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CONCENTRATOR TECHNOLOGY

Paul A. Gierow
William R. Clayton
Deborah Kromis

SRS Technologies
990 Explorer Blvd, NW
Huntsville, AL 35806

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Final Report

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Kristi K. Laug

KRISTI K. LAUG
Project Manager

Bernard R Bornhorst

BERNARD R. BORNHORST
Chief, Space Propulsion Branch

Peter A. VanSplinter

PETER A. VAN SPLINTER
Director,
Applications Engineering Division

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Paul A. Gierow, William R. Clayton

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990 Explorer Blvd, NW
Huntsville, AL 35806

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13. ABSTRACT *(Maximum 200 words)*

Development of a Solar Powered Rocket depends heavily on demonstrating the technology for lightweight space-deployable solar concentrators. Large parabolic shaped thin film reflectors can be packaged with other solar powered propulsion elements and deployed in low earth orbit. The Solar Powered Rocket Engine is expected to produce specific impulses of 1000 to 1200 seconds. This is over two to three times that of conventional liquid hydrogen/oxygen engines. This performance would significantly improve travel from low earth orbit to geostationary equitorial orbit.

A significant step in demonstrating the feasibility of large lightweight deployable concentrators has been done in Phase I research. An inflatable thin film off-axis paraboloidal concentrator of a single chamber was designed to improve high concentration ratios and ease of deployment. The feasibility of the concept has been demonstrated in Phase I, as to configurations, and manufacturing techniques. The single chamber design does not require a torus support. The design has features which are improvements over the conventional torus supported concentrator while still allowing for similar structural attachment to the vehicle.

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Table of Contents

List of Figures

INTRODUCTION

The solar thermal rocket offers the optimum propulsion means for Low Earth Orbit (LEO) to Geostationary Equatorial Orbit (GEO) transfer vehicles, provided that specific impulse (I_{SP}) on the order of 1,000 seconds at moderate thrust levels can be achieved. These I_{SP} and thrust levels are contingent on the availability of large lightweight autodeployable solar concentrators of a total concentration ratio on the order of 10,000:1. Fabricating the concentrator membrane of the optically-required configuration is a major challenge. Conventional methods of fabricating the concentrator from sections produces disruptions in the reflector surface along the seamed surface. Also, concepts which use an outer torus support structure design have difficultly in terms of maintaining in-plane shape, because of the film tension and structure interface loads. These loads must be properly distributed in order to avoid distortions and gross optical errors in the primary concentrator. Packaging and deployment of a concentrator also possesses major design problems.

Alternative concentrator concepts were evaluated and a modified design for a single chamber concentrator design was proven feasible under this Phase I effort. The single chamber design eliminates the need for an outer toroidal support structure. Elimination of the toroidal support can reduce the risk of multiple deployment paths during deployment of the concentrator in orbit. An integral secondary concentrator is also included in the single chamber design. The use of a secondary concentrator can also improve the success potential of the solar rocket system. This research continues to support the solar thermal propulsion program through furthering technology development in the design of the concentrator and the development of fabrication techniques for highly accurate inflatable doubly curved membranes.

SUMMARY

The Phase I technical objectives were to demonstrate a feasible design concept for fabrication of an inflatable concentrator for use in the Solar Thermal Propulsion program. Interface requirements such as structural support and absorber requirements were addressed in Phase I. Alternative design concepts were evaluated during the effort. Fabrication procedures were investigated and verified on a small scale with laboratory test samples. A preliminary conceptual design of an inflatable single chamber concentrator was completed and a scale laboratory model fabricated and preliminarily tested. Finally, Phase II plans were generated for providing a methodology for continued research and laboratory development of large scale concentrators.

The problems of designing and fabricating large accurate lightweight deployable solar concentrators are formidable. Advances in the state of the art are required in order to simultaneously meet the optical accuracy, weight, stowed volume, auto-deployment, and reliability requirements of deployable concentrators. Fabricating the concentrator membrane of the optically-required configuration is a major challenge. Innovative solutions to these design problems were addressed and resolved in the Phase I effort. An inflatable thin film off-axis paraboloidal concentrator of goreless construction and improved design can provide high concentration ratios, ease of deployment and increased reliability. The feasibility of a single chamber design was demonstrated in Phase I, as to configurations, materials, and manufacturing technique. The design concept that was developed and proven feasible under the Phase I effort is shown in ***Figure 1***. The membrane is a "single-chamber" design that does not include a torus. The design has features which are improvements over the conventional torus supported concentrator while still allowing for similar structural attachment to the vehicle. The single chamber is easier to fabricate, has a lower number of components, requires only a single inflation pressure and is more reliable to deploy.

A Phase II continuation will combine the design elements of configuration, materials, and processes described in this report to fabricate and demonstrate a prototype model of a flight test article. The prototype will be of a size and concentration ratio sufficient to demonstrate the practicality of solar thermal propulsion. This design, demonstrated in Phase I work, improves the success potential for developing and fabricating solar concentrators for the near term flight article test, and eventually, the orbital transfer vehicle.

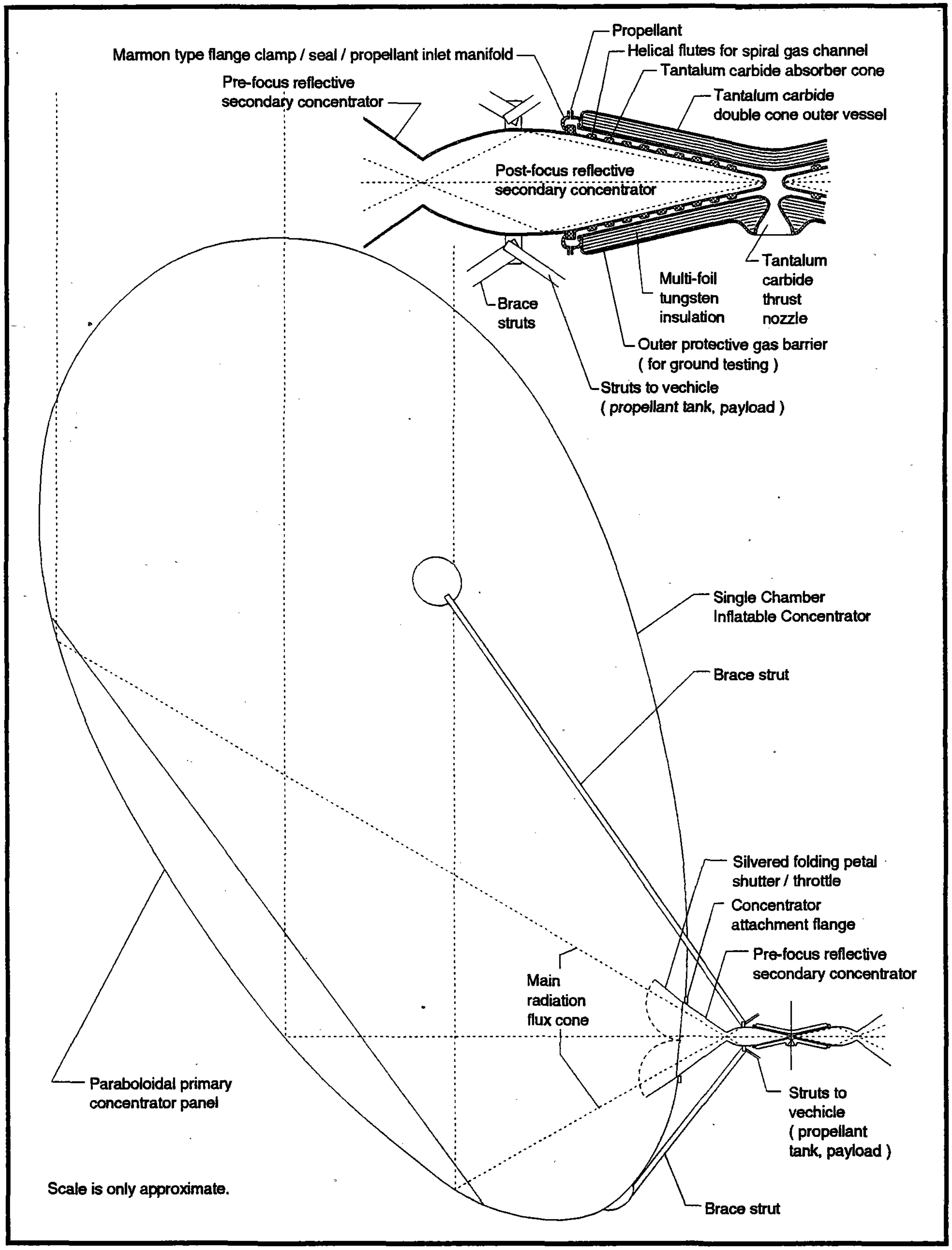


Figure 1
The Single Chamber Inflatable Concentrator

RESEARCH PERFORMED

The following section describes design studies that were performed during the Phase I effort.

Concentrator Concepts

The design of a large deployable concentrator must meet several requirements. Previous research efforts have been directed toward a torus supported concentrator. Alternative concentrator concepts including modified torus designs were investigated in Phase I studies. A single chamber concept design was also developed and eventually selected for further development. A secondary concentrator was also included in the single chamber design. A secondary concentrator is currently envisioned as necessary to achieve the high concentration ratios required for the solar thermal rocket.

Torus Supported Concentrator. The torus support concentrator design concept is shown in ***Figure 2***. The design consists of a transparent canopy, reflective membrane and elliptical support torus. Figure 2 is representative of only one design concept of a torus supported concentrator. Several derivatives of the torus supported concept are presented in the previous studies. The success of this design is dependent upon constructing a deployable support torus. The requirements of the support torus are that it must be planar and accept film tension and support structure loads of the solar rocket. If the support torus distorts, the distortions will propagate across the concentrator causing optical errors. The torus also must be packaged efficiently and follow the deployment paths of the concentrator, canopy and support structure.

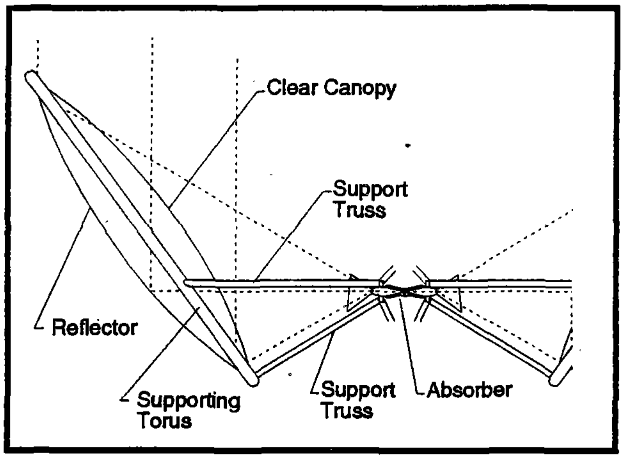


Figure 2.
Torus Supported Inflatable Concentrator

Several methods have been researched to fabricate the elliptical torus. The torus supported configuration involves very complex force-and-deflection relationships between torus and concentrator. These conditions are difficult to model analytically or refine empirically. The analysis becomes more complicated for the off-axis configuration than for a symmetrical concentrator. If a single inflation pressure is used, the torus must be very large to achieve force-balance with the concentrator. If a torus of reasonable size is used, a much higher inflation pressure is required than that used in the concentrator / canopy chamber. Deployment of the torus design concentrator can become a difficult task when fully integrating the support structure and concentrator. Specific deployment steps and paths are required for successful deployment of the concentrator system. It is also a difficult problem to design a technique for joining and transmitting the operating load distribution between the torus and the periphery of the concentrator. Improper joining can cause optically significant distortions that propagate over large regions of the concentrator.

The concerns about tori in general pertain largely to tori of constant diameter circular cross-section. An important class of toroid configurations is a revolution of non-circular cross-section. Consider the case represented by the following cross-section view, ***Figure 3***.

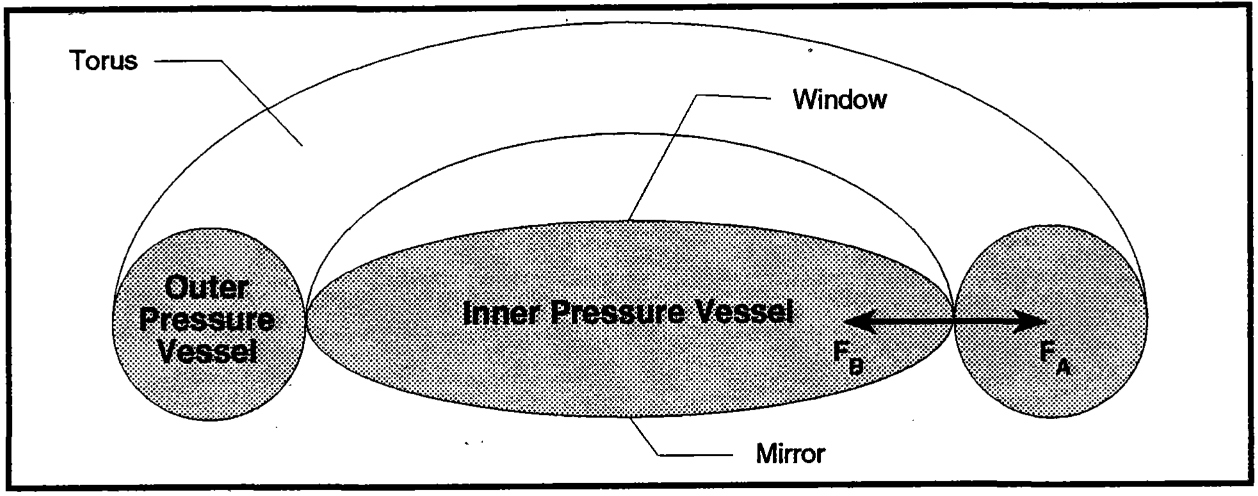


Figure 3.
Cross Section of Sling Transition Torus

An abrupt change of slope occurs where the window film and the mirror film come together at the periphery of the inner pressure vessel. Any such discontinuity of slope of the wall of a thin film pressurized vessel requires an external mechanical force, F_B, to maintain that discontinuity. When such a force must be supplied by the torus or outer pressure vessel, the latter vessel will experience a force, F_A, equal and opposite to the force F_B experienced by the periphery of the inner pressure vessel. Therefore, if the toroidal outer pressure vessel is of membrane wall design, it cannot exert force F_B (or experience force F_A) without distorting in cross-section shape such that a discontinuity in slope, or abrupt departure from circularity, occurs, as indicated in ***Figure 4***. Thus, any torus of initially circular cross-section and pressurized membrane design, when used in such an application, will distort significantly in shape and dimensions, (as compared to its unpressurized shape and dimensions) when the inner and outer pressure vessels are pressurized. A method to achieve accurate pressurized dimensions, for such an assembly, is to bias the unpressurized dimensions during fabrication, such that the distortions experienced in achieving force equilibrium during pressurization will exactly counterbalance that bias. This fact, and an analogous problem regarding a shift in major-axis-to-minor-axis ratio of an elliptical planform

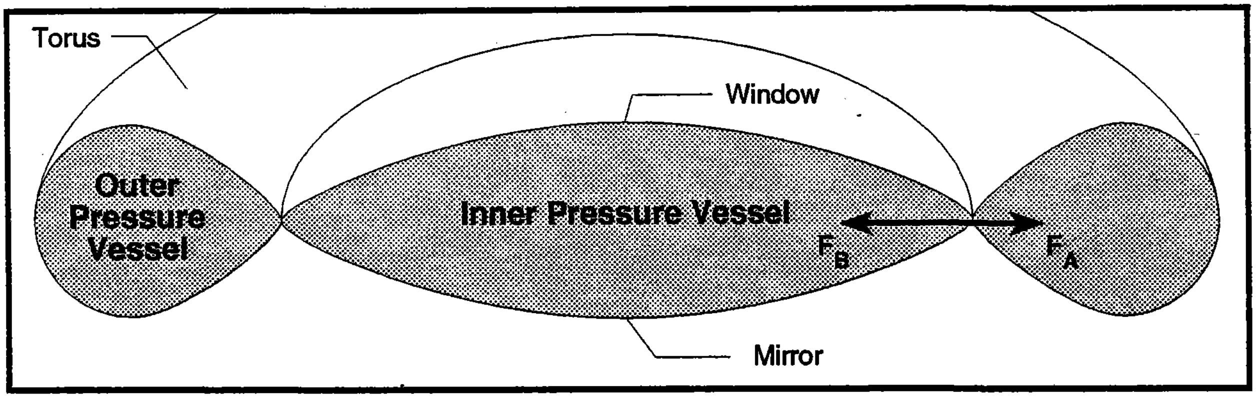


Figure 4.
Cross-Section of Non-Circular Torus

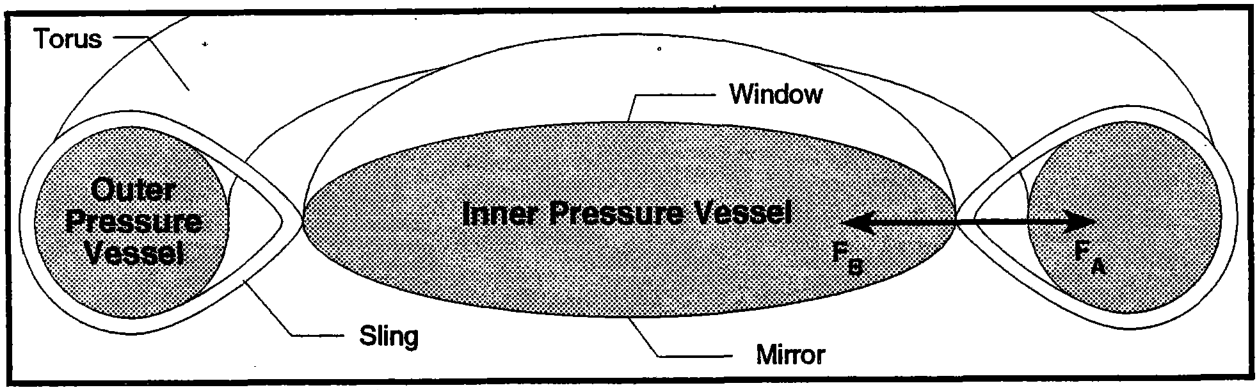


Figure 5.
Cross-Section of Sling Transition Torus

torus supporting an off axis paraboloidal concentrator, during achievement of force equilibrium accompanying pressurization, are major reasons for revising the traditional torus supported off axis concentrator concept.

The only way a circular cross-section torus can achieve force equilibrium with an inner pressure vessel of the general configuration of Figure 3 without significant distortion during pressurization is to use a sling transition piece, as indicated in ***Figure 5***, which is quite complex and does not address the planform distortion problem.

If, however, one designs a toroid with an initially non circular cross-section, it is theoretically possible to obtain force equilibrium, upon pressurization of the inner and outer pressure vessels, without experiencing any significant change in the cross-section shape or dimension of the toroid. The unpressurized cross-section of such a design should be approximately as indicated in ***Figure 6.***

If one can tolerate very large torus size (e.g., a torus major axis roughly three times the length of the concentrator paraboloid major axis) then with proper calculation of ratios among dimensions D_1, D_2, and T it should be possible to maintain the inner vessel and outer vessel at the same pressure, and utilize the same film / wall thickness for both vessels. This would allow a single pressurant control system to be used, and greatly decrease probability of damage / entanglement / malfunction during deployment unfolding from the stowage

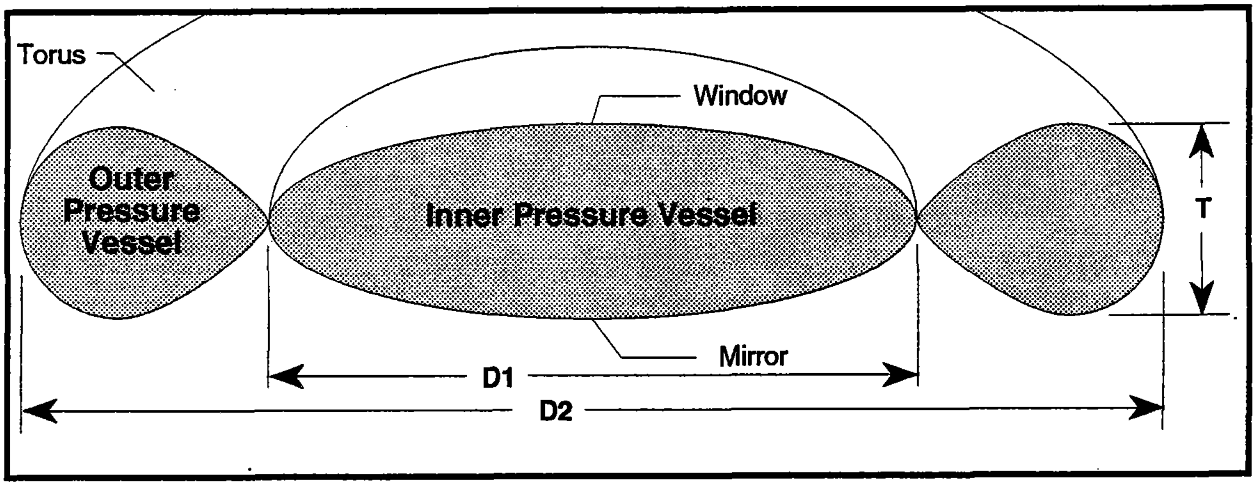


Figure 6.
Cross-Section of Large Non-Circular Torus

canister (as compared to the conventional relatively high pressure torus concept). This design would provide a system flexural moment of inertia (basic to optical accuracy) competitive with the "pillow-balloon" concept, but at similar cost in system bulkiness. If a bulky torus is unacceptable (e.g., from a plume impingement standpoint) the torus cross-section area may be reduced by a factor of N if the torus inflation pressure is increased by the same factor N, without changing the force balance between torus and inner pressure vessel.

Similarly, such a toroid when used to support an off axis paraboloidal concentrator need not, and should not, be of uniform cross-section circumferentially, but should have a planform somewhat as indicated in ***Figure 7***. Such a non-uniform cross-section will create in the toroid a pressure-dependent outward force circumferential distribution which will counterbalance, without significant deflection, the pressure-dependent inward force circumferential distribution of the elliptical planform inner vessel formed by the concentrator window and mirror films.

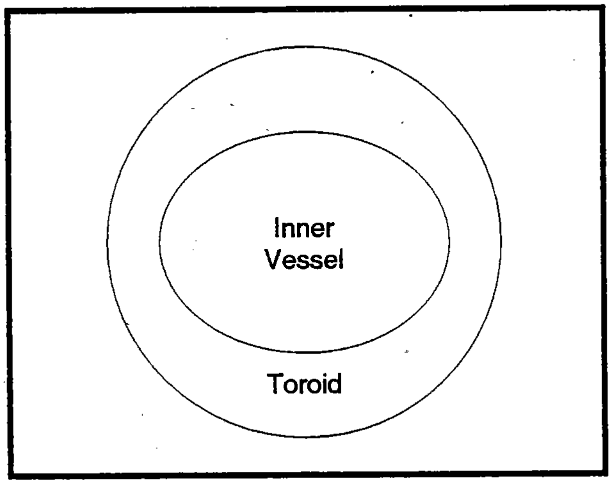
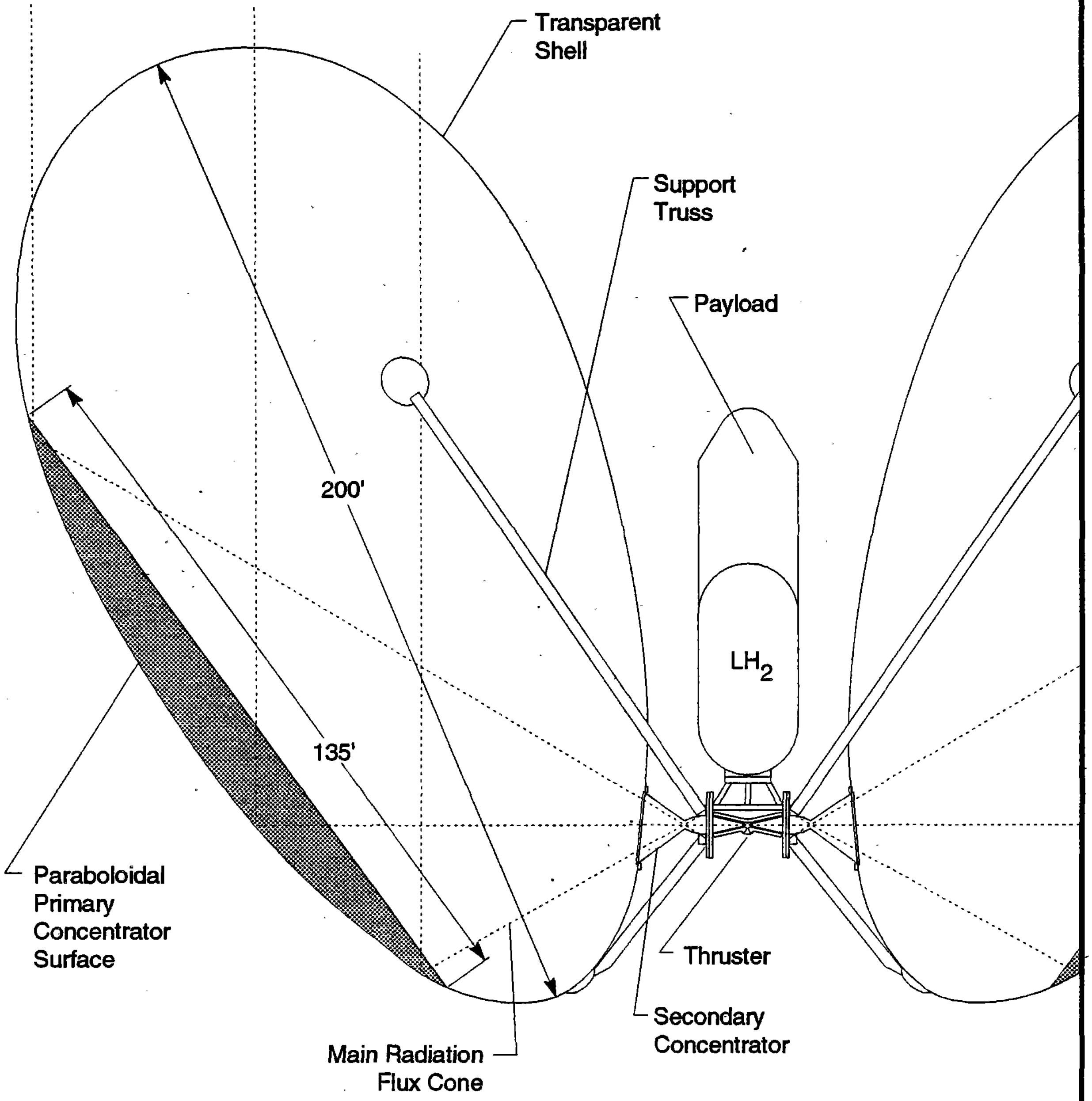


Figure 7.
Planform View of Toroid

Single Chamber Concentrator. Design problems with the outer torus support led to the investigation of an alternative concept that does not have a torus. The concept is shown in ***Figure 8***. In this design, the two-chamber concentrator plus support torus of the classical design is replaced with a single chamber configuration. An inflatable thin film off-axis paraboloidal concentrator of a single chamber design can provide high concentration ratios, ease of deployment and increased reliability. The bulbous shape of the concentrator also increases the rigidity / moment-of-inertia of the collector. The rigidity is required for good optical performance. The single chamber design allows for structural attachment to the solar propulsion vehicle similar to the torus supported design. The single chamber has a lower number of components, requires only a single inflation pressure and is more reliable to deploy than the torus supported design. The design concept is based on the fact that the skin stress distribution in a thin walled pressure vessel can be modified by appropriate geometric design. The single chamber design inherently involves a nearly-perpendicular incidence angle of incoming light striking the transparent canopy. This results in minimal Fresnel Law reflection losses from the canopy.

Preliminary models of the single chamber concentrator have been fabricated. The concentrator models deployed properly and conformed to the desired shape. Fabrication procedures for spray casting polyimide and reflective coating large area films have been demonstrated. These processes will be used to fabricate larger test articles of the single chamber concentrator design. The test articles will be used for further refinement and demonstration of the single chamber design.

Comparison of Single Chamber Design and Torus Model. The Phase I results of the single-chamber concentrator design as compared to the traditional torus supported concentrator design are summarized as follows:



- Payload to GEO – Approximately 20,000 pounds–mass
- Inert Vehicle Weight – 8,000 pounds
- Engine Thrust – 100 pounds–force
- Specific Impulse – 1,000 seconds
- Propellant Weight – 24,000 pounds

Figure 8.
Single Chamber Concentrator

- The single chamber design is simpler, and therefore easier to optimize the design, easier to fabricate and inspect, easier to fold for stowage, and more reliable to deploy.
- The torus-supported concentrator configuration involves very complex forces-and-deflections interplay between torus and concentrator, difficult to model analytically or refine empirically. The analysis becomes more complicated for the off-axis configuration than for a symmetrical concentrator. If a single inflation pressure is used, the torus must be very large to achieve force-balance with the concentrator. If a torus of reasonable size is used, a much higher inflation pressure is required than that used in the concentrator / canopy chamber. This fact requires complex coordination of two considerably different pressures during deployment and operation.
- It is a difficult problem to design a technique for joining and transmitting the operating load distribution between the torus and the periphery of the concentrator. Improper load distributions can cause optically significant distortions that propagate over large regions of the concentrator.
- The single chamber design inherently involves a high moment-of-inertia per mass, and therefore high rigidity, mandatory for good optical performance. The torus design inherently involves relatively low moment-of-inertia per mass, with resultant marginal rigidity leading to structural interference problems.
- The single chamber design inherently involves a nearly-perpendicular incidence angle of incoming light striking the canopy, resulting in minimal Fresnel Law reflection losses from the canopy. The torus-supported design typically involves a much more glancing incidence angle of the light entering the canopy. This results in significantly larger reflection losses due to transmission losses in the canopy.
- The single chamber design requires an ellipsoidal secondary concentrator to extend the focus to an acceptable distance outside of the concentrator vessel. However, such a secondary concentrator would be highly desirable for other reasons (improving system concentration ratio, reducing thruster absorber reradiation view angle, reducing system pointing accuracy requirements) even if not required for the focus extending function.

The structural support interfaces for the conventional concentrator design are located on the torus. The one piece concentrator design does not have a torus for the structural support attachment. Load distribution pads are used for the structural support interfaces on the one piece concentrator design.

The following statements can be made about the concentrator designs:

- Both concepts require three struts.
- Lengths of struts are practically identical, for both concepts.
- Load distribution pads will be slightly larger, for new concept, due to thinner wall and lower pressure.
- Load distribution pads will be of simpler shape, probably collapsible-teepee cones, for new concept, due to lesser curvature of interfacing concentrator surface.

Secondary Concentrators. The practical difficulty of simultaneously achieving the optical accuracy, weight, stowed volume, and autodeployment requirements is severe, for all the primary concentrator concepts considered. Neither weight nor concentration ratio can be compromised without destroying the performance of the solar rocket. A related element in the solar propulsion design is the use of a reflective secondary concentrator. A secondary concentrator can simultaneously increase the total system concentration ratio while reducing the primary concentrator requirements. A secondary concentrator can also reduce the thruster input energy drop-off caused by small pointing errors of the system and serve as a radiation shield. The radiation shield can protect the critical concentrator support structure main pivot and strut hub area from exposure to the concentrator focused output beam in the event of moderate-magnitude pointing errors.

In the case of the single chamber concentrator concept, the secondary concentrator also serves to extend the distance of the primary concentrator from the output focal plane. This is required for adequate clearance between the thruster plume and the bulbous front surface of the concentrator assembly. The secondary concentrator also serves as a key part of the main support structure linking the concentrator main pivot assembly of the solar rocket.

A point should be made regarding the design of a secondary concentrator for the solar rocket. The conditions for re-radiation of energy by the absorber become decisively important when the peak temperature of the absorber is critical, rather than merely incident energy flux. An appropriate parameter of the concentrator / absorber system is the concentration ratio divided by the re-radiation view angle. An example of the importance of this parameter is the fact that an improperly designed secondary concentrator may increase the system concentration ratio, but also may increase the incoming beam cone angle. The increase in beam angle will increase the absorber re-radiation view angle resulting in a drop in absorber temperature. This drop in temperature would reduce the performance of the solar rocket. A properly designed secondary concentrator can increase the performance of the total optics reducing the requirements of the primary concentrator.

Some design considerations for a secondary concentrator are presented in this report for future research studies for Solar Thermal Propulsion.

A flux beam with very high planar-disk-defined concentration ratio at the thruster entrance aperture will yield a lower propellant temperature than a flux beam of larger minimum diameter. A larger planar disk has a lower divergence angle and therefore has greater energy penetration into the absorber cavity where reradiation losses are smaller and the wall-to-fluid heat transfer temperature drop is smaller.

When a secondary concentrator is used with a primary concentrator of low focal ratio a simple reflective truncated paraboloid "light cone" secondary concentrator is quite inefficient. The light cone, shown in ***Figure 9***, reflects a large fraction of the intercepted aberrant rays back out of its entrance aperture. Optically, this concept is basically Cassegrainian with respect to the aberrant rays from the primary.

The most efficient optical design when the primary element is of low focal ratio is the Gregorian with a forward focusing truncated ellipsoid secondary as indicated in Figure 9. This configuration offers both a high efficiency and relatively small average divergence angle of the intercepted redirected rays. The small divergence angle makes possible a deep penetration of the flux beam into the thruster absorber cavity. This optical configuration also extends the distance between primary mirror and system focal point. The extension is a mandatory requirement for the single chamber primary concentrator concept. Such a Gregorian truncated ellipsoid

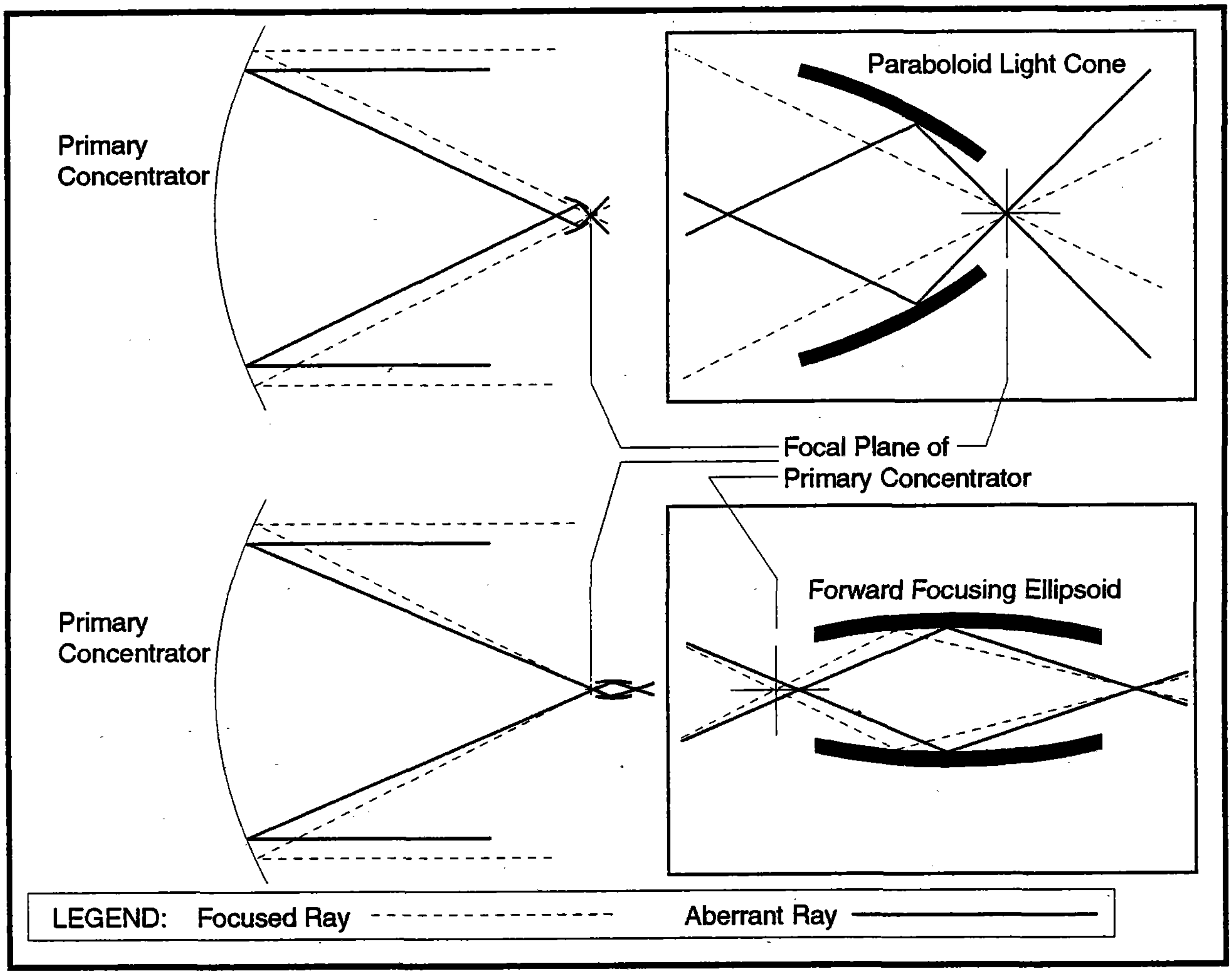


Figure 9.
Comparison of Paraboloid Light Cone and Forward Focusing Ellipsoid Secondary Concentrators used with a Low Focal Ratio Primary Concentrator

secondary has higher absorption and scatter losses than a Cassegrainian (Winstonian) truncated paraboloid secondary. Nearly 100% of the total beam flux is reflected at least once by an ellipsoid secondary. However, in a Cassegrainian (Winstonian) truncated paraboloid secondary at least 67% of the total beam flux is reflected at least once by the secondary.

The term "non-imaging concentrator" should perhaps be clarified. For any one ray path through the system, classical imaging optics principles apply. The component geometries used (truncated paraboloid or ellipsoid) are those of imaging optics. However, the various bundles of aberrant rays from the primary which are refocused by the annular secondary form an array of images which are superimposed in a random pattern on the image formed by the non-aberrant rays from the primary. This results in a composite image that is unrecognizable in the classical optical sense, hence the term "non-imaging". In some cases, the outer region of the non-aberrant-ray image may be larger in diameter than, and consequently refocused by, the rear section of the annular secondary element, further adding to the complexity of the composite image.

An approach to ray trace analysis of the single chamber concentrator was developed. The representative configuration is shown in ***Figure 10.***

The lay out configuration can be used for optimizing the design of the secondary concentrator.

Thirty-two (32) representative points on its surface will be identified as indicated in Figure 10. For each of these 32 points, the plane defined by that point, the central point "CO", and the focal point of the concentrator, can be layed out, to scale. For each candidate optical configuration of the secondary concentrator, a paper ray trace can be made. The ray trace should be made from the sun center, to primary concentrator, to secondary concentrator, to the thruster absorber wall. Rays corresponding to primary concentrator surface slope errors of 0, -7, and +7 milliradians should be traced. This configuration is shown in ***Figure 11***. For the candidate configuration(s)

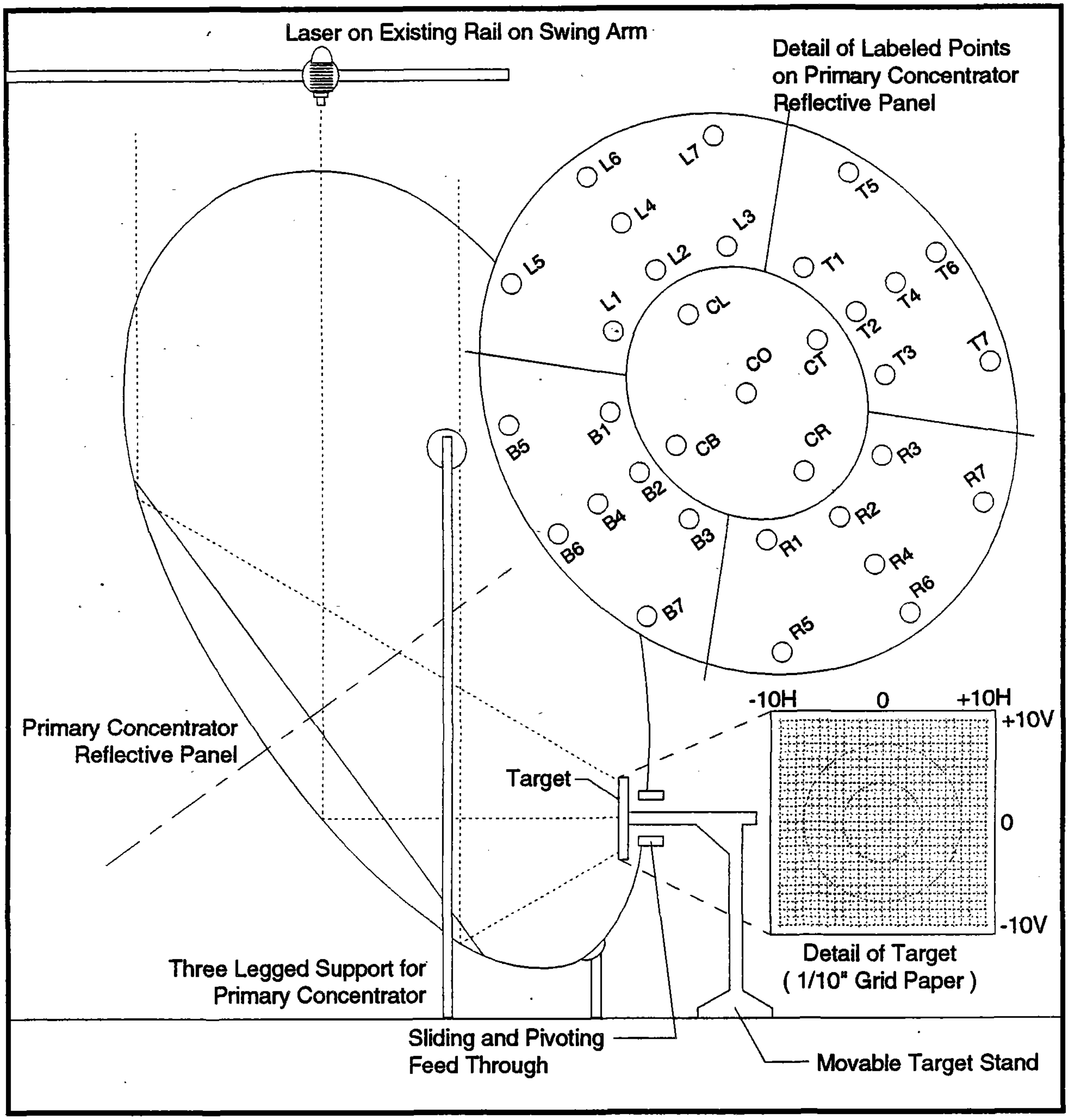


Figure 10.
Arrangement to Characterize the Focal Point Image of the Primary Concentrator

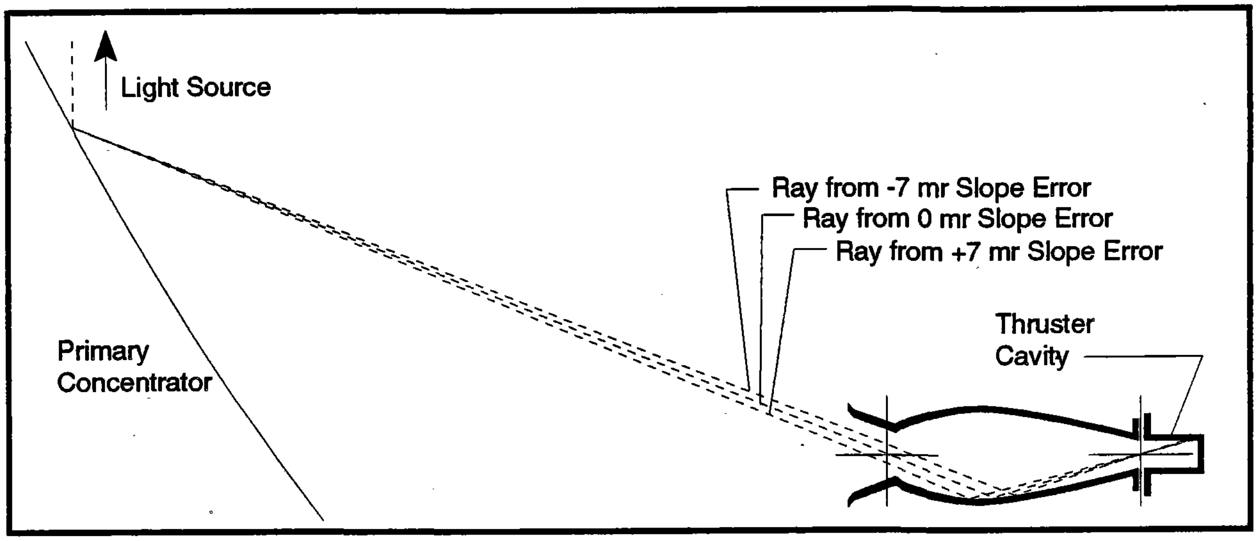


Figure 11.
Tracing Slope Errors

which appear most promising in this analysis, geometrical concentration ratio will be determined. The concentration ratio should be calculated and defined by the thruster absorber entrance aperture disk. The incident flux (number of rays impacting) per area of cylindrical absorber inner wall (divided by seradian view angle of the relevant area of absorber wall) should be plotted as a function of distance into the absorber cavity, from the entrance aperture. This procedure can aid in identifying the optimum geometry for the secondary concentrator.

Fabrication Methods for Single Chamber Concentrators

Methods to fabricate the single chamber concentrator were investigated during the Phase I effort. The selection of the proper film materials is critical for the fabrication, deployment, and performance of the Solar Thermal Propulsion vehicle. An experimental model was fabricated to demonstrate the feasibility of the single chamber design. The following section describes the work performed during Phase I related to fabrication methods.

Materials Selection. Materials selection is a key factor in development of a thin film solar concentrator. The materials selection includes the polyimide selected for the concentrator, materials used for mandrel fabrication, reflective coatings, and protective coatings for the space environment. As to the basic film material, the following factors are critical:

Mechanical properties
- Tensile strength
- Notch toughness or tear strength
- Resistance to creasing and folding stress
- Strain multipliers
- Low temperature creep during prolonged compacted stowage
- CTE
- Density

Optical properties
- Spectral absorption / transmission
- Refractive index
- Surface specularity as substrate for reflective coatings

Space environment endurance
- UV, atomic oxygen
- Temperature range
- Vacuum
- Micrometeoroid abrasion
- Puncture response

Manufacturability

- Spray casting
- Atmosphere, humidity, temperature
- Adhesive bondage
- Accept Metallization

Polyimides that have been developed by NASA Langley Research Center (LaRC) are presently the leading candidates for this film. A film spray cast in 2 layers may be optimum. One layer would have a high yield strength to resist creep and one layer of high ductility to resist tear propagation. Ms. Anne St. Clair of LaRC expects, on the basis of evidence to date, to develop a further improved high transparency insoluble polyimide optimum for this application, during the early months of a Phase II effort.

The reflective coating for the film is also critical. At present the leading candidate is electroless spray silvering, which has been demonstrated by SRS to give highly reflective uniform coatings on polyimide films, with acceptable adhesion and compatibility with silicone protective overlayers. This method does not require the very large equipment investment required for metallization of equally large-in-2-dimensions articles. This process has been developed and demonstrated by SRS in the silvering of the large films for the Solar Laboratory thin film heliostat. The development has been a major milestone in establishing the feasibility of large thin film solar concentrators. The reflective silver coating is applied by the wet chemical process. The process does not require a large vacuum chamber that is typically required for silver sputtering and vacuum metallization. Optimization of process parameters for maximum adhesion, operated reflectivity, uniformity, freedom from defects, and compatibility with protective overlayers, calls for continued development effort.

The protective overlayer for the reflective coating is also a critical factor. Silver requires protection from tarnishing agents, in the atmosphere, and from atomic oxygen (AO) in space. The protective overlayer must be adherent, non-tarnishing, able to endure and screen out reliably the factors harmful to the silver. It must also be compatible with folding / stowage / deployment of the concentrator, and compatible with suitable deposition processes such as spraying. Silicone coatings were used with limited success in the Phase I effort and heliostat effort. The silicone coatings are the leading candidates for further evaluation in Phase II. The AO Shuttle experiment in which SRS has been invited by Aerospace Corporation to participate will provide an excellent synergistic means to supplement and verify the optimum materials. The shuttle experiment will expose selected materials to a 12 hour LEO space environment. This experiment will result in film materials that have been exposed to space before the scheduled solar rocket flight test article.

Materials selection is also critical to the concentrator film fabrication technology. Machineable, lightweight, and dimensionally stable pattern masters are required, for which rigid polyurethane foam is a prime candidate. Typically, due to high film processing temperature requirements, these masters are not directly usable as film-casting mandrels or configuring substrates. The mandrels serve to configure laid-up fiberglass / silicate (or Kevlar / phenolic for better CTE match to film) shell-type film-casting mandrels. These mandrels must be coated with silicone, to achieve the required surface smoothness. In some cases the silicone must, in turn, be coated with a solid-state wetting agent such as colloidal fumed silica (Cab-o-sil) to achieve the required film precursor solution wetting properties. In some cases water activated or passive release agents to facilitate film release from the casting mandrel or substrate may be required.

Significant development work in all the above listed areas is an important part of thin film concentrator technology advancement. Preliminary development of the items has been done in the Phase I effort.

Mandrel Studies for Single Chamber Concentrators. It was decided that, in the interest of minimizing process complexity and unknowns, the initial model should be made as two identical half-vessels, on a fixed (non-inflatable) mandrel, then joined together at a single central-plane seam. The central-plane seam is placed well away from the optical areas. It was initially planned to rough-cut a styrofoam pattern-master (from a 2' x 4' x 8' block) and then coat it with Bondo car-repair putty, for smoothing and polishing. However, the Bondo polyester resin attacked and sank into the styrofoam. It was then found that covering the styrofoam pattern with plastic cling-wrap (to smooth the rough surface and prevent binder soak in), then laying up bias-cut corner-pulled fiberglass cloth impregnated with a suitable binder, produced a satisfactory shelf-type mandrel able to withstand high film processing temperatures. As binder for the fiberglass, sodium and potassium silicate solutions were tried (epoxies typically soften at film processing temperatures, silicones are too flexible, and polyimides are expensive in the quantities required for mandrel fabrication). As previous observations had indicated, the sodium silicate weakened the fiberglass greatly and foamed during elevated temperature drying, while the potassium silicate performed satisfactorily. Two layers of fiberglass cloth, soaked with 20% potassium silicate solution and dried, formed a reasonably stiff, strong, and non-brittle composite material. When dried at room temperature, the silicate could be re-dissolved by soaking in water, but after baking 30 minutes at 160°C the potassium silicate and fiberglass interacted such that the binder became insoluble, and the composite material displayed no softening during prolonged immersion in water. This insolubilized silicate / fiberglass composite appeared to be dimensionally stable up to the softening temperature of the fiberglass.

A small silicate / fiberglass shell mandrel made in the above-described manner was coated with talc / potassium silicate putty, baked, then smoothed with a file. (Talc / silicate putty, like fiberglass / silicate, becomes water-insoluble when baked at 160°C.) One third of this mandrel was coated with two layers of heat-curable polyimide solution, one third was coated with several layers of potassium silicate solution, and the other third was coated with one layer of RTV615 silicone. Both the polyimide solution and the silicate solution displayed a smooth surface when wet, but upon drying, the underlying surface imperfections (e.g., file-marks in the talc putty) transferred through to the coating surface, due to the drying-shrinkage of the coating. The silicone, because of lack of drying shrinkage, retained its specular surface after hardening. A film of 6FDA+4BDAF polyimide was cast on the silicone surface. Wetting and pre-release adhesions were acceptable, though poorer than on glass; no pre-release of the film was observed, the film released easily when desired and the film surfaces were reasonably specular. The only significant concerns noted were a slight micro-waviness noted in the surface of the film and barely visible in the surface of the silicone, and a cloudiness or translucency in very thick regions of the film.

An initial study, supporting previous observations and previous advice from the manufacturer regarding RTV 60 silicone, indicated that reducing the percent of hardness in the silicone mix eliminated the surface micro-ripples. However, subsequent studies were unable to reproduce the surface ripples, although resin / hardener ratios ranging from 100/4 to 100/100 were tried, and hardening at room temperature, hardening by prompt baking at 100°C, and hardening by delayed 100°C baking, were tried. It appeared that maximum as-cured hardness and non-tacky feel of surface, was obtained with 100/15 resin / hardener ratio, and with curing at 100°C. It was found that casting of polyimide films on the surface of an RTV 615 layer left visible marks or scars on the surface of the silicone, after polyimide film removal, if the silicone was not fully cured. When judging curing by this criterion, a more narrow range of resin / hardener ratios was required than when judging curing merely by mechanical "feel"; also, when judged by this criterion, elevated-temperature curing allowed a much wider range of resin / hardener ratios to be used than was possible with room temperatures curing.

To combat the cloudiness of thick films of soluble polyimide cast on the surface of the RTV 615, prolonged high temperature baking of the silicone, working of the silicone surface with diglyme, a wide range of silicone resin / hardener ratios, and prompt high temperature drying of the polyimide, were tried, with no perceptible effect on the clouding. The only procedure that seemed to reduce the clouding significantly was to apply the polyimide in multiple thin coats, drying between coats (this would be done anyway in spray-casting, the prime candidate procedure for this project). Leaking of contaminants from the silicone, humidity effect, and pre-release of thick sections of film, seem ruled out by the aforementioned observations, as possible explanations for the clouding observed; so the mechanism of the effect remains undetermined, at present. Since the clouding effect seemed to appear sharply at film thicknesses of about 0.7 mil and was not apparent at all in thinner films, it is not considered a major problem at present. A significant consideration in the above-described studies was that nothing was tried that was not considered potentially extendable to the scale of the Phase II deliverable models.

The construction of the single concentrator concept was started by shaping a large styrofoam block. The optical surface of the model uses a machined off-axis aluminum mandrel. The mandrel was fitted to the block at the correct intersection angle and shaping was done to minimize the discontinuities. ***Figure 12*** depicts the model in its present shape. Following the refinement of the surface, fiberglass was draped over the mandrel and coated with potassium silicate. The silicate was allowed to dry and the fiberglass was removed from the styrofoam mandrel and baked in the curing oven. The model was then coated with RTV 615 silicone.

The styrofoam pattern-master was completed, and covered with Saran Wrap® to prevent adhesion and soak-in of subsequent coating material. Cardboard templates were laid out and cut, to guide the curvature of the master. The 1 meter machined aluminum off-axis paraboloid which was bonded to the styrofoam served as basis for the curvature of the latter; radial lines 22.5° apart were drawn outward from the maximum height point of the paraboloid, and radial and circumferential radii of curvature were measured (by 3-point micrometry) at the outer limits of these lines. The templates for the styrofoam were cut to one half the average of the radial and circumferential radius of curvature of the aluminum paraboloid at the outer points of these lines, and set tangent to these lines in their outer points. The rationale was that the tensile stress in the model film would transition from biaxial to uniaxial at the periphery of the paraboloidal section; this key assumption remains to be verified experimentally. Two layers of fiberglass cloth were laid up over the styrofoam (and aluminum) master, and impregnated with potassium silicate solution, then dried at room temperature. This produced rather poor replication of the shape of the pattern-master, because of Saran Wrap wrinkles and poor adhesion between fiberglass /

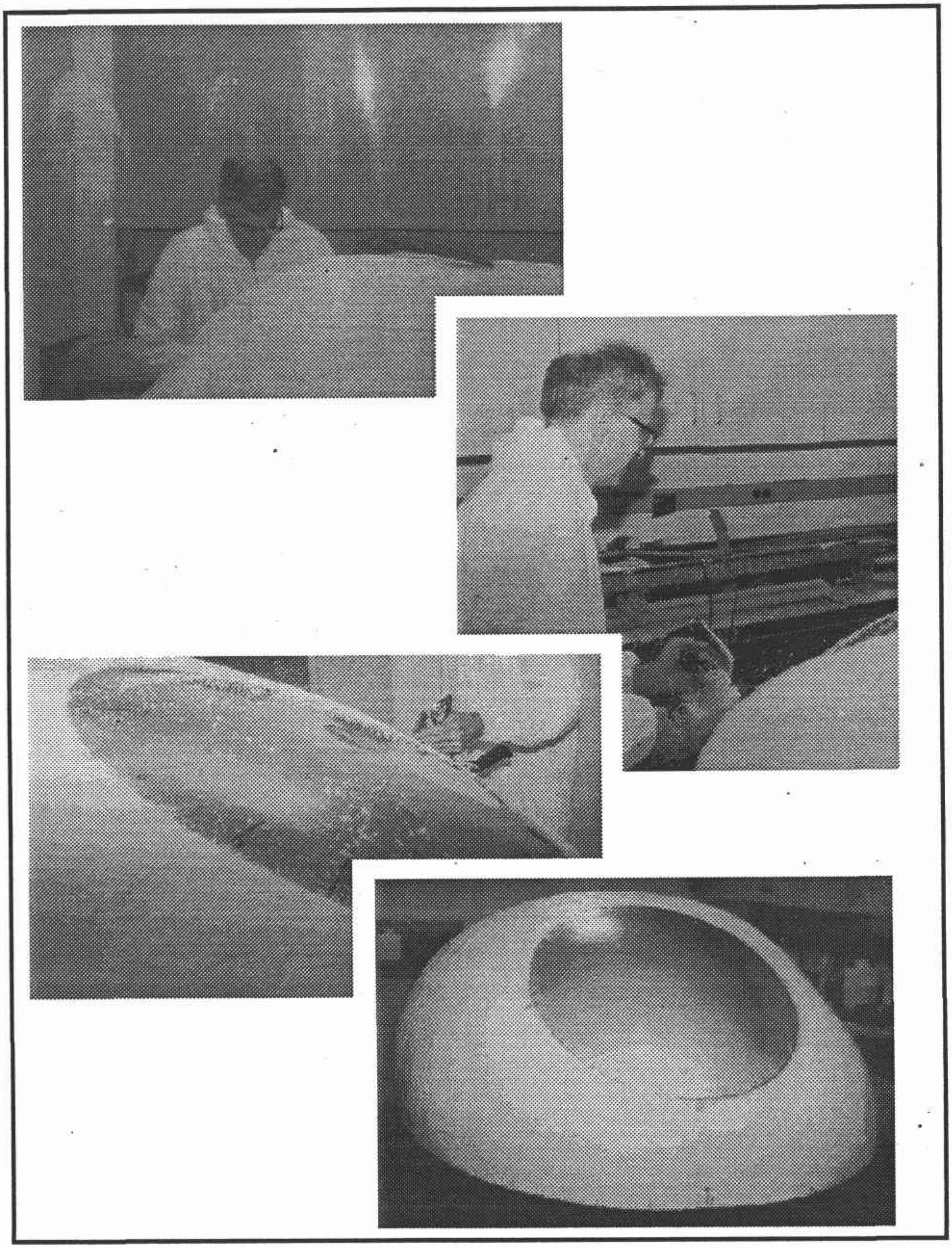


Figure 12.
Single Chamber Mandrel

silicate and wrap. The fiberglass shell (or transfer-mandrel) was then removed from the pattern-master, and Saran Wrap was cut away from the aluminum paraboloid, and the latter was sprayed with polyurethane lacquer (to prevent corrosion by the silicate solution). The fiberglass shell was then re-positioned over the pattern-master, and additional silicate solution added to re-soften it, and it was "slicked down" to conform to the aluminum paraboloid (as this region would configure the concentrator portion of the ultimate film model). This time, adhesion to the lacquered aluminum controlled the shape of the fiberglass / silicate during drying, and an acceptably smooth and accurate replication of the aluminum paraboloid shape was obtained in the fiberglass / silicate. Talc was added to the final additions of silicate solution in this region, and the surface was sandpapered when dry, resulting in considerably improved surface smoothness. The fiberglass / silicate mandrel shell was then removed from the pattern-master, and baked to 500°F to insolubilize the silicate and to determine its durability as a mandrel for casting of heat-cured films. No problems were noted. Then the shell was coated, with a paint-brush, with RTV615 silicone, to provide an optically smooth surface for film casting. The silicone was filled with Cabosil fumed colloidal silica to retard flow off of the silicone during the long hardening time of the latter.

It was intended to rub the silicone surface with Cabosil powder before film-casting. This was found to greatly increase the wettability of the silicone surface without significantly impairing the specularity of film cast on the surface. Silicone normally is wetted only by high-viscosity polyimides but de-wets when coated with low-viscosity solutions of the same materials. Various liquid surfacants were added to the solutions and to the surface but were found ineffective in improving wettability. This ability of Cabosil to make silicone surfaces highly wettable may allow spin-casting of very large diameter flat films without requiring the troublesome joints between glass segment plates as presently done for the heliostat; however, this effect was discovered too late in the concurrent heliostat program to allow development of a process based on it for the heliostat.

As film forming polyimides solution was in short supply and it was desired to keep the full film solution making facilities of LaRC employed with making the relatively large amounts of film solutions required for the heliostat fabrication, it was decided to use reprocessed 6FDA+APB film reclaimed from a failed heliostat film casting, for casting the concentrator model. The film fragments did not dissolve smoothly in DMAC solvent but remained gel like after several days of soaking. Mincing with a blender liquified the gel, but it still had a very low vicosity. Boiling in DMAC produced an acceptable vicosity, but the films cast from the resulting solution appeared relatively weak and brittle. Prolonged boiling was unable to raise the solution boiling point above 100°C (DMAC boils at 162°C) so it was concluded that a large amount of water vapor had been absorbed while the reclaimed film was soaking in the DMAC. Once water is absorbed into the polyimide solution there does not appear to be a convenient non-harmful way to remove it; indicating the imperativeness of working with hygroscopic polyimide solutions only in a room with less the 50% relative humidity.

The silicone mandrel was painted with the above described reclaimed polyimide solution, using a paint-brush. Upon drying, the resulting film was found to be unusually weak and brittle, and very non-uniform in thickness. High drying shrinkage caused thick sections of it to buckle the fiberglass / silicate mandrel inward, with the film pulling loose and spanning the resulting "valleys". Large regions of the film were very difficult to remove from the mandrel, indicating defects in the silicone coating.

The mandrel was then sprayed with heptane thinned silicone, in an effort to improve the silicone surface coating uniformity. It was decided to use sprayed acrylic resin for the next model casting attempt. This resin is very transparent and colorless, reasonably strong, more tear resistant than polyimides and readily available. Acrylic films typically are considered relatively weak or brittle, but this material appears to be plasticized sufficiently as to be rather tough. It tentatively appears that its strength properties can be controlled by the baking schedule, with hotter baking removing more of the plasticizer and resulting in a higher yield strength but more brittle film (thin acrylic film is intended to serve merely as a way station in concentrator model development, as a plasticized acrylic would embrittle in a space environment and would have poor atomic oxygen endurance, presumably). Unsuccessful casting attempts were made with the acrylic film. A proof-of-concept model was built using strips of clear acrylic. The reflective portion of the mandrel was spray cast with polyimide, reflective coated and attached to the clear acrylic section of the mandrel. The evaluation of the feasibility model is discussed later.

Robotic Spray Casting. Preliminary design work was done to identify the equipment and processes for spray casting polyimides. The size of the mandrel for concentrator manufacturing requires that the deposition of the polymer solution be accomplished by automatic or semi-automatic spray casting. Spray casting has been demonstrated to work well on large mandrels that have a large radius of curvature. The spray technique requires very close tolerance control, such that the quantity of material shall be consistently uniform in thickness over the entire mandrel area. Spraying considerations include flow control of the material, optimum viscosity of the solution, velocity of the spray head across the mandrel, spray pattern from the spray head, amount of material overlap at each pass of the head, and that the direction of the spray is normal to the parabolic surface throughout the entire spraying operation. Studies have been performed to determine the optimum spray pattern to control the amount of material deposited, and the type of spray head best suitable for this operation. Several types of spraying systems have been evaluated in other related work. High-volume low pressure (HVLP) spray guns have been used with success. The HVLP gun reduces emissions and increases the transfer efficiency to the work piece. The increased transfer efficiency can improve the finish of the sprayed polyimide film. Air-assisted airless spray guns have also demonstrated improved operation as compared to conventional spray guns. This information will be used in the Phase II program to identify the leading candidate for spraying the thin film polyimides.

An initial literature search for off-the-shelf type track systems has been made, and will be explored in Phase II to provide an adequate and economical spray head positioning system for controlling the X, Y and Z axes along the mandrel. In addition to the Z axis, a controlled mechanism requires that the spray head be tilted from 0° to approximately 45° in both X and Y axis for spraying normal to the mandrel surface during each pass of the spray head. The entire system as mentioned earlier is to be either fully-automatic or semi-automatic and to be controlled by computer software.

In parallel to the literature search, studies were done to develop an in-house positioning system design, since the costs of a vendor-supplied turnkey positioning system may be prohibitive. This preliminary design is shown in ***Figure 13***.

The in-house design considered the use of aluminum I-beam tracks and off-the-shelf trollies that are specifically designed for standard I-beam configurations. The tracks will position the spray head in X and Y of predetermined intervals. Lowering and raising of the spray head in Z axis will be controlled by a linear actuator with stepper-motor drive. The X and Y spray head tilt mechanism (positioner of the spray head normal to the surface) might be a vendor-provided item, but if not unique to our requirements, must be designed in-house. Again, the positioning can be accomplished by two-axis stepper motor drives. The Z-axis linear actuator could be an in-house design and does not appear to be a design problem, rather, a simplified actuator mechanism. Various supplier sources relating to stepper-motor drives, trolly drive mechanisms and other structural hardware have been obtained to continue the in-house design in Phase II work if needed.

Phase I
Feasibility Model

A feasibility model was constructed to verify the concept of the single chamber design. ***Figure 14*** depicts deployment of the concentrator from a small can. Regarding configuration design, observations from the testing of the first completed iteration of the Phase I single chamber model are relevant to the fabrication procedures for the collector:

- The geometry designed for this torus-equivalent region on purely theoretical grounds gave the required off-axis paraboloidal shape to the concentrator region, accurate to the degree measurable by crude mechanical means,

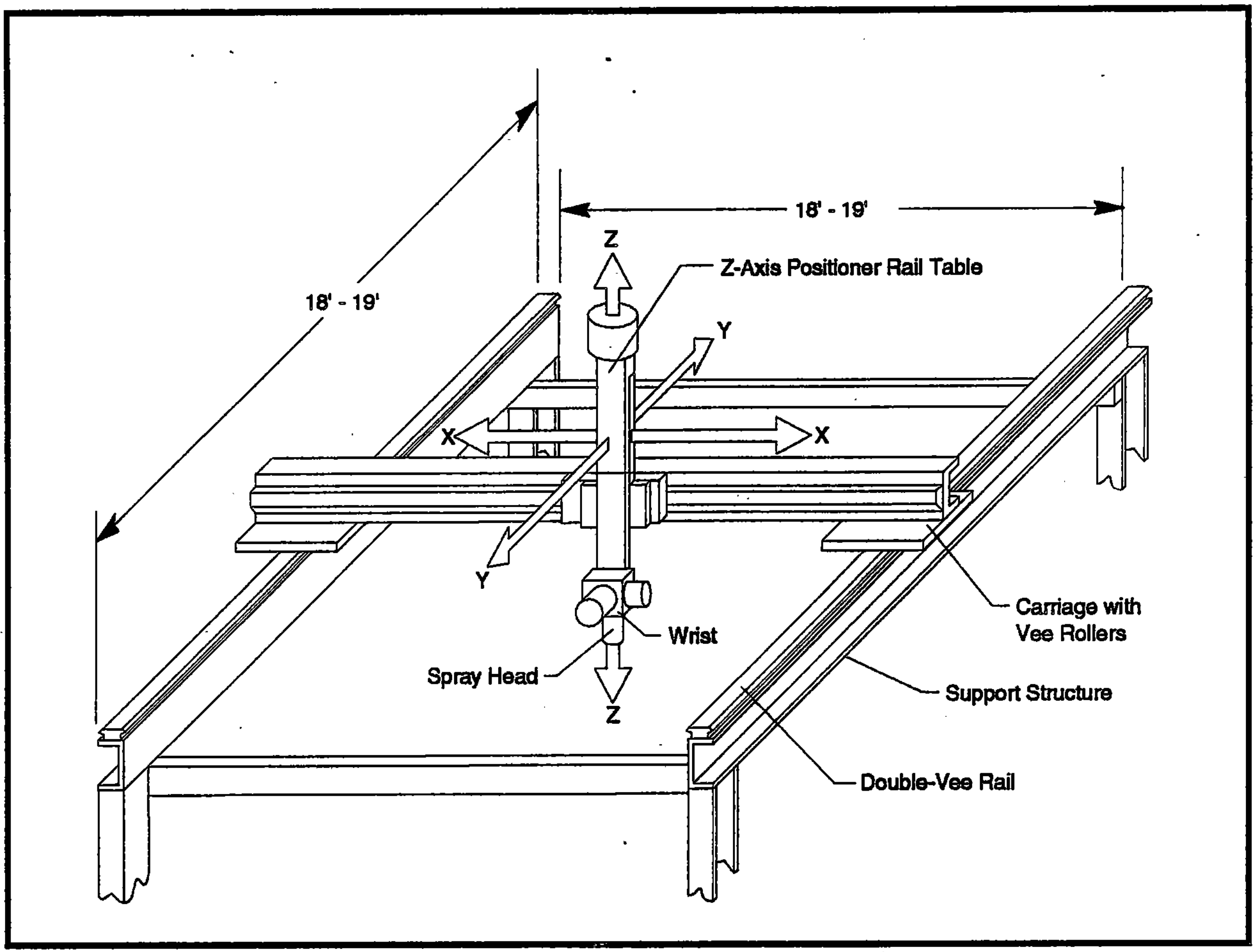


Figure 13.
Optional Automated Spray System

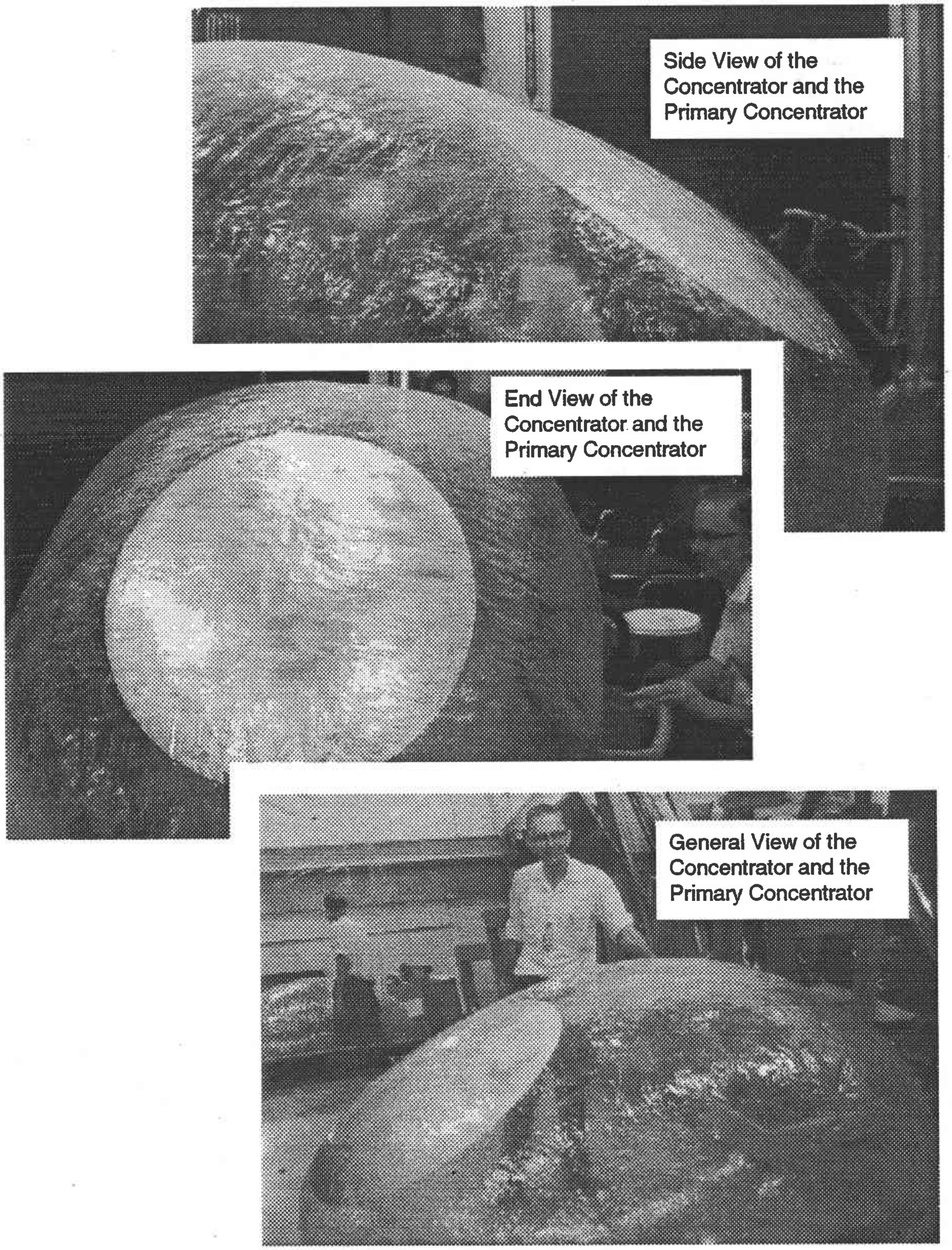


Figure 14.
Several Views of the Model after Inflation has been Completed

without requiring the expected trial-and-error fine-tuning of the torus equivalent geometry.

- The model inflation deployed easily without manual help, after being pulled manually in the collapsed compacted state from a five gallon plastic bucket.
- It had been expected that some regions of negative circumferential stress, evident as wrinkles, would occur around the midplane seam; but only one or two marginally identifiable wrinkles, at the rear (concentrator) end of the midplane seam, were seen. This suggests that much of the design was overly conservative, and that the size of the balloon's forward end of the torus equivalent region could be reduced (by a yet undetermined amount) without impairing the support of the concentrator region.
- The above listed observations appeared to be relatively independent of changes in inflation pressure.

The initial starting point for the Phase I single chamber inflatable concentrator model design was based on the concept of maintaining biaxial film stress over all the paraboloidal reflective region of the assembly and dropping to uniaxial film stress in the regions lying outside the periphery of the reflective region. The result is a 2:1 drop in average radius of curvature of the film as one moves outward from the reflective region into the supporting (torus equivalent) region of the assembly. For the single chamber concentrator design, it is assumed that only the reflective area must be seamless and goreless. The canopy and supporting structure are exempt from this requirement; as would be the case for the classical torus based design, even though, for the single chamber design, they are part of the same pressure vessel.

Ground testing can include packaging and deployment verification and operational testing. The deployment of the design consists of a single inflation pressure applied in the chamber. Optimization of the shape of the single chamber will be done to reduce the total size of the chamber. The shape refinement will be done iteratively by re-shaping the casting mandrel. Eventually analytical techniques will be incorporated to improve the prediction of the optimum single chamber shapes.

PHASE II PLANS

The Phase II technical approach consists of the development of the technology necessary for large lightweight autodeployable accurate thin film concentrators. This technology will be demonstrated by fabrication and testing of a large-scale prototype model of a flight test article in a Phase II effort. This will be accomplished by the completion of the six tasks shown in ***Figure 15***.

In Task 1, materials selection and evaluation will be done to determine what materials for fabrication of the concentrator are optimum. These materials include the polyimide thin film, reflective coating, and protective coating materials. The task also includes materials used for fabrication of the casting mandrel. The mandrel material must be compatible with the processes used in the casting / curing of the thin film concentrator. Efforts in Task 2 — Fabrication Technology will determine the methods used to construct the concentrator models. Results from Phase I studies and the recent heliostat contract will be used to develop the construction methods. Robotic spray casting will be refined under Task 2. Also, low cost mandrel fabrication techniques will be developed. A preliminary model will be fabricated in Task 3. The model will incorporate the results for the first two tasks. The purpose of Task 3 is to demonstrate the techniques that will be used to fabricate the larger scale model in Task 4. Fabrication design refinement is also expected to take place in the Task 3 work. A large scale concentrator test article will be constructed in the SRS facility in Task 4. The results of the previous tasks will be used to construct the large casting mandrel, identify the materials, and construct the casting tooling. The concentrator's performance will be

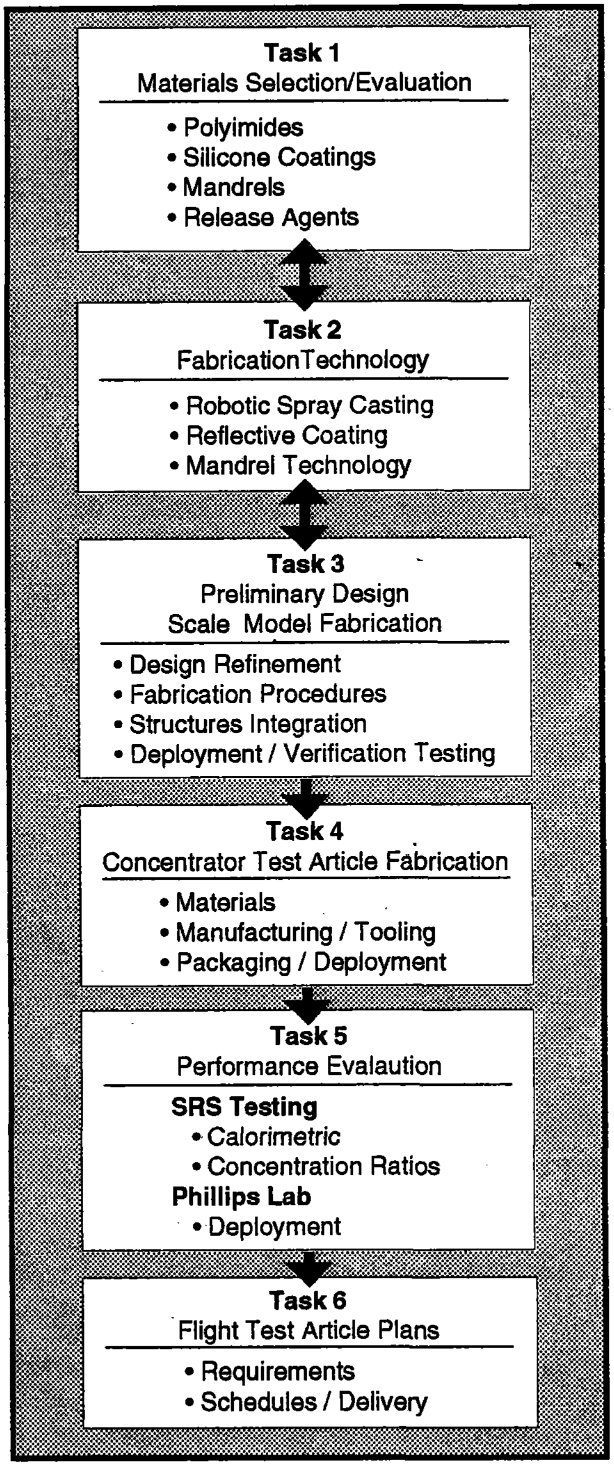


Figure 15.
Phase II Concentrator Technologies Tasks

evaluated in Task 5. Testing will include deployment testing, concentration ratio determination and calorimetric testing. The results of the research will identify the methods, materials and facilities required to manufacture a flight test article in Phase III work.

The overall technical objectives of Phase II are to refine the technology for large, lightweight, autodeployable thin film seamless, goreless, off-axis paraboloidal solar concentrators of 10,000:1 concentration ratio. SRS will demonstrate this technology by fabrication and testing of a large scale prototype model of a flight test article. Results achieved in Phase I and related work indicate a high probability of success in Phase II. Potential commercial application of this technology is attested by the interest of large aerospace companies in this technology for placement of commercial satellites into orbit.

The objectives of Phase II are as follows:

a. Refine the materials, fabrication processes, and configuration design of a goreless thin film concentrator to the level required for a large prototype model of a test article. The test article should meet the performance and space environment endurance requirements.

b. Prove these technology elements by fabrication and testing of a subscale model incorporating all of the procedures.

c. Design, prepare tooling and fabrication process flow procedures and fabricate, a large-scale prototype model of a flight test article.

d. Perform ground testing and evaluation of this prototype model. Evaluation can include dimensional and ray-trace defined optical accuracy, geometrical and overall concentration ratio. This evaluation will be defined in the context of a solar thermal rocket absorber of representative design, and auto deployment reliability. Deliver this model to Solar Lab for continued ground testing and demonstration.

e. Lay out specific plans for fabrication and delivery of GAS canister packaged flight test articles in Phase III.

CONCLUSIONS AND POTENTIAL APPLICATIONS OF RESULTS

Continued research of this Phase I work will further define the design of the solar concentrator and membrane support elements of the solar rocket. The advanced design of the single chamber concentrator has potential to reduce the complexity and weight of the solar rocket by combining the primary support structure, torus and inflatable membrane into a one piece unit. Preliminary models of the single chamber concentrator have been fabricated. The concentrator models deployed properly and conformed to the desire shape. Fabrication procedures for spray casting polyimide and reflective coating large area films have been demonstrated. These processes will be used to fabricate larger test articles of the single chamber concentrator design. The test articles will be used for further refinement and demonstration of the single chamber design. The advantages of spray casting thin film polyimide membranes as a one piece unit without a torus eliminates the problems previously encountered with joining the membrane to the torus. This improves the success potential for developing and fabricating solar concentrators for the near term flight article test, and eventually, the orbital transfer vehicle.

The results of continued research can also provide manufacturing methods for fabrication of the flight test article planned by the Air Force. This research will complement planned research in other areas of the solar thermal propulsion concept. These areas include secondary optics, support structure development, and the solar rocket absorber and thrust chamber.

Lightweight, large polyimide reflectors have many current and future space-related applications. Solar thermal propulsion, solar dynamic systems, lunar soil processing and large RF and microwave antennas are typical applications that would benefit from the effort. These applications are part of the Air Force, DOE, SDIO, and NASA planned efforts.

Low cost silvering processes have also been developed that have commercial applications where large substrates need to be reflective coated. Results of past Air Force funded contracts at SRS have led to commercial customers. SRS is currently under subcontract to a major communications corporation to provide thin film membranes for antenna purposes. The following summarizes potential commercial applications that have direct technology transfer from results of this research.

Solar Concentrators for Lunar Surfaces. Most Lunar resource production processes require significant amounts of thermal and/or electrical energy. Mass penalties associated with conventional space power systems make most Lunar materials utilization concepts only marginally profitable. Novel concepts for extracting oxygen, other useful gases, metals, and non-metals from lunar materials could be made feasible by advancements in large area construction of thin polyimide film concentrators. The innovation will reduce total system mass of lunar materials processing plants. Innovative design and fabrication of lightweight reflectors make possible very low mass power systems and direct application of thermal energy.

Space-Based Deployable Antenna Collectors. Technology needs to be developed to provide SDIO with simplified deployment procedures for specialized structural components in a space environment. Of particular concern is the need for microwave antenna reflectors (communication or energy transmission or reception) or solar concentrators which can be launched into space and autodeployed. Methods developed under this Phase II program could be extended to a space-based antenna reflector.