Cryostable Lightweight Frit Bonded Silicon Mirror

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ABSTRACT

The excellent polishability, low density and relatively high stiffness of silicon make it an attractive candidate for optical applications that require superior performance. Assembly of silicon details by means of glass frit bonding permits significant weight reduction thus enhancing the benefit of silicon mirrors. To demonstrate the performance potential, a small lightweight glass frit bonded silicon mirror was fabricated and tested for cryostability. The test mirror was 12.5cm in diameter with a 60cm spherical radius and a maximum thickness, at the perimeter, of 2.5cm. A machined silicon core was used to stiffen the two face sheets of the silicon sandwich. These three elements were assembled, by glass frit bonding, to form the substrate that was polished. The experimental evaluation, in a liquid nitrogen cryostat, demonstrated cryostability performance significantly better than required by the mirror specification.

Keywords: Cryostable, Lightweight, Silicon, Frit Bond, Spherical, Mirror

1. INTRODUCTION

Systems and components for use in space have always had requirements for high performance and low mass. A low mass component requires less weight for support and attachment. Initially, the stringent demands were imposed by the limited booster capabilities. Now these demands are dictated by the need to gather information in the most cost effective manner. The change in rationale has not changed the need for lightweight components and systems of exceptional performance. When optical subsystems and components are considered, cryostability is another important factor because many spaced-based optical systems operate at low temperatures and under conditions of significant temporal temperature variations. See Reference 1, for example.

Historically there have been two basic approaches for dealing with the cryostability issue for optical instruments/systems: 1."trial and error" adjustment between room and use temperature, and 2. adjustment at cryo-temperature by means of remotely controlled mechanisms. The first approach is rather tedious and expensive. It may involve iterative polishings at room temperature, with intermediate cool downs, until the desired figure is obtained when cold. Or it may involve figuring at room temperature and inspections at both room and the cold temperature with subsequent analysis to determine the room temperature figure that will produce the desired figure when cold, and requires secondary optical finishing operations to compensate for figure changes between the range of temperatures involved, references 2 and 3. The second approach is basically more direct but involves the addition of the adjustment mechanisms that add cost and weight to the flight system. The advantage of cryostable mirrors and instruments is obvious and warrants evaluation of various approaches.

The approach discussed here utilizes silicon as the construction material and the sandwich configuration to achieve lightweighting. Assembly is provided by glass frit bonding. The selection of silicon is based on its excellent polishability, low density, and high modulus of elasticity. See Table 1 for a comparison with other materials. With relative ease surface roughness of 0.5 nm can be achieved even on synctrotron mirrors of 1-meter lengths. In fact, in at least two instances a surface roughness in the range of 0.2 to 0.3 nm rms was achieved on a meter length mirror, References 4 and 5. Surface finishes of 0.2 to 0.3 nm rms can be achieved with relative ease on mirrors in the 10 to 15 cm range. A 40 cm long synchrotron mirror has been polished to better than 0.1 nm rms, Reference 5.

Requirement	Si	Si/ SiC	CVD SiC	C/ SiC	Zerodor	ULE	Be	Al
Polishablility, Quality (1)/ Cost	Yes/ Lo	No(2)/ Hi	Yes/ Hi	No(2)/ Hi	Yes/ Lo	Yes/ Lo	No(2)/ Hi	No/ Lo
Availability, Quality/ Size	Yes/ (3)	No/ (3)	Yes/ (3)	?/ (3)	Yes/ Yes	Yes/ Yes	Yes/ (3)	Yes/ Yes
Fabricability,								
Near Net Shaping/ Cost	No	Yes/ Hi	?/ Hi	Yes/Med	Yes/ Med	Yes/ Med	Yes/ Hi	Yes/ Med
Machining/ Cost	Yes/ Med	Yes/ Hi	Yes/ Hi	Yes/Med	Yes/ Med	Yes/ Med	Yes/ Hi	Yes/ Low
Joining/ Cost	Yes/ Med	? (4)	?	? (4)	No	No	Yes/ Hi	Yes/ Low
Stability	Good	Good	Good	?	Good	Good	Fair	Fair
Efficiency	High	High	V. High	High	Low	Low	High	Low
Affordability	Good	Fair	V. Poor	Fair	Good	Good	Fair	V. Good

1. Figure between Lambda/10
2. Requires coating that is polishable to achieve finish
3. Depends on size required, joining technology need for large sizes
4. Joining possible in green state

Table 1: Why Silicon? Overview

Many forms of lightweighting have been studied for mirrors. References 6 through 9 consider back face contouring/shaping, open faced stiffening of the face sheet, and various forms of sandwich construction. When the stiffening elements are not integrally machined major attention must be given to the means of attachment. Even thin bond lines can introduce prohibitive distortions if the coefficients of thermal expansion (CTE) of the adhesive and the adherent differ even by relatively small amounts. Polymeric adhesives are particularly undesirable for optical applications that involve large changes of temperature.

Tables 1 and 2 provide information regarding silicon as a mirror material. Table 1 is an overview of practical considerations such as polishablity, availability, fabricability, stability, efficiency, and affordability. The comments are applicable to mirrors of a wide size range from the 10 cm to meter class. For some of the materials, joining is required to achieve the larger sizes and, in general, joining technology is available. Where there are uncertainties regarding appropriate information question marks are used in the tables. As can be seen the various materials have pros and cons but, in our opinion, silicon is an outstanding favorite particularly for mirrors of 25 cm and smaller, and a promising competitor for larger sizes.

Figures of Merit	Desired	Si	Si/ SiC	CVD SiC	C/ SiC	Zerodor	ULE	Be I-220	Al 6061-T6
Specific Stiffness, E/rho	High	59	99	145	89	36	30	164	25
Transient Response, k/rho c	High	0.25	0.27	0.32	0.28	0.003	0.003	0.21	0.24
Steady State Distortion, Ek/alpha	High	7700	19840	38750	12200	2950	2900	31900	513
Dynamic Distortion, Ek/alpha c	High	10.7	29.6	55.4	18.5	3.9	4.1	17.5	0.5
Steady State Distortion, k/alpha	High	56	64	83	52	33	43	105	7.4
Dynamic Distortion, k/alpha c	High	0.08	0.1	0.12	0.08	0.04	0.06	0.06	0.01

Table 2: Why Silicon? Figures of Merit

To expand the efficiency category, Table 2 provides various figures of merit, based on room temperatures properties, commonly considered for mirror applications. Included are specific stiffness, transient and steady state parameters and various distortion parameters under static and dynamic conditions. On the basis of figure of merit parameters beryllium and the various silicon carbides are particularly attractive but this illustrates the need to consider practical considerations that are summarized in Table 1. In general, the silicon carbides and beryllium require an over-coating in order to attain a surface that can achieve a fine finish. Chemical Vapor Deposition (CVD) silicon carbide is an exception but is quite difficult to polish and there have been instances of surface defects on polished samples, Reference 10. For most materials the CTE decreases as temperature is reduced, hence performance improves. For silicon and silicon carbides thermal conductivity increases, a further enhancement for performance.

Many forms of lightweighting have been studied for mirrors. References 6 through 9 consider back face contouring/shaping, open faced stiffening of the face sheet, and various forms of sandwich construction. These references barely scratch the surface of available literature but were selected to provide an historical perspective with emphasis on more recent findings. Sandwich construction is most efficient. The source of Reference 7, NASA SP-233, contains many technical papers that deal with lightweighting of mirror blanks. Reference 4 compares many types of stiffening for both open faced and complete sandwich construction and compares their relative efficiencies. Reference 6 is particularly interesting in that it shows a relatively small difference in weight savings for hexagonal and triangular core lightweighting sandwich approaches. This suggests that optimization of the core configuration results in relatively small weight savings. This is in contrast to optimization of the core and face proportions. Stabilization of a thin face by a low-density core of small, thin wall cells, can provide maximum efficiency. Reference 9 illustrates that simply contoured solid mirrors can approach the efficiency of lightweight sandwiches.

When the stiffening elements are not integrally machined major attention must be given to the means of attachment of the various elements. If there is a significant difference in CTE's of the adhesive and adherent even thin bondlines can introduce prohibitive distortions. The use of polymeric adhesives was found to introduce unacceptable distortions when applied to water-cooled glass mirrors and to un-cooled deformable mirrors, References 11 and 12 respectively. In the case of the deformable mirrors a clever joint design essentially eliminated the problem so that a polymeric bond was acceptable. With the most obvious joining approach eliminated on the basis of the dissimilar coefficients of thermal expansion a superior joining approach is required. Glass frit bonding provides the answer. Prior to fabrication of this test mirror McCarter Technology fabricated glass-bonded plates that were subjected to immersion in liquid nitrogen without degradation and, subsequently, bend strength bars were machined from these plates and tested. The average strength of the bars from the cryo-tested plates was slightly higher than the average strength of glass-bonded bars that had not been subjected to cryo-cycling. The difference was relatively small and may not be statistically significant in view of the limited number of bars tested in each group. Nevertheless, these results provided a high level of confidence that the glass frit bonding process employed by McCarter would be successful when applied to small silicon mirrors for cryogenic service.

With these thoughts in mind it is appropriate to discuss the design and fabrication of the test mirror.

2. MIRROR DESIGN/ FABRICATION

The lightweight spherical silicon mirror was designed to provide a high level of performance without a significant fabrication risk- not an unreasonable approach for the first item of its kind. The primary objective was proof of concept rather than optimization. Requirements included concave spherical radius of 60 cm, a surface error of no more than 0.1 wave rms and a microroughness of no more than 1.0 nm rms. To allow for some edge roll off the specified figure and roughness requirements applied only to the inner 90% of the physical outside diameter. An areal density target of between 10 and 15 kg/m^2 was set as a goal, initially. However, this was compromised to minimize fabrication risk on this first of a kind component. As will be discussed later the test mirror met or bettered the optical specifications.

Figure 1 provides a drawing of the test mirror. Faces and ribs are relatively thick, 2.5 mm and 1.5 mm respectively. These thicknesses were selected to minimize the likelihood of damage during fabrication and thereby assure success without the need to fabricate spare parts. The thick faces allow the use of relatively large cells for the sandwich core. Cell geometry is somewhat unconventional but tends to resemble distortions of square cells. The geometry and the relatively thick cell walls enabled the core to be machined, with low risk, on a conventional CNC mill. The actual cell sizes were dictated by machining and polishing considerations; the former was given a slight preference. Although the cell size, particularly the outer row or ring, may seem quite large the measured print-through proved to be surprisingly small, as will be discussed as part of the optical inspection.

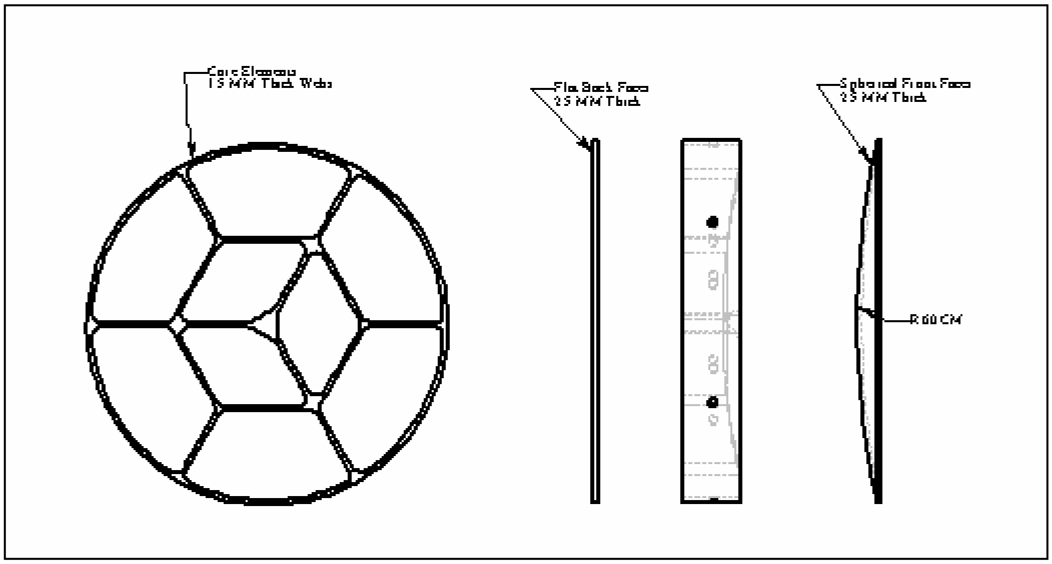


Figure 1: Design of Spherical Lightweight Silicon Mirror features machined core

Figure 2 shows the three component parts of the test mirror prior to assembly. The mirror face was machined on a standard grinder to produce a convex spherical radius slightly larger than 60 cm. This bulk shape was mounted on a stainless steel mandrel machined to the same contour. The concave surface was then machined to the 60 cm radius. Both surfaces used the McCarter Superfinish grinding technique to minimize subsurface damage and to reduce polishing time. References 13 and 14 discuss the application of Superfinishing to various silicon parts from small flats and cones to a meter sized synctrotron mirror substrate with a sagittal radius.

Figure 2: Elements of lightweight silicon mirror illustrate simplicity of design

One of our primary objectives was not met during the machining of the core. It was not possible to produce a core the very first time it was machined. Part of the reason was due to the fact that the original thickness goal for the webs was 0.8mm. Therefore, it was necessary to increase the web thickness to the 1.5mm used for the test mirror. The Superfinish machining technique was not used for the core element shown in figure 2. Before the silicon block used for the core was pocketed, a series of holes were drilled through it normal to the circumference so that all of the cells would be vented. The back plate was produced on a conventional surface grinder; the Superfinish techniques were employed. After machining there was no need to custom fit the three elements.

After the detailed parts were cleaned and dried the glass-bonding agent was installed, the unit was placed in an air furnace, and both faces were bonded during a single furnace cycle, see Figure 3 for the result. After inspection of the bondlines the mirror blank was sent to a vendor for polishing. The quality of the surface was excellent as will be discussed as part of the optical inspection. The weight of the finished mirror is 0.236 kg, 18.6 kg/m^2, a close comparison to the calculated weight of 0.213 kg.

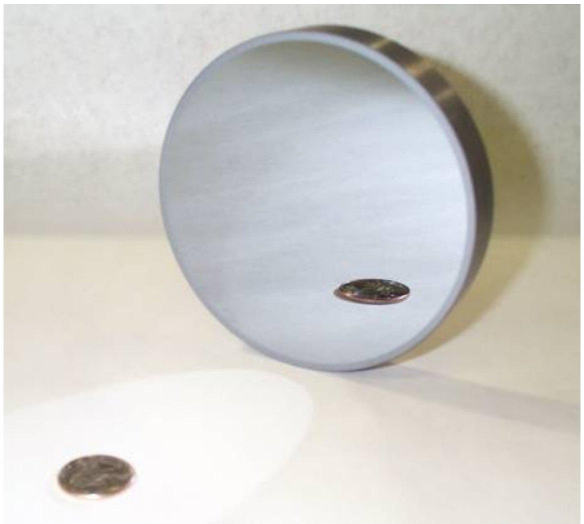


Figure 3: Glass Frit Bonded Spherical Lightweight Silicon Mirror

3. OPTICAL INSPECTION

When the test mirror was received at Goddard Space Flight Center/ NASA it was evaluated by optical metrology to determine the figure and roughness. The results are summarized in Table 3. A Wyko Model 400 interferometer was used. The figure error was within the 0.1 wave rms specification. Overall, the figure was within 0.074 wave rms. As noted in figures 4 and 5 the low frequency and high frequency characteristics of the figure error were determined by fitting the metrology data with Zernike polynomials. The low frequency error was assumed to be represented by the first 36-Zernike terms, see figure 4, and amounted to a error of 0.063 wave rms. The high frequency figure error, which is primarily weak print through, was determined by subtracting the first 36 term Zernike fit from the metrology data, see figure 5, and amounted to an error of 0.04 wave rms, only 25 nm. Note that in the central 40% of the mirror the print-through is only about one third as great.

Figure, Waves@ 633nm

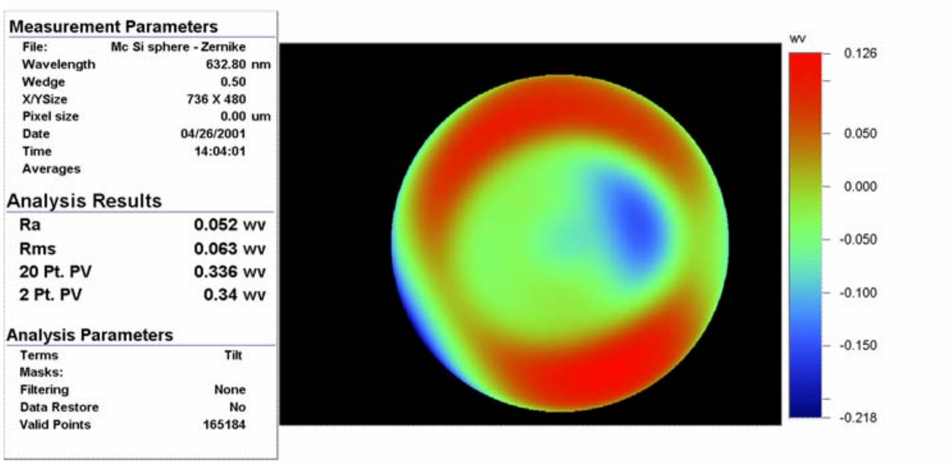
	RMS	P/V
Specification	0.1	----
Overall	0.074	0.37
Low Frequency (1)	0.063	0.34
High Frequency (2)	0.040	0.20
Overall, 10cm CA	0.067	0.33

1. Fitted to first 36 Zernike Terms
2. With first 36 Term Zernike fit subtracted

Roughness, Nanometer

	RMS	P/V
Specification	1.0	----
Loc 1	0.54	5.68
Loc 2	0.46	13.43
Loc 3	0.54	6.17
Loc 4	0.56	8.72
Avg.	0.52	8.5

Table 3: Optical Quality of Test Mirror



Measurement Parameters

File:	Mc Si sphere - Zernike
Wavelength	632.80 nm
Wedge	0.50
X/YSize	736 X 480
Pixel size	0.00 um
Date	04/26/2001
Time	14:04:01
Averages	

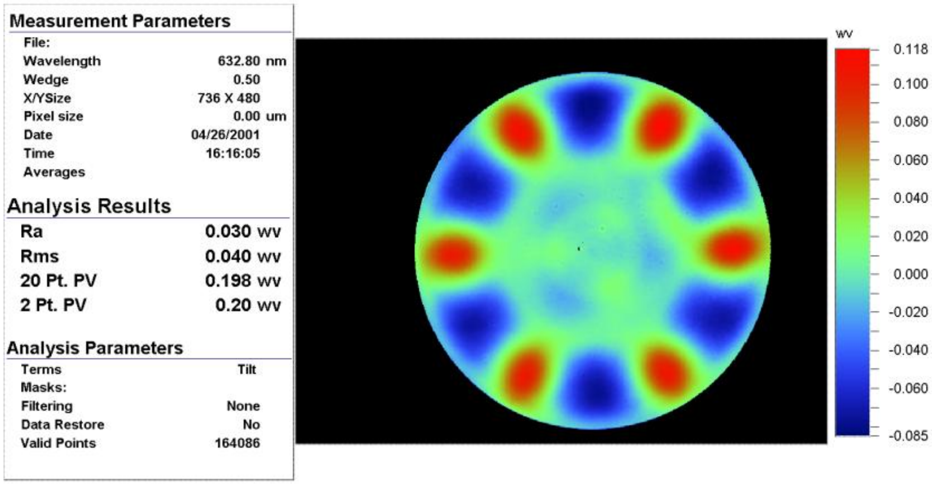
Analysis Results

Ra	0.052 wv
Rms	0.063 wv
20 Pt. PV	0.336 wv
2 Pt. PV	0.34 wv

Analysis Parameters

Terms	Tilt
Masks:	
Filtering	None
Data Restore	No
Valid Points	165184

Figure 4: 1st 36 Zernike terms of figure measurment defines low frequency error contour 100% aperture



Measurement Parameters

File:

Wavelength 632.80 nm

Wedge 0.50

X/YSize 736 X 480

Pixel size 0.00 um

Date 04/26/2001

Time 16:16:05

Averages

Analysis Results

Ra 0.030 wv

Rms 0.040 wv

20 Pt. PV 0.198 wv

2 Pt. PV 0.20 wv

Analysis Parameters

Terms Tilt

Masks:

Filtering None

Data Restore No

Valid Points 164086

Figure 5: Subtraction of 36 Zernicke fit from figure measurement defines high frequency error contour, 100% aperture

Measurements of the surface indicated it was significantly smoother than the 1.0nm rms specification. Measurements made at four different locations gave values of 0.46 to 0.56 nm, about half of the allowable. These measurements verified the evaluations by the polishing vendor that the figure met the 0.1 wave rms requirement and that the roughness was better than the 1.0nm rms specification.

4. CRYOGENIC TESTING

This section of the paper is divided into subsections as an aide to the reader. The test apparatus is described in 4.1. Operation of the test apparatus is the topic of 4.2. And, the test results are presented and discussed in 4.3.

4.1 Cryogenic Test Facility

The cryogenic test facility at GSFC/ NASA consists of a cryostat and a Zygo GPI interferometer. The 12 inch diameter cryostat contains a fast opening cold shutter. A beam expander between the interferometer and the cryostat allows the He Ne metrology beam to expand and cover the 100% full aperture of the mirror. All of these items are mounted on an isolated optical bench, see Figure 6. The test system has been used for the experimental evaluation of a number of small mirrors. Test and data reduction procedures are well established. The test mirror was supported by a V-shaped aluminum adaptor that was attached to a copper cold finger mounted off the rear plate of the cyrostat. The integration of the test mirror, aluminum plate, and cold finger with the back plate of the cryostat is depicted in Figure 7. Thermocouples were mounted on the cold finger, aluminum plate, as well as front and back sides of the test mirror. The cold shutter is a critical component of the test apparatus. Without it the mirror face sees the ambient room condition that is considerably warmer, about 300K, than the cryostat dewar, which is about 80K. Also, the dewar window can see the cold plate, such that a radial temperature gradient can set up in the window; this can induce a lensing effect which distorts the test wavefront. Because of this it is important to capture the surface condition immediately after the cold shutter is opened. Because of the thermal resistance associated with the attachment of the cold finger, aluminum plate and mirror the temperature of the mirror tends to be approximately 10K warmer than the cold finger.

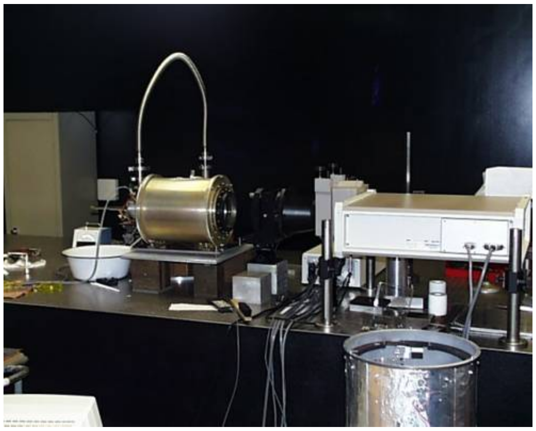


Figure 6: GSFC/NASA 12” Dewar cryogenic test facility has been used to evaluate several mirrors

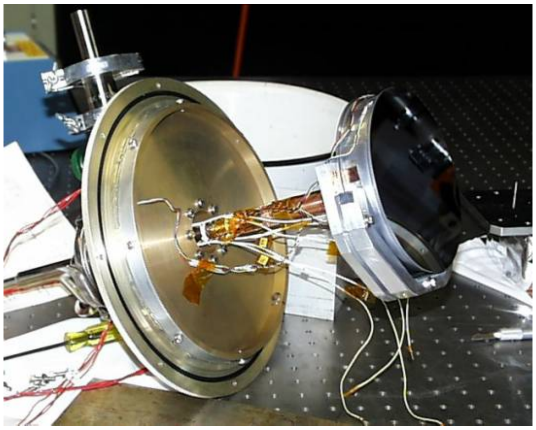


Figure 7: McCarter Lightweight Silicon Mirror ready for installation in 12” cryostat

Note Mechanical and Thermal Connections, Thermocouples

4.2 Test Operation

The sequence of testing is defined by the events listed in Table 4, for 100% “full” aperture direct data. After the sub-assembly of the mirror, aluminum plate, and cold finger were installed in the dewar and allowed to equilibrate at room temperature, optical figure data was obtained. The cryostat was sealed and evacuated. While still at room ambient temperature another set of data was recorded. Three sets of data were obtained during cool down, the first at approximately 180K, the second at 95.6K and the final at 90K. After the data was obtained at 90K the shutter remained open. The liquid nitrogen was vented and the unit was allowed to return to ambient temperature while still under vacuum. Data was taken and recorded after reaching ambient room temperature. Finally, the cryostat was vented to ambient air and after a short time the final data was recorded.

McCarter 12.5 cm SILICON SPHERICAL MIRROR

Event	PV	RMS	PWR (1)
in dewar no vacuum	0.562	0.095	-0.044
per-cold ambient vacuum	0.527	0.093	-0.031
1/2 cold @ 180k	0.673	0.131	-0.098
cold @ 95.6k	0.725	0.136	-0.056
cold @90k Shutter open	0.744	0.137	-0.075
post cold ambient vacuum	0.558	0.097	-0.032
post cold ambient no vac.	0.559	0.096	-0.014

80% (CLEAR) APERTURE

Event	PV	RMS	PWR (2)
pre-cold ambient vacuum	0.395	0.071	0.091
cold @86k. Shutter open	0.616	0.105	0.172
post cold ambient vacuum	0.435	0.073	0.087

1. Include Piston and Tilt
2. Piston and Tilt Removed

Table 4: Cold Test Data Summary: Direct Wavefront Data

McCarter 12.5 cm SILICON SPHERICAL MIRROR

100% (full) aperture			piston/ tilt removed
subtraction	**PV**	**RMS**	**PWR**
cold - (pre cold) warm	0.436	0.071	-0.047
cold - (post cold) warm	0.598	0.071	-0.053

80% (clear) aperture			piston/ tilt removed
subtraction	**PV**	**RMS**	**PWR**
cold - (pre cold) warm	0.345	**0.057**	0.068
cold - (post cold) warm	0.325	**0.053**	0.066
post cold - pre cold	0.094	0.014	0.001

Table 5: Cold Test Data Summary: Differential Wavefront Data

4.3 Discussion of Results

The data obtained is presented in Tables 4 and 5 that provide the direct wavefront data and some meaningful differential wavefront data, respectively. Results definitely indicates a high degree of cryostability.

There is a rather significant change in the power at various test conditions. This could possibly be due to the fact that there are small temperature differences though the thickness of the mirror at various times during the test. As shown in Figure 8 the temperature difference between the thermocouples on the front and back sides appears to be very small. This can be seen more clearly in Figure 9. For the 80% clear aperture, the change in power is relatively small.

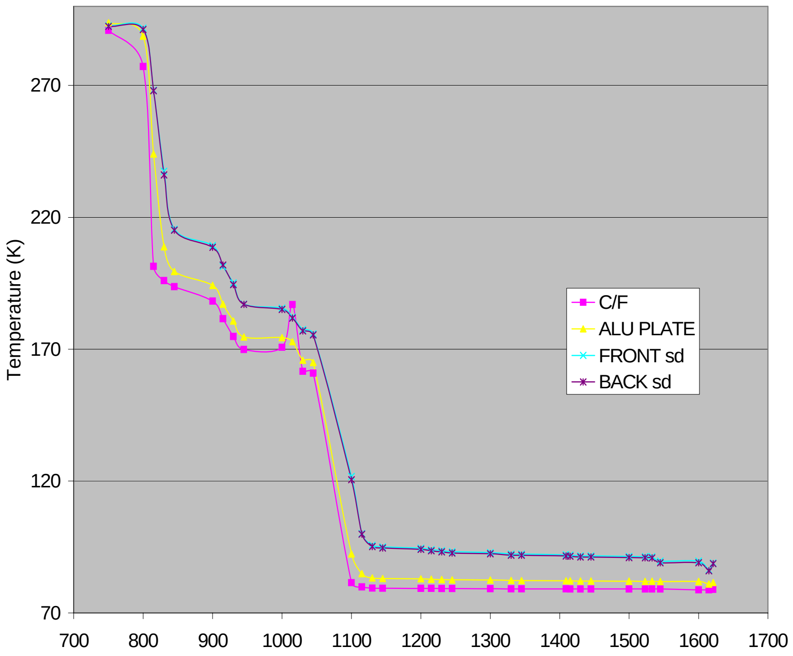


Figure 8: Temperture history of cool-down McCarter Lightweight Silicon Mirror

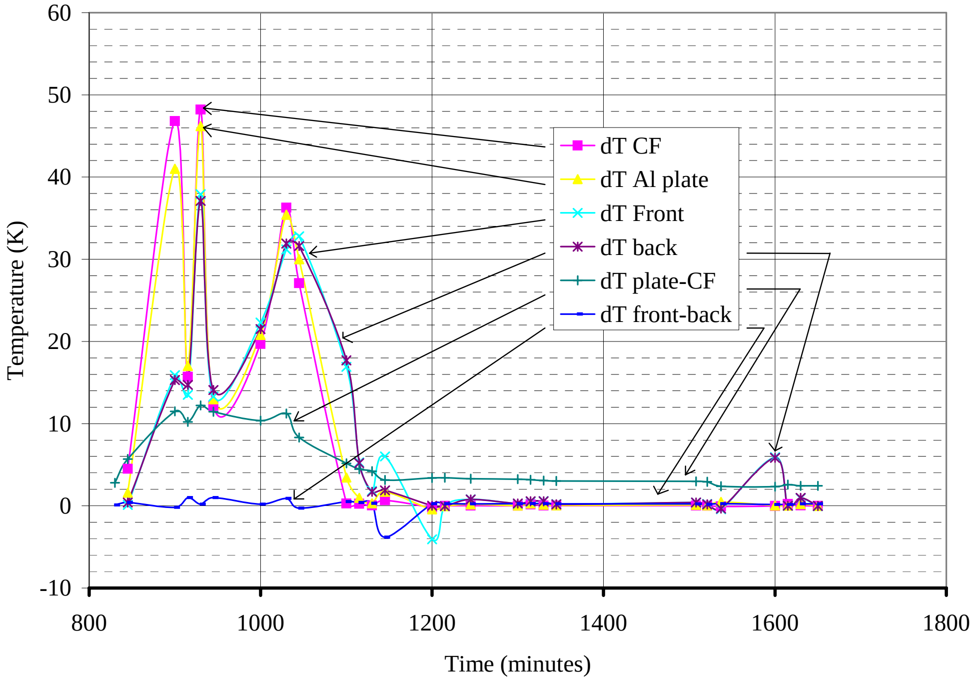


Figure 9: History of temperature differences aids in understanding deformation history

The most significant information regarding cryostability is provided in Table 5. Here, the differential wavefront data for the 100% full aperture shows identical values of rms and practically identical values of power with piston and tilt removed for both the cold condition minus the pre-cold warm as for the cold condition minus the post-cold warm. For the 80% clear aperture case the cold data minus the pre-cold warm or post-cold warm are practically identical, P/V values of 0.345 and 0.325 wave, rms values of 0.057 and 0.053 wave, and power with piston and tilt removed of 0.068 and 0.066 wave. When the data obtained prior to cool down is subtracted from the data obtained after warm-up the differences are exceedingly small, a P/V of 0.094 wave, an rms difference of 0.014 wave and a power change with piston and tilt removed of only 0.001 wave. The bottom line result clearly demonstrates cryostability within better than 0.06 wave rms over the 80% clear aperture.

5. SUMMARY

Although a little heavier than desired the spherical lightweight frit bonded silicon mirror had superior characteristics in all other areas as compared to requirements. The areal density was almost 19kg/m^2 versus a desired value in the range of 10 to 15kg/m^2. Surface quality over the full aperture was better than requirements for the 80% aperture; the rms figure error was 0.074 wave at 633nm versus a requirement of 0.10 wave. Roughness was only 0.5 nm rms versus a requirement of 1.0 nm rms. Low and high frequency figure errors were determined by fitting the surface with Zernike polynomials. The low frequency figure error is 0.063 waves rms, lambda/16. The high frequency figure error is 0.04 wave rms, lambda/25. Both are better than required for most visible optics. Deformations associated with the cryogenic exposure were also very low. The surface deformation from warm to cold is less than 0.06 wave, 38nm over the 80% CA. The surface deformation from post cold warm to pre cold warm is 0.014 wave lambda/70.

6. CONCLUSIONS

A cryostable lightweight well figured mirror was fabricated from single crystal silicon material machined elements and glass bonded into a sandwich configuration. The superior performance demonstrated seems to warrant refinement of the concept to achieve a lower areal density. Achieving such improvements would involve some risks but it should be possible to achieve an areal density of less than 15kg/m^2.

It should be noted that the excellent performance demonstrated by this cryostable, lightweight silicon mirror was achieved despite the fact that it was tested in a non-optimized mount that was available for a mirror of this size. In fact, the mount was made of aluminum. An optimized mount should result in even better performance.

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