm. Programs requiring monolithic mirrors of any size could benefit from development in this area.

## **5.0** Summary and Closing Comments

Glass and glass ceramics have played a significant role in astronomical scientific discoveries made from both the ground and from space. Continued technology development has enabled these materials to remain the technology of choice for room-temperature systems working in the visible and the UV and for cooled optical systems as well. Other developments in tangent technologies such as metrology, increased computing power for higher fidelity optical and structural models, and active dynamic control, have all contributed to the advancements in glass mirror technology and the reductions achieved in areal density and manufacturing cycle times.

Some newer optical materials and corresponding technologies have been demonstrated to be viable substrates for space-borne observatories. Spitzer's telescope and optics are fabricated from beryllium as are the JWST PM segments. Beryllium has clear advantages over most glasses when looking in the far IR where the optical systems are cooled to below 50K. Silicon carbide (SiC) was selected as the PM substrate for ESA's Hershel telescope, which operates from the far IR to the sub-millimeter. Silicon carbide has many physical properties which make it a favorable optical substrate including its high conductivity, low density, and relatively high strength. However, studies such as the TPF-C Flight Baseline-1 study managed by NASA's Navigator Program Office with contributions from JPL, Goddard and industry have indicated that extremely light-weight open-back silicon carbide optics that have comparable areal densities to a passive closed-back ULE® mirrors cannot maintain the same thermo-elastic stability as their glass counterparts. This is because SiC has a relatively high CTE, and when most of it is removed for light-weighting leaving thin ribs which increase structural efficiency , the benefits of the high conductivity are negated. Hence, a small thermal gradient can be generated which could significantly impact the mirror figure. For far IR to sub-mm systems such as Hershel, this is not an issue, because the system can tolerate fluctuations in the PM surface figure when looking at long wavelengths. The same can not be said for systems looking in the visible or shorter wavelengths. Currently, the only architecture known to the authors in which SiC can potentially compete with ULE® for visible and UV systems requires hundreds of active traction actuators that require high voltage. Though a promising technology worthy of continued investment, it is unclear if the overall system can be as light on an areal density basis (including actuators and electronics) as its ULE® counterparts, be they active or passive in nature. In addition the added risk and cost for the actuators and associated electronics need to be considered.

As mentioned previously, ITT's AMSD active segment solution requires only 10-16 actuators, and because an AMSD optic is relatively stiff, the loss of a single actuator does not significantly degrade performance. Furthermore, the force actuators which have been developed for ITT's AMSD architecture require low power and voltage, and because of the inherent stability of ULE® will not need to be continually adjusted to compensate for slight changes in a systems thermal environment.

**6.0** The glass technology for near-term, medium-class missions such as the Pupil-mapping Exoplanet Coronagraphic Observer (PECO), Advanced Cosmic Ray Composition Experiment for the Space Station (ACCESS), and JDEM exists today. It even exists for some large class missions, such as the Dilute Aperture Visible Nulling Coronagraph Imager (DAViNCI), which is comprised of 4 smaller telescopes. With minimal investment, sparsely actuated glass systems will be ready for flight. Additional investments could dramatically reduce the costs and schedules required to fabricate a JWST sized or larger segmented glass PM (such as what is needed for the 16m Advanced Technology Large-Aperture Space Telescope (ATLAS) architecture). Other investments in glass technology for monolithic PMs will also have cost, schedule and risk benefits for systems that are 1m in aperture or larger.

Table 1 contains a summary of the areas where investments could further advance mirror technologies.

*Table 1: Summary of Investment opportunities and benefits*

| **Technology Investment Area** | **Technology Benefits** | **Missions that could befit from the investment** |
|---|---|---|
| Faster AWJ cutting at depths > 50mm | Reduced cycle time and cost | Systems requiring stiff mirrors ranging in aperture from 0.5m and up |
| Borosilicate Corrugated Mirror Replication Technology | Rapid fabrication of low areal density passive or active mirrors. Processes can be leveraged to ULE® | Ground and spaced based systems. Space systems operating in the IR. |
| Flame polishing and stretching of ULE® | Shortens material prep time for corrugated or LTF mirrors | Large aperture segmented systems requiring the thermal stability of ULE® |
| Increased ULE® Boule Size | Enables blanks for LMMs or larger mirror segments to be fabricated at lower cost and schedule | All programs requiring light-weight ULE® optics with an aperture >1.4m |
| Reduction of ULE® Striae | Smoother ULE® optics | Primarily exoplanet missions which require a very smooth mirror at all spatial frequencies |
| Replicated ULE® mirrors | Reduced Cycle Time and Cost | Any large volume ground or space based system |
| Actuator Technology | Flight qualifies actuators | Large segmented space borne systems. |
| Zerodur® LTB | A new method for making light-weight closed-back mirrors | Space mission requiring a stiff closed-back optic with high thermal stability |
| Actuated SiC Nanolaminate mirrors | Another architecture for IR systems, and a potential for visible and UV systems. | Large space based segmented systems |
| ITT Active lap technology as a sub-aperture lap | More efficient smoothing of large (>2m) on-and off axis optics | Missions requiring >2m mirrors or mirror segments |
| ULE® Welding | Another method of fabricating LMMs (≥4m) with potential cost, schedule and risk benefits | Missions such as THEIA, TPF-C, and TPF-NWO |
| Closed-Back SiC Mirrors | Improved thermo-elastic performance in a SiC mirror | Various |
| Glass Pocket-Milling Technology | Mature to TRL-6 enabling lighter optics to be fabricated | Various |
| LTF/LTS in Gas Fired furnace | Eliminates tens of $M in a new electric furnace and its qualification | Missions requiring LMMs |