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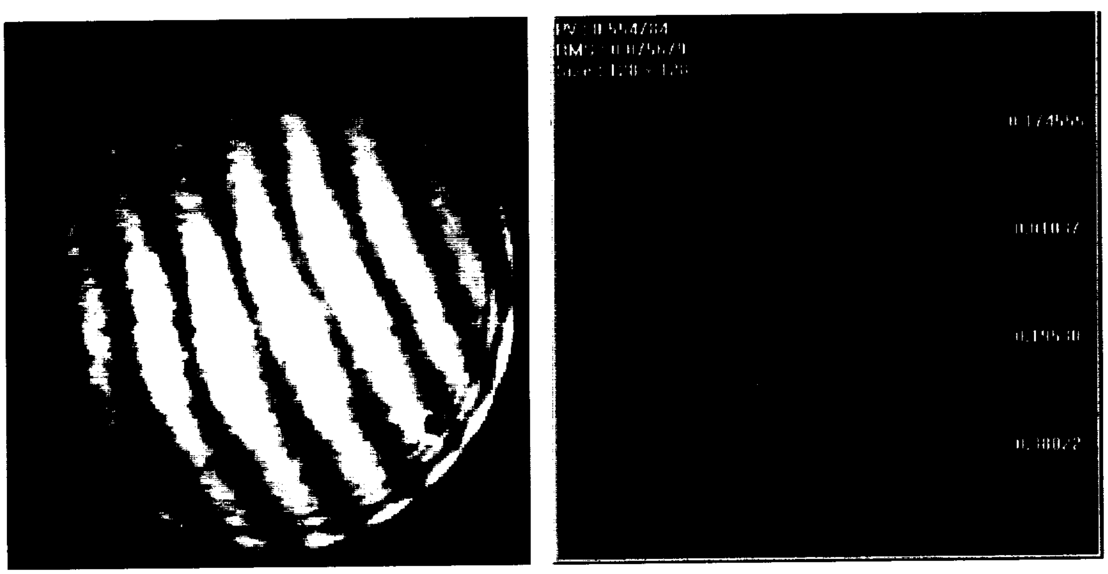

Membrane Mirrors

SRS Technologies
Contract No.: NAS8-00105
500 Discovery Drive
Huntsville, AL 35806
Principal Investigator:
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Prepared for:
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Optics Branch
Manufacturing Technology Center
NASA/MSFC
Marshall Space Flight Center

FOREWORD

This progress report was prepared by SRS Technologies under Contract Number NAS8-00105 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. This work was administered under the technical direction of the Contract Officer's Technical Representative, Mr. Whitt Brantley of the Optics Branch Manufacturing Technology Center.

This report describes work performed by SRS Technologies during the performance of this contract. Mr. James D. Moore, jmoore@stgs.srs.com, served as the SRS Technologies Principal Investigator. Other SRS project personnel who made major contributions to this research include:

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ABSTRACT

SRS Technologies and NASA Marshall Space Flight Center have conducted a research effort to explore the possibility of developing ultra-lightweight membrane optics for future imaging applications. High precision optical flats and spherical mirrors were produced under this research effort. The thin film mirrors were manufactured using surface replication casting of CP1™, a polyimide material developed specifically for UV hardness and thermal stability. In the course of this program, numerous polyimide films were cast with surface finishes better than 1.5 nanometer rms and thickness variation of less than 63 nanometers. Precision membrane optical flats were manufactured demonstrating better than l/13 figure error when measured at 633 nanometers. The aerial density of these films is .037 kilograms per square meter. Several 20-inch spherical mirrors were also manufactured. These mirrors had excellent surface finish (1.5 nanometers rms.) and figure error on the order of tens of microns. This places their figure error within the demonstrated correctability of advanced wavefront correction technologies such as real time holography being developed by the Air Force. [1]

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1.0 — Introduction

Thin film membrane optics offer the potential for order-of-magnitude aperture size increase or mass reduction for super lightweight space based optical systems. Traditional optics are limited to massive, stiff, thermally and mechanically stable materials, such as low-expansion glass, beryllium, and similar materials. These are expensive to procure and are often unnecessarily massive once in space. There is little possibility of compact storage and deployment; therefore the launch package is often large, of low density, and constrained by vehicle dimensions. A thin film or membrane mirror is potentially storable, deployable, reproducible, inexpensive compared to glass or metal optics, can be fabricated in sizes dictated largely by the available facilities, and may be seamed or joined to form very large areas.

The development of large imaging quality membrane optics fabricated from very thin space-rated polymers is a high payoff crosscutting technology that will benefit many current and future NASA, DoD and commercial missions. IR imaging membrane optics will enable development of previously impractical aperture sizes for sensors used in Earth resources exploration, weather monitoring and forecasting, intelligence gathering, and other imaging applications. Further development of thin film optics for visible wavelength imaging will enable development of very large space telescopes and other imaging applications. Thin film or membrane optics, at present state-of-the-art, are limited to non-imaging concentrators, microwave antennas, and other long wave applications because of surface and shape accuracy limitations. Research conducted in this study addresses the possibility of extending membrane optics to applications in the infrared and visible region of the spectrum. The test articles and test results generated in this study show, that with reasonable development of cast and release technology and precision mandrels, optical quality membrane mirrors for visible and near infrared imaging are possible in the immediate future. The size of these optics is currently limited by mandrel dimensions. With the development of specific enabling technologies, which appear possible and practical, segmented or seamed optics suitable for visible or infrared systems should be feasible in dimensions limited mostly by handling and metrology.

2.0 — Objectives

This effort was structured to accomplish a reasonable first step along the path to developing membrane optical elements for applications requiring very large imaging optics in space. The objective of this joint SRS-MSFC research program was to demonstrate that IR imaging quality optical elements can be manufactured from a lightweight space rated membrane material. Specifically, the goal was to develop and demonstrate cast and release technology capable of replicating the surface of an optical quality mandrel. The research plan called for demonstrating surface and shape accuracies sufficient for IR imaging on an optical flat and on a curved reflector. The proposed performance goals are listed below:

- A flat membrane mirror, of less than 25 microns thickness, capable of less than $1/8\lambda$ (λ=633nm) wave wavefront error on double pass interferometry and surface smoothness of 5 nanometers rms over 90% of the aperture or 80% of the clear area.

- A parabolic mirror, of less than 25 microns thickness, 0.5 meter in diameter, demonstrating less than 1 wave error in reflection over 90 % of the aperture or 80% of the clear area, and smoothness of 5 nanometers rms at 10 sampling locations.

Demonstrating these goals is a logical and mandatory first step toward successful development of membrane optics capable of meeting present and future requirements for large scale space-based optical systems. Test articles were developed under this program that greatly exceeded the surface finish requirements for both the flat and curved mirrors with an RMS surface roughness average of 1.78nm. A surface figure error of better than $\lambda/13$ at $\lambda = 633$ nanometers was demonstrated for flat test articles for central region flatness, also much better than the performance goal. A figure error of 39 microns was demonstrated on the curved mirror test articles, which is suitable for some IR imaging applications and correctable for shorter wavelength applications.

3.0 — Technical Approach

To achieve the performance goals significant research into materials, manufacturing methods, and metrology was required. This effort was structured into three task areas. Materials and processing research, design and manufacturing of mandrel and support hardware, and membrane metrology. The results of the work in each of these areas are documented in this report.

3.1 Materials and Processing

New manufacturing procedures and material processing methods had to be developed to advance the cast and release film manufacturing capability to the point that imaging quality films could be produced. The point of departure for this effort was derived from SRS experience in manufacturing membrane solar concentrators for the Air Force Solar Thermal Orbit Transfer Vehicle (SOTV) and for the Boeing 702 satellite bus solar power arrays. **Exhibit 1** shows SRS membrane reflectors during deployment aboard the Galaxy 11 Satellite. These reflectors are made from a polyimide material, CP1™. This material is one of two different polyimide formulations, developed by NASA/LaRC and licensed by SRS Technologies. The CP1™ and CP2™ materials have excellent thermal stability, UV degradation resistance and clarity. These materials are soluble in a number of different organic solvents. Because of this solubility it is possible to use casting procedures for manufacturing films and other components. The choices of solvent and percent solution are parameters that can be adjusted to improve the castability of thin films. Based on our experience with the material and its proven success in space applications, CP1™ was selected as the primary material of choice for this study. It was necessary to improve the processes used to cast and release

Exhibit 1 SRS Membrane Reflectors Deployed Aboard the Galaxy 11 Satelite in Orbit

films made from CP1™ polymers to improve surface replication properties. These processes can be broken down into three primary areas; polymer synthesis, casting processes, and thermal curing. Parametric studies of variables in each of these areas were performed with thickness variation, surface roughness, and quality control as the primary improvement goals.

The first area of research involved the substrate material used for casting flat films. Typical SRS castings are performed on soda-lime float glass disks, which are flat only to several waves. A comparison was made using such substrates with a Pyrex substrate flat to within $1/4\lambda$ (λ=632nm) to determine advantages and disadvantages between the two. Polymer castings typically wear substrate surfaces after repeated castings. This effect was noted much more quickly on the optical flat, which began to delaminate surface particles along with the cast film during release after only two castings. Float glass substrates can normally withstand many more castings before significant deterioration and, as will be presented in the metrology section of this report, the air side surface roughness of float glass castings can be controlled to well within the requirements. Due to this fact and the two orders of magnitude price difference between the optical flat and float glass the latter was chosen to pursue further process optimization research on flat films.

The next parameter investigated was to quantify the quality control issues of polymer production and casting related to particulate contamination. It was anticipated that some particulate introduction in the film might not drive the film out of optical specifications. The belief was that the effects of a particle in the solution would be limited to a very local area. However, this proved not to be the case. Many films were cast during this study; in a large majority of the initial castings, thickness variations were noted and associated with particulate contamination. It was found that individual particulates, present in the resin or introduced during casting, caused unacceptable streaking. The characteristic particulate streaking is shown in **Exhibit 2**. This issue was addressed by reconfiguring the resin-to-cast process to eliminate any opportunity of resin exposure to possible contamination. This began with additional filtering of the CP1™ resin and release agent through sub-micron screens to eliminate particulate contamination already present in either solution. Precise procedures were developed for cleaning and preparation of containers that would be used to hold and dispense the resin as well as the release agent. A clean-room casting environment was then implemented to minimize contamination experienced during the actual casting. The casting facility was upgraded with laminar flow benches that utilize HEPA filters to provide very clean airflow over the working surface of the bench where the films are cast. The benches are located in a restricted access area that has independent temperature and humidity control systems and is used exclusively for optical quality casting research and development. Appropriate clean room attire is also required during all resin handling and casting operations. Curing the film also provides a possible source of contamination due to the increased solubility of the film as the temperature approaches the glass transition stage (T_g). To eliminate this potential the cast substrate was placed in an enclosure with

Exhibit 2
High Frequency Thickness Variation Caused by Particulate

a sub-micron screen to vent solvents. These process changes provided the best conditions for ensuring quality control concerns during all subsequent casting during this effort.

Once the casting substrate material and process control issues had been addressed the minimization of thickness variation present in a cast film was the next area of focus. The thickness variation, in past non-imaging membranes manufactured by SRS, displayed a high frequency random pattern, which can be viewed as Fizeau fringes in the film. **Exhibit 3** shows such a film. These fringes are a result of the irregularities in the film between the top and bottom surfaces resulting in an unequal optical path difference of reflected light that leads to either constructive or destructive interference (light or dark fringes). When viewed under monochromatic light these fringes are easily detected and each represent approximately $1/3\lambda$ change in thickness. Improved thickness control is critical for any membrane optic solution that uses film stress to maintain membrane shape. A uniformly thick flat will remain flat provided the boundaries are maintained in a plane. Therefore, many iterations were conducted using 30cm diameter float glass substrates with varying casting conditions. The parameters deemed critical for thickness variation included, substrate material and condition, release agent concentration, spin speed, environmental conditions, air flow, resin application method, solvent, percent solids, vibration isolation, pre-cure drying, and cure cycle. All of these variables are under process control and were manipulated in order to determine their effect on the resulting thickness variation. Each of the parameters had to be controlled to within appropriate tolerances to achieve an optical quality film. The process had to be tuned for each particular substrate, size, etc. Once the proper process was established for a specific film size, thickness and figure, optical quality films could be repeatedly manufactured. **Exhibit 4** shows a resulting optical quality film. It should be noted that this film is nearly void of all fringes indicating in a thickness variation of less than 0.2μm across the 25cm diameter. Com-

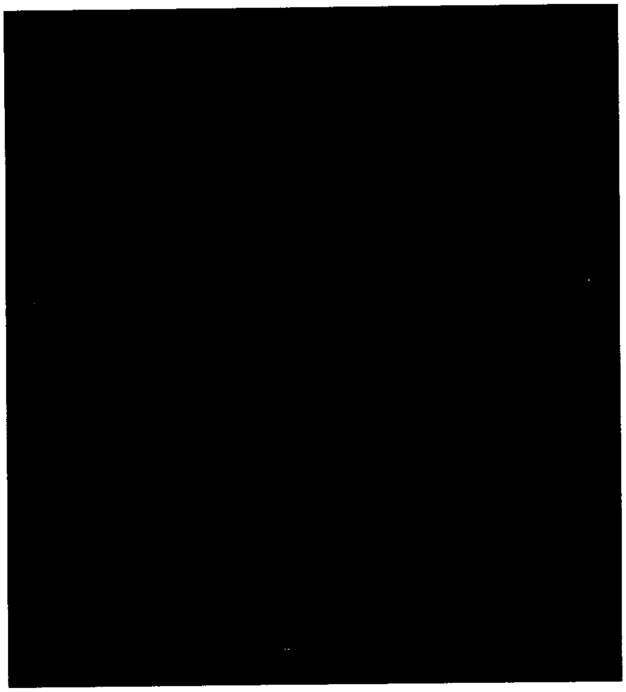

Exhibit 3 Typical High Frequency Thickness Variation Pattern

Exhibit 4 Minimized Thickness Variation Film 25cm Diameter

parison to the film shown in Exhibit 3 shows the dramatic improvement that was accomplished under this effort. These studies have yielded a considerable database of knowledge on the parameters necessary for film thickness control. This applies not only to making the films uniform, but also to being able to introduce a controlled thickness variation. An example of this is shown in **Exhibit 5**. This film has uniformly decreasing film thickness from the film center to the outer perimeter. This could be potentially applied to the development of large aperture refractive lenses made from a polymer material. Very uniform thickness variation could also be used to introduce a slight amount of power to an optical flat. This feature could simplify the design of faceted optical arrays such as those proposed by the University of Arizona. The array elements could be supported as membrane flats and still form an image at a long focal length.

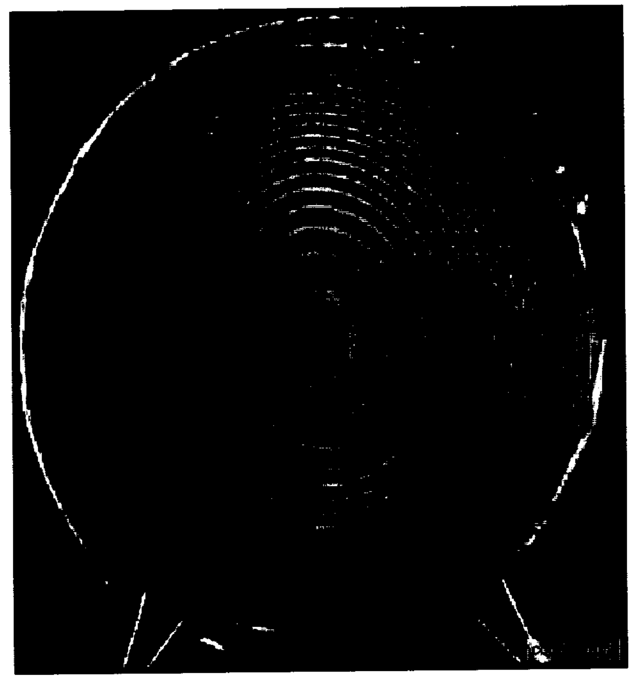

Exhibit 5 25cm Diameter Film Displaying Uniform Thickness Distribution

The success of the minimized thickness variation film was followed by an expansion up to 0.5m diameter sized flat films with some modifications to casting conditions. The next step was to transfer this achievement to the 0.5m curved mandrel provided by NASA/MSFC. The details of the mandrel design will be discussed in the next section. SRS anticipated that the slope of the mandrel would allow smoother resin distribution and provide minimum thickness variation with only minor casting process modifications. In practice, the gravity effects on resin flow had a greater effect on resin flow physics than anticipated. Consequently, the casting processes required more tuning to adjust for the mandrel figure than was anticipated. **Exhibit 6** shows an initial casting on the mandrel matching the parameters used to obtain a high quality flat. Significant changes had to be made to the casting process in order to obtain improvements in this thickness variation pattern. After numerous parameter modifications were made a combination was finally established that produced a film whose thickness variation map is shown in **Exhibit 7**. This image shows a minimized thickness variation of ap-

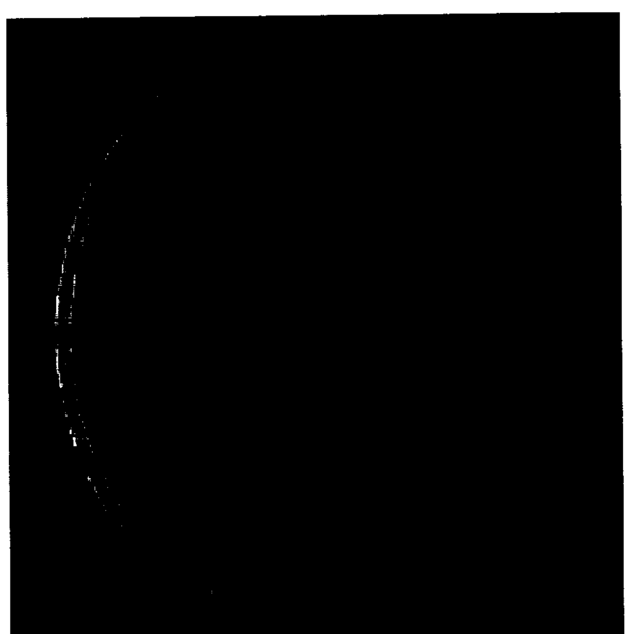

Exhibit 6 Initial Mandrel Casting with High Frequency Thickness Variation

proximately three fringes. This, again, is a tremendous improvement over initial results and demonstrates the ability to cast films of sufficient thickness uniformity on a curved surface.

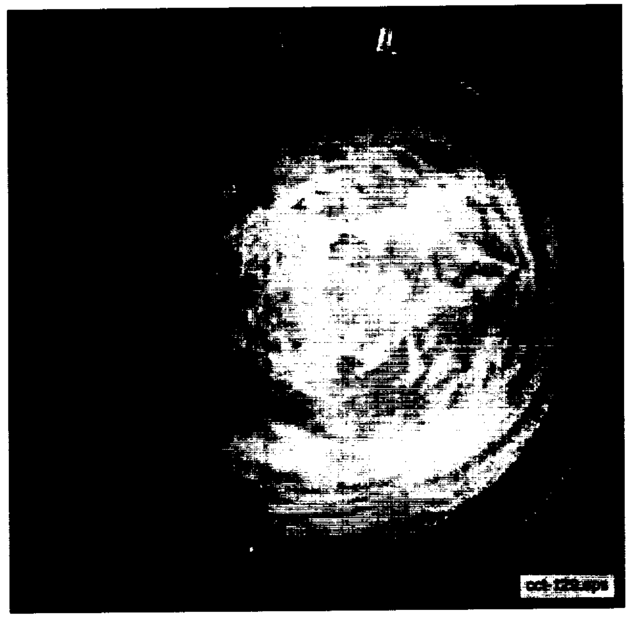

Exhibit 7 Mandrel Casting with Minimized Thickness Variations

The studies completed under the materials and processing task demonstrated that it is possible to accomplish casting of precision optics from lightweight space rated polymer materials. We were able to generate membrane optical element with highly specular polished surfaces; surface roughness on the order of 1 nanometer rms. We were able to achieve this quality of surface finish on flats and curved membranes of multiple sizes. We encountered no effects that would diminish the surface quality as casting size is scaled up. Membrane thickness control was demonstrated on flats and curved elements to fractional wavelength tolerances. Membrane thickness control is critical because thickness variations manifest themselves as low and mid spacial frequency figure errors in stressed membrane optical elements. Thickness control was more variable with size and curvature. In general, the difficulty of tuning the processing parameters for uniform thickness increased with size. However, we currently do not know the size at which this will become a factor. To date we have been able to get uniform films in sizes up to 68 inches in diameter. The conclusion of this task is that surface replication casting of thin film membrane optical elements for visible and larger wavelengths is possible and practical for larger aperture applications.

3.2 Design and Manufacturing of Mandrel and Support Hardware

By definition a membrane has no bending stiffness, thus the only restoring forces available to maintain the figure of a membrane mirror comes from the edge support constraints and the geometric stiffness caused by curvature. For flat membrane mirrors, edge planarity is a sufficient constraint to ensure that the membrane will be planar, assuming no dynamic loading or out of plane static loads. Therefore, serious consideration was given to the design and fabrication of the fixturing hardware used to test the membranes that were manufactured under this effort. The test fixture was designed such that it could be used to test both flats and curved mirrors. The curvature in the mounting area of the fixture was diamond turned to match the curvature of the cast films. The curved membrane mirrors were originally going to be cast from a custom parabolic mandrel manufactured specifically for this study. Unfortunately, problems with the bearings in the NASA/MSFC diamond turning facility precluded manufacture of the parabolic mandrel. Fortunately, NASA/MSFC was able to provide a suitable 0.5 meter precision spherical mandrel for film casting. The mandrel, shown in **Exhibit 8**, is nickel plated stainless steel with a radius of curvature of 1.9 meters. The membrane

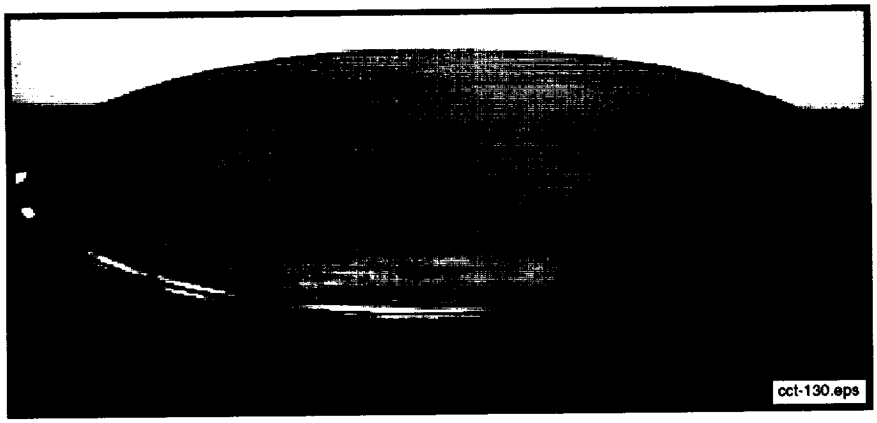

Exhibit 8 Spherical Mandrel

mount was designed specifically for this mandrel. This test fixture design was based on a concept which utilizes an inexpensive mounting ring that initially secures and positions the films of interest over an optically flat surface, diamond turned to a 1/4λ figure accuracy. Multiple rings allow for a low investment fixture that can be rapidly and repeatedly used. These inexpensive rings are rough machined to the same radius of curvature as the mandrel and are adhered to the film using five-minute epoxy around the perimeter. The mounted membrane is then placed onto the precision mount and secured using a three-point spring tensioned system. Both the ring and precision mount are shown in **Exhibits 9** and **10**. The diamond turned edge of the precision mount is turned to match the mandrel radius of curvature and it has a small 0.25cm radius lip turned flat to 1/4λ. This lip was added to allow the apparatus to be used for testing 0.5m flat membranes in addition to the curved ones. The precision mount has a backing plate that was designed to form a chamber in which a slight vacuum could be used seat the curved membranes in the precision fixture. For flat films the non-precision ring holding the film is tensioned across the diamond turned ring using the spring compression fasteners so only the 1/4λ flat lip is in contact with the film. For curved films the spring compression fasteners are tightened only enough to seat the film against the precision ring. The vacuum can then be released or reduced to maintain a very slight tension in the film.. The entire mount is attached to a kinematic base that allows proper alignment of the test article through rotation about two axes. This was accomplished by the use of three adjustable screws that have two, three, and four degrees of freedom respectively. These screws vary the position of the test fixture relative to the mounting base. The entire mount is configured to rest horizontally on the ground for curved membrane testing, but can be configured upright as well for flat film testing. Final fabrication of the test fixture was delayed by several months due to the same problems with the NASA/MSFC diamond turning machine that prevented a custom mandrel manufacturing. The machine was eventually repaired enough to turn the precision mount but was still experiencing some vibration induced errors resulting in a high surface roughness finish and the possibility of trefoil or other similar shape error was suspected by NASA/MSFC staff. Unfortunately the problem was not corrected during the remainder of this effort and refinishing of the precision mount was not possible. In spite of these problems, the mount functioned relatively well for the testing accomplished in the final task of this effort.

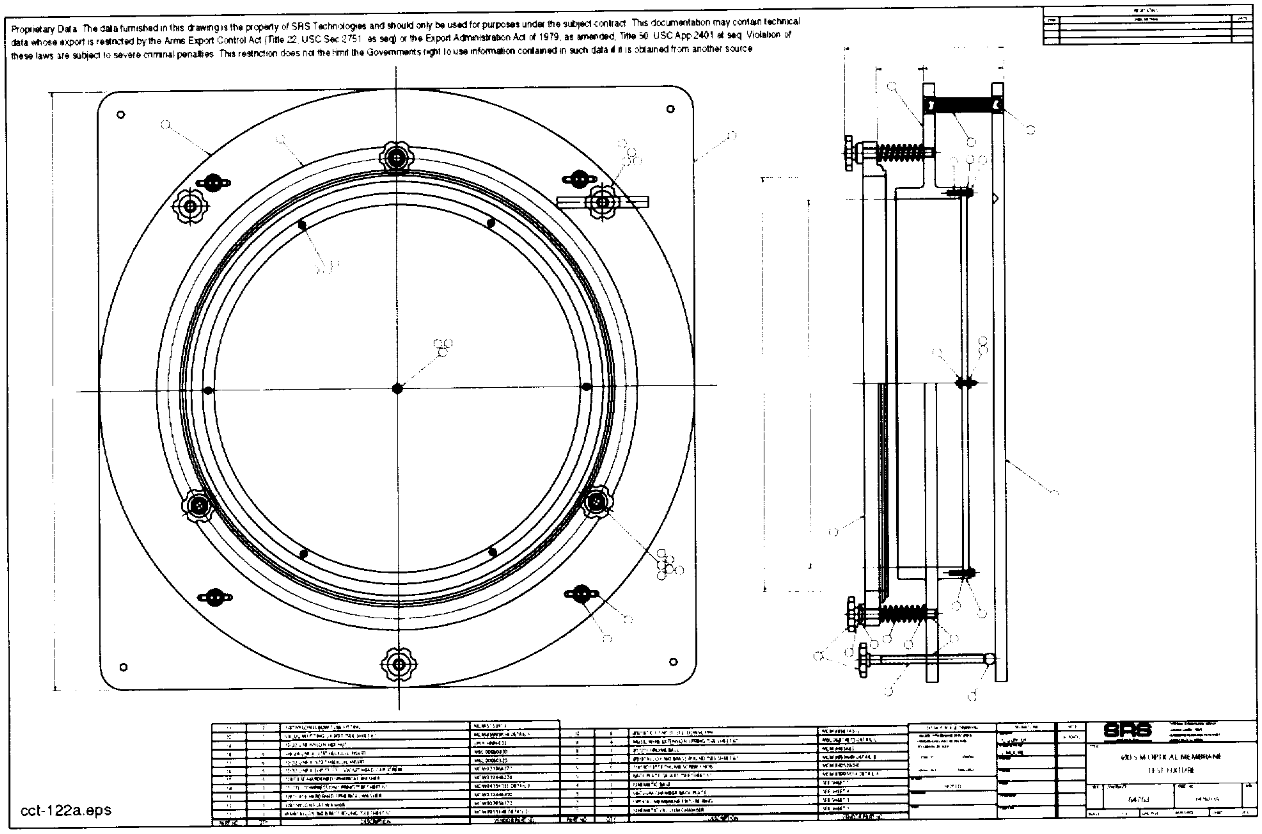

Exhibit 9 Membrane Precision Test Mount

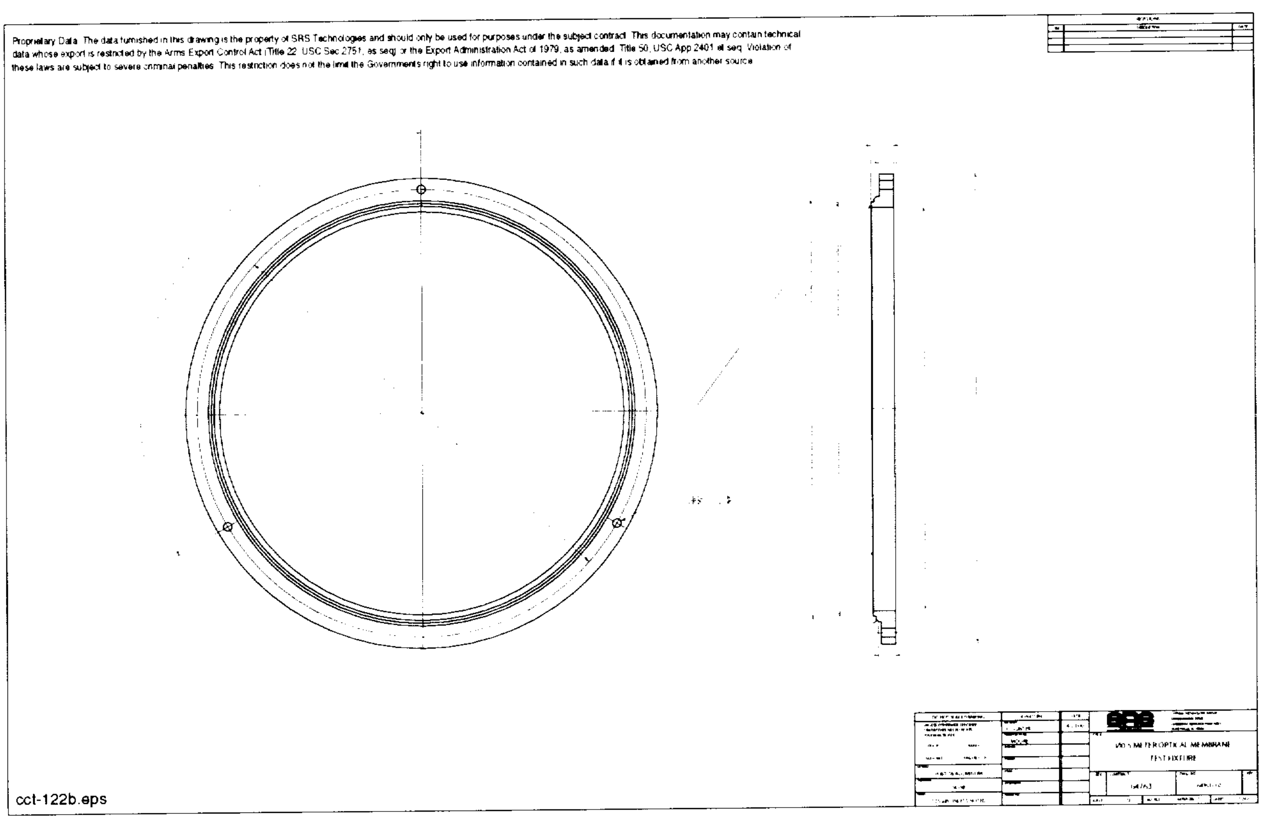

Exhibit 10 Membrane Ring Mount

3.3 Test and Evaluation

During the course of this study, many test samples were cast and measured for surface roughness and figure errors. This testing provided feedback for the manufacturing process optimization enabling the significant membrane quality improvements that were achieved. Much of the metrology was accomplished at MSFC and Dr. Phil Stahl provided software that was used to reduce the Ronchi test data.

3.3.1 Surface Roughness Measurement

Surface roughness is a measure of how smooth a surface is when evaluated at high spacial frequency. A highly specular surface with low surface roughness is critical for most imaging applications. Unlike low frequency figure errors, surface roughness causes scattering that cannot easily be corrected with secondary optics on active figure control. Thus the ability to manufacture membrane elements with low surface roughness is a prerequisite for any membrane optical application. The data acquired during this task demonstrates this ability.

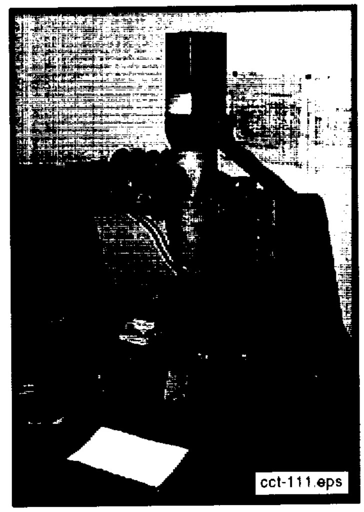

Exhibit 11
WYKO Surface Roughness Interferometer at MSFC

Surface roughness measurements of the CP1™ samples were conducted by MSFC staff using a WYKO surface interferometer as shown in **Exhibit 11**. This instrument gives a 3-D contour plot of local surface area and also computes several statistical measurements including RMS roughness, average roughness, and maximum peak to valley variation. **Exhibit 12** shows the WYKO data taken from typical cast CP1™ membrane films manufactured by SRS prior to the manufacturing optimization that was accomplished under this program. These films exhibited surface roughness on the order of four to six nanometers RMS. This is not a bad finish for many applications and close to the stated goals for this program (< 5 nanometers RMS). During the course of this program we were able to improve the manufacturing processes and improve surface finish by better than a factor of two. **Exhibit 13** shows surface roughness measurements typical of membranes produced at the end of the effort. The data includes measurements for film cast from the spherical mandrel and for film cast from float glass. For measurement purposes the film samples were mounted to 6.35 cm diameter rings. The rings have a precision lapped surface contacting the film. The mounted test samples are shown in **Exhibit 14**. The WYKO could not be configured to measure the entire film surface at once so multiple sub-aperture measurements were made to quantify the surface. Measurements were taken at five different locations on the airside of each film. Sample A, taken from the curved mandrel, shows an average

		RMS Surface Roughness (Rq) (nanometers)		Surface Roughness Average (Ra) (nanometers)	
Sample	Trial	Measurement	Average	Measurement	Average
Float Glass Film	1	5.290	5.550	4.230	4.020
	2	5.810		3.810	

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Exhibit 12 Surface Roughness Data from Previous Analysis

RMS of 2.528 nm. This includes a noticeable inclusion in the film, which was included for reference and is represented in the 6.36 nm RMS value of Trial 1. Eliminating this value from the sample average results in an RMS value of 1.57 nm. The data for sample B, taken from the flat, shows a 75% improvement to the data previously obtained on float glass-cast films. The 1.025 nm RMS value of sample B is characteristic of a highly polished rigid optic for imaging applications. The results generated in this task show that membrane optics can provide a specular finish suitable for most potential applications. No significant scaling issues were identified relative to surface finish. It is currently believed that 1 nanometer RMS films could be manufactured on films of 10 meter or more.

		RMS Surface Roughness (Rq) (nanometers)		Surface Roughness Average (Ra) (nanometers)	
Sample	Trial	Measurement	Average	Measurement	Average
2.5-3P Curved Mandrel Film	1	6.360	2.528	2.600	1.267
	2	1.190		0.818	
	3	1.110		0.712	
	4	2.810		1.360	
	5	1.170		0.847	
2.5-1P Flat Film	1	1.260	1.0254	0.657	0.640
	2	1.250		0.825	
	3	0.789		0.575	
	4	1.170		0.631	
	5	0.658		0.512	

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Exhibit 13 Surface Roughness Data from Current Film Samples

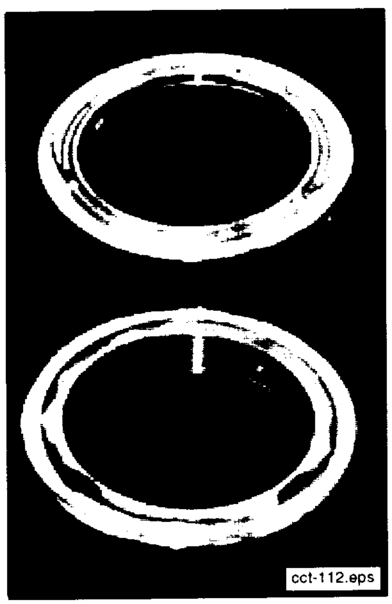


Exhibit 14
Mounted Films for Surface Roughness Measure

3.3.2 Curved Film Testing

Several options were considered in determining what type of metrology would be used to measure the figure accuracy of the curved membrane mirror test articles. Those readily available at MSFC include an interferometer setup using the 0.46 m ZYGO, and a generic Ronchi test setup. Due to the high acoustic sensitivity of membrane optics we were unable to acquire interferometric measurements on the films. Consequently, Ronchi testing was selected for the majority of the tests because this test is relatively insensitive to vibration. Ronchi testing also has a greater dynamic range which was required for measuring some of the poorer samples that had larger figure errors. In spite of the high dynamic range, the Ronchi test can still produce highly accurate figure measurements. The test setup used is illustrated in **Exhibits 15** and **16**. A point source is placed at the center of curvature of the membrane test article (1.9 m nominal for this case). The light is projected onto the membrane and focused back to the center of curvature. The light path is such that the beam passes through a cell with parallel lines spaced at a know distance (a grating) and is then imaged on to a CCD camera. The resulting image is a projection of the grating pattern affected by the aberrations present in the optic under test. This pattern is recorded for orthogonal orientations of the grating. These resulting fringe patterns (known as Ronchigrams) are typically used to qualitatively determine the aberrations present in the test piece. In this case the data was quantitatively reduced using a fringe analysis software tool, THIN, that was provided by MSFC.

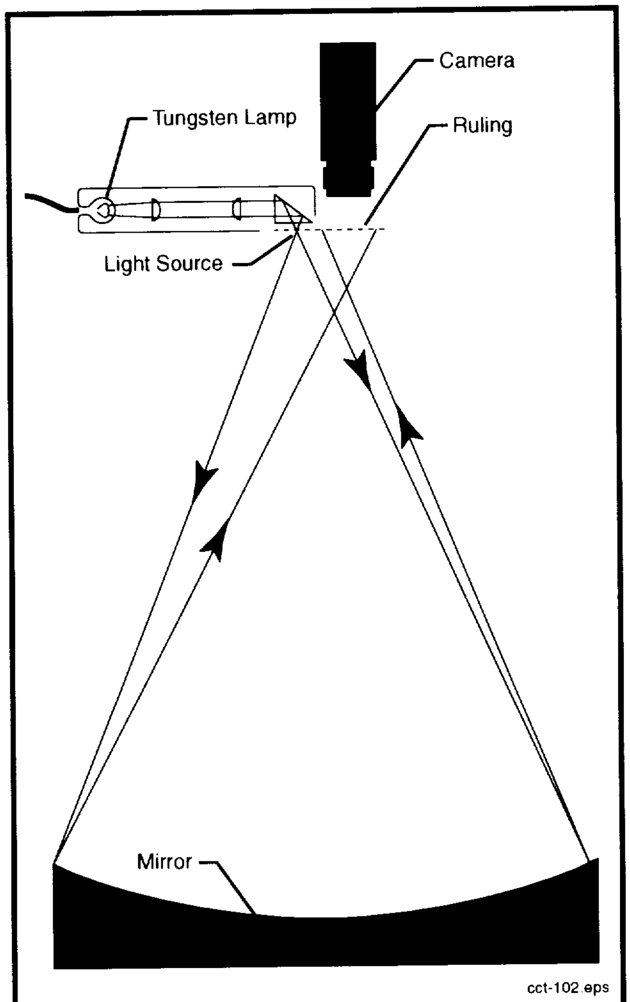


Exhibit 15 Ronchi Test Setup Schematic.

The diamond turned rigid support, previously described, was used for the Ronchi tests. Once the film is evenly rested against this fixture, a vacuum is pulled using a hand pump and the pressure is monitored on a manometer. The correct focus is obtained on the film by the appearance of the full aperture Ronchi pattern which will appear only when the curvature of the membrane is in close proximity to the 75 meter target. The manometer level was maintained and images of the resulting Ronchigram were taken using a 0.5 lp/mm grating positioned first in a vertical direction and then a horizontal direction. This is required in order to obtain full slope variation across both axis of the membrane. One of the main objectives of this effort was to see how well a membrane mirror could be replicated from a precision

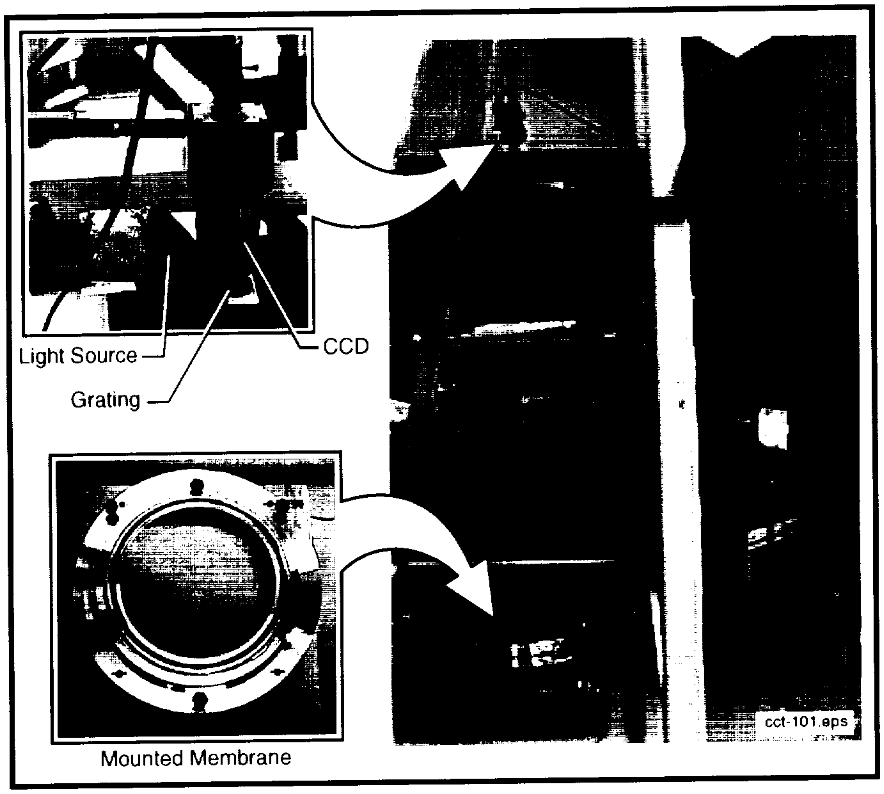


Exhibit 16 Actual Ronchi Test Setup at NASA/MSFC Facility

cast mandrel. The test setup allowed precision cast pre-formed membranes to be compared with initially flat membranes pressure formed into a curved shape. Ideally, there would be no vacuum applied to the precision cast membrane during testing. Unfortunately, the Ronchi test was setup for testing at a fixed nominal focal length which did not always correspond to the best focus of the membrane mirror. Consequently, a small amount of vacuum was typically used during testing of the curved membrane mirrors to make fine adjustments to the mirror focal length. This procedure seemed to work fairly well and the precision cast mirrors showed much better figure than the initially 1λ flat pressure formed curved mirrors in spite of the small vacuum present during the test.

Testing, using the discussed Ronchi setup, began with the membrane flats pulled to the required focal length with a vacuum. This is a typical method of forming a curved surface from a flat thin film. Two flat films coated with approximately 1200 angstroms of aluminum were tested on the mount. An average vacuum pressure of 2.2cm of H_2O was required to pull the films to the desired 1.9m radius of curvature. The resulting Ronchigrams of the horizontal and vertical grating positions taken of each film are shown in **Exhibit 17**. For each film a similar pattern resulted. These images show smooth well-behaved lines of fairly good symmetry displaying varying degrees of astigmatism and coma as the primary sources of error. Using the THIN software for analysis resulted in the quantitative results shown in **Exhibit 18**. These results show an RMS value of 65.5 microns for the flat pulled to

Exhibit 17 Horizontal and Vertical Grating Position Ronchigrams Taken of Membrane

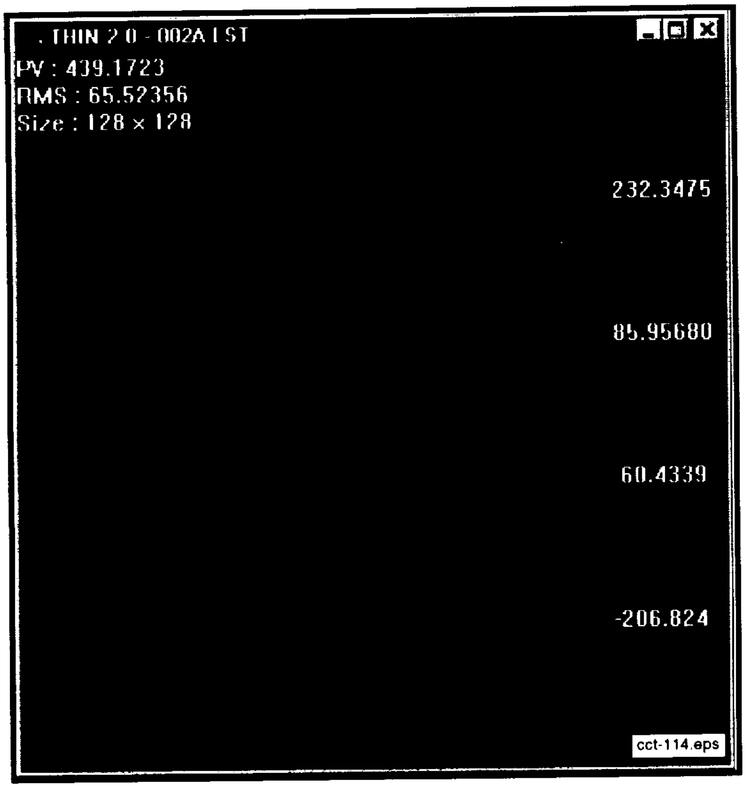


Exhibit 18 THIN Software Analysis Results of Flat Pulled to 1.9m Radius of Curvature

a 1.9m radius of curvature (see Appendix A for additional data). While two orders of magnitude away from imaging in the visible region of the spectrum the films do fall within the imaging capabilities of the far infrared. These films, however, were not intended for curved use and were tested simply to understand the capability variance between a flat and precision cast preformed film when used as a focusing element. Data was also taken for this film after varying the pressure to adjust the focal length. **Exhibit 19** shows the resulting optical path difference for radii of curvature of 1.87m and 1.93m. These results show the focus adjustment capability of a flat film with no significant change in aberrations over the 5cm focus shift. This is possible since there is no preformed shape in the film driving it to an optimum shape. The positioning of the grating was adjusted to accommodate each new focus.

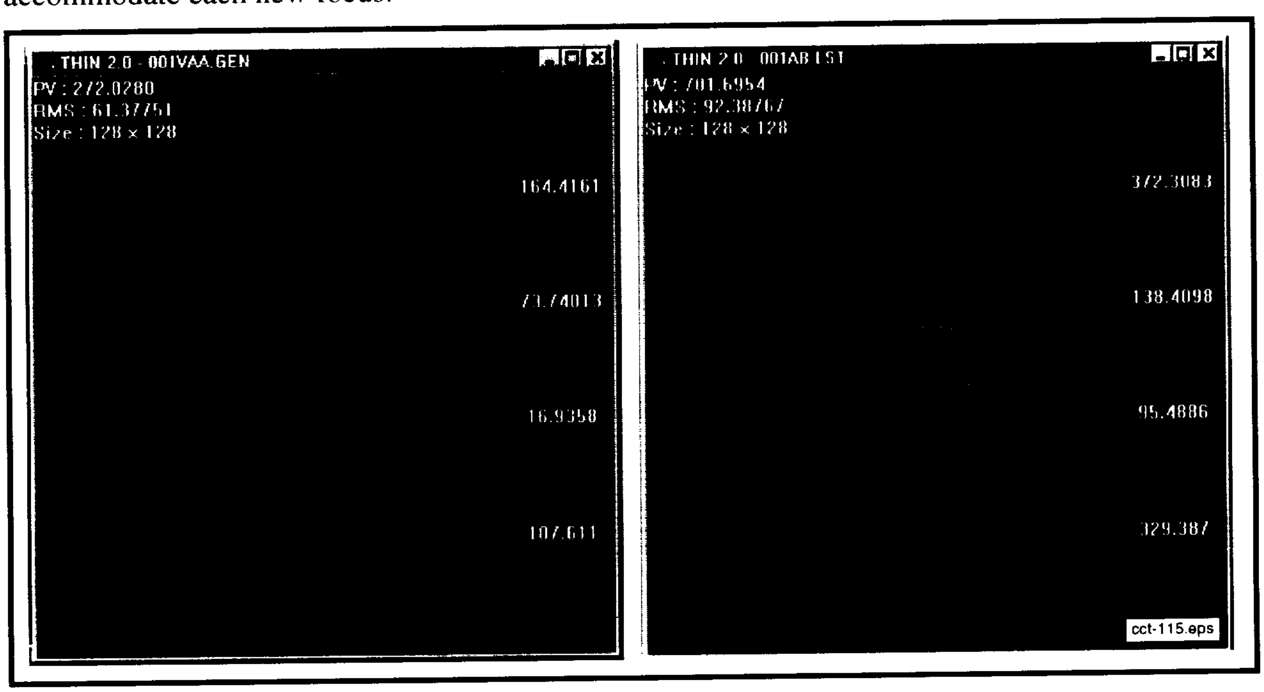


Exhibit 19 THIN Software Analysis Results of Flat Pulled to 1.87m and 1.93m Radius of Curvature

Films cast on the 0.5m convex mandrel were then tested using the same setup and procedures. An average vacuum pressure of 0.75cm of water was required to seat the membrane and tune the focus. As discussed in section 3.1 the curved film casting took several iterations to achieve optimized film quality. The same proved true for the release and mounting of these films. It is critical to the integrity of the film shape to establish a clean bond between the film and the ring. Any unevenly distributed stress in the film resulted in a very unpredictable shape. **Exhibit 20** shows a film that did not release evenly from the substrate onto the ring mount. This resulted in a different level of tension at the 9 o'clock position on the film and it is clear how this impacted the rest of the film's shape. It was also noted that evaporative deposited Aluminum also introduced uneven stresses in the film. However, for the test setup used the reflection from an uncoated film was sufficient to obtain the desired data. Therefore , the majority of the cast films were tested without coating. **Exhibit 21** shows a Ronchigram of a film successfully released from the convex mandrel. This shows a similar pattern obtained by the flat films pulled to a curve. This is in part due to the resulting drying shrinkage experienced by the film while being cured. As a result, the film is tensioned upon release onto a ring and the tension increases the mirror radius of curvature. In order to combat this effect the ring the film is mounted to was heated to approximately 100°C to allow thermal expansion in the ring which shrinks back after being cooled, counteracting the residual shrinkage effects of the film. Initial attempts with the heated mount resulted in the Ronchigram shown in **Exhibit 22**. The bonding process was slightly complicated due to the high mounting ring temperature and some of the epoxy cured at a varying rate around the ring perimeter resulting in slight distortions of portions of the film. The result, while clearly more unpredictable, does contain an increase in straight fringes in the central region for both grating orientations, which indicates a decrease in the aberrations present. This is evident by comparing the resulting RMS values with those of the flats pulled to a curve. Improvements in the bonding process led to the film shown in **Exhibit 23**. A drastic improvement in overall film quality, indicated by the RMS value, resulted. The fringes are much straighter and do not close as those shown in the previous exhibits. This indicates a great reduction in the aberrations present and the resulting focusing improvement of the grating. While still not at visible imaging capabilities the indicated RMS value of 39 microns does place it in the mid to far

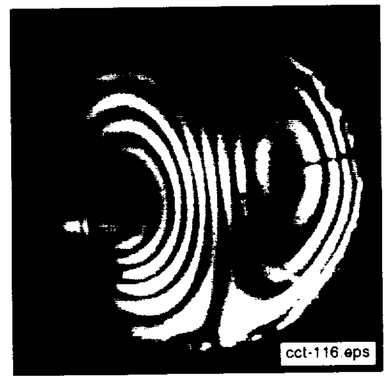


Exhibit 20 Ronchigram of Unevenly Released Film from Curved Mandrel

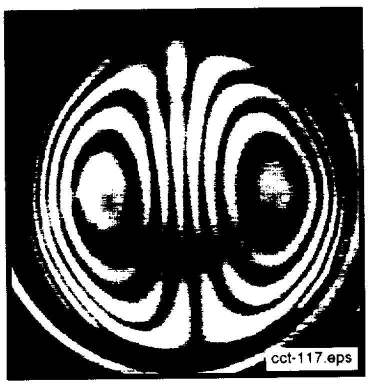


Exhibit 21 Ronchigram of Unevenly Released Film from Curved Mandrel Tightened by Film Shrinkage

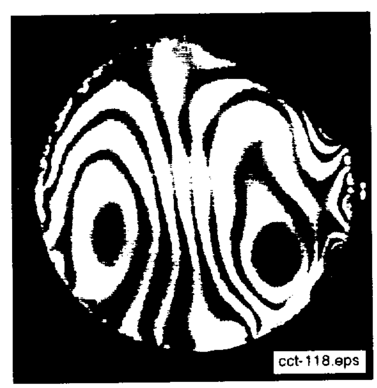


Exhibit 22 Ronchigram of Unevenly Released Film from Curved Mandrel Using Heated Ring Method

infrared region of the spectrum. There are several reasons these films were limited to such results. One major reason is the high surface roughness of the diamond turned ring. As previously stated, MSFC operators of the diamond turning machine noted to SRS that a vibration-induced error was present at the time of turning the ring and could not be eliminated. The problem with the machine could not be corrected in time for refinishing the ring, therefore requiring SRS to press ahead with membrane testing. Another source of error is the fact that the convex mandrel the films were cast on began to degrade over time due to the cast and release process. These degradations evolved in the mandrel making film release increasingly difficult. The mandrel errors were adding up while casting and mounting procedures were being improved. SRS feels that refinishing of both the diamond turned ring and the convex mandrel would allow a drastic improvement of achievable membrane shape. (See Appendix A for complete analysis results of tested films)

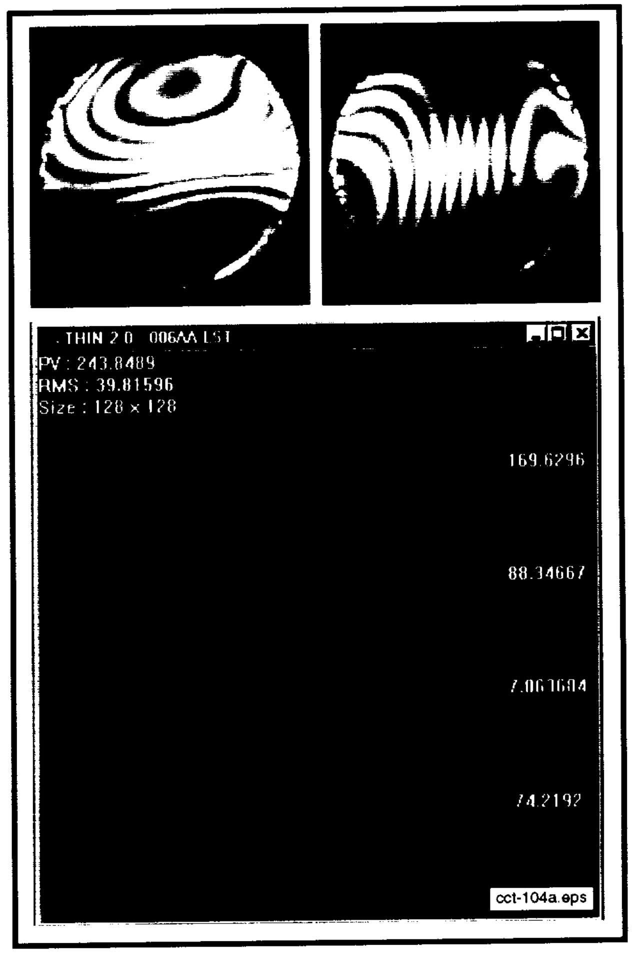


Exhibit 23 Ronchigram and Analysis Results of Evenly Released Film from Curved Mandrel Using Heated Ring Method Units in Microns

3.3.3 Flat Film Testing

The Cross Enterprise work conducted by SRS also called for 0.5m flat films to be produced. These were manufactured on basic float glass since SRS casting procedures allow high quality flats to be manufactured from these substrates. Since the flat film has no power, the Ronchi test setup could not be used. The 0.46m ZYGO at MSFC was the only means to quantify the flatness of the film. **Exhibit 24** shows the film mount placed in the ZYGO system. Unfortunately, the amount of acoustic presence in the ZYGO lab would not allow stable fringes for phase measurement. The large diameter of the film, 0.45m, only added to the acoustic pickup of the membrane. Several options were explored to

Exhibit 24 Membrane Mount Placed in ZYGO System at NASA/MSFC

try and eliminate this including, greasing the diamond turned ring and pulling the film taunt to the breaking point. While this did lower the amplitude of vibration in the membrane it did not reduce it enough to allow data collection. It is the position of SRS that a figure of planar film is dependent on two characteristics of the film: the surface roughness and thickness variation. If these two variables are brought within optical tolerance then the fixture the film is mounted to is what determines the degree of flatness. These two variables, as discussed, have been brought within tolerance by SRS. Demonstrating this was difficult due to the extreme acoustic sensitivity of the flats. However, sub-aperture data was obtained showing excellent figure.

The mount used for testing the flat membranes was optimized for supporting the curved films, which are not as prone to acoustic pickup due to the additional stiffness provided by curvature. The AFRL has developed a modification of the SRS mount for testing flat films. This mount uses vacuum in an exterior annulus to tension a flat over an interior annulus. This type of mount might be advantageous for future testing of flats. The 10.16cm ZYGO interferometer owned by SRS was used to obtain sub-aperture measurements form the flat film mirrors. **Exhibit 25** shows the resulting fringe pattern and analysis for apertures of 33mm and 102mm. Clearly the 33mm is better than 1/13 λ flat. The 102mm aperture of the membrane shows an increase in error due to the impact of edge effects in the film. **Exhibit 26** shows two areas on the outer perimeter of the film suffering from boundary induced displacements. This is due to the non-pristine finish of the diamond turned surface. These images show the error propagation caused by such irregularities in the planar boundary. The edge effects diminish quickly as the distance from the edge increases.

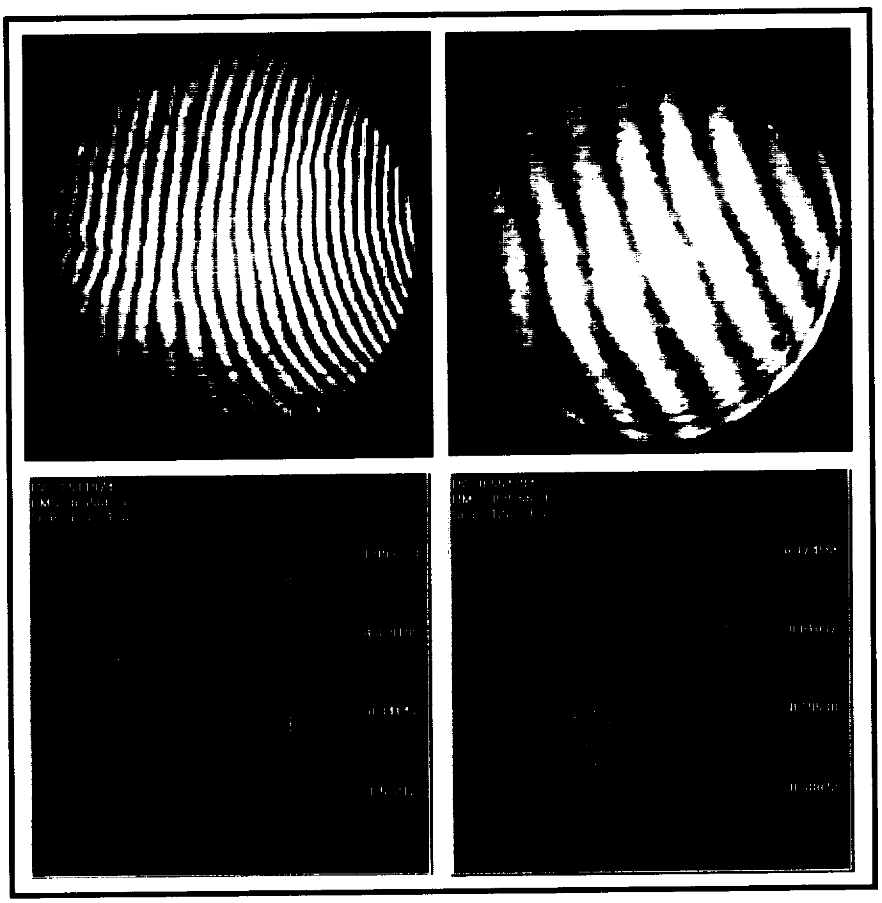


Exhibit 25 Fringe Pattern and Analysis of 102mm and 33mm Aperture Sizes Respectively Taken by SRS ZYGO Units in Waves for λ = 633nm

The quality of the membrane flats produced under this effort proved to be comparable to relatively expensive precision polished optical flats. Consequently, several companies have expressed a commercial interest in these products. SRS is currently negotiating to supply these flats to a major optical components supplier for sale as thin film pellicles.

4.0 — Conclusions

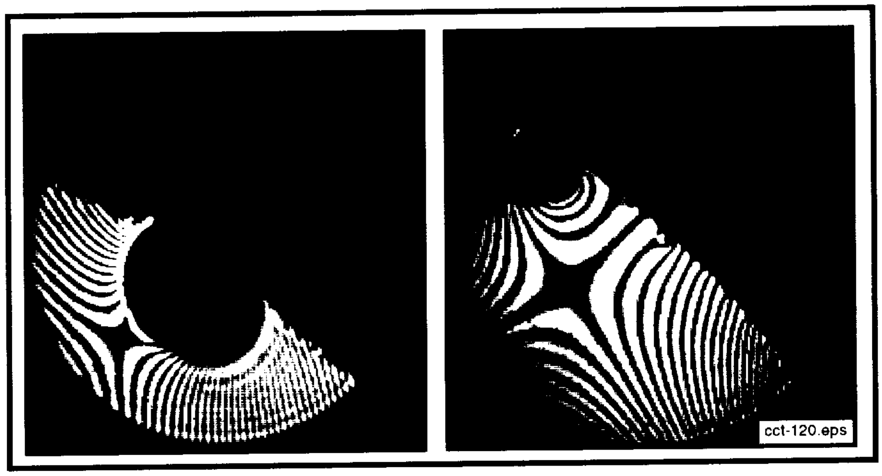


Exhibit 26 Two Boundary Induced Displacements Taken by SRS ZYGO

The research conducted in the course of this effort demonstrated that precision optical elements can be manufactured using surface replication casting methods. Casting methods were developed that enabled CP1™ polyimide material to be cast into thin membrane sheets (5µm - 50 µm thickness) with highly specular smooth surfaces. Surface finish as good as 1 nanometer RMS was achieved on both flat and curved films. There were no scaling issues identified relative to surface finish.

Membrane flats were manufactured demonstrating 1/13 λ flatness away from boundaries and sub-wavelength flatness over the full aperture. The ability to cast flat films is most strongly a function of the ability to control casting thickness variation. Many parametric studies were conducted to evaluate film thickness variations. It was found that the processes for casting had to be modified as the scale of the casting changed. It proved to be difficult to separate the effects of the process control parameters and predict, apriori, a set of parameters that would yield a uniform film for a given size casting. However, once the proper parameter values were established, precision films could be repeatedly cast from the same substrate. No limiting size for casting precision flats was found during this research.

Precision replicated spherical mirrors were also cast during this study. The precision cast mirrors showed a factor of two figure improvement over vacuum stretched flats for imaging. Similar to the flats, precision casting required tuning to the particular substrate. Once the optimized processes was developed, the mirrors could be repeatedly optimized. In all of these studies boundary effects seemed to be the largest source of error.

At the conclusion of this research it appears that precision casting of membrane optical elements is practical and feasible. The next logical milestone for development of large optical systems using membrane elements is to accomplish integration of a precision optical membrane with a lightweight deployable boundary element.

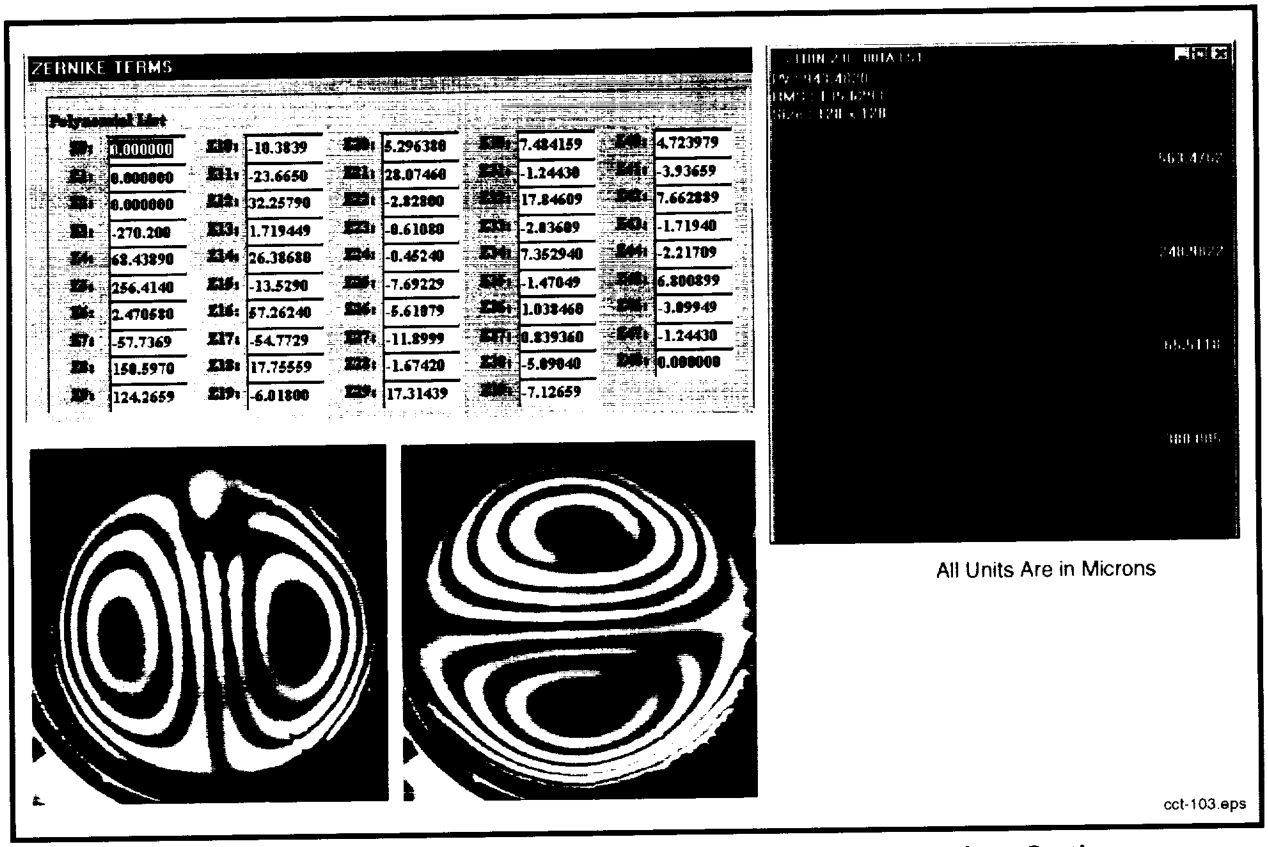
5.0 — References

1) R. Carreras, D. Marker, J. Wilkes, Tunable membrane mirrors used with real time holography, Air Force Research Lab, SPIE 3432 1998
2) D. Malacara, Optical shop testing, Wiley,1992.
3) E. Hecht, Optics, 3ed, Adison Wesley, 1998

APPENDIX A

RONCHI TEST DATA AND ANALYSIS

FLAT FILMS PULLED TO CURVATURE



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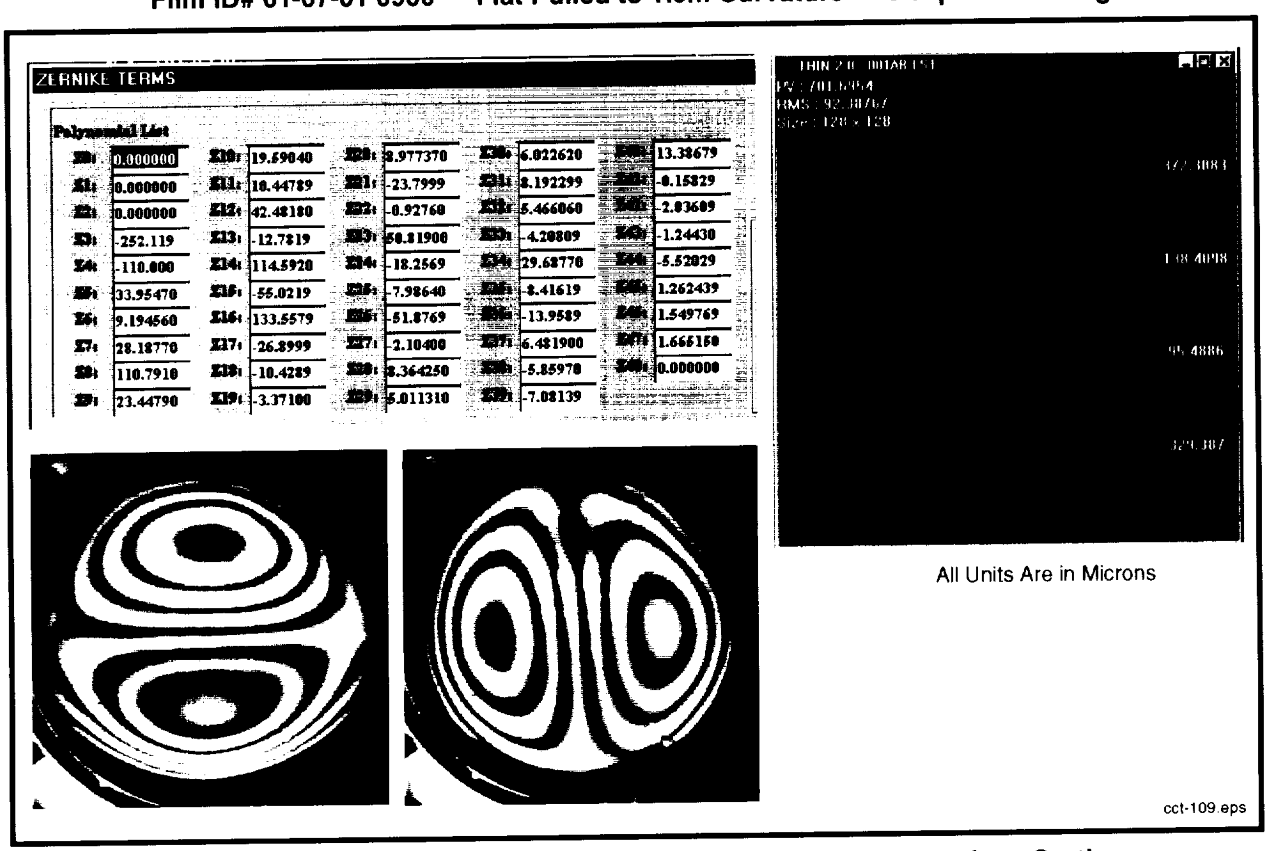

Film ID# 01-07-01 0900 — Flat Pulled to 1.93m Curvature — 0.5 lp/mm Grating

ZERNIKE TERMS

Polynomial List

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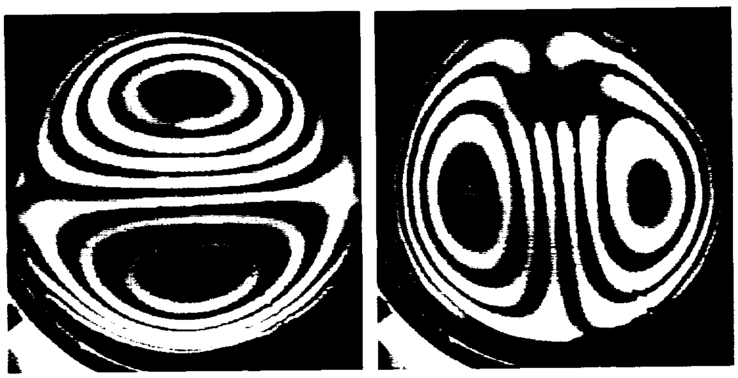
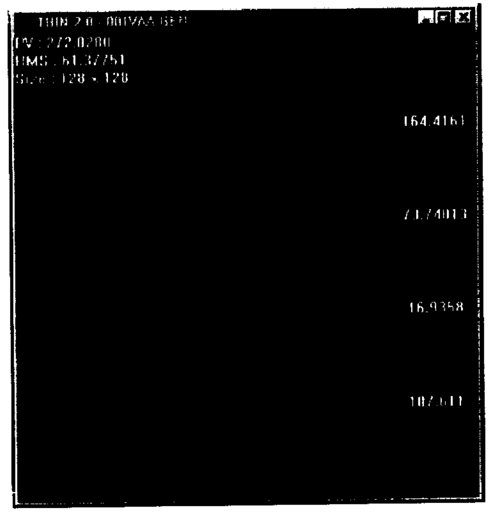
Z1:	0.000000	Z11:	-14.0410	Z21:	5.751788	Z31:	-0.55310	Z41:	-0.00079
Z2:	0.000000	Z12:	-8.84249	Z22:	-2.18589	Z32:	1.553249	Z42:	-0.00039
Z3:	-183.570	Z13:	-1.46169	Z23:	7.730269	Z33:	-0.89990	Z43:	-0.00079
Z4:	8.610509	Z14:	13.33230	Z24:	-0.94079	Z34:	1.621269	Z44:	-0.00939
Z5:	3.677870	Z15:	-2.01399	Z25:	4.360919	Z35:	2.322959	Z45:	0.001509
Z6:	8.788200	Z16:	16.00860	Z26:	-10.5970	Z36:	-1.46439	Z46:	0.002649
Z7:	-41.0890	Z17:	-5.10550	Z27:	-2.72740	Z37:	-0.00999	Z47:	-0.00170
Z8:	132.1770	Z18:	-7.33300	Z28:	5.196670	Z38:	-0.01180	Z48:	0.000000
Z9:	-5.50159	Z19:	1.077399	Z29:	3.103940	Z39:	0.018799		





All Units Are in Microns

cct-110.eps

Film ID# 01-07-01 0900 — Flat Pulled to 1.8m Curvature — 0.5 lp/mm Grating

ZERNIKE TERMS

Polynomial List

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Z2:	0.000000	Z12:	26.46829	Z22:	-7.87330	Z32:	1.248860	Z42:	0.357469
Z3:	-237.419	Z13:	-19.1849	Z23:	7.904970	Z33:	-6.47049	Z43:	3.884609
Z4:	-73.6869	Z14:	17.95470	Z24:	-12.8500	Z34:	4.886869	Z44:	-5.56559
Z5:	27.97509	Z15:	-34.7280	Z25:	4.493209	Z35:	-9.38910	Z45:	-0.67869
Z6:	-5.79180	Z16:	70.05419	Z26:	-13.3479	Z36:	-2.03609	Z46:	-1.15380
Z7:	21.13120	Z17:	1.907229	Z27:	1.604069	Z37:	-4.36649	Z47:	-0.79180
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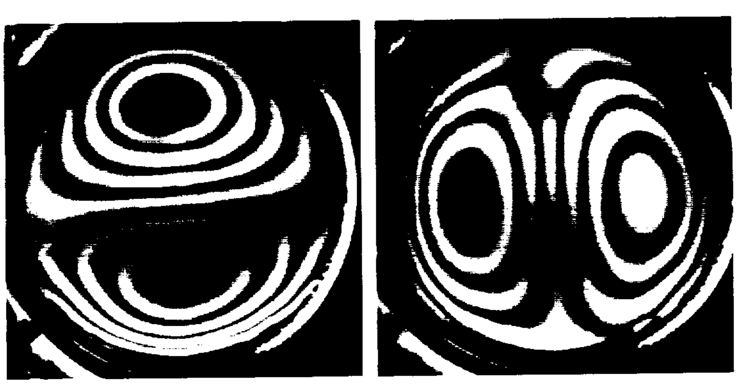
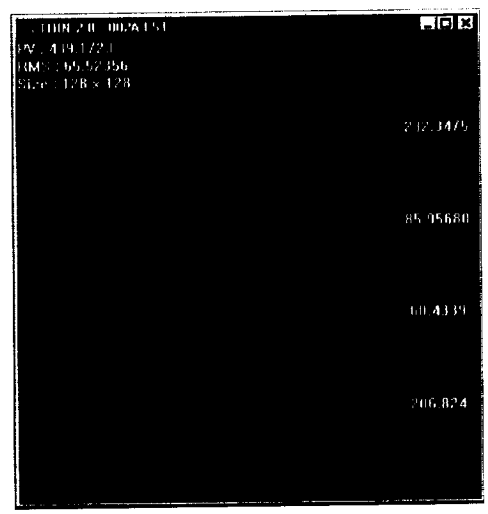


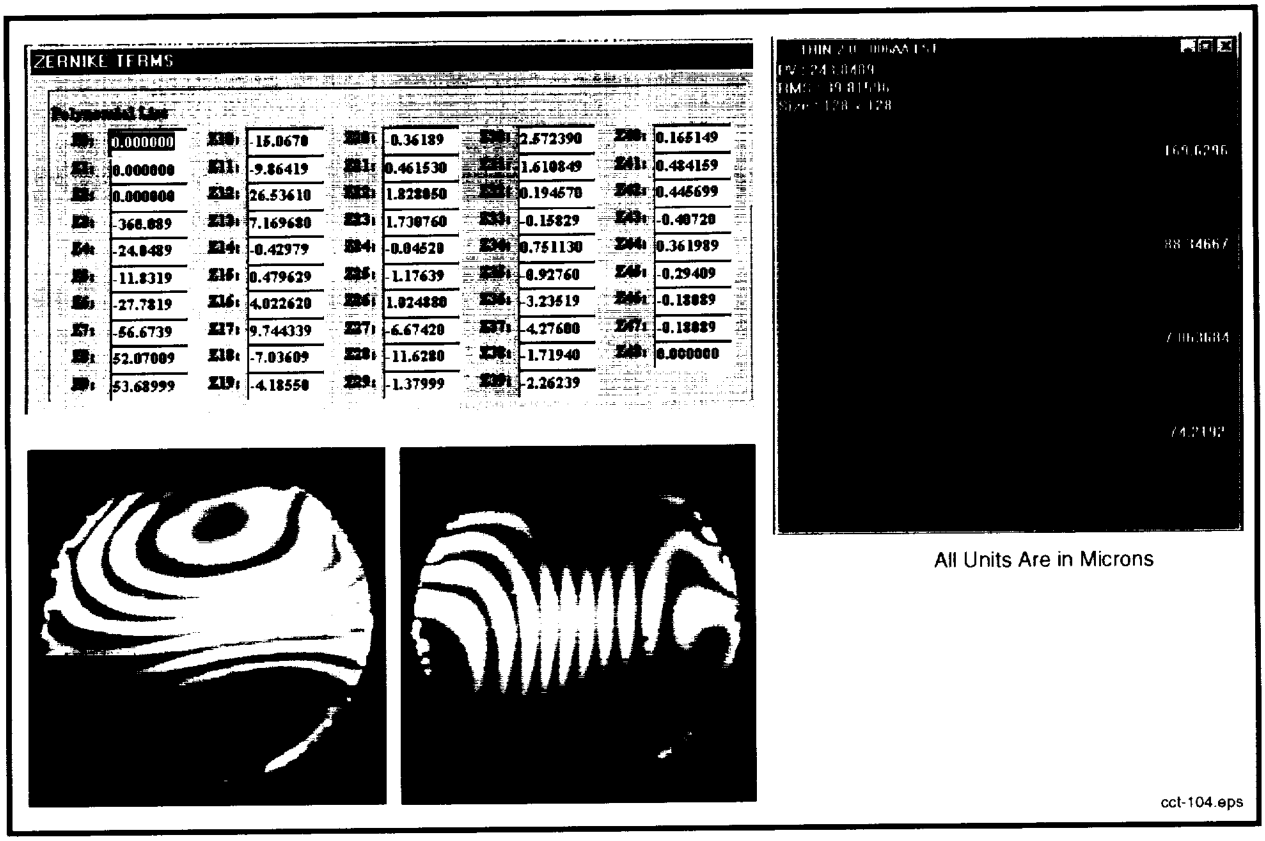


All Units Are in Microns

cct-108.eps

Film ID# 01-07-01 1035 — Flat Pulled to 1.9m Curvature — 0.5 lp/mm Grating

PREFORMED CURVED FILMS



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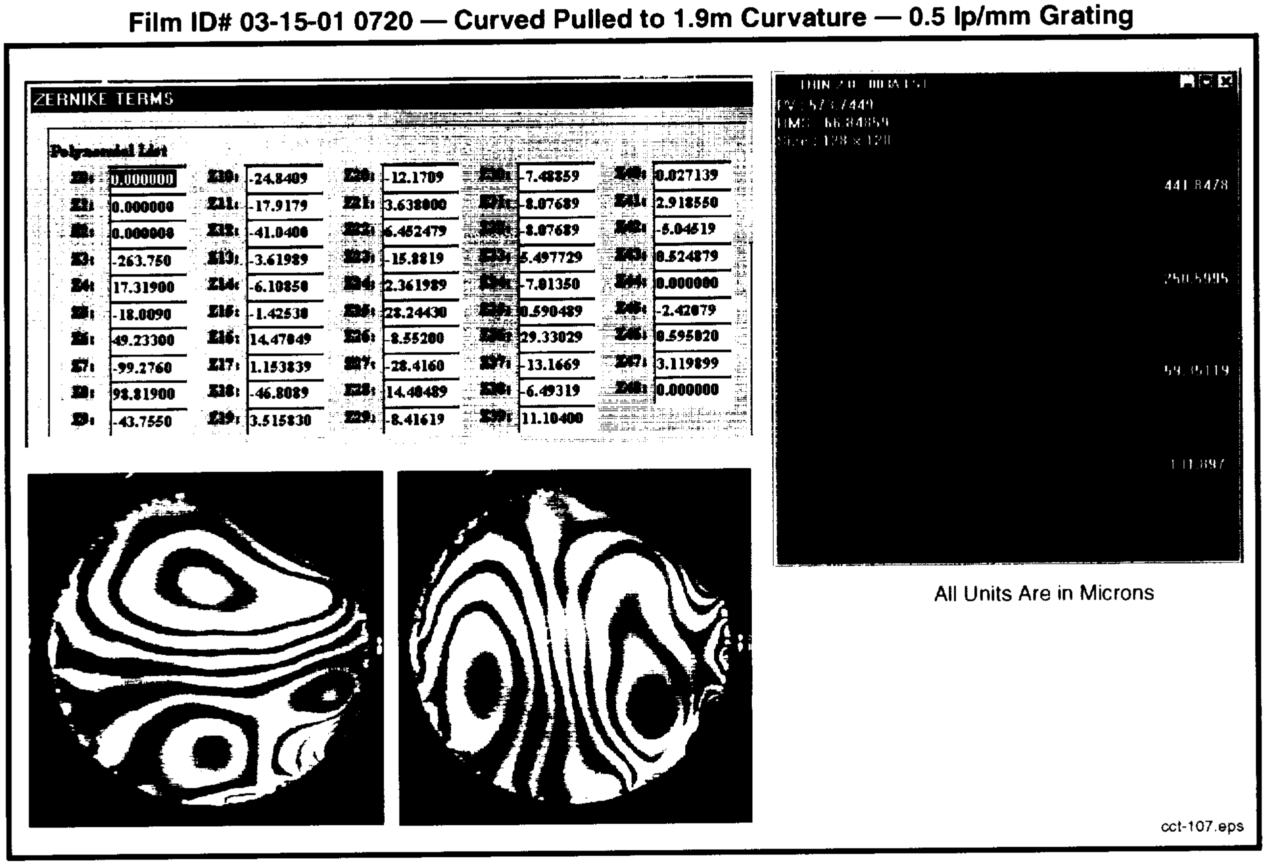

Film ID# 02-07-01 1245 — Curved Pulled to 1.9m Curvature — 0.5 lp/mm Grating

ZERNIKE TERMS

Polynomial List

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Z1:	0.000000	Z11:	61.25559	Z21:	-18.5060	Z31:	-6.74200	Z41:	1.823519
Z2:	0.000000	Z12:	-31.6959	Z22:	-16.4020	Z32:	-10.5200	Z42:	-0.22620
Z3:	-252.639	Z13:	-10.1800	Z23:	-16.9899	Z33:	-8.32569	Z43:	-4.79629
Z4:	-182.279	Z14:	-26.0629	Z24:	-8.39360	Z34:	-6.58370	Z44:	-2.82800
Z5:	-31.5830	Z15:	-23.2800	Z25:	9.771490	Z35:	-2.44339	Z45:	-1.33480
Z6:	-84.0039	Z16:	43.55419	Z26:	24.09950	Z36:	-0.97280	Z46:	-0.49770
Z7:	34.77140	Z17:	-22.4200	Z27:	18.93429	Z37:	13.62440	Z47:	0.000000
Z8:	90.56099	Z18:	-20.4750	Z28:	-0.63340	Z38:	-6.76469	Z48:	0.000000
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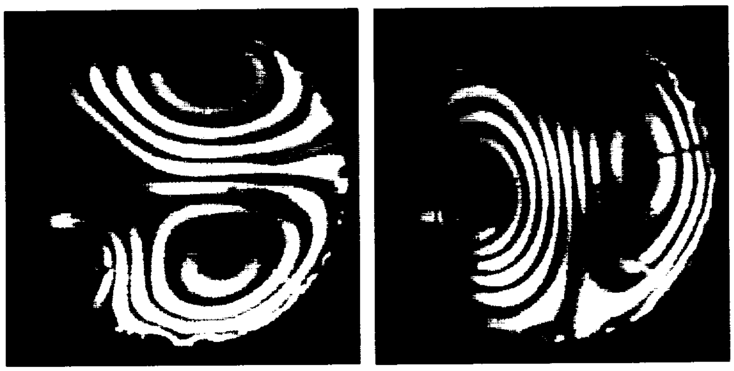

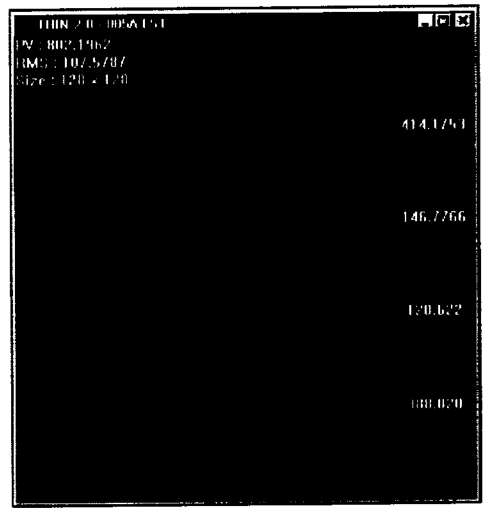

All Units Are in Microns

cct-105.eps

Film ID# 03-11-01 1035 — Curved Pulled to 1.9m Curvature — 0.5 lp/mm Grating

ZERNIKE TERMS

Polynomial List

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Z4:	149.8139	Z14:	5.009039	Z24:	-7.28499	Z34:	7.735290	Z44:	6.524879
Z5:	-234.610	Z15:	-41.3339	Z25:	-4.11759	Z35:	-13.3479	Z45:	-2.87330
Z6:	-71.4700	Z16:	116.7799	Z26:	5.843890	Z36:	-10.7460	Z46:	-1.69679
Z7:	41.97959	Z17:	-53.7099	Z27:	-10.2709	Z37:	-7.73750	Z47:	3.970580
Z8:	144.7689	Z18:	-7.66960	Z28:	-1.31219	Z38:	-10.0670	Z48:	0.000000
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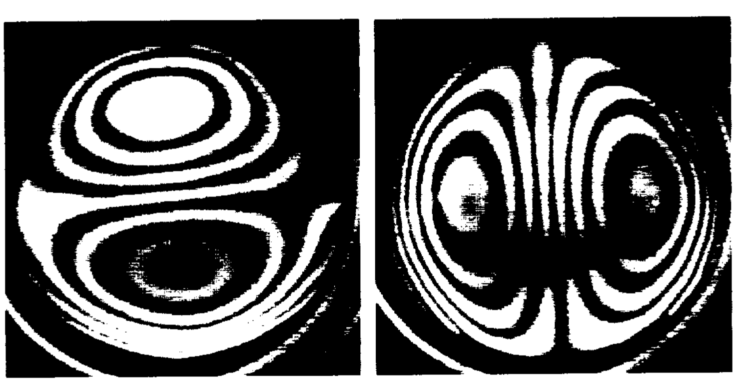

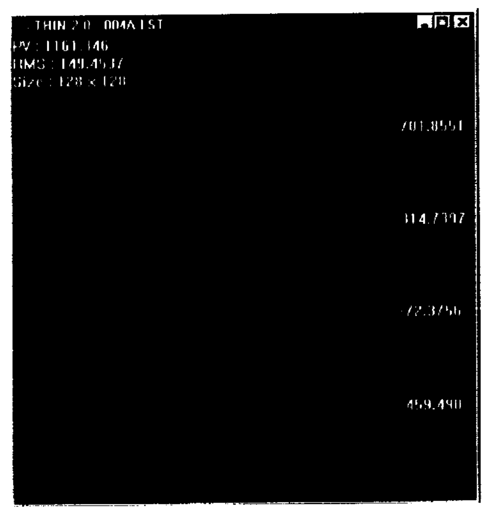

All Units Are in Microns

cct-106.eps

Film ID# 02-08-01 1105 — Curved Pulled to 1.9m Curvature — 0.5 lp/mm Grating

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12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

SRS Technologies and NASA Marshall Space Flight Center have conducted a research effort to explore the possibility of developing ultra-lightweight membrane optics for future imaging applications. High precision optical flats and spherical mirrors were produced under this research effort. The thin film mirrors were manufactured using surface replication casting of CP1™, a polyimide material developed specifically for UV hardness and thermal stability. In the course of this program, numerous polyimide films were cast with surface finishes better than 1.5 nanometers rms and thickness variation of less than 63 nanometers. Precision membrane optical flats were manufactured demonstrating better than 1/13 wave figure error when measured at 633 nanometers. The aerial density of these films is 0.037 kilograms per square meter. Several 0.5-meter spherical mirrors were also manufactured. These mirrors had excellent surface finish (1.5 nanometers rms) and figure error on the order of tens of microns. This places their figure error within the demonstrated correctability of advanced wavefront correction technologies such as real time holography.

14. SUBJECT TERMS
Membrane Optics, Thin Film Mirrors, Lightweight Optics

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