FINAL TECHNICAL REPORT

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Project Title: Low-Cost Inflatable-Support Heliostats to Enable Cost-Effective Large-Scale Solar Thermal Power

Project Period Covered: April 1, 2001 through August 31, 2002 (plus additional testing and Final Report after August 31, 2002)

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Executive Project Summary

This project is in the area of cost-reduction technology development for solar thermal powerplants. More specifically, this project aimed to demonstrate the viability of low-cost inflatable-support heliostats to enable cost-effective large-scale solar thermal power. The approach taken in the project was to start with some design trade studies; to then design a subscale prototype of a representative inflatable-support heliostat; and to then construct and test this prototype to accomplish the project objectives. All these tasks were successfully accomplished, and this Final Report documents the technical details involved. The resulting prototype heliostat was also displayed to members of government, industry and academia at the "Solar 2002" National Solar Energy Engineering. The advanced low-cost heliostat technology which has been validated by this concept validation project, is now ready for further development steps leading to commercialization.

Introduction and Context

Solar Thermal Power has tremendous potential to meet the electric power needs of the United States and the World. As shown in Figure 1, just 0.52% of the land area of the United States is enough to match 100% of U.S. electric power production, using renewable, "green" power from central receiver solar thermal powerplants. Total U.S. electric power production can be satisfied using only 2.1% of land area in the arid / desert areas of the states of California, Arizona, New Mexico, Texas, Nevada and Utah. The corresponding statistic for the whole World is that only 0.14% of World land area is enough to match 100% of World electric power production, using renewable, "green" power from central receiver solar thermal powerplants. This tremendous solar power potential is currently not exploited on a large scale, simply because solar thermal power or environmentally risky nuclear power generation.

FIGURE 1

SOLAR THERMAL POWER POTENTIAL

0.14 % of World land area is enough to match 100% of World electric power production, using renewable, "green" power from central receiver solar thermal powerplants!

0.52 % of U.S. land area is enough to match 100% of U.S. electric power production, using renewable, "green" power from central receiver solar thermal powerplants!

2.1 % of the land area of CA, AZ, NM, TX, NV & UT is enough to match 100% of total U.S. electric power production, using renewable, "green" power from central receiver solar thermal powerplants!

Assumptions:

Assume California high desert average insolation of 7.4 kW-hr / sq.m. / day as representative of preferred sites. Assume ratio of heliostats total area to land area of 19.7%, based on "Solar Two" (1926 x 39.3 sq.m. / 384,450 sq.m.) Assume average energy per heliostat face area / average energy per ground surface of 1.1 (bit over 1 @ field perimeter, bit under sort2 near tower base) Assume 70% annual capacity (% of year can deliver @ rated power, with thermal storage for typical 3 hr) Assume average efficiency 19% (including receiver, thermodynamic cycle, turbine) This gives (7.4 kW-hr / sq.m. / day) x (.197) x (1.1) x (.70) x (.19) x (365 days / year) x (2,589,988 sq.m. / sq.mi.) = 2.0 x 10⁸ kWe-hr / sq.mi. / year = 200 GWe-hr / sq.mi. / year The above assumptions are based on data from: http://www.eren.doe.gov/power/success_stories/pdfs/power_tower.pdf http://www.eren.doe.gov/power/pdfs/solar_tower.pdf http://www.eren.doe.gov/sunlab/documents/solarpaces/SP99 Tec.htm http://www.voyagepub.com/publish Total area of countries & territories, excluding Antarctica = 51,217,000 sq.mi. World total electricity production = 13,960 billion kW-hr/yr = 13,960,000 GW-hr/yr U.S. area = 3,535,000 sq.mi. Area of CA 163,696 + AZ 113,998 + NM 121,589 + TX 268,581 + NV 110,561 + UT 84,899 = 863,324 sq.mi. U.S. total electricity production = 3,670 billion kW-hr = 3,670,000 GW-hr/yr The above given data are from The World Almanac and Book of Facts 2002 13,960,000 / 200 = 69,800 sq.mi to match current total world electric power production with solar thermal powerplants 69,800 / 51,217,000 = .00136 = 0.14 % is percentage of world land area excluding Antarctica 3,670,000 / 200 = 18,350 sq.mi. to match current total U.S. electric power production with solar thermal powerplants

18,350 / 863,324 = .0213 = 2.1% is percentage of land area of CA, AZ, NM, TX, NV, UT

18,350 / 3,535,000 = .00519 = 0.52 % is percentage of U.S. land area

The largest single cost element of central receiver solar thermal powerplants is the heliostats, or pointable mirrors which reflect incident sunlight onto the central receiver of the powerplant. This fact is illustrated in the cost breakdown pie chart shown in Figure 2. Thus the largest single opportunity to reduce costs so as to enable cost-effective solar thermal power is to come up with a heliostat design which dramatically reduces heliostat cost while accomplishing engineering and operational objectives. This sets the context for the present project, and provides a strong rationale for validating the technical and cost-reduction potential of applying lightweight, low-cost inflatable-structure technology to heliostat design.



Project Goals & Participants

Key goals of this project, which have not varied over the duration of the project, comprise the following:

- 1. Conduct trade studies and component / subassembly tests to evolve a preferred subscale prototype design for a lightweight, low-cost inflatable-structure heliostat.
- 2. Refine the design as necessary, then construct a prototype which will enable achievement of test objectives.
- 3. Test the prototype with respect to the ability of the heliostat pointing system to accurately aim the heliostat without distorting the reflective surface.
- 4. Test the prototype with respect to beam shape and size (concentration) on a simulated target.
- 5. Test the prototype with respect to pointing accuracy and beam shape in the presence of environmental factors, particularly wind and gusts.
- 6. Evaluate the ability of the prototype to survive undamaged under adverse environmental conditions such as high winds or precipitation.
- 7. Develop a preliminary design for a production heliostat, which applies the technology demonstrated by the prototype.
- 8. Develop and document conclusions and recommendations for further work needed for the commercialization of this low-cost inflatable-structure heliostat technology, and for thereby enabling cost-effective large-scale solar thermal power generation.

Key participants were the Principal Investigators:

Mithra Sankrithi President & CEO RSV Invention Enterprises Gary Reysa Chief Engineer, Product Development RSV Invention Enterprises

Voluntary contributions and support were also provided by:

Usha Sankrithi Siva Sankrithi Joan Reysa Michelle Reysa Gail Reysa

Desktop Prototyping, Trade Studies and Refined Prototype Design

At the start of the project, some pre-prototype studies and tests were conducted to help evolve a preferred prototype design, to fulfill goal 1 of the Project Goals. The first pre-prototype approach involved evaluation of the feasibility of an inflatable heliostat support comprising a base balloon, which rolls on the ground surface to accomplish orientation control in elevation and azimuth. A "blue balloon" desktop prototype was used for this purpose, and is illustrated in Figure 3.

The "blue balloon" model is a 15-inch heavy-duty child's play ball. A toroidal balloon for supporting a reflective surface, is represented in this pre-prototype by a circular wood structure, to which the stranded wire tethers are attached. The tethers are steel wire, and are wrapped on "winches" made from half-inch diameter bolts. The winches are turned with a ratchet wrench that provides 10 deg increments, or about 0.04 inches of cable movement per ratchet click. The tether cables were typically tensioned to 20 to 30 lbs. The balloon was typically inflated to 50 to 70 inches of water (1.8 to 2.5 psi) – similar to heavy-duty rubber rafts. Inflation pressure was measured using a water manometer.



Figure 3 – "Blue Balloon" Desktop Prototype

Based on the "blue balloon" pre-prototype studies, it was concluded that it would be very difficult to achieve desired pointing accuracies with a design which rolls on the ground surface, because of issues of base balloon deflections, distortions, and hysteresis effects associated with the roll-to-point paradigm, and also because of an inability to reach high tilt angles. Several variants of the "blue balloon" configuration were tried, including a version with in which the tethers were attached to an equatorial band, and a version in which the toroidal mirror support element was installed with a tilt angle bias. These variants were also unsuccessful in achieving the kind of pointing control that is necessary.

Trade studies were conducted to examine alternate design concepts utilizing inflatable-structure support for the reflective surface, but wherein the base balloon does not roll over the ground to accomplish the two degree-of-freedom pointing function. An initial prototype design was developed which used a base balloon, which rotated on a ring base with a ring of ball bearings supporting the base balloon in a spatially fixed location while permitting it to change orientation in elevation and azimuth. The base balloon in turn supported a toroidal (donut-shaped) balloon above it, which in turn supported a reflective membrane mounted on a lightweight perimeter frame. Pointing control was achieved by motorized winches accomplishing differential length control of several control tethers located around the perimeter of the heliostat. This initial prototype design was constructed, and is illustrated in Figures 4a through 4e.

Unfortunately, the initial prototype design was also found to have significant problems in precision pointing control and stability for high tilt (low elevation) angles. Upon study, the principal investigators concluded that such control problems were due to the overturning moment associated with the weight of the toroidal balloon and the reflective surface it supported, at the high tilt angles. The high overturning moments in turn caused substantially imbalanced tether loads for control tethers on opposite sides of the heliostat, and also resulted in the base spherical balloon lifting off the support bearing ring on one side.



Figure 4a – Overview of Prototype Version 1



Figures 4b to 4e – Details of Prototype Version 1

The principal investigators considered various potential fixes to these issues, but on further study concluded that a more major design refinement would be needed, to avoid the control and stability problems encountered with the initial prototype design. The test work on the preprototypes and on the initial prototype, indicated that a refined inflatable heliostat design with a reflective surface internal to a spherical inflatable and with a transparent upper surface, would be the most promising approach to pursue toward achieving a workable light-weight, low-cost inflatable heliostat that could avoid the pointing control problems encountered with the initial prototype's toroid-above-sphere design. The preferred major design refinement with the reflective surface moved to an equatorial position within the base spherical inflatable, and with the upper covering surface of the inflatable being transparent, would clearly result in an avoidance of the overturning moment deficiency of the initial prototype design, and would also provide an added advantage of the upper transparent cover providing wind and precipitation protection for the reflective surface. The new configuration also has the advantage of providing a good aerodynamic shape. It has a relatively low drag coefficient, does not generate unwanted lift forces, and has the same aerodynamic properties from all directions. In addition, all aerodynamic and inertia forces act directly through the support system.

It was recognized that an added potential issue with this design refinement would be the effect of the transparent upper cover on distorting or diminishing the reflected light beam, and the principal investigators decided that this potential issue should be examined with suitable component and subassembly evaluation, prior to construction and test of a full prototype incorporating the design refinement.

A subassembly was built with a focusable stretched membrane reflector, and a removable transparent acrylic dome to serve as the transparent upper cover (Figures 5a, b). A subassembly evaluation was conducted, and indicated that the reflected light beam distortion was modest, when the reflector was in a focusing configuration. In view of these encouraging results, the principal investigators decided to go ahead with the detail design, fabrication and test of a refined prototype incorporating the preferred design refinement concept.



Figures 5a, b – Acrylic Dome Test

Refined Prototype Design & Construction

Annotated pictures shown in Figure 6 show the refined prototype design. The development and construction of the refined prototype design fulfills goal 2 of the Project Goals. In addition to the deletion of the toroidal balloon and the movement of the reflective surface to the equator under a transparent-upper-surface substantially spherical balloon, the refined prototype design also features a new pointing control system with stepper motor controlled toothed belts for elevation and azimuth control, as illustrated. The reflective surface is mounted to the base balloon through a lightweight aluminum ring, and can be focused by applying differential pressure between the upper and lower hemispheres of the balloon. For the prototype, a mylar membrane was used for the reflective surface, and optical vinyl with heat-seamed joints was used for the transparent upper surface. These prototype material and construction selections were made based on exigencies of cost and availability, and with the recognition that better solutions could be found for production applications

In summary, the refined design concept offers the following advantages:

- Simple drive system using only two motors, and having low torque requirements.
- Inertia and aerodynamic loads act directly through the support system (no overhanging moments).
- Aerodynamic loads from winds and gusts are relatively low due to low drag coefficient of the spherical shape.
- No unsymmetrical aerodynamic loads regardless of heliostat orientation or wind direction.
- Mirror can readily be focused using differential pressure.
- Inflated domes protect mirror from exposure to weather.
- The combination of low loads, direct load paths, and the inherent efficiency of inflated structures result in a lightweight, low-cost design.

A video description of the prototype is also included in on the CD-ROM. The prototype was transported and shown at the Solar2002 National Solar Energy Conference held in Reno, Nevada, in June 2002. The prototype has also been featured in the August edition of the Journal of Solar Energy Engineering published by the American Society of Mechanical Engineers, with the photographic illustration shown in Figure 8.



Low-Cost Inflatable Heliostat for Solar Thermal Powerplants

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A proof-of-concept subscale prototype of a lightweight, low-cost inflatable heliostat features a spherical inflatable structure with a reflective Mylar membrane mirror on its equatorial plane. The reflective surface is protected from rain, dust, sand, and wind by the transparent upper hemisphere, and can be shaped to achieve varying focal distances through differential air pressure between the upper and lower hemispheres. While the prototype transparent surface is made of heatthe prototype transparent surface is made of near-seamed optical vinyl panels, a potential produc-tion application would use single-sheet thermo-formed Tefzel, which features high transparency, long field life, and a self-cleaning characteristic. The inflated sphere is stably supported by a com-bination of polar bearings and base rollers, and the active sphere can be precisely policited in elthe entire sphere can be precisely pointed in elevation and azimuth angle using two stepper control motors. Preliminary estimates indicate that inflatable heliostats could potentially reduce heliostat cost from around \$192/m2 for conventional glass mirror heliostats down to around \$67/m² for the inflatable heliostats. The photograph was taken by Gary Reysa, Chief Engineer, Product Development, for RSV Invention Enterprises.

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Figure 6a – Overview of Heliostat Prototype



Figure 6b – Overview of Heliostat Prototype

Prototype Construction

This section provides some detail on the construction of the final version of the heliostat prototype. The heliostat consists of an inflated sphere with a membrane mirror mounted at the mid-plane of the sphere. The mirror is supported by an extruded aluminum ring, which in turn is supported by the two Polar Arms. The Polar Arms rest on an Azimuth Platform that can be rotated by the azimuth drive to provide pointing in the azimuth direction. Pointing the elevation direction is accomplished by turning the sphere about bearings located at the upper end of the Polar Arms. The inflatable sphere is supported by a combination of the Polar Arms and Ball Rollers. Figures 6a and 6b provide an overview of the heliostat. Additional details are provided below for each component.

It should be noted that in a number of cases materials and construction techniques used for the prototype would not meet production design requirements. These compromises in materials and construction techniques were made to keep the cost and construction time within the scope of the project. None of the project goals were sacrificed to any significant degree by the compromises.

Domes:

The upper dome is constructed from heat seamed Vinyl. The upper dome and Mylar mirror form the upper airtight chamber. The lower dome is constructed from PVC coated Polyester fabric. A latex bladder is used inside the lower dome to provide an airtight chamber. Each of the domes is constructed from 12 panels that are cut beach-ball-style to form a sphere. The air pressure in each of the domes can be independently controlled. In operation a slightly higher pressure is maintained in the upper dome to focus the Mylar film mirror. The domes are normally inflated to approximately 4 inches of water. The differential pressure to maintain focus is small – of the order of 0.1 inches of water. It should be noted that the production design will probably utilize a single piece, thermoformed dome constructed from a material with a longer life (such as DuPont Tefzel).

Polar Arms:

The polar arms support the sphere formed by the two domes, and allow rotation of the domes in elevation. The lower ends of the polar arms are rigidly attached to the Azimuth Platform. The upper end of the arms each have a bearing that carries a shaft mounted to the mirror support ring. This allows the sphere to be rotated in elevation about the top of the polar arms. The bearings are 5/16th inch nylon bushings. The polar arms are constructed from MDO (this is a high quality, dimensionally stable plywood that is overlain on both sides with resin impregnated membrane for strength and stability). Two aluminum braces between the azimuth platform and each polar arms stiffen the polar arms.

Azimuth Platform:

The Azimuth Platform provides the support base for the polar arms and for the ball rollers. The entire Azimuth Platform is supported on edge rollers and is free to rotate about a vertical axis through the center of the Azimuth Platform – this provides for aiming the heliostat in the azimuth direction. The Azimuth Platform is shown in figure 6c. A detail of the edge rollers is shown in Fig. 6d. The Azimuth Platform is also constructed from MDO.



Figure 6c – Azimuth Platform



Figure 6d – Azimuth Platform Edge Support Rollers (4 places)

Azimuth Drive:

The azimuth drive consists of a stepper motor driving a belt which encircles the Azimuth Platform. The belt used is toothed neoprene belt that is reinforced with polyester fabric – it provides very positive and stiff control of the heliostat. A toothed pulley mounted the stepper motor shaft drives the belt. One step of the stepper motor provides 0.03 degrees of rotation in azimuth. Guides were added to support the belt and prevent vibration over the unsupported part of the belt between the drive gear and Azimuth Platform. The guides are lined with UHMW plastic to provide a low friction surface. A groove is routed in the edge of the Azimuth Platform to retain the drive belt. The drive belt is rigidly fastened to the North side of the Azimuth Platform to prevent any possibility of belt slippage – this allows approximately 270 degrees of

azimuth rotation. The stepper motor is driven by an Axis Technology driver, which is in turn controlled by a Personal Computer. The choice of a PC was a convenience for the prototype -- in a production design, and small micro-computer would suffice. Figure 6e shows the azimuth drive.



Figure 6e Azimuth Drive Detail

Elevation Drive:

The elevation drive (Figure 6d) uses the same type of stepper motor, belt and drive gear as described above for the azimuth drive. As shown in the Figure, the drive motor is attached to the Azimuth Platform. Each end of the elevation drive belt is secured to the mirror support ring. One step of the stepper motor provides approximately 0.02 deg of rotation. Guides similar to the azimuth drive guides are provided to support free spans of the drive belt. Figure 6f shows the elevation drive unit.



Figure 6f – Elevation Drive Detail

Mirror:

The mirror is made from 7 mil thick Mylar film on which a thin coating of aluminum has been deposited. The aluminum coating provides a reflectance of approximately 95%. The fact that the mirror is sealed inside the two domes should act to maintain a high level of reflectivity. The mirror is supported around the edges and tensioned by an extruded aluminum right angle ring. The ring was fabricated by roll forming a straight extrusion. The ring is a right angle shape with 1.5 inch by 0.125 inch thick legs. The lacing arrangement shown in figure 6g was used to tension the mirror to about 20 lb/in (the mirror sounds like a bass drum when struck). The ring was then attached to the Mylar using a polyurethane adhesive. After the adhesive cured the lacing arrangement was cut off.

The upper and lower domes are bonded to the other leg of the mirror support ring. 3M VHB foam tape was used to bond the domes to the ring on the inside surface of the dome. Then, a 1.5 inch band of Vinyl was tensioned around the outside of the domes at the ring and solvent welded to the upper and lower domes.



Figure 6g – Mirror Construction Detail

Ball Rollers:

5 pairs of ball rollers support the lower inflated dome. The ball rollers share the task of supporting the sphere with the polar arms, and provide additional stability and damping. Each ball roller consists of a 1 inch metal ball which is fitted into a housing. The 1 inch ball rolls on ball bearings, and provides a low friction support of the lower inflatable dome.

Prototype Testing and Results

Summary of Test Results

Prototype testing has been accomplished to satisfy the Project Goals. Figure 9a through 9f illustrate photographic and tabular results of the prototype testing. The following is a summary of testing done and the results – further detail on each item is provided in the sections that follow.

With respect to goal 3 of the Project Goals, the prototype tests indicate that the heliostat pointing system does accurately aim the heliostat without distorting the reflective surface.

With respect to goal 4 of the Project Goals, a good near-circular beam shape was achieved on the simulated target; and geometric concentration ratios of up to 8.7 were achieved using differential

pressure between the upper and lower hemispheres of the inflatable structure housing the reflective membrane.

With respect to goal 5 of the Project Goals, encouraging results were obtained on pointing accuracy and beam shape stability in the presence of environmental factors, particularly winds and gusts. Temperature effects also had no adverse impacts on pointing accuracy and beam shapes, to the extent that ambient and heliostat internal (upper and lower hemisphere) temperatures varied during the test period.

With respect to goal 6 of the Project Goals, the heliostat prototype successfully survived some adverse environmental conditions including wind gusts up to 30 mph, and precipitation in the form of rain, snow and light hail. Survival in high winds and survival under severe winter conditions remains to be established by future prototype testing efforts.

In summary, the construction and testing of a subscale prototype of a lightweight, low-cost inflatable structure supported heliostat has been successfully accomplished, and has satisfactorily met the Project Goals. The sections below provide additional detail on the testing done to satisfy each of the project goals.

Pointing Accuracy

The aiming system uses stepper motors and polyester reinforced neoprene toothed belts to drive the heliostat in azimuth and elevation. Our tests indicate that the aiming system provides accurate and repeatable aiming of the heliostat. To verify repeatability indoor and outdoor tests were performed. In the indoor test, targets were secured to walls and ceiling at a range of pointing angles. A laser pointer was rigidly attached to the mirror support ring, and aimed in the same direction as the mirror (Figure 9a). The heliostat was commanded by the control software to point at each target in turn, and the initial spot on the target was marked. This cycle was repeated multiple times in each direction to observe how closely the laser beam matched the original marked spot on successive cycles. Within the accuracy that the spot positions could be measured, there was no deviation from the original spots on successive trials. The outdoor test consisted of using the aiming system to keep the heliostat's focused beam tracked on the target. Figure 9b shows the test setup for outdoor testing. The center of the target is 57 ft from the heliostat mirror. The target squares are one foot on a side. Note that the target color was changed to white after this picture was taken, for better visibility. Figure 9c shows the beam focused on the target - the heliostat was able to track the focused beam on the center of the target. In addition, tests were done in which the heliostat beam was centered on the target, then commanded to a position well off the target, then commanded back to the center of the target. In these tests, the beam returned to the same position on the target within the accuracy that could be visually observed.

The absolute accuracy of the aiming system could not be tested to a high level of precision due to the requirement to measure angles and positions to very small tolerances. It is our belief based on the repeatability tests described above and the simple geometry of the heliostat that the absolute pointing accuracy will meet the requirements. If, however, small and consistent errors in absolute pointing accuracy do occur, then software corrections could be introduced to correct them.

In summary, high pointing precision has been demonstrated. High absolute pointing accuracy can be inferred, or, if need be, obtained with software adjustments.



Figure 9a – Indoor Aiming Test



Figure 9b – Outdoor Aiming and Tracking Setup

Beam shape

The beam shape on the target is shown in Figure 9c for the unfocused beam and focused beam (the target squares are 1 ft. on edge). Focusing is accomplished by slightly increasing the pressure in the upper dome of the sphere. The small differential pressure deflects the mirror membrane into the parabolic shape required to focus the beam. The differential pressure required is small (of the order of 0.1 inches of water). The area of the bright spot of the focused beam on the target is 2.05 sq ft. If the area of the bright spot is divided into the total area of the mirror (18.85 sq ft), a geometric concentration factor of 8.7 is achieved. The video that accompanies this report has a sequence in which the beam is taken from unfocused to focused.

The ability of the heliostat to maintain the focused beam shape over a long period of time (hours) could not be tested due to a slow air leakage problem with the prototype. However, there is no reason to believe this could not be easily accomplished in a production application.

No significant heating of the upper dome (which could cause pressure change and focus loss) was observed, as it was exposed to sunlight. No thermal problems of any kind were observed during the testing period.

The effect of the tracking motor movement on the beam shape and position is minimal. When a stepper motor is activated to keep the aim point of the heliostat on the target, there is an oscillation of the position of the beam on the target with an initial magnitude of less than plus/minus 1 inch (less than 0.1 deg) – the oscillation dies out within a couple seconds to the point where the displacement is not visible. There is no visible change in the shape of the beam on the target when a tracking motor pulse occurs. The small oscillation of the beam that occurs when the stepper motor is activated can be observed on the video that accompanies this report. The stepper motors are normally activated at approximately 30 second intervals.

In summary, good focused beam shape with concentration factors of 8.7 have been demonstrated. Beam shape is not affected by tracking motor motions, or other transient effects.



Figure 9c – Focused and Unfocused Beam Shape On Target

Operation in Wind

Deflection of the beam on the target due to wind gusts was initially anticipated to be major concern. Tests were conducted during windy/gusty conditions up to 20 mph. Video recordings of the movement of the beam on the target during windy conditions were made. The video that accompanies this report shows one such test. The maximum movement of the beam on the target for winds and wind gusts up to 20 mph was approximately plus/minus 1.5 inches (approximately plus/minus0.12 deg) in the vertical direction, and mush less in the horizontal direction. While this maximum movement is relatively small, the average displacement of the beam from its nominal position is much less. The accompanying video illustrates that there are occasional maximum movements, but the time averaged displacement is much less.

There is more movement of the beam in the vertical direction than the horizontal direction because the heliostat mounting is less stiff perpendicular to the polar axis than parallel to the polar axis (see Force/Deflection curve below). Although the current design probably provides adequate stiffness, changes could be made in the production design to provide additional stiffness perpendicular to the polar axis to reduce vertical deflections.

It should be noted that:

- The wind velocity was measured at a height of 5 ft above ground level. If this were corrected to the standard wind measurement height of 33 ft, the wind velocities would be increased by a factor of approximately 1.46. This means that the 20 mph maximum wind speeds that were measured in our tests at a height of 5 ft are roughly equivalent to 29 mph at the standard wind reporting height of 33 ft.
- The wind measurement instrument (a Kestrel 1000) reports 3 second averages of wind velocity so high wind gusts of shorter duration get averaged down to lower values.

As can be seen in the video, the focused beam shape on the target was changed very little as wind gusts occurred.

In addition to the beam on target tests described above, tests were conducted in which a laser beam was mounted approximately 5 ft in front of the heliostat. The laser beam was reflected off the heliostat mirror, and onto a target located 55 ft in front of the heliostat. Defections of the heliostat resulted in changes in the laser spot on the target in much the same way as the sun beam was deflected in the tests above. The result of this testing confirmed the results described above.

In summary, the prototype exhibited the ability to keep the beam well focused on the target while operating in wind velocities up to 20 mph.

Environmental Exposure

The heliostat has been exposed to and operated in an outdoor environment since August of 2002. The test area is just North of Bozeman, MT. Bozeman experiences a wide variety of weather conditions including a wide range of temperatures, wide daily temperature swings, strong winds, precipitation in the form of rain, snow and hail, and long periods of direct sun exposure at 5000 ft elevation. Our plans call for continuing the weather exposure through the winter of 2002-2003.

It should be noted that some of the materials and equipment used in the prototype were chosen to keep the cost and construction time for the prototype within the scope of the project. The production design will substitute materials and equipment with a long service life in mind.

Temperature Range Exposure:

To date, the heliostat has been exposed to temperatures ranging from 0 F to 90 F, with daily variations up to 50 deg F. No temperature related failures or deterioration have been observed to date.

Winds Exposure:

Demonstrating the capability of the heliostat design to survive in high winds is a major goal of the project. One of the primary reasons for choosing the spherical shape for the heliostat is its low drag coefficient, and its lack of sensitivity to wind direction and heliostat orientation.

To date, the heliostat has been exposed to winds up to approximately 30 mph with no failures. Its behavior to date can be characterized as follows:

- There is no observed tendency for inflated (or non-inflated) surfaces to flutter.
- Deflections due to wind are small, and well controlled.
- Small oscillations in gusty winds have been observed these are low in magnitude and well damped.
- The behavior of the heliostat is consistent regardless of wind direction and heliostat orientation (as would be expected for a spherical shape).

While our plan calls for direct observation the behavior of the heliostat in winds well in excess of 30 mph, a rough estimate of its performance in higher winds has been attempted in the interim:

A force-deflection curve has been determined by test. This provides the relationship between a force applied horizontally to the mirror support ring and the resulting horizontal deflection of the mirror ring. This relationship was established for forces acting along the polar axis, and perpendicular to the polar axis. The results are shown in Figure 9d. The horizontal force is believed to be roughly equivalent to the force applied by a wind from the same direction.

The equivalent horizontal deflection for a wind speed of 18 mph was also measured, and found to be 0.25 cm. Using 1) the measured deflection for this wind speed, 2) the force deflection relationship discussed above, and 3) assuming that the wind dynamic pressure and wind force on the heliostat increase with the square of the wind velocity, the following <u>rough estimate</u> of severe wind survival performance of the prototype heliostat is provided:

- The approximate wind force on the heliostat at a wind speed of 18 mph is 7 lb. (from the 0.25cm deflection at 18 mph and the force-deflection curve).
- The approximate force on the heliostat for a design wind speed of 60 mph is 77 lb (from the dynamic pressure relationship, and estimated wind force at 18 mph)
- Forces of 60 to 80 lb were applied to the heliostat in the building of the Force/Deflection curve this would imply a wind survival speed of at least 50 to

60 mph (since the forces applied during in developing the force-deflection curve were not taken to the point of failure, the wind capability of the prototype is likely to be in excess of this)

While the above gives a very rough estimate of the prototypes wind survival speed, the plan is to test performance in higher winds as soon as Mother Nature provides the winds.

It should also be noted that large inflated structures (e.g. tennis court enclosures) routinely withstand high winds with no damage.

In summary, the heliostat has demonstrated good, stable behavior in winds up to 30 mph. Further testing in higher winds is planned, but a rough analysis indicates that the performance in higher winds will be acceptable. Testing to date has demonstrated that the spherical shape is a good one for stable performance in high winds.



Force/Deflection Curve for Heliostat Prototype

Figure 9d – Force/Deflection Curve for Prototype Heliostat

Exposure to Precipitation

In the course of the testing, the prototype has been exposed to rain, light hail, and snow. It has also been exposed to condensation especially on days following clear, cold nights.

No adverse effects on the operation of the heliostat have been observed as a result of these exposures. It is likely that the production design will require some form of shielding over the belts and drive gears to prevent ice accumulation (if icing is a possibility in the area of use).

In some cases, precipitation (e.g. snow, rain, or condensation) persists on the clear dome for some period of time into the next sunny period (Figure 9f). If precipitation of this type is likely in the intended use areas, this problem should be addressed in the design. If a material such as DuPont Tefzel is used for the dome in the production design, the dome should shed precipitation better than the Vinyl dome used on the prototype due to the "self-cleaning" capability of the Tefzel. In addition, the ability to turn the transparent dome downward during periods of precipitation would be desirable, and should be feasible with a modification of the current design.

In summary, the heliostat has been exposed to a moderate variety of outdoor conditions with no failures. Some issues have been uncovered (e.g. persistence of precipitation on the dome) which will have to be addressed on a production design, particularly in geographic areas where these conditions occur frequently.



Figure 9f – Heliostat Exposed to Various Weather Conditions

Preliminary Production Design

Goal 7 of the Project Goals has been accomplished with the development of a preliminary design for a production heliostat, which applies the technology demonstrated by the prototype. The preliminary production design is illustrated in Figures 10a and 10b, using four views. Note that the production design is fundamentally the same as the prototype design, with a few design refinements and a general scale-up in size. The size selected for this embodiment of a production design features a reflector diameter of 13.5 feet, as large as feasible to permit transport on flatbed trailers using the road system. The reflector is proposed to be made of 7 mil highly-reflective Mylar, with a reflective area of 143.1 sq.ft. or 13.30 sq.m. The reflective membrane is mounted on a .125" guage 2"x2" aluminum L-bend ring, and can be deflected into a desired concaveupward focusing configuration using differential pressure between the upper and lower inflated hemispheres. Alternate production designs are clearly possible at much larger scale for megascale solar thermal powerplants - however these alternate designs may not be road or rail transportable, or possibly may be road or rail transportable in sub-modules which then have to be assembled in-situ at the powerplant site.

The upper transparent hemisphere is proposed to be constructed of 15 mil Tefzel, thermoformed into the desired hemispherical shape out of a single sheet of material. The lower hemisphere is constructed of 20 mil vinyl or other plastic sheet, to reduce cost relative to the Tefzel. The upper and lower hemispheres are both fastened to the L-bend ring and thus to the reflective membrane. The L-bend ring is fitted with sphere-side pivot bearings, which connect it to curved support members, as illustrated. The curved support members are mounted on a base turntable structure, and are also stabilized by brace members. The lower inflated hemisphere also rests on a ring of sphere support bearing posts, which are also mounted on the turntable. The combination of the braced curved support members and the bearing posts will provide a lightweight, low-cost method of supporting the inflated sphere while holding it precisely and stably in a desired position. The turntable is fitted with a turntable edge ring, which in turn is engaged and held in position by a plurality of anchor legs secured in the ground surface. This preliminary design illustrates the use of four anchor legs, but based on performance and cost trade studies, a final design may use somewhere between three and six anchor legs.

Precise pointing control of the heliostat reflective surface is accomplished through the use of a turntable-mounted elevation control motor and winch for elevation control, and an azimuth control motor engaging a toothed surface on the turntable edge ring, for azimuth control.









Figure 11 presents a rough-order-of-magnitude cost estimation for the preliminary production design heliostat of Figure 10. Based on this spreadsheet, the estimated cost of the production heliostat is \$890 per heliostat, or \$66.9 per square meter of reflective area.

FIGURE 11

NOTE: A Finite-Elen	ent-Model (FEM) and Loads A	nalysis will be needed to obtain	n accurately sized	d elements, weight	and costs.								
Component	Material(s)	Length or Area	Volume	Density	Weight	Quantity	Total Weight Lb.	Material Cost	Material Cost \$	Fab/Assly Cost \$	Total Cost \$	Comments	
Transparent Hemisphere	Tefzel (15 mil)	286.3 sq.ft.	0.3578 cu.ft.	109 lb/cu.ft	39.0 lb.	- 1	39	\$6.00 / lb.	\$234.00	\$15.00	\$249.00	Thermoform fab	rication
Lower Hemisphere	Vinvl / plastic sheet (20 mil)	286.3 sq.ft.	0.4772 cu.ft.	85 lb/cu.ft.	40.6 lb.	1	40.6	\$0.60 / Ib.	\$24.40	\$14.60	\$39.00	Thermoform fab	rication
Reflective Surface	Reflective Mylar (7 mil)	143.1 sq.ft.		.105 lb/sq.ft.	15.0 lb.	1	15	\$0.435 / sq.ft.	\$62.20	\$1.80	\$64.00	Metallized polys	sester film
L-bend Ring	Aluminum (125" gage)	42.4' perimeter, 2."x2."	0.1472 cu.ft.	164 lb/cu.ft.	24.1 lb.	1	24.1	\$0.60 / lb.	\$14.50	\$7.50	\$22.00	Rolled Extrusion	n
		L-section w/.50 sq.in. XC											
Pivot Bearings	Various		.006 cu.ft.	150 lb/cu.ft.	0.9 lb.	2	1.8	\$2.00 / 16.	\$3.60	\$2.40	\$6.00		
Curved Support Member	Aluminum (.15" gage)	33.0' length, 4."x2." rect.	.4125 cu.ft.	164 lb/cu.ft.	67.7 lb.	1	67.7	\$0.60 / lb.	\$40.60	\$14.40	\$55.00		
		section w/1.8 sq.in. XC					1						
Brace Members	Aluminum (.125" gage)	7.4' length, 1.5" diam. Circ.	.0303 cu.fl.	164 lb/cu.ft.	5.0 lb.	4	20	\$0.60 / lb.	\$12.00	\$3.00	\$15.00		
		section w/.589 sq.in. XC				1							
Elevation Control Strap	Toothed Polyester Belt	21.4' long, 1."x.15"(avg)	.0223 cu.ft.	150 lb/cu.ft.	3.3 lb.	1	3.3	\$0.60 / lb.	\$2.00	\$8.00	\$10.00		
Sphere Support Bearings	Rigid Plastic				1.0 lb.	10	10	\$5.00 each	\$50.00		\$50.00		
Bearing Posts	Aluminum				6.0 lb.	8	48	\$7.00 each	\$56.00	\$4.00	\$60.00		
Turntable	Aluminum	8.95' equiv diam., 1.5" thick,	.5898 cu.ft.	164 lb/cu.ft.	96.7 lb.	1	96	\$0.60 / lb.	\$58.00	\$32.00	\$90.00		
		7.5% volumetric solidity	-										
Furntable Edge Ring	Aluminum (.175" gage)	9.05' equiv. Diam, 4" diam	.4342 cu.ft.	164 lb/cu.ft.	71.2 lb.	1	71.2	\$0.60 / lb.	\$42.70	\$12.30	\$55.00		
		circ XC with 2.199 sq.in. XC											
Elevation Control Motor	Various			_	10.0 lb	1	10	\$35 each			\$35.00		
Anchor Leg	Various				10.0 lb.		40	\$12 each	\$48.00	\$17.00	\$65.00		
Azimuth Control Motor	Various				10.0 lb.	1	10	\$35. Each			\$35.00		
nitial Setup Cost											\$40		
TOTAL				_			496.7	1			\$890.00		
Reflector area = pi * (13.5)	2)**2 = 143. Sq.ft. = 13.30 sq.n	n.					37.4 lbs. / sq.m.				\$66.9 / sq.m.		
							16.95 kg. / sq.m	n,					
								1				1	
							1						

Figure 12 then summarizes in a bar chart how the present inflatable structure heliostat technology can potentially reduce heliostat cost from \$192 /sq.m. for a conventional glass heliostat to \$67 /sq.m. for the inflatable structure heliostat. A bar is also shown for a state-of-the-art stretched membrane (non-inflatable) heliostat, such as those tested at Sandia National Laboratories. If these levels of heliostat cost reduction are truly achievable, this inflatable heliostat technology can clearly be instrumental in enabling large-scale commercial viability of solar thermal power, given that heliostats comprise the single largest cost element of solar thermal powerplants.



Conclusions and Recommendations

The goals set out at the beginning of this concept validation study were accomplished. A preferred design for a lightweight, low-cost heliostat was developed. A subscale prototype was built and tested, and the test results support the technical feasibility of such a heliostat design. The heliostat was able to track the Sun, to develop a precisely pointed reflected beam, to focus that beam to achieve increased concentration, and to adequately resist deflections due to wind and gust loads. Based on the prototype tests, we conclude that the concept is technically feasible and shows definite promise to enable a paradigm shift cost reduction for heliostats and solar thermal powerplants.

A summary of recommendations for the development steps leading to commercialization is presented in Figure 13. The next steps include a refined production design, integration with one or more solar thermal powerplant designs (may be at different power scales); cost engineering; manufacturing and construction plan; risk identification and mitigation; design and test of full scale pre-production prototype; design, construction and operation of a full pilot powerplant; and finally the design, construction and operation of many full-scale commercial powerplants to benefit consumers, benefit the environment, and benefit the United States and the World.

FIGURE 13

Development Steps & Commercialization Opportunity

- 1) Obtain Patent License for comprehensive Intellectual Property coverage for a whole new class of lightweight low-cost heliostats.
- 2) Use results & "lessons learned" from current Prototype design, construction & test, plus additional FEM-based design & analysis work, to synthesize a preferred engineering design for a production application to a commercial solar thermal powerplant.
- 3) Do trade studies to optimize material selection, tooling, fabrication, assembly and operational concepts all with the objectives of minimizing capital cost and life-cycle cost for this new class of low-cost heliostats.
- 4) Work on integration into a solar thermal powerplant, which also includes improvements in other elements (e.g., solar receiver, energy storage, thermodynamic cycle heat engine, electric power generation, etc.).
- 5) Work out a detailed development & implementation plan including business case, schedule, and risk mitigation.
- 6) Obtain suitable financing, suitable government incentives / credits for renewable energy, & environmental impacts approval at implementation sites- then actually implement the first set of truly cost-effective, commercially viable central-receiver solar thermal powerplants in the United States!
- 7) Produce "green" clean renewable energy; get global reputation; enhance shareholder value and profits; grow the industry successfully; and greatly reduce U.S. dependence on foreign energy sources.
- 8) Help make America and the World a better place for our children and the generations to come!

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Attachment A **Milestone Table**

	Milestone/Task Title	Original/	Revised	Actual	Responsible	Original	Revised	Actual	Milestone Notes
		Previously	Planned	Completion	Organization	Projected	Projected	Completed	
		Planned	Completion	Date		Cost	Cost	Cost	
		Completion	Date			(Fed/	(Fed/	(Fed/	
		Date				Non-Fed)	Non-Fed)	Non-Fed)	
1	Prototype Design Trade Studies	6/1/01		6/10/01	RSV	\$4,500/ \$4,860		\$6301.25/ \$8368.75	Developed Requirements & Objectives. Tested subscale models. Researched materials. Developed 3D stat computer modeling. Developed and analyzed a number of alternate concepts. Selected design for prototype and finalized req't.s & objectives
2	Prototype Design	7/1/01		8/30/01	RSV	\$5,180/ \$5,595		\$5370.75/ \$7184.25	Completed analysis, component prototypes, testing, and design for: Winch and tether system Base Balloon Toroid Ball roller base Reflector Developed prototype test plan.
3	Prototype Construction & Refinement	12/15/01	4/30/02	7/11/2002	RSV	\$10,240/ \$11,060	\$15234/ \$13926	\$22396.34/ \$20703.	 Procured parts. Constructed & assembled: Platform & Base Stepper driver Designed and contracted for: Winches Base & Toroidal Balloons Refined design to alternate based on control problems with initial prototype at high tilt angles.

	Milestone/Task Title	Original/	Revised	Actual	Responsible	Original	Revised	Actual	Milestone Notes
		Previously	Planned	Completion	Organization	Projected	Projected	Completed	
		Planned	Completion	Date		Cost	Cost	Cost	
		Completion	Date			(Fed/	(Fed/	(Fed/	
		Date				Non-Fed)	Non-Fed)	Non-Fed)	
4	Semi Annual Report	10/31/01 4/1/02		10/31/01 4/1/02	RSV				Completed with no charge to DOE.
5	Prototype Testing	4/1/01	7/15/02	8/31/02	RSV	\$11,360/	\$8886/	\$3930.33/	Test plan completed.
	& Refinement			+ non-billed wrap-up		\$12,265	\$8731	\$6806.75	Refined design has been built and tested and data recorded.
6	Attend Annual Review	N/A	N/A	N/A	RSV	Included			N/A
						in task 8			
	Preliminary Production	4/15/02	6/20/02	8/31/02	RSV	\$6,240/	\$2442/	\$539/	A preliminary production
	Design					\$6,740	\$3255	\$721.	completed and
7									documented.
8	Benefits Update &	7/15/02	7/30/02	8/31/02	RSV	\$2,480/	\$1765/	\$1462.33/	Benefits have been
	Conclusions			+ non-billed		\$3,280	\$2335	\$3037.67	have been documented.
				wrap-up					
9	Final Report	6/15/02	8/30/02	8/31/02	RSV	Included			A Final Report has been
				+ non-billed		in task 8			to the DOE.
				wrap-up					
				to 11/30/02					
Final				11/30/02				\$40000.00/	
Mile-								\$46821.42	
stone									

Attachment B

Gantt Chart

Milestone/	Milestone/Task Title	2 nd Quarter	3 rd Quarter	4 th Quarter	1 st Quarter	2 nd Quarter	3 rd Quarter	4 th Quarter
Task		2001	2001	2001	2002	2002	2002	2002
Number								
1	Prototype Design Trade	Х						
	Studies							
2	Prototype Design	X	X					
3	Prototype Construction	Х	X	Х	Х	Х	Х	
	& Refinement							
4	Semi-Annual Report		X	X	Х	Х		
5	Prototype Testing &		X	Х	Х	Х	Х	wrap-up
	Refinement							
6	Attend Annual Review							
7	Preliminary Production		X	Х	Х	Х	Х	
	Design							
8	Benefits Update &				X	Х	Х	wrap-up
	Conclusions							
9	Final Report						X	X

Attachment C

Energy, Environmental, and Economic Savings for I&I

The extent of energy, environmental and economic savings which lightweight, low-cost inflatable technology heliostats can enable, will be a strong function of the rapidity and extent of commercialization. This technology can be pivotal in enabling cost-effective, large-scale solar thermal power, as the single largest cost element of solar thermal powerplants is the field of heliostats. The proposed technology presented here could potentially reduce heliostat cost from around \$192 / sq.m. for conventional heliostats, to around \$67 /sq.m. for these advanced technology inflatable-structure heliostats. As noted earlier in Figure 1, only 0.52% of U.S. land area utilized for solar thermal powerplants, has the potential to meet 100% of U.S. electric power production with environmentally clean, renewable solar energy. Even at a fraction of this, the potential benefit to our country will be in the trillions of dollars in energy, economic and environmental savings over the long term, plus additional benefits in building freedom from reliance on foreign energy sources, dirty coal, or dangerous nuclear fission sources to meet the growing energy needs of the future.

Attachment D

Fuel Source	Btu/Barrel	Btu/Gallon	Btu/Pound	<u>Btu/ft³</u>
Crude Oil	6 x 10 ⁶	142 x 10 ³	18.6 x 10 ³	$1 \ge 10^{6}$
	6.2 x 10 ⁶	$150 \ge 10^3$	17.8 x 10 ³	1.1 x 10 ⁶
	6 x 10 ⁶			
Gasoline				
Propane – L				
· ·			6.5×10^3	148 x 10 ³
	87 x 10 ⁶			
Methane				
Methanol				
			$20 \text{ x } 10^3$	1.8 x 10 ³
	3.7 x 10 ⁶			
Hydrogen				
CO				
			12.6×10^3	800 x 10 ³
Coal - Ant.				
Carbon				
			20 x 10 ³	1,477

Fuel /Energy Source Btu Conversion

Electrical Generation (32.4% efficient Power Plant) - 10,500 Btu/kWh

Attachment E

Commercialization Table

(Not Applicable Here: For I&I Category 2 Projects Only)

Attachment F

Final Cost Sharing

#	Company Name	Company Type*	In-Kind Contribution	Cash Contribution	Total
1	RSV Invention Enterprises	Non-profit	\$46821.42		\$46821.42
2	DOE			\$40,000.	\$40,000.
	Total		\$46821.42	\$40,000.	\$86821.42

Only Include Cost-sharing Partners

* small business, business, non-profit, university, state agency, or utility

Attachment G

Partners and Contractors

N/A