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Fresnel Concentrators for Space Solar Power and Solar Thermal Propulsion

Final Report

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Prepared for
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Foreword

This Final Report describes work accomplished under NASA contract NAS8-40844 with the George C. Marshall Space Flight Center. The Contracting Officer was Harry B. Craig. The Contracting Officer's Technical Representative was Daniel A. ONeil.

United Applied Technologies' project staff members included Rodney Bradford (Principal Investigator), Robert W. Parks (Co-Investigator), Donald O. Schaper, James H. Burroughs, James S. Casper, and Chris R. Abbott.

Abstract

Large deployable Fresnel concentrators are applicable to solar thermal propulsion and multiple space solar power generation concepts. These concentrators can be used with thermophotovoltaic, solar thermionic, and solar dynamic conversion systems. Thin polyimide Fresnel lenses and reflectors can provide tailored flux distribution and concentration ratios matched to receiver requirements. Thin, preformed polyimide film structure components assembled into support structures for Fresnel concentrators provide the capability to produce large inflation-deployed concentrator assemblies. The polyimide film is resistant to the space environment and allows large lightweight assemblies to be fabricated that can be compactly stowed for launch. This work addressed design and fabrication of lightweight polyimide film Fresnel concentrators, alternate materials evaluation, and data management functions for space solar power concepts, architectures, and supporting technology development.

1. Project Objectives

Concentrating solar collectors use lenses or mirrors to redirect, focus and concentrate solar flux onto a receiving surface or cavity. The main benefit of concentration is that a small receiver looses less heat than a large one and it can operate at a higher temperature. Point focus collectors have the highest concentration ratios and receiver temperatures of all concentrating collector technologies.

Fresnel lenses are refractive optical devices that replace the curved surface of a conventional lens with parallel setbacks or grooves that serve as individual refracting surfaces which bend parallel rays to a near common focal point. Their most frequent application is for light collection. Major benefits of these lenses include their thinness, flatness which simplifies their support structures, low light absorption and thus low heat retention. Thin, flat Fresnel reflectors also have parallel setbacks or grooves that have reflective coatings that reflect light to a common focal point. When constructed from thin polymer film material that can withstand the space environment, Fresnel lenses and reflectors offer the capability for large aperture light concentrators with small mass and compact stowage volume.

The overall thrust of this effort was to evaluate the practicability of using thin-film Fresnel lenses and reflectors with inflatable structures to concentrate solar energy for space solar power generation and solar thermal propulsion systems. The specific objectives were to:

1. Identify and evaluate alternate materials for Fresnel lenses and reflectors;
2. Evaluate fabrication approaches for production of large-scale Fresnel concentrators;
3. Identify alternate metallization approaches for Fresnel reflectors;
4. Compile and archive space solar power generation system concepts, programmatic and engineering data in NASA/MSFC's Virtual Research Center (VRC);
5. Support the definition and implementation of administrative and data management approaches for control of VRC data; and
6. Support enhancement activities for the VRC computing resources.

2. Materials Evaluation

Four groups of polymer materials were considered for application to thin-film Fresnel concentrators (lenses and reflectors) and structures. These were polyesters, fluoroplastics, polyimides, and silicones.

The polyesters (polyethylene terephthalate - PET) can be thermoset and thermoplastic. DuPont Mylar® was first available in 1952 as a thermoset and later in a thermoplastic form. Its use temperature is -70° to 150°C (-94° to 302°F). It has relatively low resistance to long-term UV and gamma radiation exposure without protective coatings.

The fluoroplastics are thermoplastic polymers derived from partially or fully fluorinated monomers. Examples are polytetrafluoroethylene (PTFE), e.g., Teflon® by DuPont, fluorinated ethylene propylene (FEP) and polyvinylidene fluoride (PVDF) in which piezoelectric properties can be instigated. The use temperatures of PTFE are cryo to 260°C (500°F). These materials have the lowest coefficient of friction and permeability. They generally have high chemical resistance and impact strength but tensile strength, wear resistance, creep resistance, and space radiation resistance are less than other engineering plastics.

Polyimides are a class of high temperature-resistant polymers that contain the imide group (-CONCO-) that are produced either as thermosets (cross-linked) or pseudo-thermoplastics (linear form). These materials have high UV and gamma radiation resistance; excellent abrasion, wear, and chemical resistance; and high tensile strength with low creep. Their use temperatures are cryo to 400°C (752°F). Polyimide films have a characteristic orange color, e.g., Kapton® by

DuPont. The CP1 and CP2 colorless polyimides developed by NASA/LaRC have visible light transmissivity approaching that of the polyesters (90+%).

Silicone is the group name for heat stable, semiorganic polymers. Their structure is made up of alternating silicon and oxygen atoms rather than the carbon-to-carbon backbone of organic polymers. Silicon is a nonmetallic element occurring naturally as silica and silicates. It has an amorphous and a crystalline form of structure (allotrope) and is used doped or in combination with other materials in semiconducting devices, silicones, and in silicon alloys.

These synthetic polymeric materials have a wide range of physical properties. They can be low- or high-viscosity liquids, solid resins, or vulcanizable gums. Silicones are characteristically resistant to extremes of temperature, to ultraviolet and infrared radiation, and to oxidative degradation. Silicone elastomers maintain their properties, with little or no loss, at elevated and reduced temperatures. The siloxane polymer structure is responsible for properties not seen in carbon-based polymers with one reason being the inherent flexibility of the siloxane molecule. Thermal stability can be enhanced with the incorporation of heat-resistant fillers and additives. References state that a high temperature elastomeric adhesive can be made that will withstand heating in air for up to a year at 400°F without significant property loses. Further, resistance to even higher temperatures can be achieved for shorter periods. A disadvantage of the silicone elastomers is their very low tensile strength (600 to 1350 psi) and low abrasion resistance. However, they do retain their flexibility to -51°C (-60°F) and are used as sealants and gaskets. They are also used as biomedical implants because of their inertness.

Concentrator Coatings. The use of polymer coatings on Fresnel lens and reflector films can provide reinforcement to allow for more compact folding and packaging, rip propagation termination (ripstop), prevention of tears caused by punctures, and to prevent or reduce material creasing. Candidate coating materials considered are described below.

Polytetrafluoroethylene (PTFE) is in the fluoroplastic class of paraffinic polymers that have some or all of the hydrogen replaced by fluorine. PTFE is a completely fluorinated polymer manufactured by free radical polymerization of tetrafluoroethylene. With a linear molecular structure of repeating $-CF_2-CF_2-$units, PTFE is a crystalline polymer with a melting point of about 621°F. Over 50 years ago DuPont chemist Roy Plunkett discovered PTFE. This technology has evolved to provide several new generations of fluorocarbon resins. Teflon® AF, an amorphous fluoropolymer, is similar to other amorphous polymers in optical clarity and mechanical properties, including strength. It also resembles fluoropolymers in performance over a wide range of temperatures, electrical properties, and chemical resistance. It is distinct from other fluoropolymers in that it is soluble in selected solvents; has high gas permeability, high compressibility, high creep resistance, low thermal conductivity, and the lowest dielectric constant of any known fluoropolymer; and can be used as a low-refractive index (1.29-1.31) coating or covering for optical devices, including those that must operate over a wide temperature range and in chemically aggressive environments. It has high transmission throughout the optical spectrum from infrared through ultraviolet, thus making it applicable to thin-film lenses.

Acrylic plastics comprise a broad array of polymers in which the major monomeric constituents belong to two families of esters – acrylates and methacrylates. These are used singly or in combination, sometimes with other monomers, to give products ranging from soft, flexible elastomers to hard, stiff thermoplastics and thermosets. Acrylics have a combination of properties: high clarity, good surface hardness, chemical and environmental resistance, and mechanical stability. Because of their optics and compatibility with dyes and pigments, they also are used in a range of transparent and translucent colors and are used to control transmittance in the ultraviolet, visible, and near infrared spectral regions. Polymer modifications include copolymers of methyl methacrylate with other monomers such as methyl and ethyl acrylate, acryonitrile, and styrene. Acrylics are blended with vinyls, butadiene, and other acrylic rubbers and with polyester resins to achieve tailored physical and processing characteristics. Acrylic compounds are available that are tailored for adhesion as thin coatings to pliable substrates, e.g., acrylic polymers in perchloroethylene.

Polyurethane is one of the thermoplastic elastomers that as a group are materials with recoverable elasticity and strength between engineering plastics and rubber. These elastomers have superior adhesive properties and formulations can be made from a range of esters and ethers, which yield a variety of properties. Two-component urethane elastomer compounds are available that are optically clear, room temperature curing, and provide high bond strength in layer thicknesses of 3-6 mils (76-152 μm).

Aromatic Hydrocarbons are a class of hydrocarbons, of which benzene is the first member, consisting of assemblages of repeated joined carbon atoms. An aromatic hydrocarbon ethylene tripolymer elastomeric sealant, commercially produced by Geocel Corporation, was designed to combine the flexibility of urethanes, the paintability of acrylics, the long life expectancy of silicones, and superior adhesion to a wide range of substrates. This formulation provides improved flexibility, adhesion, UV resistance, and life expectancy. Because of the inherent flexibility of this material blend, the sealant does not contain plasticizers (added to many sealants to promote flexibility) which tend to migrate out of other sealants, causing hardening and shortening their useful life. Its inherent weather and ultraviolet resistance, combined with its lasting flexibility, provide a terrestrial application life expectancy exceeding 50 years. Its clear formulation is optically transmissive as glass.

Rubber-Based Adhesive Coatings formulated from a variety of synthetic and natural elastomers have been used extensively in plastics lamination applications. Commercially available in one-part, solvent, or latex form, these products have a low application viscosity suitable for spraying or roll coating, and are activated by the evaporation of the water or solvent. The rubber, most commonly butadiene-styrene, butyl, polyisobutylene, or nitrile rubber, is compounded with tackifiying agents and plasticizers. These products are not generally useful for structural applications unless the elastomer is thermally vulcanized. Rubber-based adhesives are more commonly formulated to give non-crosslinking pressure-sensitive materials. Disadvantages of this type of product are the low service temperature (<158°F) and the negative environmental issues associated with a solvent-based product. There are, however, blended rubber-based adhesives in which the rubber is blended with a thermosetting resin system such as a phenolic. These blended adhesives can be used for structural applications, e.g., polychloroprene/phenolic.

3. Fresnel Concentrator Design and Fabrication

Fresnel lenses and reflectors can be designed for specific solar concentrator applications. The Fresnel lens design (Figure 3-1) is based on the basic law of refraction (Snell) which states that the path of light refracted at the interface between two media is exactly reversible and the ratio of the sines of the angle of incidence (θ1) and angle of refraction (θ2), relative to a line normal to the interface of two media is equal to the index of refraction (ratio of speed of light in vacuum-to-speed of light in the media for space applications). A standard Fresnel lens uses concentric rings of flat refractive surfaces which act like prisms. The desired focal length of the lens defines θ3 for any radial position from the center point of the lens. This focal point can be varied for each groove (facet) or zone of the lens to accurately control the flux distribution and concentration ratio.

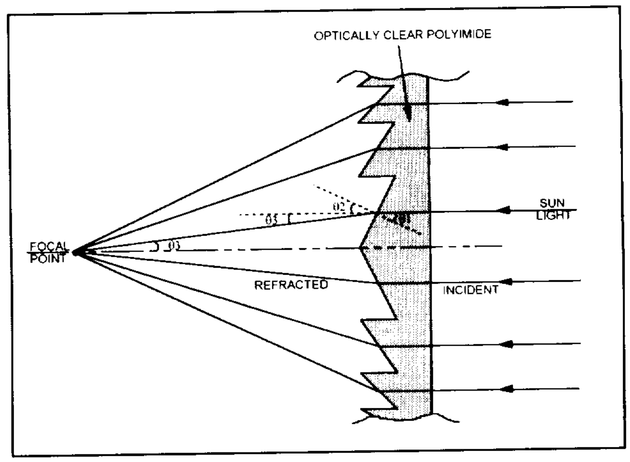


Figure 3-1. Fresnel Refracting Surfaces

CP2 polyimide has an index of refraction of 1.58-1.64 over the solar spectrum (400-2000 nm). This index of refraction varies little over the range of lens thickness (from 0.25 μm at bottom of groove to 0.76 μm at the top). UAT produces polyimide Fresnel lenses from mandrels/molds with machined parallel (curved or straight, concentric or off-axis) grooves. Depending on the requirements of a particular application, each flat refracting surface focus can be independent to tailor flux distribution or have a common focus to maximize concentration.

Fresnel reflectors are defined by a family of parabolas with a fixed focal point that define a flat Fresnel type reflecting surface. As depicted in Figure 3-2, a constant groove depth surface is defined for a mandrel/mold that is used to replicate the groove geometry in a thin film. This family of parabolas is described by the equation in Figure 3-2, where F, the focal point, is fixed with respect to the x-y coordinate system. The change in vertex and focal length for each parabola is identical and the equation(s) is evaluated at x = 0.0 and x = desired groove depth. Chords of the resulting parabolic segments define the reflector surface (and the mandrel surface) as shown in the figure. Depending on the requirements of a particular application, each flat reflecting surface focus can be independent to tailor flux distribution or common to maximize concentration.

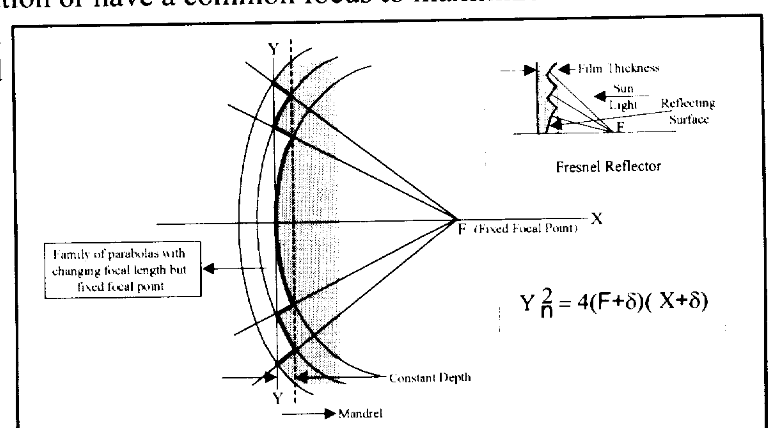


Figure 3-2. Fresnel Reflecting Surfaces

Evaluation and relative weighting of several lens design variables and materials properties are necessary to maximize power input to the receiver. Tradeoffs between performance and the number, width and depth of grooves are considered. High groove density increases power concentration efficiency but mandrel/mold machining time and cost must be taken into account. For thin (76-130 μm total thickness) film lenses, groove depth must be limited to maintain adequate lens tensile strength and tear resistance. Groove geometry variables include limited depths, varying widths and facet angles along the lens radius with constant and varying groove depths. The effects of facet shading are also a consideration because of the performance degradation which can be caused by lens-to-sunline misalignments.

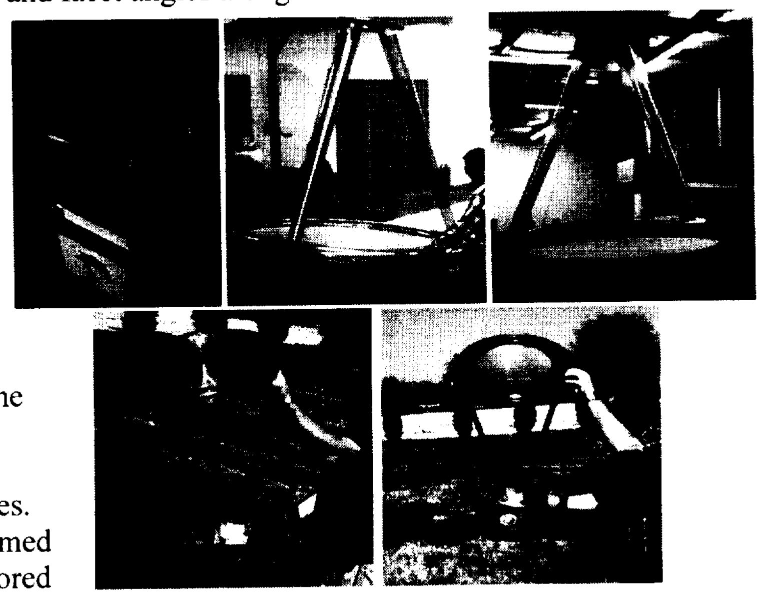


Figure 3-3. Symmetrical and Off-Axis Fresnel Lenses With Inflatable Support Structures

Fresnel Concentrator Fabrication. UAT produced on- and off-axis Fresnel lenses and reflectors, and preformed inflatable structures from the NASA/LaRC CP1 and CP2 colorless polyimides using both liquid solution casting and flat sheet forming processes. Fresnel reflector substrates and preformed structures are also produced using colored polyimides. Illustrative examples are shown in Figure 3-3. The upper photographs in this figure show the Shooting Star solar thermal propulsion experiment Fresnel lens support structure assembly that underwent thermal-vacuum and modal testing at NASA/MSFC. The bottom photographs show quarter-scale Shooting Star models with 76 μm thick on-and off-axis Fresnel lenses made from CP2 polyimide using precision metal molds fabricated at the MSFC Space Optics Manufacturing Technology Center.

A CP2 Fresnel lens is shown attached to an inflatable, formed polyimide torus/strut support structure in Figure 3-4 where the top photograph shows the "as assembled" model focusing light from a collimated light source. The insert photograph shows the model nonoptimally folded. The bottom photo shows the folded model after inflation with air injected through the fill tube in the support base. After deployment the structure is self-supporting in vertical orientation without internal gas pressure. Lens concentration effectiveness was maintained after folding and deployment. The halo around the focal spot is shown in the photographs.

Figure 3-4. Fresnel Concentrator Assembly Folding and Deployment Test

Thin-Film Structures Manufacturing Processes. Forming is a method of producing contours in a material by causing it to be stretched to an extent greater than its yield strength but less than its tensile strength. The UAT polyimide film shape-preforming process entails plastic deformation of flat sheet stock affected by tooling design and variation of pressure and temperature over time. The combined temperature and pressure profiles determine the amount of deformation or strain. Advantages of preformed thin-film support structures include:

- Desired shape is permanently formed in the film material;
- Reduced number of pieces to be assembled because three-dimensional seamless elements can be formed;
- Minimal seams or joints provide more uniform loading and thus fewer stress concentration areas; and
- Easier deployment because the stresses induced in the support structure elements during folding and packaging are self-relieving as the preformed equilibrium geometry is attained.

Fresnel Lens/Thermophotovoltaic Space Solar Power System. High light concentration levels and temperatures are desirable for high receiver efficiency but not desirable for solar cells. Cell open circuit voltage drops with increasing temperature, thus also reducing the power output. For example, a silicon cell at 200°C has lost about 90% of its output at room temperature. High concentration levels cause two problems - one, heat removal and secondly, design of the cell to reduce series resistance caused by the front grid without increasing the surface area covered by the grid. The high heat input generally requires cooling which adds undesirable weight. It is most desirable to use multijunction solar cells (2-4 cells grown epitaxially above one another), however, the bottom cell in this tandem structure usually has a band gap lower than silicon, hence exacerbating the problem.

NASA eliminated thermophotovoltaics (TPVs) from consideration for deep space missions for three factors: (1) the large size of radiators needed to maintain the photovoltaic cells at sufficiently low operating temperatures led to spacecraft integration issues and sensor obscuration; (2) the large radiation doses expected in orbit around Jupiter would cause substantial radiation damage to the solar cells, especially given their low operating temperatures in that environment; and (3) there was insufficient life data on the emitters to show they would survive the mission and also would not vaporize and deposit sufficient material to obscure the solar cells.

Technology resident and under development at the Auburn University (AU) Space Research Institute is addressing all three of these issues and could make large-scale space solar power systems viable by the use of a new solar cell for TPV applications coupled to a long-lived, stable, durable selective emitter matched to the band gap of the new solar cell. The solar cell has a band gap in the 1.0 to 1.2 eV range and will still operate with good efficiency at temperatures in the range of 150 to 225°C (423 to 498 K). The spectrally matched emitter has its emission primarily in a narrow band centered at 1.0 μm (1.24 eV) which provides photons just slightly above the band gap of the solar cell. This ensures that the excess energy of the photogenerated electrons is minimal, maximizing cell efficiency. Furthermore, the selected materials all have direct band gaps so photon absorption is maximized.

The key components of the receiver-emitter were designed, fabricated and tested as a joint UAT/AU effort. These components included the graphite receiver cavity and Er_2O_3 selective emitter housed in a vacuum chamber fitted with sapphire viewports. The receiver-emitter is shown in Figure 3-5 which is a photograph of the engineering demonstration model fabricated that incorporated a quarter-scale Shooting Star-type Fresnel lens concentrator assembly. The receiver was tested in sunlight. An 88-cm diameter cast polymer Fresnel lens with focal spot diameter of 0.71 cm was used as the sunlight concentrator. At a solar intensity of 0.09 W/cm^2, the emitter temperature reached around 1000°C. Due to the sun movement and lack of an automatic tracking system, the focal spot moved to the joining section between the sapphire window and the stainless steel end cap. The resulting heat on the cap caused the sapphire window to fracture before the I-V curve from the cell could be measured. However, achieving a temperature of 1000°C at the emitter was impressive. Considering the difficulty in alignment between the receiver entry and the focal spot, the focal spot might not have completely entered the receiver. By automatically tracking the focal spot, it is expected that the temperature can reach or exceed 1200°C. Even at an emitter temperature of 1000°C, test results showed that the InAsP cell delivered 8 mW/cm^2. Although the test was not completed due to the sapphire window fracture, it demonstrated the feasibility of the concept.

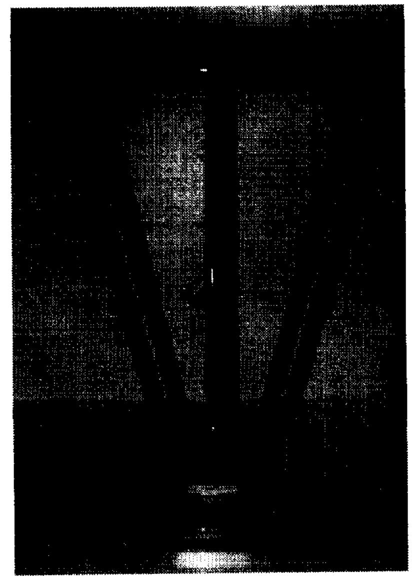
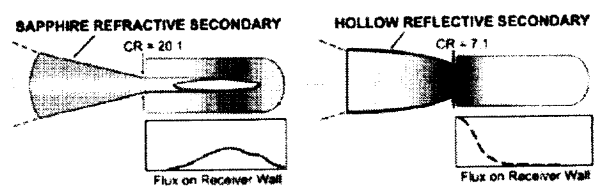


Figure 3-5. TPV Engineering Demonstration Model

Secondary Concentrators. In combination with either of the primary Fresnel concentrators, secondary concentrators offer much higher concentration ratios than the primary alone. Higher concentration ratios allow for much smaller receiver apertures which reduce reradiation losses out of the hot receiver. Additionally, the secondary relaxes the performance and pointing and tracking requirements of the primary.

A refractive secondary concentrator under development at the NASA/Glenn Research Center (GRC) is made of solid single crystal material and uses refraction and total internal reflection to focus and direct the solar flux. This refractive secondary has numerous design advantages over the conventional reflective secondary, typically envisioned as a hollow cone with a reflective internal surface. Figure 3-6 illustrates these advantages that include high throughput efficiency, high concentration ratio, tailored energy distribution and it does not require active cooling.



	Refractive Secondary	Reflective Secondary
Throughput Efficiency	> 90 %	65 %
Concentration Ratio	20:1	7:1
Energy Flux on Receiver	Lower peak flux, tailored distribution	120% higher peak flux at receiver entrance

Figure 3-6.

Figure 3-7 is a photograph of a prototype refractive secondary and prototype holder. GRC recently completed solar thermal vacuum testing of a sapphire refractive secondary concentrator and successfully demonstrated throughput efficiency of 87%. It is anticipated that the use of an antireflective coating will improve efficiency to 93%. Tests will be conducted in the summer of 2001 to demonstrate high temperature (~2000 K) operation and high power throughput (~5 kW).

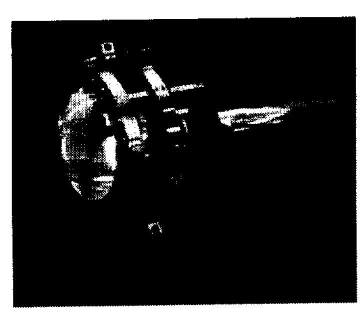


Figure 3-7. Prototype Refractive Secondary Concentrator

4. Fresnel Concentrator Scalability

A flat reflective Fresnel concentrator with preformed thin film support structure configuration for a Solar Orbit Transfer Vehicle Space Experiment (SOTV-SE) is shown in Figure 4-1. The articulating boom shown is used to point the Fresnel concentrator. The refractive secondary concentrator is the Glenn Research Center concept described in the previous section. In this secondary, refraction and internal reflection are used to further concentrate and direct the solar flux from the Fresnel.

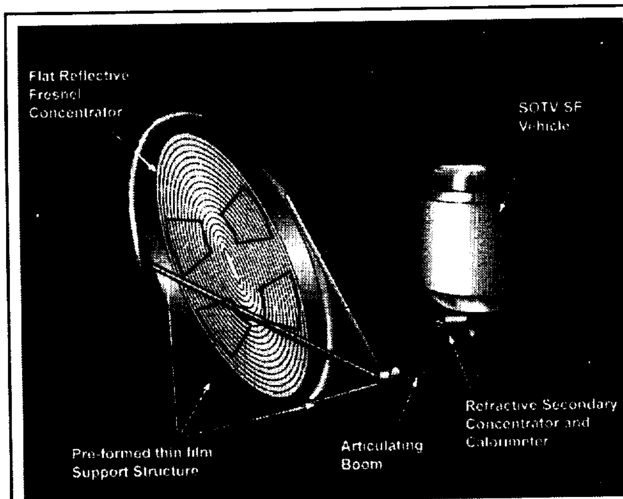


Figure 4-1. Fresnel Concentrator SOTV Space Experiment Configuration

The Fresnel reflector design considers mandrel fabrication and film segment processing issues to provide practical guidelines for designing and constructing a SOTV flight experiment-type Fresnel reflector. The system performance and interface requirements are the initial reference boundaries for groove geometry definition and design iteration. The use of mandrel segments to construct large-scale Fresnel reflector films is illustrated in Figure 4-2. Mandrel segments produce portions of the complete lens. Sufficient quantities of film segments produced from these mandrels are then aligned and joined to provide the complete reflector film. The film segments, all of which are flat, can be arranged in different planform configurations to provide extensive concentrator and support structure design and applications flexibility. If beneficial to a particular application, all flat segments can have the same focus with any planform geometry, e.g., circular, elliptical, hexagonal, truncated star pattern, etc., in which every part of a groove focuses to the same point. The flat segments can be juxtaposed or separated as long as focal orientation is maintained.

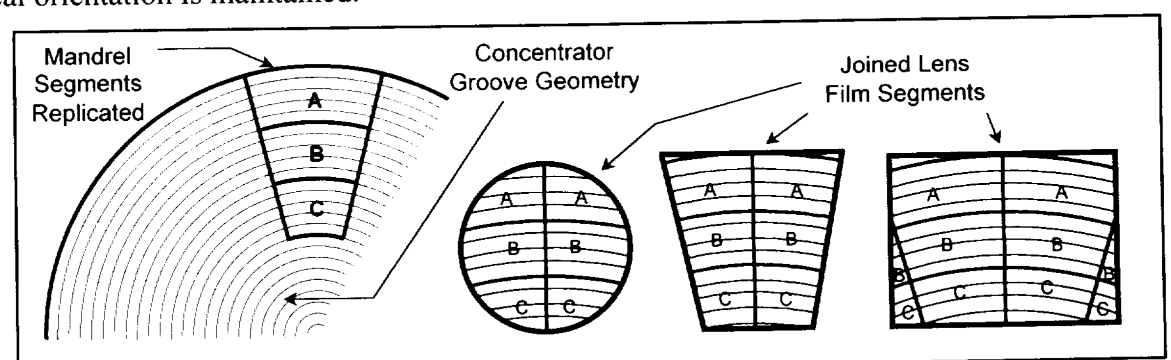


Figure 4-2. Seamed Lens Segment Configurations

Fresnel reflector film segments are illustrated for the SOTV-SE in Figure 4-1 by the four highlighted areas. This configuration shows biaxial symmetry which means mandrels for only one quadrant of reflector planform would be needed. In a uniaxial symmetry configuration comprised of non-centrally symmetric elliptical grooves, mandrels would be needed for one half of the reflector planform. An additional mandrel fabrication consideration beyond optimal groove contours and segment shapes is the tolerances assigned to the groove/facet surfaces.

Slope errors in the fabrication of the facets will cause the light rays to be displaced at the secondary concentrator.

Figure 4-3 shows two thin-film lenses (76 microns thick) produced by casting CP2 in solution on a 0.3-meter diameter aluminum mold. One lens was cut into irregular sections. The grooves on these sections were aligned and the sections were then bonded with a flexible UV resistant optically clear tripolymer sealant. The top photographs show a single-piece lens and the joined-section lens held by hand and illuminated by a collimated light source. The concentration effectiveness was maintained with the reassembled lens. These photos do not show the high intensity center focal spot because of camera film exposure time. The joined-section lens demonstrates the feasibility of bonding larger lens sections to produce large diameter concentrators in different planform configurations.

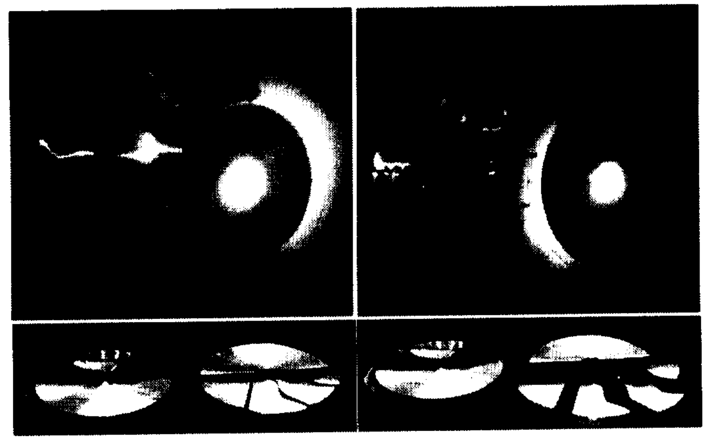


Figure 4-3. Unitary and Joined Section Polyimide Fresnel Lenses

The scalability of the UAT thin-film structures manufacturing technology was further demonstrated in a related applications effort by the fabrication of the torus shown in Figure 4-4. This structure has the following characteristics:

- Dimensions: 7.3-meter OD, 6.1-meter ID
- Material: space environment resistant colored polyimide film
- Construction: 30 identical preformed segments permanently bonded with space-qualified flexible epoxy adhesive
- Preformed segment thickness: 20-76 μm
- Total mass: 3.6 kg (8 lb)
- Surface areal density: 0.09 kg/m^2 (0.02 lb/ft^2)
- Stowage volume compactness ratio (volume inflated/volume stowed): >160-to-1
- Self-deploying by inflation.

All 30 torus segments were produced with the same manufacturing process and tooling. The consistent shape accuracy and assembly repeatability was demonstrated when the 30 segments were joined to produce a planar torus. The same methods and processes can be

Figure 4-4. 7.3-Meter Torus

used to produce much larger ultralightweight precision toruses and other structures such as very large inflatable beams and trusses with preformed connectors that provide high-precision alignment of members. With this demonstrated technology, the only limit to the size of toruses and other structure components that can be produced is the practical size of the processing equipment and tooling.

The deployment of the 7.3 meter torus demonstrated that a large ultralightweight structure could be compactly stowed and inflated to its preformed geometry in one-G using only gas pressure. In microgravity on the KC-135, University of Kentucky students found that a UAT 0.5 meter preformed polyimide film torus/strut assembly after being stowed would self-deploy without gas injection. This implies that in near zero gravity and vacuum the 7.3 meter torus could self-deploy with little or no gas injection after removal from its carrier container. Various approaches for deployment control are available.

5. Fresnel Reflector Film Metallization

Under a UAT funded IR&D effort the groove geometry for a 0.25-meter diameter Fresnel reflector was designed and a matching aluminum mandrel was fabricated on a diamond turning machine by Speedring-Detroit. This mandrel was used to form LaRC CP2 polyimide to produce the two reflectors shown in the photographs in Figure 5-1. One of the reflector films shown is attached to a torus made from formed CP2 film and the other is attached to a rigid aluminum ring. Both of these concentrators were sputter coated (~1000 angstroms thick) with aluminum in UAT's lab vacuum chamber. Reflectors produced with this mandrel and fabrication process were measured in sunlight to have geometric concentration ratios greater than 3000-1.

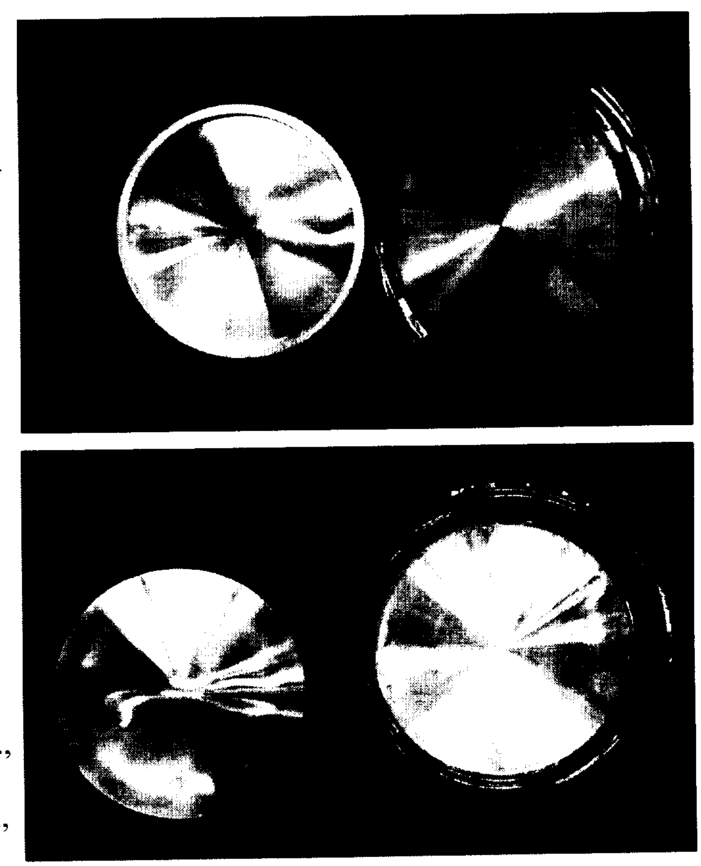


Figure 5-1. 76-Micron Thick CP2 Polyimide Film Fresnel Reflectors

Efficient metallization of larger Fresnel reflector film segments requires equipment of compatible size and capability. UAT has dealt with several commercial film metallizers (e.g., Courtaulds Performance Films, Metallized Engineering, Inc., Vacuum Depositing, Inc., others) who have equipment for accurate controlled vacuum deposition of aluminum, gold, and silver coatings on film widths of 80 inches and greater for high quantity production runs. These companies and others were evaluated as potential sources for small production lot metallization of Fresnel segments for large-scale reflectors. One company that has thin-film metallization expertise and the facilities and equipment for metallizing Fresnel reflector segments is Thin Film Technology, Inc. of Buellton, CA, located near Vandenberg AFB. Its capabilities range from prototype quantities to large production runs for electron beam evaporation, R.F. and D.C. magnetron sputtering, ion beam assisted deposition, and reactive sputtering.

An approach was defined for using the vacuum evaporator equipment at Thin Film Technology to apply 1000-1100 angstroms thick reflective (90+%) aluminum coatings to Fresnel reflector film segments up to 48 inches wide and 10 feet long. This approach entails tape-bonding the smooth nongrooved sides of the thermoformed polyimide film reflector segments to flat polymer film carrier sheets to facilitate placement and holding of the segments groove sides-up in the position required inside the coating equipment. This approach was reviewed with Thin Film Technology personnel who agreed that it was a practical and cost effective way of metallizing the Fresnel reflector segments. The turnaround time for metallizing five batches of reflector segments was projected to be three to four weeks.

Another potential option for film reflective coating is MSFC's 18-foot diameter vacuum chamber which was used to aluminize a 12-foot diameter seamless CP2 film cast by UAT. This was done as part of a Boeing/UAT/MSFC Aerospace Industries Technology Program in which Boeing, UAT and other organizations were cost-sharing participants.

The discussions in Sections 6, 7, and 8 that follow address the work performed to:

- *Support the definition and implementation of administrative and data management approaches for MSFC's Virtual Research Center;*
- *Compile and archive space solar power generation system concepts, programmatic and engineering data in the Virtual Research Center; and*
- *Support computing resources enhancement activities.*

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6. Virtual Research Center Administrative and Data Management Support

The VRC contains a collection of unique software tools which allows easy access to and the sharing of information such as documents, specifications, drawings, memos, briefing materials, analytical data and models and other similar information pertaining to discrete projects. Information volumes are maintained on many different projects and activities and are organized into Project Wings. The VRC is a widely used tool in the management and control of many different activities including the Space Solar Power project. Efforts were expended in maintaining the integrity of the VRC by removing or eliminating inactive accounts. For example, client accounts on the former PA Admin Wing of the Virtual Research Center (VRC) were deleted since the accounts were no longer needed due to the MSFC reorganization of May 23, 1999 which eliminated the Program Development Directorate and created the Flight Projects Directorate (FD). A new Wing was established in the VRC to archive data and information that would be forthcoming due to responses from the NASA Research Announcement (NRA) for the Space Solar Power Exploratory Research and Technology Program (issued April 12, 1999). It was anticipated that the majority of the data and information to be archived would not begin to be available until around contract midterms.

A Work Group Server was established for accommodating the Advanced Projects Office (FD02). Individual user accounts were established and instructions and direct technical assistance was provided to users for gaining access to their individual accounts. This server was utilized for archiving and sharing voluminous Space Solar Power technical data and programmatic information generated by members of the FD02 Work Group.

Compilation of Space Solar Power (SSP) Research and Development Results. SSP literature was researched and volumes of technical data and information were identified which depicted historical progress and highlights from SSP research and technology efforts over the past 25 years. Voluminous information was obtained that provided results from early concept feasibility studies, extensive SSP system analyses, and prototype hardware developments and demonstrations conducted by a wide variety of participants within government and industry. The materials and publications reviewed addressed the technical and economic aspects required to determine the feasibility of using solar energy to produce electrical power for domestic and international markets. The information collected was electronically scanned and placed on CD-ROMs for appropriate distribution. It serves as a valuable informational tool and readily available reference source for supporting current and future planning for the continuation of SSP research and technology initiatives. Coordination with the MSFC Repository resulted in the scanning of numerous documents containing information from the SSP Fresh Look Study and other pertinent studies and technology development efforts and storage of the data on compact disks for easy retrieval and portability.

National Space Science and Technology Center (NSSTC). The move of the FD02 personnel located in Building 4610 to the NSSTC located at 320 Sparkman Drive in Cummings Research Park occurred during the second week in December 2000. Extensive coordination and activities scheduling with MSFC facilities and operations personnel was required since the move involved relocation of office furniture, computers and related equipment. Assistance was provided for the transfer of voluminous SSP data and information and preserving and restoring operational integrity and functionality for the Advanced Projects Office following the actual relocation; coordination of requirements and assisting with assuring operational continuity for computational and communication resources in the NSSTC environment; trouble shooting and assisting with the resolution of related data and information problems and issues.

Computer Security. Increased emphasis is being placed on computer security at all levels within government and industry and is essential to protect intellectual assets. The Advanced Projects Office frequently generates data and information in the definition and implementation of many new activities and projects such as Space Solar Power. Also, this office receives through contracted technical definition studies, volumes of data and information from industry which in some cases is proprietary and must be appropriately safeguarded. In recognition of security requirements, an Information Technology (IT) Security Plan including a vulnerability assessment was prepared for the Virtual Research Center Online Project Management System (VRC/OPMS). This required coordination with laboratory personnel and documenting the VRC technical configuration and the detailed IT Security Plan. This plan incorporated NASA IT security policies, guidelines and practices and served as the baseline for subsequent electronic scans of the software and major hardware elements to establish overall security integrity of the VRC/OPMS.

An IT Security Plan was also developed and submitted for the FD02 Work Group Server that services all of the Advanced Projects Office technical personnel who are engaged in project definition efforts including Space Solar Power project activities. Server administration services were provided for the FD02 Work Group Server. This entailed keeping the serving operationally viable and functional, adding and deleting user accounts, and maintaining and applying security patches to the server software. Electronic scans of all FD02 computer systems utilized by Advanced Project Office personnel were initiated to identify security vulnerabilities that could lead to potential breaches in computer security. Extensive coordination was accomplished with MSFC computer security specialists in scanning applicable specific hardware and operating systems and implementing appropriate corrective actions to eliminate potential information security breaches. With support from MSFC computer security specialists, the electronic vulnerability scans were completed for all FD02 computing equipment including the FD02 Work Group Server containing voluminous Space Solar Power project data and information. No major security vulnerabilities or violations were found. Investigations were conducted to determine if the installation of system security patches were warranted in a small number of instances to eliminate the potential for security breaches. Appropriate corrective action was taken as warranted.

Computer Equipment Inventory and Upgrades. An inventory was conducted of computer equipment that comprises the VRC. Extensive coordination with various contacts was accomplished to obtain data and information for characterizing hardware maintenance costs for the VRC. These efforts facilitated the identification and assigning of maintenance cost at the component level which directly affect the continued availability and operation of the VRC. Efforts continued in exploring avenues and defining alternative courses of action for the continued operational support and periodic maintenance of the VRC as it approaches full production status. This entailed exercising a knowledge of MSFC's computing resources and capabilities including detailed discussions with internal sources for a variety of computer support services to define effective technical and low-cost approaches for obtaining essential support arrangements for the VRC.

Computing requirements for diverse FD02 project activities at the NSSTC were analyzed and requests were initiated to obtain new hardware/software to change/revitalize and reestablish Computer Aided Design System (CADS) capabilities within the Advanced Projects Office. This effort entailed making arrangements for upgrading and installation of software to result in the latest state of the art software for advanced systems analysis, preliminary design, and layout work. Extensive coordination was accomplished with representatives of the Structural Dynamics Research Corporation (SDRC) to identify specific CADS software needs and to negotiate low-cost software upgrades for the IDEAS software. These efforts resulted in a cost reduction from an original quote of approximately $89k to approximately $59k for the same software and maintenance from SDRC. Also, efforts were successfully initiated and resulted in obtaining a Silicon Graphic Workstation which functions as a server for supporting the CADS system network and for containing the new IDEAS software which greatly enhances existing computing resources and capabilities within FD02. A procurement action was initiated to obtain refreshes and upgrades for several new Windows PC platforms with hardware such as dual processors which have more advanced computing capabilities to permit the IDEAS graphics software to run on the enhanced PC instead of a more expensive Silicon Graphics Workstation. Assistance was also provided to FD02 project personnel in engaging periodic automatic electronic backup of SSP data and information contained on personal computers to assure functional integrity and continuity within the office.

7. Computer Hardware and Software Requirements

An extensive review of specific Program Development Directorate hardware and software requirements was conducted to ensure that these requirements would be covered under the new Outsourcing Desktop Initiative for NASA (ODIN) contract which became effective May 1, 1999. Significant data and information governing the nature of, and coverage by, the ODIN contract was obtained through several meetings with the MSFC Information Systems Services Office personnel. This data and information was used to determine specific hardware and software to be furnished through the ODIN contract in support of Program Development technical functions.

Support efforts were continued to define hardware and software that would be needed by Program Development personnel in their new capacities following the major reorganization at Marshall. These requirements were captured and identified for continued coverage under the Outsourcing Desktop Initiative for NASA (ODIN) contract. Extensive meetings and coordination was accomplished in concert with the MSFC Information Systems Services Office representative who provided extensive instructions and guidance in preparation for conversion to the new ODIN contract. Extensive interfacing with Program Development users was accomplished to interpret guidance and instructions and to assure users that their specific requirements and needs were being appropriately addressed during the contract changeover.

Transition to the Flight Projects Directorate. Considerable effort was expended in preparation for the move of a large volume of equipment plus identification of equipment in excess of current needs. Support as a point of contact was provided for the actual physical equipment moves for former Program Development personnel moving to the new Flight Projects Directorate offices in Building 4610. This involved extensive coordination with the technicians actually moving the hardware to assure that the equipment would be relocated to new destinations in tact and that the equipment would be fully functional on different networks following the move. Discrepancy reports for appropriate corrective action where warranted were prepared and submitted. A large volume of equipment was marked as excess and arrangements were made for the turn-in of the excess equipment consistent with the personnel moves and the MSFC Property Management and Disposal Procedures.

Following the massive personnel moves, support was provided to track hardware and determine the status of specific items that did not get relocated with the intended users and taking appropriate corrective action. This involved finding misplaced equipment, checking to see if it was functional following the move, and initiating appropriate action to have the equipment installed on the internal MSFC Communication Network. Requests were initiated for access to MSFC computer systems containing standard suites of office automation software and obtaining equipment and related communication services for temporary use by faculty and graduate student personnel during their summer employment term with the Flight Projects Directorate. The mechanisms used in acquiring the equipment for the summer personnel were among the first actions/test cases of requirements submitted under the ODIN support contract. Although some delay was experienced in actually obtaining, installing, and getting several equipment items fully operational, results were achieved which proved that appropriate ODIN support contract mechanisms were in place and reasonably reliable.

ADP hardware/Software Requirements Database. A new approach was initiated for updating the large ADP Hardware/Software Requirements Database for use by NASA in transitioning all desktop computers, printers, peripherals, networks and other related ADP equipment to the new ODIN service provider OAO. The new approach required each MSFC organization at the Directorate level to reverify all ADP equipment holdings to be placed under the ODIN contract and to develop an individual organizational database for consolidation by OAO. The required information was reverified for all former Program Development Directorate personnel. This required extensive efforts in coordinating directly with a large number of personnel including NASA and OAO employees, researching and incorporating the information in several different organizational databases within MSFC which were ultimately forwarded to OAO to serve as the major reference database for the computer services contract.

The existing equipment and software that had to be serviced by the ODIN contractor, OAO, as well as other equipment which had to be serviced under the existing PRISMS contract with the Computer Science Corporation (CSC) were reviewed and updated. The accuracy and currency of this major database was of paramount concern during the contract changeover between ODIN and CSC. Evaluations of various internal hardware/software system elements were also conducted for assessment of Y2K compliance.

Numerous changes and refinements were made to the Program Development portion of the ADP database. Numerous meetings were held with MSFC Information Systems Services Office personnel to obtain new information and assist with interpreting guidance received regarding ADP equipment coverage under the new ODIN contract. The general trend appeared to be that more equipment and applications, e.g., laboratory type equipment, would be placed for maintenance and refreshment under the ODIN contract. The ADP is maintained since it serves as the basis for contract charge accruals.

This ADP database essentially contains an inventory of computer hardware and software used by individual MSFC users plus a large volume of institutional system equipment where no specific users are identified and equipment and software used by all on-site support contract personnel at MSFC. This database contains data for twelve to fifteen thousand line item entries which change frequently. A significant problem arose throughout MSFC with the updating of this database due to the fact that there were a large number of personnel using different techniques while making input changes to the "live" database and as a result the integrity of the information in the database became questionable. As a result, a different approach was implemented to update the database which requires each point of contact to reverify all changes and input by specific organizations and users at MSFC. This increased reliability and input accuracy.

A complete wall-to-wall inventory of ADP equipment at MSFC was conducted by OAO. Data from this extensive inventory was furnished to NASA for analysis and use as an equipment location source. This information also served as a basis for determining which equipment in that inventory would be placed under contract for maintenance and refurbishment by the ODIN contractor. The use of this inventory data generated intensive coordination and efforts to identify specific equipment holdings and determine what equipment items and technical configurations which had to be refreshed by OAO under its current contract. A considerable number of change reports were generated to add, delete, and/or correct existing information in the ADP database.

8. Collaborative Engineering Center Enhancements

The Collaborative Engineering Center (CEC) is a relatively new analytical facility at MSFC used primarily by Space Transportation Directorate technical personnel for collaborative work in establishing design criteria, parameters, and requirements for future launch systems and in related advanced technology assessments. This facility is utilized in preliminary design of large scale propulsion and launch vehicle systems to meet future needs and launch requirements for projects including Space Solar Power which involves transporting massive structures, photo-optical and electronic components, and robotic servicing mechanisms to orbit. In support of the CEC, enhancements were identified and 22 new workstations were ordered for placement in the CEC. A factory representative was contacted and a site visit was accomplished for consultation on the assembly, checkout, and operation of the new workstations. However, actual installation was delayed due to the disruption caused by the extensive reorganization and personnel moves at

MSFC and the fact that the CEC was experiencing a complete overhaul relative to the physical layout of the area and supporting communications and electrical/facility requirements. Many meetings were held with the using organizations, facilities, and communications personnel at MSFC to establish a strategy for implementing the CEC enhancements. The knowledge gained from this effort provided information useful in forecasting cost and support requirements for similar facilities considered by other MSFC organizations.

Several additional informational meetings and detailed technical discussions were held with MSFC Facilities and Communications Office representatives to convey specific operational requirements for the CEC upgrade. Facility requirements for supporting new workstation configurations were discussed in-depth and based on these discussions the Facilities Office initiated the preliminary design for the delivery of required services in support of the new workstation configurations. Additionally, technical communications requirements essential for connecting all the workstations and to provide the capability to project CRT screen images from any one or two of the 22 workstations to two overhead projectors for group meetings were conveyed to the Communications Office technical personnel who designed an electro-mechanical switching system for potential use in the CEC. While this hardware design effort was ongoing, a more cost effective and suitable software solution was investigated for potential application within the CEC in lieu of the more expensive electronic switching method proposed.

In parallel with the ongoing enhancements to the CEC, coordination continued with the same Facilities and Communications Office representatives for upgrading and bringing four more conference rooms on-line as Management Information Centers (MIC) within the Flight Projects Directorate occupied areas in Building 4610. This effort was viewed as an extension of the CEC enhancement effort since at least one of these new conference rooms was being considered for conversion to a Collaborative Engineering Center. This was part of the overall thrust to develop and implement more CECs as new sophisticated design tools for collaborative engineering in an intelligent synthesis environment.

Efforts were initiated to refresh, on a selective basis, an increment of twelve PC and Macintosh Workstations in the CEC. Those workstations selected for refresh were older ones bordering on technology obsolescence that could not handle a heavy and sophisticated computation workload.

Technical personnel responsible for the operation and maintenance of the CEC regarding its secure operation were contacted in response to outside attempts to break into the various data systems. As a result of these discussions, decisions were made to take various systems off-line and to rebuild the operating systems with appropriate safeguards to prevent future attempts to break in and to avoid the potential loss or compromising of the data and information contained on these systems. A detailed outline of an applicable security plan was provided to appropriate individuals for implementation.

9. Conclusions and Recommendations

This section provides conclusions reached based on the application of UAT manufacturing technology to thin-film Fresnel concentrators and support structures. Recommendations are made concerning space solar power subscale systems and component performance validation demonstrations.

This work demonstrated that: (1) thin-film Fresnel concentrators provide sufficient energy concentration and other operational characteristics necessary for their use with solar orbit transfer vehicles, space solar power and other space-based systems; (2) large-area flat film concentrators can be assembled from segments produced using low-cost tooling and fabrication processes; (3)

thin-film Fresnel concentrators can be permanently attached to preformed thin film support structures, compactly folded, then deployed and maintain their energy concentration capability; and (4) UAT's polyimide film preforming technology provides enabling capability for the fabrication of large-scale inflatable structures.

Thin Film Fresnel Reflectors. The efficacy of the manufacturing processes and assembly procedures for Fresnel concentrator assemblies were demonstrated for subscale prototypes. The advantages of this technology over pressure shaped inflatable lenticular concentrators include:

- Operationally simpler, eliminates the need for gas-pressure to maintain the concentrator shape, and thus the clear canopy cover and its associated losses (20%) caused by solar flux passing through it twice (through to reach the reflecting/concentrating surface and back out to the receiver);
- Micrometeoroid and debris punctures will not significantly degrade performance;
- Reduced loading on the concentrator support structure, only single flat film sheet needs to be supported;
- Tolerant of support structure nonplanarity, distortion, and vibration. Required dimensional accuracy of support structure is greatly reduced;
- Lighter in weight, conducive to smaller package volume;
- Can be fabricated using LaRC ultraviolet radiation and atomic oxygen resistant or other polyimide material using precision machined metal mandrels with high groove pattern reproduction precision; and
- Offers low-cost scalability to very large sizes with modular tooling and processing techniques.

The design, fabrication, and assembly processes for Fresnel reflectors were verified at the prototype level. The thin-film Fresnel reflectors provide the energy concentration and design flexibility for their use with solar orbit transfer vehicles, space solar power systems and materials processing in space that requires high power levels and temperatures. The inherent characteristics of Fresnel concentrators combined with the proven fabrication methods and processes offer a wide range of applications. Meeting application-specific performance and interface requirements is facilitated because focal length, power level and power distribution can be tailored by variation of design parameters, e.g. groove depths, groove widths/number of grooves, and segment configurations. Film segment joining provides low-cost scalability for varied planform geometries and sizes.

Concentrator Thin-Film Support Structures. The repeatability and accuracy of the UAT preforming and assembly processes for inflatable thin polyimide film doubly-curved and non-symmetrical structural elements were demonstrated for subscale prototypes. The advantages of this technology include:

- Desired shape is permanently formed in the film material;
- Reduced number of pieces to be assembled because three-dimensional seamless elements can be formed;
- Reduced number of seams or joints provides more uniform loading and thus fewer stress concentration areas;
- Easier deployment because the stresses induced in the support structure elements during folding and packaging are self-relieving as the preformed equilibrium geometry is attained; and

- Can be made inherently self-rigidizing after deployment by incorporation of internal and/or external preformed thin-film stiffeners.

The manufacturing processes and tooling designs were verified by fabrication of additional polymer film structures at the prototype level. The torus-strut model assembly deployment accuracy and repeatability and robustness were demonstrated. The same methods and processes can be used to produce much larger ultralightweight precision toruses and other structures such as very large inflatable beams and trusses with preformed connectors that provide high-precision alignment of members. With this demonstrated technology, the only limit to the size of toruses and other structure components that can be produced is the practical size of the processing equipment and tooling.

Recommendations. The results summarized above provide the basis for further thin-film concentrator assembly performance verification and application with space solar power system elements. The recommended next step is application of the technology to the design, fabrication, and ground test of engineering demonstration models of flight test articles. The thin polyimide film solar concentrator and support structures technology can be integrated with thermophotovoltaic, solar thermionic, and solar dynamic power generation system/component performance validation demonstrations.

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Large deployable Fresnel concentrators are applicable to solar thermal propulsion and multiple space solar power generation concepts. These concentrators can be used with thermophotovoltaic, solar thermionic, and solar dynamic conversion systems. Thin polyimide Fresnel lenses and reflectors can provide tailored flux distribution and concentration ratios matched to receiver requirements. Thin, preformed polyimide film structure components assembled into support structures for Fresnel concentrators provide the capability to produce large inflation-deployed concentrator assemblies. The polyimide film is resistant to the space environment and allows large lightweight assemblies to be fabricated that can be compactly stowed for launch. This work addressed design and fabrication of lightweight polyimide film Fresnel concentrators, alternate materials evaluation, and data management functions for space solar power concepts, architectures, and supporting technology development.

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