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SILICA FRESNEL LENS FOR LASER COMMUNICATIONS

FINAL TECHNICAL REPORT

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13. ABSTRACT (Maximum 200 words)

This document presents the results of the study on the fabrication and characterization of pure silica Fresnel lenses by a replication process. To demonstrate the replication capability of diffractive or Fresnel optics, Fresnel lenses were prepared by a sol-gel molding technique. The optical quality and performance and dimensional characteristics of the lenses are reported. Optical and physical properties tested included glass homogeneity, UV/VIS/NIR transmission, light scattering and surface profilometry. Optical performance testing indicated that these glass Fresnel lenses are as good as their parent plastic Fresnel lenses. Success in this development is to open an avenue to many other applications where silica glass Fresnel lenses would be superior to plastics, both in optical quality and environmental stability.

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A publication is planned to be presented at the conference on "Current Developments in Optical Design and Optical Engineering" at the SPIE Annual Meeting organized on July 24-29, 1994 in San Diego, CA.

EXECUTIVE SUMMARY

With the present trends toward miniaturization, the demand for complex optical elements with surface features is increasing. If these complex optical elements, such as Fresnel and diffractive optics, are fabricated in glass, they should be superior to plastics, both in optical quality and environmental stability. The goal of this research effort was to demonstrate the feasibility of a manufacturing process to prepare a pure silica prototype of a Fresnel lens for use in applications such as laser communications.

The most important conclusion of this research effort is that the optical performance testing performed at the Center for Research and Education in Optics and Lasers (CREOL) of the University of Central Florida showed that these glass Fresnel lens prototypes were as good as their parent plastic Fresnel lenses. This demonstrates for the first time the feasibility of fabricating silica glass Fresnel lenses as well as numerous other surface feature optics via a replication process which will have acceptable cost for the industry.

The technical objectives of this research effort were:

1) to investigate optical designs of the lenses including overall geometry and the design of the Fresnel surface for a laser communication system.

2) to fabricate the mold active surface as a negative of the final lens once the lens geometry was chosen and the Fresnel surface design was determined.

3) to design and to fabricate the complete mold system to incorporate the negative Fresnel surface.

4) to scale up the process used to manufacture windows up to 1" diameter in order to fabricate prototypes with a diameter of 1.5".

5) to produce surface feature optics by incorporating the geometric details on the surface of an optical element having high quality and performance such as those required by a Fresnel surface.

To demonstrate the feasibility of fabricating by replication glass Fresnel optics, or other surface feature components such as diffractive or microlens arrays, silica Fresnel lens prototypes were successfully prepared by a sol-gel molding technique. The material quality, the optical performance and the dimensional characteristics of the lenses including glass homogeneity, UV/VIS/NIR transmission, light scattering, and surface profilometry were extensively investigated.

Major accomplishments which were made during the course of this research include:

1) Based on an investigation of the optics designs for the lens, a set of designs was selected. Several active surfaces were designed and fabricated. **Molds incorporating Fresnel active surfaces were successfully designed and fabricated.**

2) Pure silica windows of 1.5" diameter were successfully produced; Fresnel patterns of 1" diameter were replicated on the surface of 1.5" diameter lenses. Crack-free Fresnel lenses were produced after major modifications in the processing and the

design of the mold assemblies, especially for the plastic active surfaces. **These results led to the successful replication of a 1.5" diameter Fresnel pattern on 1.5" diameter pure silica glass windows, which was the target of this Phase I program.**

3) The techniques used to characterize pure silica prototype Fresnel lenses were selected and implemented. **The excellent replication capability of Fresnel surfaces by the room temperature net-shape casting was successfully demonstrated.**

Success in this development opens an avenue to any application where silica glass Fresnel lenses would be superior to plastics, both in optical quality and environmental stability. This accomplishment also has tremendous implications for the development of novel surface feature optics which cannot at the present time be manufactured in glass, or which have extremely high fabrication costs making them unrealistic for industrial applications. The need for these new optics will multiply greatly the benefits from this development program because the required production volumes will be several orders of magnitude greater than those of the specific Fresnel optics applications. These new optical elements, that GELTECH would like to aggressively develop in the near future, include gratings, diffractive-binary optics elements (DOE's-BOE's), total internal reflection components (TIR) and microlens arrays which will be required for military, space and commercial applications.

I. INTRODUCTION

1.1 Need for Silica Fresnel Lenses in Laser Communication Systems

Fresnel lenses are most commonly manufactured in plastics, which are not suitable for space applications due to the effects of radiation and outgassing of the material. A glass Fresnel lens would be a practical solution to this problem, but these are not available at the present time because they cannot be fabricated by the conventional manufacturing methods. In searching for alternative technologies, GELTECH was identified by Thermotrex and subsequently Rome Laboratory as having a technology which showed great promise for the fabrication of Fresnel lenses in silica glass [1].

In recent years development work at GELTECH using the sol-gel process has made it possible to replicate fine-patterned surfaces in high purity silica glass by a room temperature molding technique [2]. Based on this sol-gel technology, GELTECH proposed in Phase I to demonstrate the feasibility of manufacturing a silica Fresnel lens which would satisfy, in a cost-effective way, the optics requirements of laser communication systems, including those currently being developed at Thermotrex Corporation.

Although the specific focus of this Phase I research effort has been for an optical element suitable for the laser communications receiver to be incorporated in the architectures under development at Thermotrex Corporation, the development work is generic in nature and will be applicable to a wide range of applications. Success in this development is expected to open an avenue to many other applications, both military and civilian, where silica glass Fresnel lenses would be far superior to plastics, and in some cases, absolutely necessary. Technology development pursued here would also enhance the capability of manufacturing other types of unique surface feature optical components in silica, including microlens arrays, gratings, binary optical elements (BOE) and total internal reflection optics (TIR) which will be needed in the near future for a whole range of photonic and electro-optic applications.

1.2 Sol-Gel Replication Process for Surface Feature Optics

1.2.1 Overall Process Description

The overall process for making molded silica optics is indicated in Figure 1 [3]. The conception of the desired optics leads to an appropriate lens design, which then defines the design of the molds to be used to produce the optical components. The manufacture of the mold requires the fabrication of a tooling which contains the microscopic relief pattern and shape to be molded. The mold is fabricated and used in the sol-gel process to produce prototype parts. Quality control then provides necessary input to determine what, if any, changes are necessary in either the mold or processing to produce the final part.

For prototypes or small production quantities, a simplified tooling can be designed to produce an "active surface" containing the pattern to be reproduced. This active surface is then incorporated into a mold cavity to be used in the sol-gel process. This approach is the one use for this research program.

Each different optical component requires the design of a custom mold and minor adjustments to the sol-gel process to meet the requirements of that design. These operations are performed only once, and their cost could be amortized over a large volume of parts.

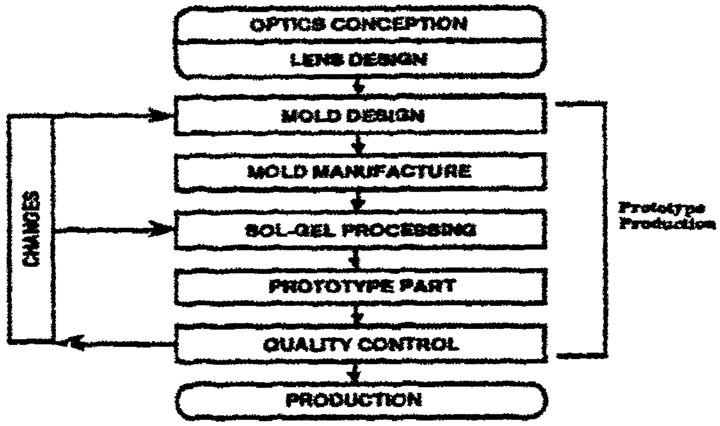

Figure 1: The Sol-Gel Replication Process.

1.2.2 Advantages of the Sol-Gel Replication Process

There are two very important advantages of the sol-gel replication process:

1) It provides a cost-effective way to produce fine-featured optical elements. As described above, once a master mold has been fabricated in an appropriate material it can then be replicated in large quantities. Techniques to make master mold surfaces are normally too expensive for high volume production, but with the replication process the cost of the master is only incurred once, and can be amortized over a large volume of parts, making individual part costs relatively low.

2) The process produces optical elements in silica glass, one of the best optical materials available. Advantages of silica include:

   - a very high transmission over the broad wavelength range of 0.2 to 3.2 microns
   - excellent mechanical strength and hardness
   - excellent chemical durability
   - very low coefficient of thermal expansion
   - excellent thermal stability
   - excellent radiation hardness
   - very high laser damage threshold

These advantages make silica the material of choice for high quality optical elements, and virtually required for applications involving harsh environments such as space or military uses.

The goal of this Phase I research effort was to demonstrate the feasibility of accurately replicating high quality Fresnel surfaces in silica glass by this technique. The following sections summarize the results of this work:

- Section 2 describes the overall objectives of the Phase I program.
- Section 3 describes the methods and procedures used to make and characterize the Fresnel lenses
- Section 4 gives the experimental results, including optical performance evaluation and profilometry of the mold and glass lenses.
- Section 5 gives final conclusions.

II. PHASE I TECHNICAL OBJECTIVES

The overall goal of the Phase I research effort was to demonstrate the feasibility of a manufacturing process to produce pure silica Fresnel lenses such as the ones required for use in laser communication systems. The accomplishment of this goal required the fabrication of 1.5" diameter Fresnel lens prototypes and the completion of the following technical objectives.

2.1 Lens Design Selection

This objective involved the selection of a lens design which included the overall lens geometry, as well as the specific design of the Fresnel surface. The selection of possible designs for the Fresnel surface was to be done in collaboration with Fresnel Optics, Inc., Rochester, New York.

2.2 Mold Development and Fabrication

Once the lens geometry was chosen and the Fresnel surface design was determined, the mold active surface was to be fabricated from a diamond turned tooling. This Fresnel active surface is the negative of the final lens. At the same time the complete mold system needed to be designed and fabricated to incorporate this Fresnel active surface.

2.3 Sol-Gel Process Development

There were two basic development issues to consider for making 1.5" Fresnel lens prototypes:

a) Scale-up of the process currently used to manufacture windows up to 1" in diameter in order to fabricate prototypes with a diameter of 1.5". This work involved modification of existing equipment schedules and gel handling methods for the larger gels. New fixtures for supporting the gels needed to be designed and fabricated.

b) Incorporation of geometric details on the surface of an optical element to produce surface feature optics having high quality and performance, such as required by a Fresnel surface.

The next section discusses the methods and procedures which were designed to best tackle the difficulties involved in this research project.

III. METHODS AND PROCEDURES

3.1 Optical Design Investigation and Mold Fabrication

Optical design of the lenses was investigated and the final choice of lens designs for the prototypes was based on expected optical performance and feasibility of production of both the Fresnel surface details and the overall geometry of the glass lens. Several different geometries as shown in Figure 2 along with seven facet spacings were considered including aspheric and lenticular lenses.

The tooling used to produce the active surface for the mold is an enlarged positive of the desired Fresnel surface. From this tooling the active surface for the mold was made as an enlarged negative of the desired Fresnel surface. Fresnel Optics, Inc. fabricated the tooling by diamond machining and electroforming, and prepared the plastics mold active surfaces via compression forming.

Key factors that were considered in the design of the mold included:

a) Incorporation of the active surface into the overall mold cavity, both for ease of assembly and formation of high quality parts.

b) Ease of use, including filling the mold with sol and removing the gel from the mold during processing.

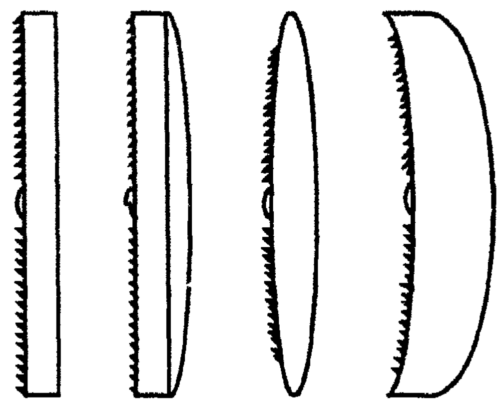

Figure 2: Alternative Designs for Fresnel Lens Optics.

The molds to be used for the sol-gel process needed to incorporate an active surface presenting the enlarged negative profile of the desired features into a mold cavity designed to produce the final geometry of the lens. Design, fabrication, and assembly of the mold cavity were done at GELTECH. For the small quantities required for the prototype development phase, the quickest and most economical method of mold fabrication has proven to be the machining of the individual cavities to a design which easily incorporates the active surface. For this work GELTECH has in house a computer numerically controlled milling machine which it uses regularly for this type of work.

3.2 Sol-Gel Processing

There were six major steps involved in the sol-gel process, mixing, casting, gelation, aging, drying and densification. Each step required careful control of the process variables in order to produce a successful part. Figure 3 shows the entire process with the temperature range and relative time for each of the processing step. Also shown in the figure are the changes in the gel network with the elimination of the pores when the gel reached complete densification.

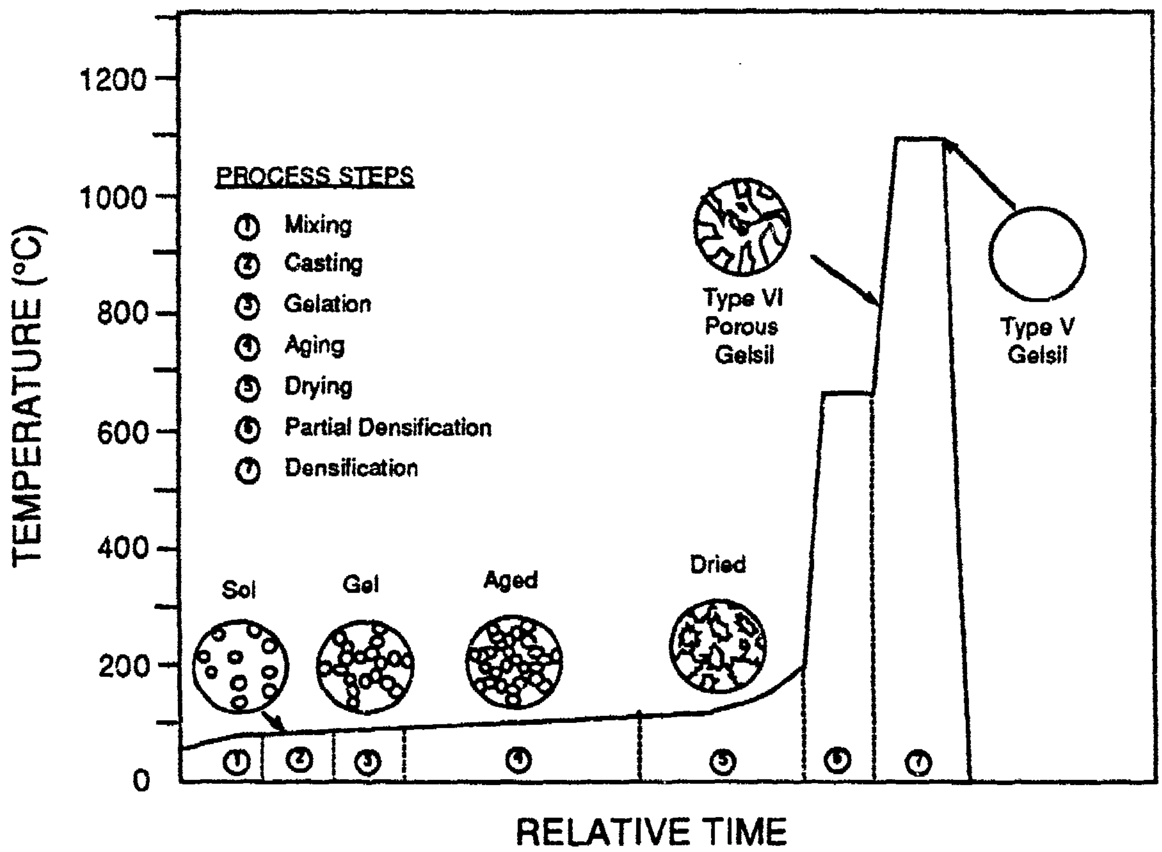

Figure 3: Gel-Silica Process Sequence.

Typical silica precursors are silicon alkoxides which were available in the U.S. at various level of purity. The silica sol was prepared by hydrolyzing the alkoxide with deionized water and small amount of catalyst to speed up the hydrolysis reaction of the precursor. After the sol was completely homogenized, it was cast into custom molds of desired shapes. Polycondensation reactions make the silica particles linked together to form a three-dimensional network and result in a rigid, wet gel having the shape and surface profile of the mold.

The subsequent drying step results in an ultraporous, monolithic body with the shape and surface details of the original mold.

The last step of this process corresponded to densification of the dried gel via elimination of the porosity by heat treatment [4].

3.3 Materials Characterization

The material properties characterized are all related to its optical quality which included glass homogeneity, UV/VIS/NIR transmission and light scattering.

An optical interferometer (Zygo Production Test Interferometer, Zygo Corporation, Middle Field, CT) was used to test glass homogeneity based on the interference phenomenon from the wave properties of light. This interferometer functions by dividing a wavefront into two or more parts, principally a reference wavefront and a measurement wavefront, which travel different paths and then recombine to form an interference fringe pattern. The geometrical properties of the interference fringe pattern are determined by the difference in optical path traveled by the combined wavefronts. An interferometer measures the difference in optical paths in units of the wavelength of the light used. Since the optical path is the product of the geometrical path and the refractive index, the instrument measures either the difference in geometrical path when the beams traverse the same medium or the difference of the refractive index when the geometrical paths are equal.

The transmission spectra were obtained for the 1.5" silica glass windows using UV/VIS/NIR spectrometry. The spectrometer (Perking Elmer Model 9, Perking Elmer Corporation, Norwalk, CT) provides a spectral range of 185-3200 nm and spectral resolution of 0.2 nm (UV/VIS) and 0.8 nm (NIR). The lambda 9 spectrometer has a double beam, double monochromator optical layout with high energy optimized optics which provides superior signal to noise ratio of 0.0002 A (900-3200 nm at 240 nm/min scan speed in air).

Light scattering was measured using a He-Ne laser. The width and the pattern of the light path in a glass specimen was compared with a set of standards and a number rating (from 0 to 10 with 0 being no scatter of light) was given to represent the scattering for this particular specimen.

3.4 Optical Properties Evaluation

3.4.1 Surface profilometry

The surface profiles were obtained with a three dimensional imaging surface structure analyzer (New View 100, Zygo Corporation,Middlefield, CT). The instrument provides both imaged surface details of test parts and accurate measurements to characterize these details. The New View uses coherence scanning white light interferometry to image and measure the microstructure and topography of surfaces in three dimensions without contacting the test surface. Light from the microscope divides; one part reflects from the test surface and another part reflects from an internal reference surface. Both parts are then directed onto a solid-state camera.

Interference between the two light wavefronts results in an image of bright and dark bands, called fringes, that indicates the surface structure of the part being tested. The test part is scanned by vertically moving the objective with a piezoelectric transducer (PZT). As the objective scans, a video system captures intensities at each camera pixel. These intensities are converted into images by a software called MetroPro. In addition, surface images are displayed on a video monitor, which magnifies the objective image 20 times.

Measurements are three dimensional. Vertical measurements, normal to the surface, are performed interferometrically. Lateral measurements, in the plane of the surface, are performed by calculating the pixel size from the field of view of the objective in use. The New View analyzes and quantifies the surface topography of parts. Depths up to 100 microns, with 0.1 nm resolution and 0.3 nm RMS repeatability, are imaged independent of objective magnification. Results are displayed on a color monitor as solid images, plots, and numeric representations of the surface.

3.4.2 Focal length determination

The focal length of the active surface was determined by noting where the lens focused collimated light (Figure 4).

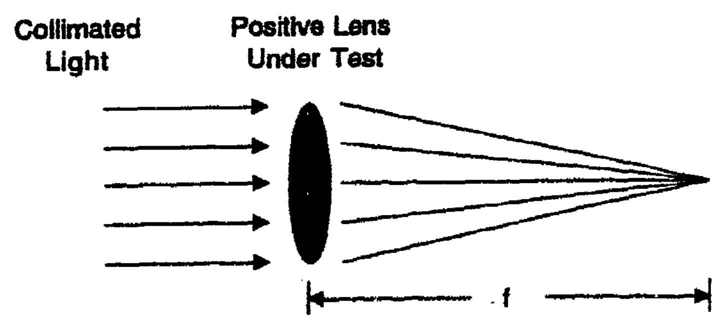

Figure 4: Determining the Focal Length of a Positive Lens.

As shown in Figure 5, the focal length of the replicated (negative) lens was determined by measuring the distance between the back focal point of a positive lens and itself when the converging light from the positive lens was collimated. This measurement is accurate to approximately 1 mm.

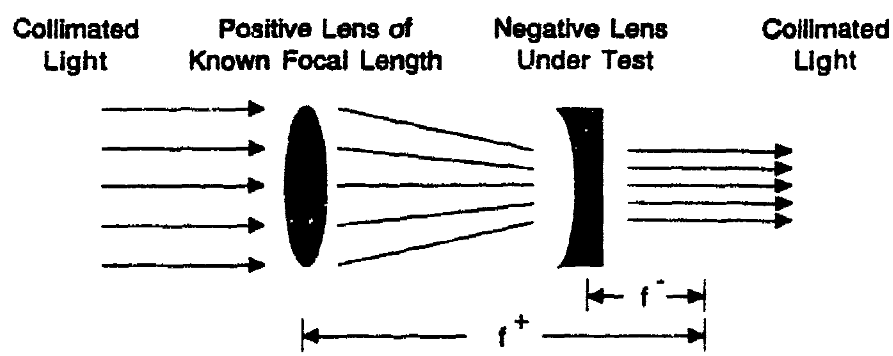

Figure 5: Determining the Focal Length of a Negative Lens.

3.4.3 Optical performance testing

The image quality criterion chosen for this comparative characterization was the square wave response (SWR), a modification of the more common modulation transfer function (MTF) or sine wave response. A conventional three-bar target which fully conforms to the USAF-1951 resolution target standard was used as an object, and the image modulation versus spatial frequency was measured and plotted for the active surface and the silica Fresnel lens replica.

Before the testing began it was important to determine which type of illumination (coherent or incoherent) was to be used in characterizing the lenses. The SWR of perfect lenses for both coherent and incoherent imaging is shown in Figure 6, where the contrast is defined by equation (1) and ξ, is the spatial frequency of the image (cycles/mm).

$$\text{Contrast} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad (1)$$

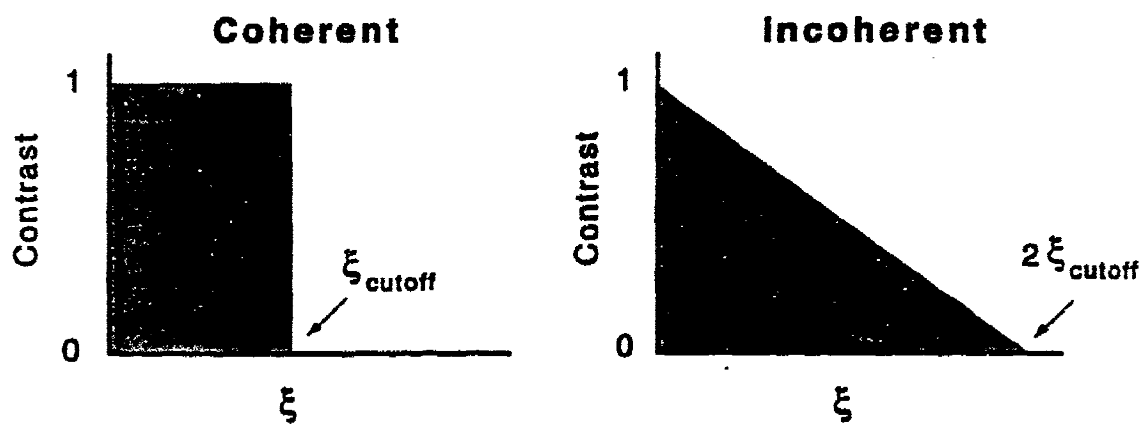

Figure 6: Square Wave Responses for an Ideal Lens.

The incoherent MTF has become an almost universally applicable measure of the performance of imaging forming systems in recent times [5]. Therefore the coherent SWR was chosen as the measure of optical performance in this comparison. Since diffractive optical elements inherently exhibit severe chromatic effects, monochromatic laser light was used to illuminate the object in the test set-up. The spatial coherence of the laser illumination was destroyed by inserting a rotating ground glass plate in the incident beam.

Separate optical systems were needed for each lens, since the active surface is positive and the replica negative. The optical system for the optical lens shown in Figure 7 is the simpler of the two and will be discussed first.

A collimated He-Ne laser was rendered spatially incoherent (rotating ground glass) and was impinging upon a Transmissive Air Force Resolution Target (Newport RES-1). The active surface was placed so that it imaged the bar targets onto the detector array of CCD camera (Star 1 Photometrics). The lens of the camera had been removed.

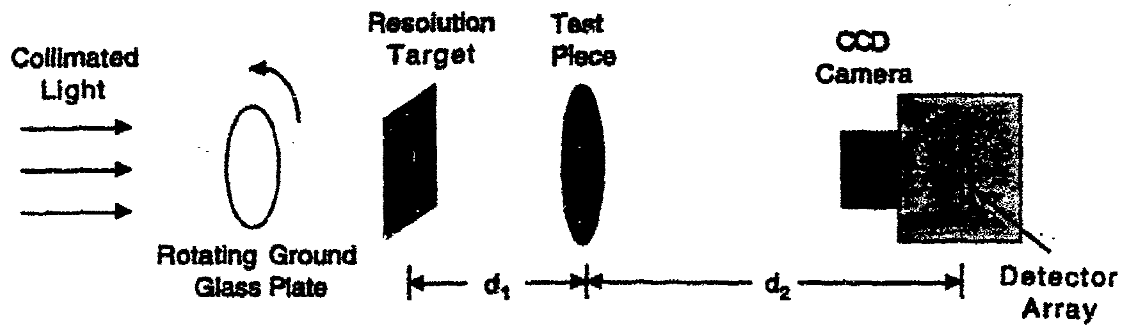

Figure 7: Optical System for Positive Optical Elements.

Note that the resolution chart was directly imaged onto the detector array with no auxiliary optics. The distances d_1 and d_2 were gauged to insure sufficient magnification of the targets on to the detector ($m=d_2/d_1$). Each bar target has a different spatial frequency. Thus, the SWR was generated by imaging multiple bar targets and determining the contrast of each target.

Since negative lenses do not focus light, additional optics were required to generate the SWR for the replicate lens, as shown in Figure 8. A fast positive lens was required to convert the light from diverging to converging in order to form an image on the detector. Additionally, the lens needed to be of high quality so that the SWR of the piece under test was not corrupted. Also, the positive lens needed to be of large diameter to insure that all of the diverging light was captured. A lens of d=80 mm and f=60 mm was used in this system.

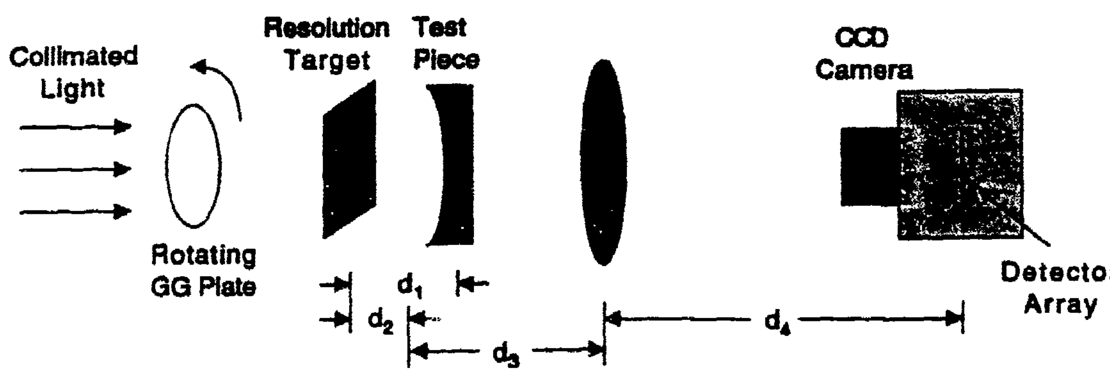

Figure 8: Optical System for Negative Optical Elements.

As with the positive optical element system, the magnification of the optical system was controlled by the distances, d_1, d_2, d_3, and d_4 ($m=[d_4 x d_2]/[d_1 x d_3]$). Finally, multiple bar targets were imaged to generate the SWR for the negative lens.

IV. RESULTS AND DISCUSSION

4.1 Optical Design Investigation and Mold Fabrication

4.1.1 Optical design investigation

After meeting with Thermotrex Corporation and Fresnel Optics, Inc. regarding the design of the overall geometric shape of the prototypes to be produced, it was decided to focus at the beginning on a plano-plano Fresnel lens and to attempt to produce, in a second effort, a prototype of Fresnel with a convex second surface by direct casting or post-polishing. Due to the uncertainty of the initial proposed design for the surface features, it was decided to try to produce an array of Fresnel surfaces instead of a single profile in order to investigate more completely the possibility of the sol-gel process and cover the range of geometry which would be needed in future requirements. These different profiles are described in the next section.

4.1.2 Design and production of active surfaces

Fresnel designs with a wide range of surface feature geometries such as aspheric, lenticular, prismatic, positive and negative lenses can be used as active surfaces for the fabrication of silica prototypes. Table 1 lists several plastic Fresnel lenses which were prepared by Fresnel Optics, Inc. in various materials. This table shows five aspheric profiles of various dimensions and one lenticular (cylindrical) shape, that were used as active surfaces for this work and were incorporated into the mold assembly described in the next section. The materials selected for the fabrication of the active surfaces were acrylic and polycarbonate. This materials selection represented the best combination between the compression molding limitations and the sol-gel processing requirements. By using these active surfaces fabricated by Fresnel Optics, Inc., it was possible to produce Fresnel lens prototypes with a clear aperture of 1 and 1.5" in an overall optical part of 1.5" in diameter.

Table 1: Optical Parameters of Selected Fresnel Profiles for Active Surfaces.

Ref.#	Type	Focal Length (mm)	Facet Spacing (mm)	Aperture (mm)	Plastic
SC 256	Aspheric	25.4	0.508	61.47	Polycarbonate, Acrylic
SC 244	Aspheric	40.1	0.381	87.00	Polycarbonate
SC 241	Aspheric	50.8	0.762	109.20	Polycarbonate
SC 255	Aspheric	127.0	0.254	108.00	Polycarbonate
SC 206	Aspheric	144.8	0.051	127.00	Polycarbonate
LN 615	Lenticular	0.38 (radius)	0.762	88.90x88.90	Polycarbonate

4.1.3 Design and fabrication of the molds

Figure 9 is a schematic of the mold assembly used to make silica Fresnel lenses. As shown in this figure, a mold holder keeps an active surface and a ring in place to form a volume to be filled with the sol. The principal advantage of this mold design was its flexibility of accommodating different active surfaces for casting different types of Fresnel lenses. Molds to produce 1", 1.5" Fresnel lenses, as well as 1.5" windows were fabricated and used to produce the results presented below.

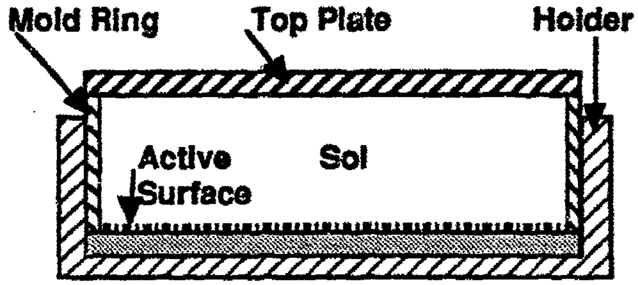

Figure 9: Mold Assembly.

4.2 Process Refinement for 1.5" Windows

The production of silica windows at GELTECH by sol-gel technology has been routinely done in high yields (>75%) for plano-plano lenses up to 1" in diameter. This provided a baseline from which the scale up to 1.5" diameters was initiated. The production of 1.5" optics, as required by this research necessitated process development to optimize yields and lens quality. This was done on plano-plano blanks fist, in order to separate the issue of increased lens diameter from the effect of the application of the Fresnel surface to the lens. The process development involved the modification of equipment schedules for the larger diameter parts.

Under this task, scaling up of 1" to 1.5" diameter windows (plano-plano) was made with success. This refinement of the process provided a baseline representing the overall processing yield and glass quality which could be obtained at the present time for parts of this diameter. The results to date indicated that an average of 75% could be reached for 1.5" windows using a modified set of process variables. The principal process variables which were adjusted were temperature and the duration of the various steps involved in the sol-gel processing. In section 4.5, data from materials characterization will be presented including glass homogeneity, UV/VIS/NIR transmission and light scattering of the Fresnel lenses of 1.5" diameter.

4.3 Process Refinement for 1" Fresnel Lens Working Model

While the process refinements were worked out for the larger, 1.5" blanks, Fresnel surfaces were applied to 1" blanks. Since 1" plano-plano blanks are presently manufactured routinely in high yield (>75%), the effects of the application of the Fresnel surface on the processing of the gel could be clearly identified and delineated by this approach. This allowed process adjustments to be made more accurately and efficiently to give a high surface quality on the lenses with a Fresnel pattern. Process refinements involved procedures for handling and supporting the gels while they were in process, and for the storage of the gels between process steps. Methods of handling molds during casting, and for handling of the gels during subsequent processing were developed for easy and rapid processing.

At certain stages in the processing of the gel it must be supported by fixtures in a manner that protects its surface from foreign matter and maintains the integrity of the active surface. The primary approach was to develop supporting fixtures from inert, non-sticking materials which maximize the weight distribution of the gel over the support in order to eliminate deformations.

Storage of the parts between process steps was done in a controlled manner to avoid absorption of large amount of moisture and other contaminants from the atmosphere. In each of theses cases routine procedures were established to facilitate processing of the parts, protect the quality of the parts, and allow for monitoring of the quality of the parts throughout the process.

Silica Fresnel lenses of 1" diameter were made using polycarbonate and acrylic surfaces, reference SC 256, shown in Table 1. It was found that the acrylic molds deformed during the process inducing damage on the surface of the gel. Polycarbonate molds did not deform during processing and allowed the preparation of a first set of 1" Fresnel samples almost free of defects. The defect on the parts corresponded to ring-type cracks and "angel wings" which were typical to Fresnel surfaces. Figure 10 shows the central portion of a silica glass Fresnel prototype.

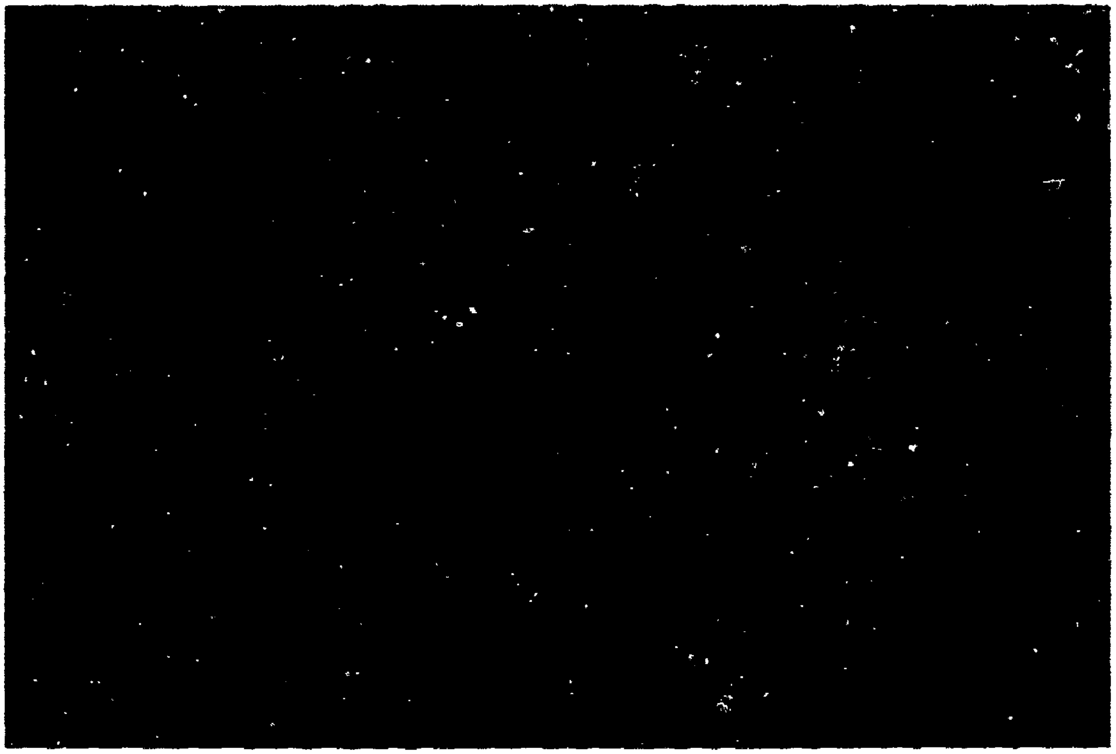

Figure 10: First Silica Fresnel Lens Prototype.

Two major changes were made in an attempt to produce crack-free lenses and well-replicated Fresnel surfaces. First, polycarbonate aspheric Fresnel lenses were used as the active surfaces instead of acrylic. Active surfaces of different thicknesses were incorporated into the mold assemblies. It was found that plastic active surfaces of thickness >2.5 mm do not deform during the processing of the gel and produced good replication patterns. The increase in the active surface thickness eliminated so-called "angel wings" resulting from the deformation of the plastic against the gel surface during processing.

Second, processing schedules were modified to minimize stress concentration which should be responsible for the ring-type cracks developed in the earlier prototypes. Modification involved every processing step, but major effort was focused on the drying stage where the gel underwent considerable shrinkage. Catastrophic breaking usually occurs when stress due to capillary pressure in the gel exceeds the strength of the gel network. At the corner of two neighboring facets of the Fresnel pattern, the sudden change in the radius of curvature imposed a situation where stress concentration develops. The stress level at that localized region can be much higher than in other regions having a gradual change in the radius of curvature. By modifying the rate of change of the process parameters, an aged gel could maintain its monolithicity and avoid the formation of microcracks during the drying step of the process.

All these changes were critical to a successful fabrication of a 1" Fresnel pattern on a 1.5" diameter lens. Figure 11 is a picture of two of these lenses.

Figure 11: Pure Silica Fresnel Lenses Made by Sol-Gel Processing.
(Each numbered division shown at the bottom of the picture represent one inch)

4.4 Fabrication of a 1.5" Prototype Fresnel Lens

The knowledge and expertise gained in the work described in the previous two sections allowed for the molding of 1.5" diameter Fresnel lens prototypes with a full aperture of 1.5". This was the overall objective of this first phase research effort.

Data collected from making a 1" Fresnel pattern on the surface of a 1.5" diameter lenses were used in designing the processing in this task. In order to accomplish this task, an experimental matrix was established and is given in Table 2.

In the next several sections, an investigation of the characterization techniques leads to a complete evaluation of the prototype lenses and the material. Both Optical quality evaluation and physical dimensional measurements were considered which included glass homogeneity, UV/VIS/NIR transmission, light scattering, surface profilometry and optical performance testing.

These results show an excellent capability of replication of Fresnel features by sol-gel processing. A photograph of the silica Fresnel prototypes is shown in Figure 12.

Table 2: Experimental Matrix for Making Silica Glass Fresnel Lenses.

Factor(s) Studied	Process Step	Optical Prop. impacted	Experimental Variables
Sol Chemistry: Hydrolysis Polymerization Particle growth Gelation mechanism	Mixing, Casting, Aging, Gelation	Homogeneity and Scatter	Sol Recipe Time/Temperature Cleanliness Casting method
Network evolution Network modification Stress pattern formation	Drying	Homogeneity and Scatter	Time/Temperature Drying method Cleanliness
Network evolution Dehydration Viscous sintering	Stabilization	[OH]	Time/Temperature Atmosphere Polarized light Light scattering
Dehydration Viscous sintering	Densification	Homogeneity and Scatter and [OH]	Time/Temperature Cleanliness Atmosphere Dilatometry

Figure 12: 1.5" Prototype Fresnel Lenses.
(Each numbered division shown at the bottom of the picture represent one inch)

4.5 Characterization of Pure Silica Glass

A quantitative analysis for the 1.5" windows was completed and the following results represent the glass quality of the 1.5" diameter blanks on a reproducible basis.

Properties	Test Results
Optical Homogeneity (ppm)	<30
Scatter (0-10)	<3
[OH] (ppm)	<10
Monolith yield (%)	75

Figure 13 is a typical UV/VIS/NIR transmission spectrum for the 1.5" silica glass windows without the Fresnel surface features on them. The residual chemical water or silanol groups in the silica glass was estimated based on the transmission at 2730 nm using the following formula.

$$OH\ (ppm) = -42.69 \times \log (I_1/I_2)/t\ (cm)$$

where I_1 is the internal transmission of sample at 2730 nm, I_2, the internal transmission of sample without OH at 2730 nm and t, the sample thickness.

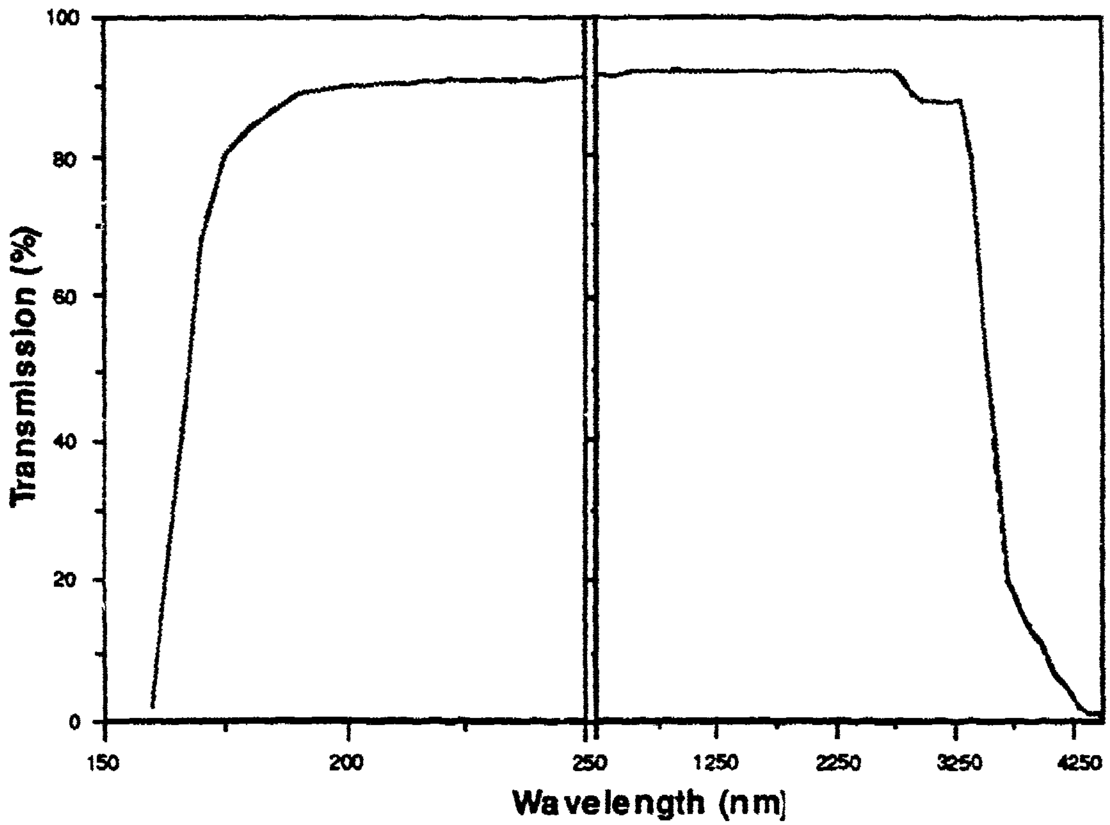

Figure 13: Typical UV/VIS/NIR Transmission Spectrum of Sol-Gel Derived Pure Silica.

4.6 Lens Surface Quality Evaluation

As discussed in section 3.4.1, the surface profiles were obtained with a three-dimensional optical profilometer/interferometer. Both the mold and the replicated Fresnel surfaces were measured, and the profiles are given in Figures 14 and 15. The results demonstrate an excellent capability of the sol-gel process to replicate very small surface features such as those on diffractive or Fresnel optics. Three different perspectives are given in the figures: 1) top view (upper left), 2) three dimensional view (upper right), and 3) cross section (bottom). The cross sections were plotted to get statistical analyses on the facet angles and facet widths of both the plastic active surface and the glass replica. Due to the shrinkage during the processing, the facet width of the replica surface is smaller than that of the mold surface by a consistent factor. An objective of 5x magnification was used in profiling the replicated glass Fresnel lens instead of using 2.5x for the active surface.

Figure 14 shows the central portion of the active surface having a positive aspheric curvature and a facet width of approximately 0.25 mm. A more accurate statistical analysis indicates that the average facet width is 0.251± 0.004 mm. This statistical analysis was made on a total of 28 facet width readings from two cross sectional profiles of the active surface tested. The standard deviation of the facet dimension on the active surface is somewhat larger than the value claimed by the mold manufacturer, which is ±0.0025 mm. Although no attempt was made in controlling the cleanliness of the air during the testing, the surface shown in the figure is generally free of dust except for one spot at the upper left corner of the top view surface map. Also, slight distortions can be seen at the top of some facets in the lower right portion of both the top view and three dimensional maps. The facet angles for the first four facets counting from the center of the active surface are given in Table 3.

For comparison, the same type of surface profiles are plotted in Figure 15 for the glass Fresnel replica having a negative aspheric curvature. Note that the test surface of the glass lens has well defined profiles with a facet width of approximately 0.10 mm. A statistical analysis based on 36 measurements indicates the facet width of the glass Fresnel lens is 0.101±0.002 mm, and that the standard deviation is only half of that for the mold active surface. This reduction in the facet width tolerance is due to the shrinkage occurring in the processing and is one of the advantages of this sol-gel process.

Table 3 summarizes the facet angles measured from the cross sectional profiles for both the active surface and the Fresnel lens replica. Measurement of the first four facet angles of the glass Fresnel replica indicates that these angles are within 0.033 degrees of the facet angle of the active surface, which is well within the tolerance of 0.25°given by Fresnel Optics, Inc., the supplier of the active surface. **The greatest significance of these results is the fact that the facet angle in the replica is essentially the same as that of the parent active surface. This proves that the shrinkage of the small surface features which occurs during processing is very uniform in all three dimensions, making accurate replicas of these types of features possible.**

It is worth noting that the 0.5 micron curvature at the bottom of the plastic active surface (Figure 14) was accurately replicated in the glass Fresnel lens (Figure 15).

In summary, surface profilometry results clearly indicate that the glass lens is an accurate replica of the parent active surface. However, in addition to mapping the physical dimensions of the parts, their optical performance was also tested, and the results,given in the next section even more forcefully indicate that the glass replica is an accurate copy.

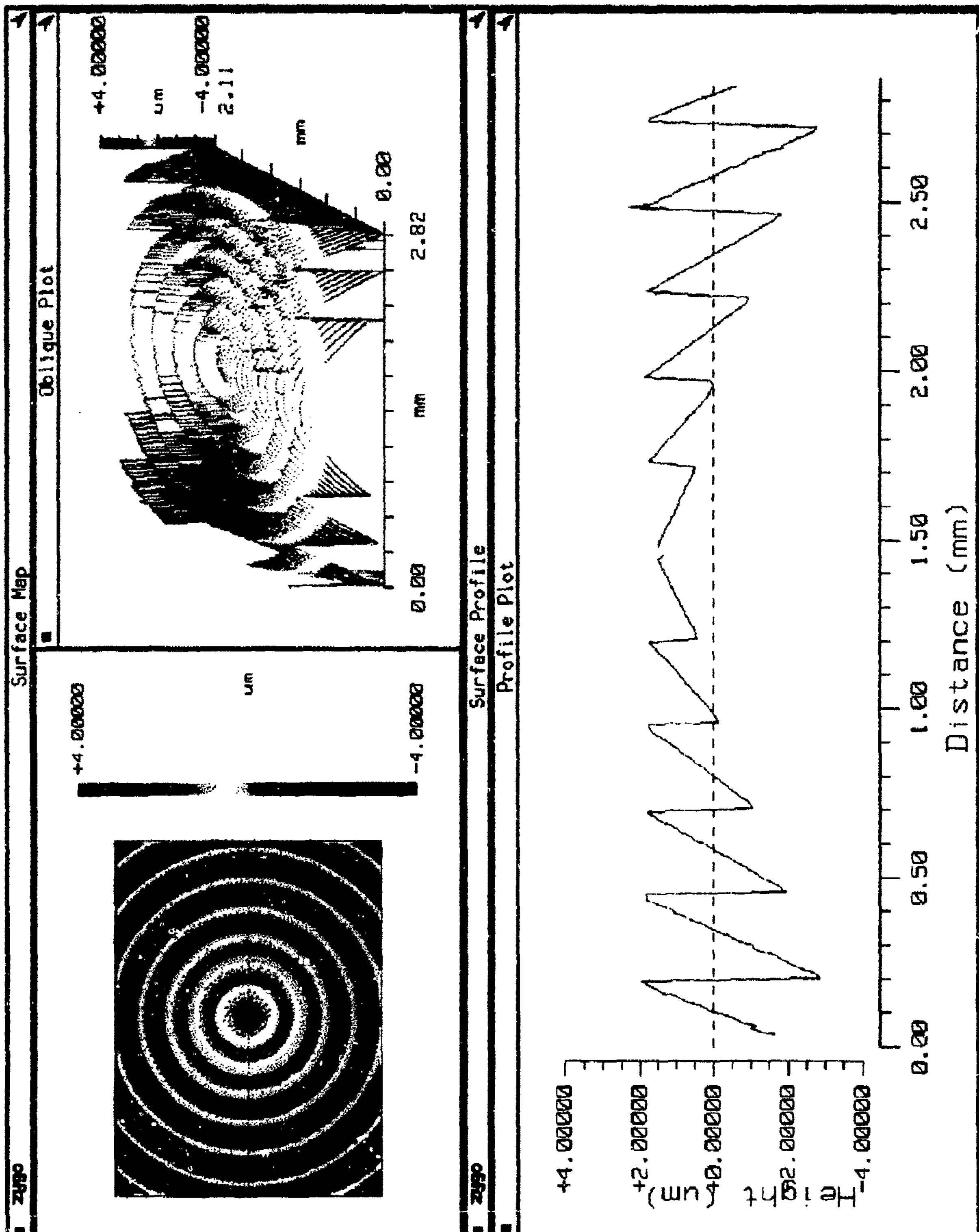

Figure 14: Mold Active Surface Having a Positive Aspheric Curvature.

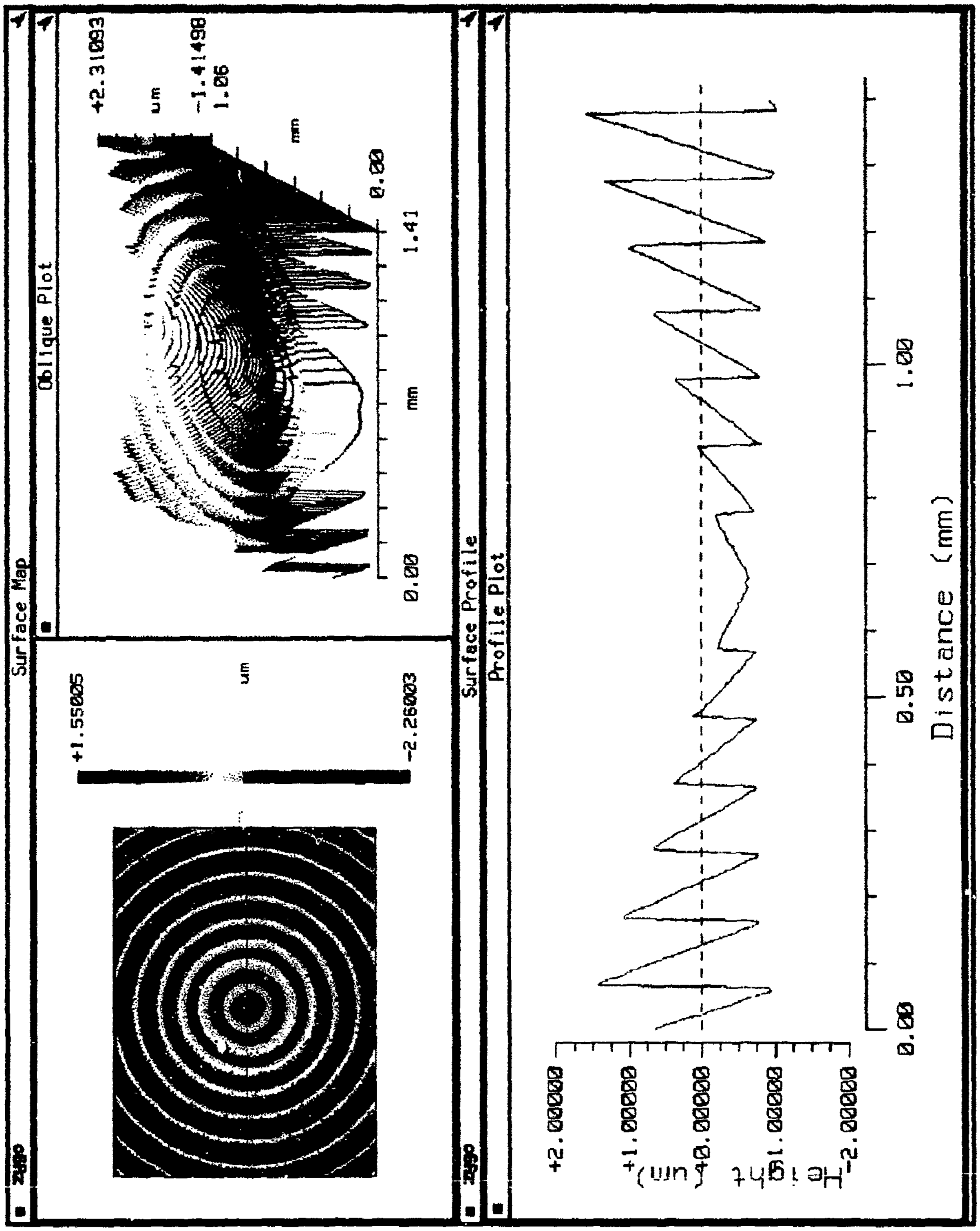

Figure 15: Replicated Glass Fresnel Surface Having a Negative Aspheric Curvature.

Table 3: Comparison of Facet Angles for Active Surface and Silica Fresnel Lens.

Facet Number	Active Surface		Silica Replica		Variance (degree)
	Facet Angle (degree)	Std. Dev. (degree)	Facet Angle (degree)	Std. Dev. (degree)	
1	0.263	0.007	0.264	0.010	0.001
2	0.446	0.003	0.476	0.027	0.030
3	0.672	0.013	0.677	0.021	0.005
4	0.904	0.018	0.890	0.031	-0.014

4.7 Optical Performance Testing

The objective of this effort was to test the optical performance of a replicated Fresnel optical element relative to the active surface from which it was fabricated. This comparison will thus serve to evaluate the materials and replication process used in fabricating optical elements of this type. These tests were conducted at the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida.

Table 4 presents the lens data of both the active surface and the replica of the Fresnel lenses. As expected, the silica Fresnel lens replica is an inverted (negative) lens with smaller dimensions in comparison with the original active surface.

Table 4: Focal Length and f Number of the Active Surface and Silica Fresnel Replica.

	Focal Length (mm)	Diameter (mm)	f Number
Active surface	104	101.6	1.02
Silica replica	-52	38.1	1.36

The image quality criterion chosen for this comparative characterization was the square wave response (SWR), a modification of the more common modulation transfer function (MTF) or sine wave response. A conventional three-bar target which fully conforms to the USAF-1951 resolution target standard was used as an object, and the image modulation versus spatial frequency was measured and plotted for both the active surface and the silica Fresnel lens replica.

The resulting SWR data indicate that the replicated silica Fresnel lens is essentially as good as the active surface from which it was made. In the testing, three data pixels were taken for each bright and dark line in the three-bar target resolution chart and averaged, giving an average intensity for each line. Imax was found by averaging the values for the three bright lines. Similarly, Imin was found by averaging the values for the two dark lines.

The contrast of 7 targets was determined for the active surface and the contrast of 18 targets was determined for the replicated lens. The resulting SWR for the lenses is shown in Figure 16. The SWR of the sol-gel derived pure silica lens matched that of the plastic active surface over the entire range of spatial frequencies tested. This indicates that the optical quality of the duplicate lens tested is equal to that of the active surface.

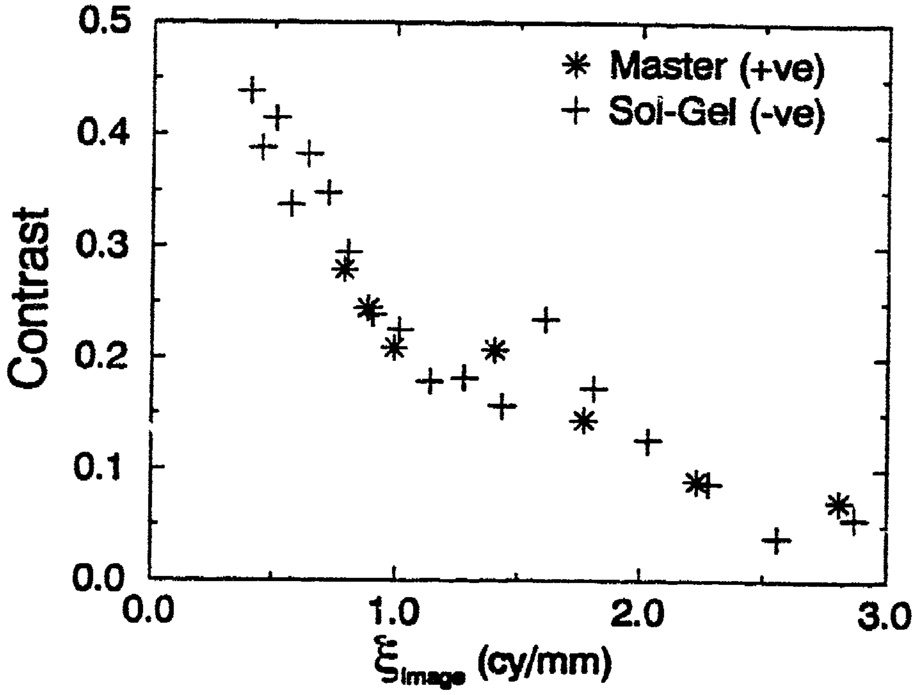

Figure 16: Comparison of the Modulation Transfer Functions.

Therefore, the quality of the silica Fresnel lenses produced by replication via sol-gel processing of an active surface demonstrate successfully that this process could potentially be developed for the low cost manufacture of glass surface feature optics such as Fresnel lenses but also diffractive optical elements (DOE), gratings, microlens arrays and total internal reflection components (TIR).

V. CONCLUSIONS

To demonstrate the feasibility of fabricating by replication glass Fresnel optics, or other surface feature components such as diffractive or microlens arrays, silica Fresnel lens prototypes were successfully prepared by a sol-gel molding technique. The material quality, the optical performance and the dimensional characteristics of the lenses including glass homogeneity, UV/VIS/NIR transmission, light scattering, and surface profilometry were extensively investigated.

The most important conclusion of this research effort is that the optical performance testing performed at the Center for Research and Education in Optics and Lasers (CREOL) of the University of Central Florida showed that these glass Fresnel lens prototypes were as good as their parent plastic Fresnel lenses. This demonstrates for the first time the feasibility of fabricating silica glass Fresnel lenses as well as numerous other surface feature optics via a replication process which will have acceptable cost for the industry.

Major accomplishments which were made during the course of this research include:

1) Based on an investigation of the optics designs for the lens, a set of designs was selected. Several active surfaces were designed and fabricated. **Molds incorporating Fresnel active surfaces were successfully designed and fabricated.**

2) Pure silica windows of 1.5" diameter were successfully produced; Fresnel patterns of 1" diameter were replicated on the surface of 1.5" diameter lenses. Crack-free Fresnel lenses were produced after major modifications in the processing and the design of the mold assemblies, especially for the plastic active surfaces. **These results led to the successful replication of a 1.5" diameter Fresnel pattern on 1.5" diameter pure silica glass windows, which was the target of this Phase I program.**

3) The techniques used to characterize pure silica prototype Fresnel lenses were selected and implemented. **The excellent replication capability of Fresnel surfaces by the room temperature net-shape casting was successfully demonstrated.**

Success in this development opens an avenue to any application where silica glass Fresnel lenses would be superior to plastics, both in optical quality and environmental stability. This accomplishment also has tremendous implications for the development of novel surface feature optics which cannot at the present time be manufactured in glass, or which have extremely high fabrication costs making them unrealistic for industrial applications. The need for these new optics will multiply greatly the benefits from this development program because the required production volumes will be several orders of magnitude greater than those of the specific Fresnel optics applications. These new optical elements, that GELTECH would like to aggressively develop in the near future, include gratings, diffractive-binary optics elements (DOE's-BOE's), total internal reflection components (TIR) and microlens arrays which will be required for military, space and commercial applications.

VI. REFERENCES

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