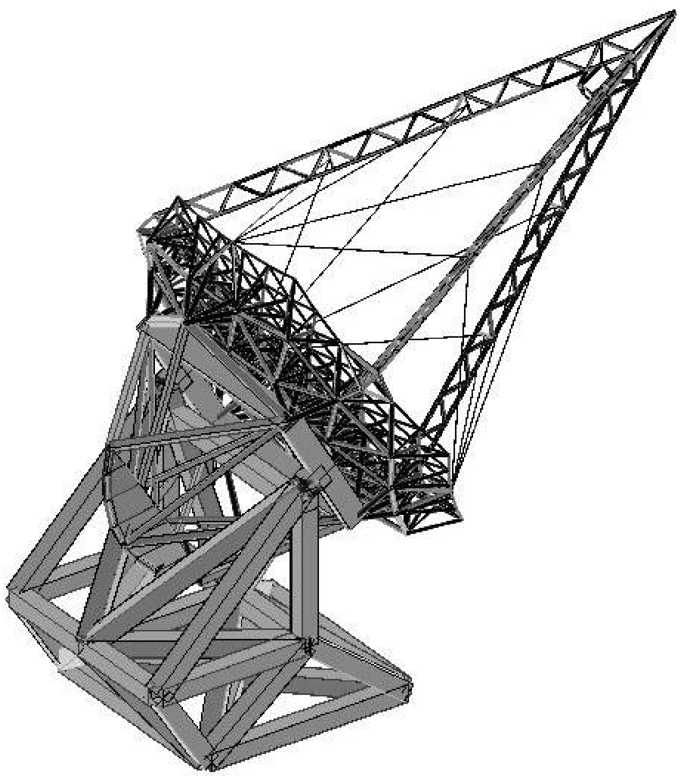
AURA New Initiatives Office
30m Telescope Project

NIO-RPT-0002

Fabrication of GSMT Optics



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January, 2001

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1. ABSTRACT

This report evaluates the technical feasibility and cost drivers for fabrication of the optical elements for the Giant Segmented Mirror Telescope (GSMT) based on discussions with several large optics polishing companies. It also compares the GSMT optical fabrication requirements to those of the proposed design for the California Extremely Large Telescope (CELT).

Our discussions with polishers have confirmed that the production of off-axis aspheric segments for the GSMT primary mirror and the production of the lightweight high-performance GSMT secondary mirror are not beyond the current state of the art and could be completed within a reasonable time frame. It is clear there are several polishers who would be well qualified to bid on this work.

It also appears likely that, with the proper procurement strategy, the optical elements can be produced for an affordable price. However, to minimize the cost risk it is recommended that further studies be conducted before initiating the vendor selection process.

2. INTRODUCTION

The point design of the GSMT incorporates a 30-meter diameter f/1 segmented primary mirror and a 2-meter diameter secondary mirror. The optical design and projected mechanical properties of the optical elements are discussed in another GSMT report[1]. The main characteristics are summarized in Table 1.

Primary Mirror	
Diameter:	30 meters
Focal Ratio:	f/1
Conic constant:	-1.00
Type:	Segmented, with hexagonal segments
Segment Size:	0.665 meter length of each side
Segment Thickness:	50 mm
Segment Material:	Zero expansion glass or glass ceramic (Zerodur, ULE, etc.)
Mass of segment:	115 kg (glass only)
Number of segments:	618 plus spares
Secondary Mirror	
Diameter:	2.0 meters
Final Focal Ratio:	f/15
Conic Constant:	-1.306
Type:	Lightweight structured monolith
Material:	High-specific-stiffness material (beryllium or SiC)
Mass:	200 kg

Table 1. The GSMT point design optical and optomechanical parameters.

Figure 1 shows the arrangement of the segments in the primary mirror according to the point structural design.[2]

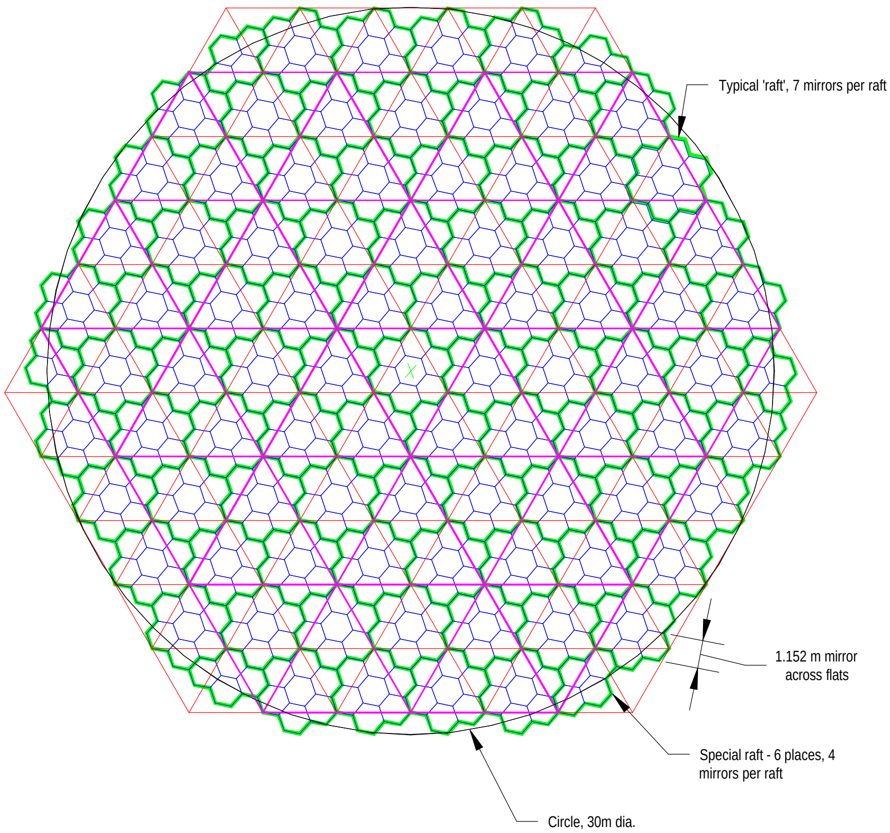

Figure 1. The arrangement of segments in the GSMT primary mirror.

The primary mirror segments will be off-axis aspheres. The highest asphericity occurs in the segments at the outer edge of the aperture, where the center of the outermost segment is just over 15 meters off axis. The largest amount of astigmatic departure from the sphere for any segment is a Zernike coefficient of 109 microns (218 microns peak-to-valley). The largest amount of comatic departure from the sphere for any segment is a Zernike coefficient of 8.8 microns (17.6 microns peak-to-valley). This is approximately equal to the worst-case Keck segments, which have an astigmatism coefficient of 101 microns and a coma coefficient of 13 microns.

In contrast, the California Extremely Large Telescope (CELT) project has put forward their proposed optical design for a 30-meter telescope[3]. Some of the parameters of their design are summarized in Table 2.

The maximum amount of astigmatic departure from a sphere in the CELT segments is a Zernike coefficient of 19 microns (38 microns peak-to-valley). The maximum amount of comatic departure from the sphere is a Zernike coefficient of 0.4 microns (0.8 microns peak-to-valley)

Jerry Nelson has commented that for CELT he would recommend some changes from the approach that was used for Keck. For example, he would prefer minimizing the number of holes that must be bored into the blanks (each Keck segments has several dozen holes).

Primary Mirror	
Diameter:	30 meters
Focal Ratio:	f/1.5
Conic constant:	-1.0028
Type:	Segmented, with hexagonal segments
Segment Size:	0.50 meter length of each side
Segment Thickness:	45 mm
Segment Material:	Zero expansion glass or glass ceramic (Zerodur, ULE, etc.)
Mass of segment:	74 kg (glass only)
Number of segments:	1080 plus spares
Secondary Mirror	
Diameter:	3.6 meters
Final Focal Ratio:	f/15
Conic Constant:	-1.525

Table 2. The CELT design optical and optomechanical parameters.

The Keck segments are 0.9 meters along each side (1.8 meters point-to-point) and 75 mm thick. To get an adequate mirror figure, the Keck segments are supported on 36-point whiffletree structures. Jerry said these were difficult to adjust, and he would prefer smaller segments that could be adequately supported on an 18-point whiffletree.

Smaller segments also have less overall asphericity. The worst-case astigmatism coefficient varies as the square of the segment radius. The worst-case coma coefficient varies as the cube of the segment radius, but the coma tends to be an order of magnitude smaller than the astigmatism.

A desire to limit segment asphericity also affects the choice of primary mirror focal ratio. The segment asphericity varies essentially as the inverse cube of the radius of curvature.

The most critical alignment sensitivity is to rotation of the segment, which can be thought of in terms of the change in surface height with rotation angle, $dZ/d\Theta$. This depends primarily on the amount of astigmatism in the segment.

3. PROPOSED FABRICATION APPROACH FOR PRIMARY MIRROR SEGMENTS

CELT scientists have proposed primary mirror segment fabrication techniques based on the stressed-mirror approach used for the Keck segments[4]. The CELT approach was taken as a starting point for discussions with optical finishers. Their proposed sequence of fabrication operations is listed below.

CELT Fabrication Approach:

1. Acquire generated circular mirror blanks; diameter 1.1 m

2. Grind and polish back surface spherical
3. Install stressing fixture on perimeter and back region
4. Stress blank to desired deformation, test with profilometer
5. Grind front surface spherical, testing with profilometer
6. Polish front surface, using planetary polisher, test with profilometer, polish to within ~100 nm RMS of desired surface
7. Optical test of circular mirror
8. Cut to desired hexagon (some warping expected, ~ 100 nm RMS)
9. Stress relieve the cut edge (polishing, etching, etc.)
10. Install passive support system. This should require gluing only, on the back.
11. Optical test of hexagonal segment
12. Ion figure out residual errors
13. Optical test of hexagonal segment, with and without warping harnesses
14. Ion figure if needed
15. Ship to site

CELT has also proposed the following manufacturing tolerances:

Optical Figure Accuracy	$\leq$ 20 nm RMS (some active optics warping allowed)
Surface Finish	< 2 nm RMS
Machining tolerances	< 0.1 mm
Edge bevels	< 1 mm

4. DISCUSSIONS WITH OPTICAL FINISHERS

Larry Stepp and Eric Hansen of the Gemini Observatories and Jerry Nelson of the CELT Project visited several optical finishers in late 2000 to discuss fabrication of large numbers of segments for GSMT/CELT. The companies visited included:

Brashear LP
Eastman Kodak
Rayleigh Optical
Space Optics Research Labs
Tinsley
Zygo

Each company was asked to comment on the proposed stressed-mirror fabrication approach. These comments are summarized below in Section 4.1. They were also asked to comment on a number of other fabrication issues; the specific questions and associated answers are listed in Section 4.2.

4.1. Comments on proposed stressed-mirror approach

1. Acquire generated circular mirror blanks; diameter 1.1 m

In general, the polishers prefer to procure the blanks themselves rather than have the project supply them. This gives them more direct control of quality and schedule.

We were told Schott is now producing up to 1-m diameter zerodur blanks in Durier, PA. Reportedly, the quality of the material they are producing there is excellent.

One polisher commented that the amount of material required to make the segments would be comparable to the total amount of zero-expansion glass currently made by one of the large glass suppliers in a year. Therefore, a significant expansion of production would be required to deliver all the segment blanks over a period of just a few years, though this is not expected to pose a problem.

The polishers all agreed with the desire to minimize the number of holes that must be bored into each blank, to control cost and minimize risk. However, if holes are needed they don't see this as a significant problem.

2. Grind and polish back surface spherical

More than one of the polishers asked if it would be acceptable to leave the back of the segments flat. For example, the (spherical) segments of the Hobby Eberly Telescope primary mirror have flat backs. Jerry Nelson said this would be acceptable; he could make appropriate allowances in the stressing calculations.

Some of the polishers suggested acid etching the backs of the segments rather than polishing them. They suggested this could reduce cost, and they believe it would be adequate to remove sub-surface damage left over from grinding. It would also provide a good surface to bond to support mechanisms.

3. Install stressing fixture on perimeter and back region

Virtually all vendors had concerns about the design of the stressing fixture, whether it would work reliably and whether it would be compatible with their continuous polishing (CP) machines.

On a CP machine (also known as a planetary polisher), the edge of the optic must be free so that the septum of the machine can bear against it to move it laterally. Several of the polishers commented that it would be better if the stressing fixture was not attached on the edge of the mirror blank.

Several polishers also expressed a desire for the stressing fixture to be as low as possible on the back of the mirror blank, to ensure adequate clearance and keep the center of mass of the blank plus fixture as low as possible.

One polisher pointed out the need to provide uniform pressure between the part and the lap by making sure any loading on the blank is spread out evenly. This will be difficult if the stressing fixture is attached only at the outer edge of the blank. The design of the fixture may need to allow clearance so additional weights can be distributed on the back of the blank during polishing.

4. Stress blank to desired deformation, test with profilometer

Jerry Nelson reported the amplitude of warping of the Keck segments was accurate to 1% based only on their calculations and it was routinely adjusted to within 0.1% with feedback from the profilometer used by ITEK.

Depending on the specific process flow the polishers had in mind and the number of parts that would be in work at one time, the number of stressing fixtures could vary from a few to several dozen. This highlights the need to keep the design simple and inexpensive.

5. Grind front surface spherical, testing with profilometer

Some polishers considered grinding the segments on a CP machine, others anticipated using different machines to do the grinding.

The polishers had different ideas about the best type of profilometer to use, but all their ideas were based on the use of multiple LVDTs in a configuration similar to that used by Steward Mirror

Lab to calibrate their stressed lap. The measurements would be relative to a standard reference surface.

One polisher mentioned there is a type of speckle interferometer used in the automotive industry to measure large surfaces with fairly large departures, for example measuring a 12" x 12" area with a height range of 40 microns. This type of device might be used to measure the warping of the segments. The area covered by the device is defined by the size of beam expander used.

6. Polish front surface, using planetary polisher, test with profilometer, polish to within ~100 nm RMS of desired surface

Kodak reported they were able to hold the 26.18-meter radius of curvature on the 97 HET segments constant within +/- 0.5 mm.

A CP machine uses a large stone or glass conditioner plate, about half the diameter of the table, to help maintain the shape of the pitch surface. The largest mirrors that can be polished on a CP machine are about 1/3 the diameter of the table. Therefore, to polish the size of segments anticipated by the CELT design would require at least a 3.5-meter diameter CP machine. The segment size envisioned by the GSMT strawman design would require about a 4.4-meter diameter table if the mirrors were polished as discs and then cut to hexagons. It would require a 4-meter table if the segments were polished as pre-cut hexagons.

Kodak currently has a 4-meter CP machine, as well as several slightly smaller ones. Tinsley currently has a 4-meter CP machine. Zygo has three 4.3-meter CP machines. Other polishers reportedly have similarly large machines.

7. Optical test of circular mirror

Several possible optical test methods have been proposed by CELT (reference 4). However, the polishers have their own ideas about testing the segments. Several of the polishers favor tests using computer generated holograms to produce the required asphericity in the test setup. One example of this approach has been described in a paper by Jim Burge[5]. The polishers expressed confidence they would be able to test the segments to the level of accuracy specified.

8. Cut to desired hexagon (some warping expected, ~ 100 nm RMS)

Jerry Nelson said Keck allowed the location of the hexagon within the circular blank to be adjusted when the mirror was cut, which made it easier to meet tolerances. This could be an important factor in reducing the average length of time each segment needs to be worked.

The polishers discussed different methods to cut the hexagons, including the use of diamond saws or a water jet. They indicated meeting the mechanical tolerances should not be a problem.

The polishers would prefer to have larger bevels than 1 mm, but they can work to that tolerance if necessary. We discussed the possibility that there might inevitably be a few edge chips because of the small bevels allowed. The specifications should be written with this possibility in mind.

Fiducials must be placed on the mirrors at the time the hexagon is cut.

9. Ion figure out residual errors

Kodak has direct experience ion figuring the Keck segments and the segments for the Hobby Eberly Telescope. They have an existing chamber with 2.5-meter diameter capacity. Most of the other polishers we visited do not have existing ion figuring chambers large enough for the segments, although some other polishers do (for example, REOSC).

Kodak recommends minimizing the amount of material to be removed by ion figuring to save time and cost. Also, it takes a long time to remove material with a narrow ion beam, so it will be important to avoid high-spatial frequency errors in the polished surface.

The segments will need to be supported downward-looking in the chamber and it probably does not make sense to remove them from their mounts to install them on a separate support in the chamber. This implies the design of the mirror mount should be vacuum compatible and the mount should work well upside down (neither of which is expected to be a significant problem).

There is at least one competing technology to ion figuring – magneto-rheological finishing (MRF). Although we don't know of a polisher with the capability currently to finish 1-meter segments by MRF, MRF should compare favorably to ion figuring for the following reasons:

1. It appears to be as deterministic as ion figuring
2. It does not require a vacuum chamber so it should be less expensive to set up and to run
3. It should be relatively easy to scale up in terms of the part size
4. It is a polishing process, so it improves the surface finish rather than degrading it.

4.2. Answers to questions about segment fabrication

1. Various sets of parameters have been discussed for hexagonal segments, ranging for example from approximately 1000 segments 1-meter across and 40 mm thick that are part of an f/1.5 parent paraboloid, to approximately 700 segments 1.2-meters across and 50 mm thick that are part of an f/1 parent. Within this range, how would you estimate the difficulty and total cost would vary with the following parameters?

Segment width
Segment thickness
Mirror focal ratio

Within this parameter space, where would you guess the minimum cost solution would lie?

All the polishers we talked to preferred segments in the size range we were discussing, between 0.8 and 1.2 meters. The consensus is that within this range, segment size is not a strong cost driver.

The range of segment thickness between 40 and 50 mm was considered acceptable for this size of part.

The job will be easier if the segments are less aspheric, so the polishers generally favor a longer focal ratio.

2. Do you think it is worth the effort to correct coma by stressed mirror polishing, or should it be corrected entirely by ion figuring?

To minimize the amount of material to be removed by ion figuring, the polishers generally thought it would be good to correct at least some of the coma by stressed mirror polishing, at least on the more aspheric segments.

3. Can the blanks be cut into hexagons before polishing, or do they need to be polished as circles and then cut?

Jerry explained that it is very difficult to predict the warping effects when the segments are cut. The direction of stress in the material that will warp a mirror when it is cut does not cause birefringence when measured through the thickness, so there is no good way to predict the shape of the warping by measuring the residual stress before cutting.

Most of the polishers would prefer to polish the segments as hexes, to minimize problems caused when the segments are cut. However, they also expressed concern whether a warping fixture could be designed to avoid local distortion where the levers are attached. In general they are not confident that the stressed-mirror approach will work if you don't start with oversized circular blanks.

4. Would it be economically feasible to equip a dedicated facility just for making these aspheric segments?

All the polishers felt some dedicated equipment would be necessary, but some would use parts of their existing facilities for certain process steps. Some of the vendors could modify their existing facilities to do this work, others would need new facilities. Several vendors emphasized the need to carefully design the entire facility to factor in the handling and storage of the segments, to ensure an efficient process flow and safeguard the parts in work. In general, the polishers would need 1-2 years after the start of the contract to set up an efficient facility.

5. Will it be more cost effective to perform the final optical acceptance tests on individual segments, or on a raft of 7 or 19 segments?

The polishers we talked to would all prefer to test individual segments, to avoid holding up the tests waiting for multiple segments to be finished. However, several of the polishers emphasized the utility of having a test setup that could be used for more than one type of segment, for example, by having an aspheric compensator that could cover a range of off-axis radii.

In contrast, REOSC is planning to test the segments for the Gran Telescopio Canarias in groups of seven segements[6].

6. If the segments were manufactured in radial order, that is, with the segments closest to the center produced first, followed by the next ones out, etc., would it be possible to adjust the radius of curvature of the lap slightly between each set of six segments, so it would not be necessary to bend power into the segments?

All of the polishers agreed in general with the idea of adjusting the radius of curvature of the lap over time, to minimize the amount of curvature that would need to be bent into the segments. However, they would not adjust the radius between each set of six.

The stressing fixtures would still need to be able to control the focus term. This could be important if a segment were scratched and had to be reworked out of sequence, for example.

7. Would it be cost effective to equip the vacuum chamber used for the final ion figuring run with a coating capability, so the coating could be applied to the pristine ion-figured surface?

The polishers were uniformly negative about this approach. They said it could be done, but they saw no advantages to it. The ion figuring chamber will be an expensive facility whose throughput should be maximized. Also, there would be issues of controlling contamination from the coating material.

8. There would likely be some advantages and disadvantages of making the segments sector-shaped instead of hexagonal, as illustrated. How do you think the fabrication difficulty and cost would compare between sectors and hexagons?

Most of the polishers would prefer to produce hexagons, although they felt they could produce sectors if required. They said there would be more wasted material to produce sectors, and it would be difficult to control the mirror figure at the relative sharp (90^o) corners. In general, from the polishing standpoint, the closer the blanks can be to round disks, the better.

They predict it would be cheaper to produce hexagons.

4.3. General comments

These polishers routinely work on mirrors 1-2 meters in diameter, several of them had work of this size ongoing when we visited.

Some of the polishers were interested in developing the stressed-mirror process. However, a couple of them were openly skeptical – one said the process is not economically viable, or optical shops would already be using it routinely. These vendors have other techniques they would favor for finishing the segments.

In defense of the stressed-mirror approach, Jerry Nelson has pointed out it will tend to converge on the proper figure the longer you polish, as opposed to other approaches that wear away the glass differentially, requiring careful control of pressure, dwell time, etc.

One polisher made the point that the optics industry is quite busy right now and there will be a significant opportunity cost if they assign people to work on proposals or technology development efforts for telescopes that have not yet been funded. On the other hand, some of the smaller vendors would be happy to do development work for us if there were funding available to cover their costs.

One reason several of the polishers are busy is that they have contracts to produce large numbers of flat optical elements for the National Ignition Facility (NIF). Some of these parts (the amplifier slabs) are nearly a meter long and they have length-to-thickness ratios similar to the proposed GSMT segments. Their surface figure specifications are also similar to the requirements for GSMT. The NIF needs more than 7500 large optical elements (larger than 30 cm across) to be produced within the next 5 years, so the production rates in terms of square meters of polished surfaces per month are similar to the requirements of GSMT.

We were told that in some cases NIF was able to reduce the cost per part by approximately a factor of 5 by working with the polishers in advance. NIF funded some development work, allowed enough time for special machines to be fabricated and experiments to be run, and then solicited new bids based on highly-optimized production schemes. This approach required significant funding in advance, involved a certain amount of financial risk, and took 2-3 years to accomplish, but the resulting cost savings paid for the effort many times over.

In France, there are similar laser fusion development programs. For example, last year REOSC produced a batch of 158 amplifier slabs that are 81 x 45 cm in size on their 4-meter CP machine, for the Laser MagaJoule (LMJ) project[7].

5. COST OF PRIMARY MIRROR SEGMENTS

The spherical segments of the primary mirror for the Hobby-Eberly Telescope were produced by Kodak on their 4-meter continuous polishing machine between 1996 and 1998, at a cost of $20,000 per square meter. For a 30-meter GSMT, the primary mirror area would be about 706 square meters. If the GSMT primary mirror were made of HET-type spherical segments, the cost (including some spares) could be estimated at $15M, plus inflation, minus some savings from high-volume production. A reasonable estimate for a full set of spherical segments might be $15-20M.

If current small-quantity techniques for making off-axis paraboloidal segments were used, their cost would be expected to be 5-10 times the cost of making spherical ones. A realistic goal would be to produce the required aspheric segments for no more than twice the cost of spherical ones. To make this possible, several risk-reduction measures will probably be needed, as described in Section 7.

6. FABRICATION OF THE SECONDARY MIRROR

Fabrication of the GSMT secondary mirror involves two key issues – availability of a high-performance mirror blank, and development of an effective optical test. In both of these respects, the current state of the art is in the range needed for GSMT, so it should be possible to obtain credible cost estimates for producing the GSMT secondary mirror.

6.1. Secondary mirror substrates

REOSC has finished four lightweight, 1.2-meter diameter nickel plated beryllium secondary mirrors for the VLT. These mirrors have an areal density of 50 kg per square meter. The mirror blanks were produced by Brush Wellman.

Tom Parsonage of Brush Wellman was consulted regarding their ability to produce a beryllium blank 2 meters in diameter. Part of his answer is copied below:

"Concerning the technical ability to produce beryllium segments 2 meters in diameter, we can vacuum hot press up to 1.9 meters in diameter with current facilities and equipment. The thickness is not an issue, as we have vacuum hot pressed beryllium this large for the space shuttle umbilical doors close to this thickness. This vacuum hot pressing process provides densities around 99.5% of theoretical density, not quite as good as HIP'ing, but close. We can vacuum hot press, I220, S200F, or O-30 beryllium depending on whether or not the optic will be bare beryllium or nickel plated."

Another candidate material is silicon carbide. Xin?tics has already produced a mirror substrate 1.2 meters in diameter, and has plans to expand to larger sizes in the next 2-3 years. IABG in Germany reportedly has furnaces capable of producing silicon carbide parts up to 3 meters across, though we have not yet determined the largest size of mirror blank they have produced.

At present the straw man secondary mirror substrate should be beryllium, but SiC may be a viable competitor within a year or two.

6.2. Secondary mirror testing

The limitation in finishing large secondary mirrors is optical testing. Other aspects (polishing, handling, coating, etc.) are not a problem.

The largest secondary mirrors produced to date are the 1.4-meter diameter mirrors for the Keck Telescopes[8]. However, Steward Observatory Mirror Lab is currently polishing a 1.7-meter diameter secondary mirror, for the MMT, that they are testing with a 1.8-meter diameter holographic test plate. This approach can be extended to test the 2-meter secondary mirror proposed for GSMT, but it would be very difficult to extend it to the 3.6-meter size needed for the CELT design.

7. RISK MANAGEMENT

Our discussions with vendors indicate there is little technical risk, or schedule risk, in producing the optical elements required for the GSMT point design. The principal risk issues relate to the costs. To minimize the cost risk, further initiatives are needed. The following are recommended:

1. Visit additional polishers to discuss production of the primary mirror segments and/or the secondary mirror. These should include:

    Lick Observatory
    Raytheon
    REOSC
    Zeiss

2. Reconsider the point optical and optomechanical designs after a detailed error budget has been developed. It may be advisable to reduce the asphericity of the segments by lengthening the primary focal ratio and reducing the diameter of the segments, though it shouldn't be necessary to shift as far as the current CELT design.

3. The primary concerns of the polishers who are interested in using the stressed-mirror approach relate to the stressing fixture. Prototype fixture designs need to be developed and optimized using finite-element analysis.

4. Once a promising design has been developed, prototype stressing fixtures should be fabricated and used to produce aspheric parts on CP machines. They could be subscale, perhaps half the final segment size, and the base mirror figure could be flat instead of spherical, to make it easy to integrate the tests into normal polishing runs. The results of these tests should be made available to all potential bidders.

5. To get the best price for producing the segments, GSMT should consider funding manufacturing development studies at several polishers in advance of contract award. The polishers should be allowed time to develop their process plans in detail and should be encouraged (perhaps through funding support) to test key process steps using prototypes.

8. ACKNOWLEDGEMENTS

I would like to thank Jerry Nelson, Eric Hansen, and the engineers and managers at Brashear LP, Eastman Kodak, Rayleigh Optical, Space Optics Research Labs, Tinsley, and Zygo for very helpful discussions of the GSMT optical fabrication requirements.

The New Initiatives Office is a partnership between two divisions of the Association of Universities for Research in Astronomy (AURA), Inc.: the National Optical Astronomy Observatory (NOAO) and the Gemini Observatory.

NOAO is operated by AURA under cooperative agreement with the National Science Foundation (NSF).

The Gemini Observatory is operated by AURA under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

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