Proceedings of the ASME 2009 3rd International Conference of Energy Sustainability
ES2009
July 19-23, 2009, San Francisco, California, USA

ES2009-90090

# The SkyTrough™ Parabolic Trough Solar Collector

**Adrian Farr**
SkyFuel, Inc.
18300 West Highway 72
Arvada, CO 80007 USA

**Randy Gee**
SkyFuel, Inc.
18300 West Highway 72
Arvada, CO 80007 USA

## ABSTRACT

The SkyTrough™ is a new high-efficiency parabolic trough solar collector that has been designed with features to reduce capital cost, shorten installation time, and reduce O&M cost. This collector builds on the excellent success of prior generation utility-scale parabolic trough designs, but incorporates several engineering and material innovations, listed below.

1. Lightweight, low cost, unbreakable non-glass reflectors using ReflecTech® Mirror Film with reflectance equal to silvered glass mirrors - and easy to install and replace,
2. Large aperture area parabolic trough module with more than double the aperture area of the Nevada Solar One (NSO) module,
3. Longer linear receiver (SCHOTT PTR™80) utilized to match the larger aperture width SkyTrough,
4. Aluminum space frame structure that is considerably lighter per unit of aperture area compared to NSO,
5. Total component "part count" that is considerably reduced per unit of aperture area, yielding a shorter assembly time per unit of aperture than the NSO modules,
6. Hydraulic-based rotary actuation system that provides built-in "stow" locking capability and higher torque capability compared to NSO,
7. SkyTrakker™ control system reduces inrush currents and reduces parasitic power consumption associated with collector sun tracking.

## INTRODUCTION

SkyFuel is a commercial solar energy technology provider, specializing in parabolic trough and linear Fresnel technologies for Concentrating Solar Power (CSP) plants. Research and development has been underway at SkyFuel for two years on the parabolic trough structures, reflectors, and the electronics and drive controls.

## LOCATION

Field related research, development and test activities have been performed at SkyFuel's Arvada, Colorado test field which includes a Solar Collector Assembly (SCA) and the electronics and drive controls needed to move the SCA.

**Figure 1 – SkyTrough™ SCA, Tracking the Sun**

## PREVIOUS ART

Utility-scale parabolic trough systems have been in operation since the mid 1980's when the Solar Energy Generating Systems (SEGS I & II) facilities began operation in 1985 and 1986. A total of 354 MW of SEGS projects were built in California, and in general the SEGS plants are operating well [1]. In 2007, a 64-MW system began operation (the Nevada Solar One project), and several large parabolic trough plants are under construction in Spain.

<u>Collector Structures</u>

In general, the support structure used to support the mirrors and the thermal receivers can be divided into two framing or support schemes: 1. Space frames, and 2. Torque tubes. These frames are the structural backbone that is used to support the reflectors (mirrors) and the thermal receivers.

The LS-3 collector used on several of the SEGS systems is a galvanized steel-based space frame, as is the EuroTrough [2]. The space frame used at Nevada Solar One, is aluminum. SkyFuel also uses an aluminum space frame design for the SkyTrough™. In all these cases, the idea was to design a highly accurate space frame that could be manufactured off site, easily transported to the solar field, and field assembled quickly and efficiently.

<u>Reflectors</u>

All utility-scale parabolic troughs to date have utilized silvered glass mirrors as reflectors. These reflectors are limited in size (under 2 meters in both arc length and width). Size limitations are typically driven by manufacturing limitations, strength, handling, shipping, and installation issues. These parabolic trough modules will have between 20 and 40 mirrors mounted to a single space frame module. The mirrors are typically 4 – 5 mm thick and are mounted to the structural frame with four bolted connections per mirror.

<u>Receivers</u>

The solar energy is focused onto receivers, stainless steel tubes with a high-absorbance, and low-emittance coating, enclosed in a vacuum sealed glass cylinder to insulate the receiver tube and minimize heat loss. Prior-generation receiver tubes for utility-scale parabolic troughs were 70-mm in diameter and just over 4-meters long. Solar fields typically experience a small percentage of receiver glass breakage annually. This breakage is typically due to either failure of the receiver support system (i.e. clamps, etc) or due to falling glass from glass mirror breakage [3].

<u>Drives and Controls</u>

Control systems typically include local controllers at each SCA pylon and a central computer located at the power plant control room (often called the 'supervisory' controller). In early parabolic trough systems, the local controller did not have the processing power to compute the sun position so the supervisory controller computed the sun position data and transmitted it to the local controllers in the field. Operational data obtained from the local controllers was limited to: a) mode of operation (tracking, follow, idle), b) SCA position data and basic motor status. Advances in microprocessor and communications technology have allowed the local controllers to compute the sun position, track the sun and provide operational and maintenance data to the supervisory controller.

Drive systems for parabolic trough collectors have changed significantly over the last 25 years. As the optical precision, of the parabolic concentrators, has improved and concentration ratios have increased the need for more accurate collector positioning has also increased. Additionally as the trough collectors have gotten lager there is a greater need for robust drive units that can accurately position the collectors (with minimal back lash), with the ability to lock the SCA in a downward-facing stow position to prevent damage to the collectors during extreme wind events.

## DESIGN

Parabolic trough solar collector fields are made up of several primary components:

1. Space Frames (or other structures)
2. Reflectors and Supports
3. Receivers and Supports
4. Drive Units
5. Controls Systems
6. Foundations
7. Pylons and Supports
8. Heat Transfer Fluid Loop (HTF)

For the purposes of this paper, we will be focusing on items 1 -5. And for the purposes of making the most meaningful comparisons possible, we will often refer to the NSO parabolic trough collector. The NSO project became operational in 2007, and is the largest system installed in the United States in the last 15 years. Hence, the NSO project provides a useful and rational benchmark for comparison.

Over the past 25 years, parabolic trough technology has advanced to the point where only small additional gains in sunlight-to-heat conversion efficiency are expected. SkyFuel has therefore aggressively pursued cost economies: the development of more structurally efficient space frames (i.e. lighter and stiffer), unbreakable and lower-cost reflectors, reductions in the time to bring the plant on line due to improved assembly procedures, and better drive units and controls (i.e. reduced cost, less maintenance, lower power consumption, etc).

The reflector panels for the SkyTrough™ are made with ReflecTech® Mirror Film adhered to an aluminum substrate. ReflecTech® Mirror Film was co-developed with the National Renewable Energy Laboratory (NREL). Each reflector panel spans the entire width of the collector in one continuous panel and measures approximately 22 feet long (6.7 meters) x 5 feet wide (1.5 meters). Each Solar Collector Assembly (SCA) requires seventy-two (72) reflector panels (as there are 9 panels per module and 8 modules per SCA). The panels are initially flat and are subsequently held in place and made to conform to their parabolic shape by a series of parallel ribs attached to the structural space frame.

The backbone for the SkyTrough™ SCA is a field assembled, highly accurate aluminum space frame that provides the structural skeleton, integrity and shape for the parabolic trough. The space frame also provides support for the mirrors and receivers (structural supports), maintains their optical alignment, and withstands external forces (such as wind). Each space frame is composed of extruded aluminum tubular struts that are assembled on-site, with no need for in-field welding. Each SkyTrough™ space frame has 215% of the NSO aperture area, achieved with less than a 20% increase in parts (or 44% fewer parts per $m^2$ of mirror aperture area) demonstrating a significantly simplified design and reduced assembly labor on a per unit aperture area basis.

Space Frame

The SkyTrough space frame was designed to fulfill the following criteria:

1. A light weight space frame that is torsionally stiff, to carry the wind loads of interconnected modules to the drive units.
2. Designed to support an approximately 22 foot long monolithic mirror (6 m aperture) (see Figure 1).
3. Frame accuracy sufficient enough to support the mirrors with less than 3.5 mrad slope error under operating conditions.
4. Frame must support the receivers and hold them in position.
5. Frame must be cost effective and inexpensive to transport to the project site.
6. Frame must be easily and quickly assembled with minimal skilled labor.

The space frame that has been developed meets all of these criteria, and a key way of achieving our preferred solution was through the engineering design of a space frame with a larger aperture area than the prior art. The larger space frame was enabled by use of a larger receiver (i.e. Schott's PTR-80 x 4.72 m) and also by the ability to go beyond the current limitations of glass mirrors, through the use of ReflecTech® Mirror Film. Some of the advantages of the larger space frame design include fewer foundations, fewer support pylons, fewer support bearings, and some less obvious structural economies in the design of the space frame that reduce the part count of the space frame itself, on a per unit area basis. This reduced number of components, plus techniques used to speed field assembly, will shorten the project construction timetable for the solar field.

The table below summarizes basic geometric information for the SkyTrough™ and compares this information to the Nevada Solar One space frame.

| | SkyFuel SkyTrough | Solargenix NSO |
|---|---|---|
| Module Aperture (m) | 6 | 5 |
| Module Length (m) | 13.9 | 8 |
| Module Aperture Area ($m^2$) | 83 | 40 |
| Number of Modules per SCA | 8 | 12 |
| Total Length of SCA (m) | 115 | 96 |

**Table 1 – Comparison of SkyTrough™ -vs. - NSO frames**

The completed frame weighs approximately 950 lbs (not including the steel torque plates that are used to transfer the torsional load between the space frame modules). This torsional load is transferred from the outermost frames back to the center frames and ultimately to the drive unit or locking mechanism. All space frame components are extruded aluminum, and have been sized to provide the necessary strength and rigidity to satisfy the design criteria at minimal cost.

**Figure 2 – back side view of the SkyTrough™ space frame**

Multiple analyses were performed looking at the optimum depth and length of the space frame. This analysis factored in the estimated cost to assemble the frame, the material cost of the frame, deflections, torsional stiffness of the frame, transportability, etc.

The design loads for the space frame were developed using data from comprehensive wind tunnel testing [4]. The SkyTrough™ frame has been designed for an 84 mph wind (3 second gust) for survivability (at this point the solar collector will be in the stow position). The maximum operational wind speed for the solar collector is 40 mph (3 second gust) or alternatively a 25 mph sustained wind speed. While all of the design loads must be considered it was noted that the torsional load on the frame, as a result of the cumulative wind load on successive frames, was the dominate contributor to the frame stresses.

The space frame is built off of 5 axial chords, as shown (in red) in Figure 3. These members run axially along the length of the space frame and help define the final shape and length of the space frame. These axial chords also function as the reference points to support the mirrors and the receiver tubes.

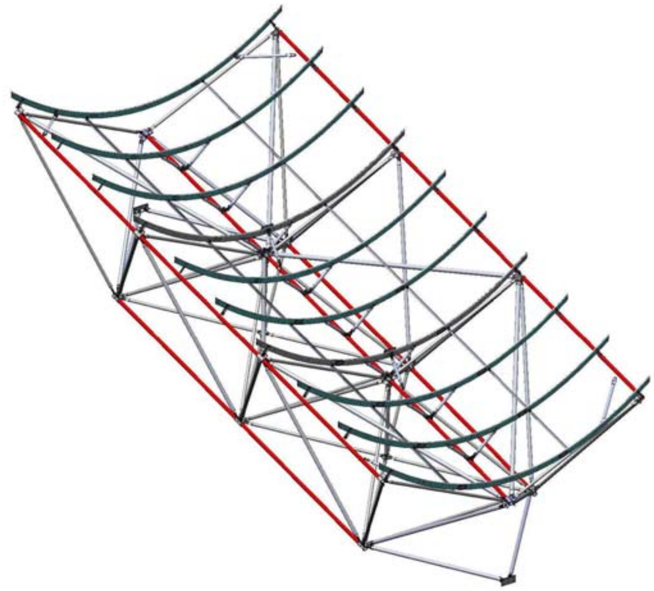


**Figure 3 – Solid model of the frame with the mirror mounting ribs shown.**

Joints for the frame consist of extruded members with machined holes for the strut fasteners (Figure 4). The ends of the “struts” are formed (with punched holes) so that they fit over the joint flanges as shown. This joint geometry (patent pending) is simple to manufacture and easy to assemble in the field.

**Figure 4 – Solid model of a typical joint on the SkyTrough**

The frame structural members use standard Aluminum Association cross sections and readily available alloys. The SkyTrough™ uses 6061-T6 for the joint materials and 6005-T5 for the strut and axial chord members. The space frame has been modeled using Solid Works (a 3 dimensional solids modeling program) and analyzed using the SolidWorks Simulation finite element analysis (FEA) program. Solid Works Simulation is a fully integrated finite element analysis tool that works with the Solid Works solid modeling software. A prototype SkyTrough$^{TM}$ frame was built and tested (see Figure 5) to verify torsional rigidity and torsional strength. The structure successfully withstood 100.4% of anticipated load, at which point one of the frame struts buckled under compressive loading, as expected. (The peak design load was 943000 in-lbs and it achieved 980,720 in-lbs.)

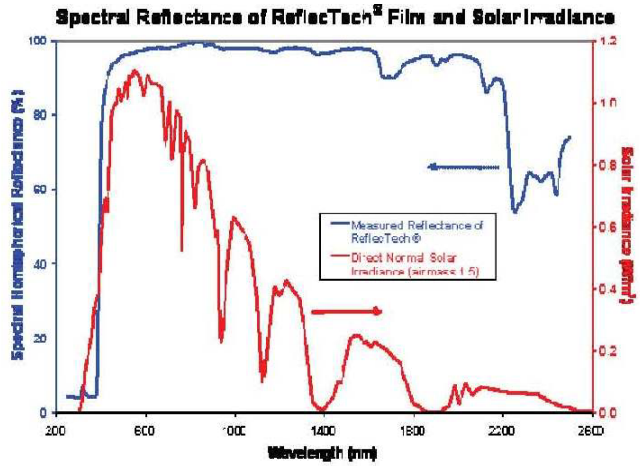
**Figure 5 – Space frame load test. Note buckled member in middle of picture.**

Material costs and parts count are the two single most important cost drivers for parabolic trough collectors. Compared to the NSO troughs, the SkyTrough™ reduces the mass of the space frame by 30% and its part count by 40% (both figures are calculated per unit area of mirror aperture). It is designed for rapid field assembly—the space frame is assembled two times faster than that of Nevada Solar One (per unit area).

Reflectors and Supports

SkyTrough$^{TM}$ reflectors use a UV-stabilized mirror film (ReflecTech® Mirror Film) laminated onto a 0.05 inch thick aluminum substrate. ReflecTech® Mirror Film was developed in collaboration with the National Renewable Energy Laboratories (NREL) and has a solar-weighted hemispherical reflectance of 94%, and a specular reflectance of 94% at 660nm and 25 mrad (1.4°) acceptance angle. (See Figure 6) A separate technical paper [5] on ReflecTech® Mirror Film is available that thoroughly discusses its UV-stability and high weatherability.

**Figure 6 – Spectral Reflectance of ReflecTech Mirror Film**




One of the advantages of using reflective film on an aluminum substrate is that the mirror is no longer susceptible to breakage. Another advantage is that mirror fabrication is done in house, removing any reliance on outside overseas vendors to supply this key component of the SkyTrough$^{TM}$. The reflector substrate has a rolled edge to restrain the mirror, which also allows for the mirrors to be slid into place at virtually any time during the solar field construction process. If for some reason a reflector panel is damaged, the damaged panel can be replaced relatively quickly and inexpensively.

**Figure 7 – Lamination of ReflecTech® to aluminum sheets for SkyTrough$^{TM}$ mirror panels**

The reflective panels that are used by SkyFuel

utilize a 0.05 inch thick aluminum substrate. This translates to a weight per square meter of reflective surface of 3.5 kg/m$^2$ (~0.72 lbf/ft$^2$) verses 10 kg/m$^2$ (2.1 lbf/ft$^2$) for glass mirrors. The use of ReflecTech® Mirror Film laminated (see Figure 7) onto an aluminum substrate allows for a lower cost, lightweight durable mirror when compared to traditional glass mirrors.

Receiver Tubes and Supports

The SkyTrough™ uses the SCHOTT PTR™80 as its thermal receiver. The PTR™80 was developed by SCHOTT in collaboration with SkyFuel, and has a highly selective absorber coating on an 80-mm outside diameter x 3mm wall thickness stainless steel tube. The tube is enclosed in a glass cylinder and vacuum insulated. (see Figure 8) The primary changes that were made to the PTR 80 include:

- Larger tube diameter (80-mm vs. 70-mm (PTR 70))
- Longer tube length (4.72-m vs. 4.06-m (PTR 70))

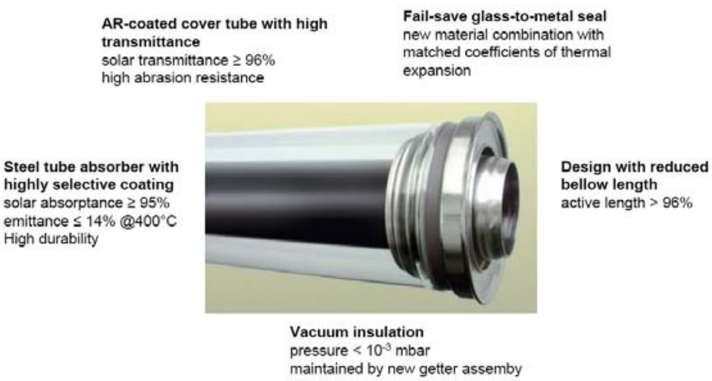



**Figure 8 – Typical section of a Schott solar receiver**

The receiver tube supports have been designed to minimize deflection that would otherwise place the receiver out of focus. In addition it was also desirable that the receiver supports create minimal blockage of sunlight , including when operating at off-normal incidence angles. The receiver supports must also accommodate a large amount of movement due to thermal expansion, approximately 9 inches at the end of the SCA (the thermal growth that occurs between installation temperature and maximum operating temperature).

Drive Units & Controls Systems

The drive unit and Control system developed for the SkyTrough™, comprises the SkyTrakker™ embedded controller (see Figure 9), a rotary hydraulic actuator (see Figure 10) and the supervisory controller. The controls system is capable of positioning the SCA within +/- 0.06° (+/- 1 milliradian) and operates the rotary actuator at a maximum rotation speed of 18°/min.

**Figure 9 – NEMA Enclosure with Control Electronics**

The SkyTrakker™ controls and drive systems were designed with a goal of reducing costs, increasing reliability, and increasing efficiency over previous parabolic trough positioning systems. The rotary hydraulic actuator reduces the number of mechanical components used to position and hold a solar collector assembly. Helical gearing is used, which allows for high overload capability, an important virtue when high winds occur and the drive unit must react very high loads. The result of this design effort is a drive unit that sits atop the center drive pylon as shown in Figure 10. The rotary positioning design is much simpler than linear positioning devices because it does not convert a linear motion into rotational movement. And, unlike rack-and-pinion rotary actuators, secondary locking mechanisms are not required with the SkyTrough™ rotary hydraulic actuator. The actuator has a total range of travel of -60° to +180° (240° total).

**Figure 10 - Center Pylon with Drive Components**

One key design goal was to reduce power consumption of the SkyTrough™ controls and drive systems. Compared to the prior-generation control/drive systems (e.g. Nevada Solar One) the SkyTrakker™ cuts power consumption in half. Supporting analysis is provided in [6], a separate technical paper on the SkyTrakker™ controls system.

## INSTALLATION

One complete SCA has been installed at our test facility in Arvada, CO. This SCA has served as our “proving ground” for the SkyTrough™. We have been able to evaluate ease of space frame assembly, various assembly methods, reflector installation, reflector replacement, drive functionality, controls operation and communications, etc. The SCA also functions as an operational thermal loop for thermal efficiency testing, verification of tracking accuracy, and verification of controls software and drive unit tests.

In addition to the testing we are performing on the SCA in Arvada, CO, NREL is conducting optical efficiency tests on a SkyTrough™ module, and Sandia National Labs in Albuquerque, NM is conducting high temperature efficiency testing on the SkyTrough™ using the Sandia AZTRAK rotating platform. The installation at NREL is underway, and we anticipate data collection will be completed during the summer of 2009. The SkyTrough™ installation at Sandia National Labs is scheduled for summer 2009, and we anticipate that data collection during the late summer or early fall of 2009.

Extensive testing of the various components and subsystems that comprise the SkyTrough™ have been conducted during the last 12 months of engineering development, such as VSHOT [7] optical tests, optical material characterizations, receiver thermal testing, and drive/control testing. Based on these tests, the projected efficiency of the SkyTrough™ is shown below in Figure 11, for a direct normal irradiance of 1000 W/m$^2$, at normal incidence.

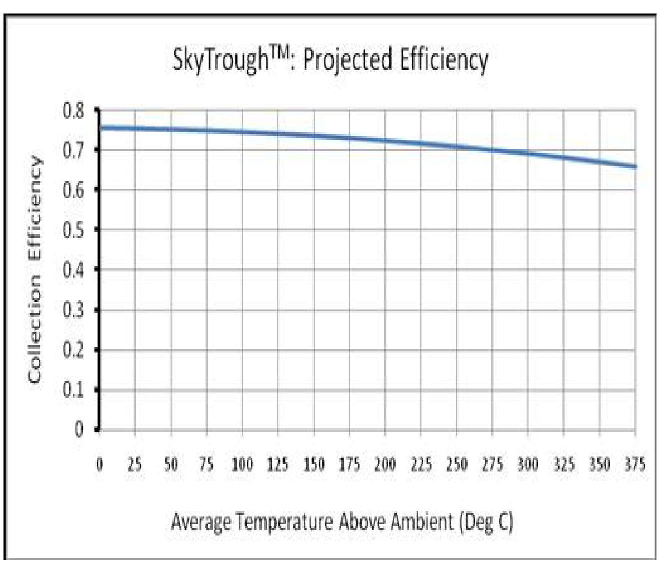



**Figure 11 – Projected SkyTrough™ Efficiencies**

## CONCLUSIONS

Parabolic trough technology is a well-proven utility-scale solar energy technology, with many years of successful operation. Parabolic trough collectors operate very efficiently and have increased to levels where significant gains in performance are now very difficult to achieve. So, SkyFuel has taken a different approach to driving down the cost per MWhr for utility-scale parabolic trough collector systems -- focusing on capital cost reduction, quicker and more efficient collector installation, and reduced operation and maintenance of the solar field.

The SkyTrough™ parabolic solar concentrator has been designed with the following features:

- Lightweight, low-cost, high-reflectance parabolic reflectors, using ReflecTech® Mirror Film, that are lightweight (compared to glass mirrors), unbreakable, and easy to install and replace,
- Increased aperture area concentrator modules (more than double the aperture area of the NSO module), yielding production economies, installation economies, and fewer pylons, foundations, etc.
- Longer linear receiver (SCHOTT PTR™80) are used to match the larger aperture width (6 meters) SkyTrough modules,
- Reduced cost of the space frame because of considerably reduced space frame weight on a per unit of aperture area (30% less, compared to NSO),
- Total component “part count” that is 40% lower (compared to NSO) per square meter of aperture area, yielding a shorter assembly time per unit of aperture,
- Simpler, lower-cost hydraulic-based rotary actuation is used to rotate the SkyTrough, and it provides built-in “stow” locking capability and higher torque capability compared to NSO,
- SkyTrakker™ control system reduces inrush currents and reduces (i.e. cuts in half) the parasitic power consumption associated with parabolic trough collector sun tracking.

As engineers, we often find that changing one design feature of a product will impact the design of other inter-related components. This is what occurred with the design of the SkyTrough™. The use of non-glass reflectors opened up the "design space", led to a larger concentrator aperture width and the use of a larger/longer more cost effective thermal receiver, etc. On a per unit aperture area basis, this holistic design approach has reduced the collector part count, reduced the space frame weight, reduced the number of other required components (e.g. support pylons, drilled pier foundations), and reduced the installation time of the collector. And a new advanced sun tracking drive and control system has been developed, which offers lower costs, higher torque capability, and reduced power consumption.

## NOMENCLATURE

| | |
|---|---|
| CSP | Concentrating Solar Power |
| HTF | Heat Transfer Fluid |
| mph | Miles per hour |
| mrad | Milliradian (approx 0.057°) |
| NSO | Nevada Solar One |
| SCA | Solar Collector Assembly |
| SEGS | Solar Energy Generating Systems |

## ACKNOWLEDGMENTS

SkyFuel extends sincere thanks to U.S. Department of Energy and the National Laboratories (NREL and Sandia) for their ongoing support in the testing of the SkyTrough™, both at the complete module level and at the component level testing. This support is much appreciated, and has been critical to the rapid development pace of the SkyTrough™.

## REFERENCES

1. Stoddard, L., Abiecunas, J., O'Connell, R., "Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California", NREL/SR-550-39291, Appendix A.1.1, National Renewable Energy Laboratory, Golden, CO, April 2006.
2. Geyer, M. et al., "EUROTROUGH DESIGN ISSUES AND PROTOTYPE TESTING AT PSA", Proceedings of Solar Forum 2001, April 21-25, 2001, Washington, DC.
3. Cohen, G., Kearney, D., Kolb, G., "Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants, SAND99-1290, Sandia National Labs, June 1999.
4. Hosoya, N., Peterka, J., Gee, R., Kearney, D. "Wind Tunnel Tests of Parabolic Trough Solar Collectors", National Renewable Energy Laboratory, Golden, CO, NREL/SR-550-32282, May 2008.
5. DiGrazia, M., Jorgensen, G., 2009, "ReflecTech® – Mirror Film Attributes and Durability for CSP Applications", Paper ASME ES2009-90336, proceedings of ES2009, Energy Sustainability 2009.
6. Moore, C, LeSuer, D., 2009, "SkyTrakker™ – an Advanced SCA Control System", Paper ASME ES2009-90160, Proceedings of ES2009, Energy Sustainability 2009.
7. Wendelin, T., "Optical Characterization of CSP Technologies at NREL", National Renewable Energy Laboratory, Golden, CO, poster session, www.nrel.gov/csp/troughnet/pdfs/2007/41421.pdf May 2008.