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# Development of a High-Concentration, Low-Cost Parabolic Trough System for Baseload CSP Generation

SkyFuel

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Phase II Report

# Foreword

This work was prepared under DOE contract DE-EE0003584.00. The entire SkyFuel technical staff contributed to the project, including the following individuals:

Adam Savoie, Adrian Farr, Gary Jorgensen, Graeme Hoste, James Kruse, Jason Henderson, Jenni McDaniel, Kirk McCullough, Mike DiGrazia, Mitch McCullough, Nathan Schuknecht, Nolan Viljoen, Patrick Stoever, Randy Gee, Ryan Gee

David L. White, Principal Investigator

## Executive Summary

The SkyTrough DSP will advance the state-of-the-art in parabolic troughs for utility applications, with a larger aperture, higher operating temperature, and lower cost.

The goal of this project was to develop a parabolic trough collector that enables solar electricity generation in the 2020 marketplace for a 216MWe nameplate baseload power plant. This plant requires an LCOE of 9¢/kWhe, given a capacity factor of 75%, a fossil fuel limit of 15%, a fossil fuel cost of $6.75/MMBtu, $25.00/kWht thermal storage cost, and a domestic installation corresponding to Daggett, CA.

The result of our optimization was a trough design of larger aperture and operating temperature than has been fielded in large, utility scale parabolic trough applications:

> 7.6m width x 150m SCA length (1,118m$^2$ aperture), with four 90mm diameter × 4.7m receivers per mirror module and an operating temperature of 500°C.

The results from physical modeling in the System Advisory Model indicate that, for a capacity factor of 75%:

> The LCOE will be 8.87¢/kWhe.

SkyFuel examined the design of almost every parabolic trough component from a perspective of load and performance at aperture areas from 500 to 2,900m$^2$. Aperture-dependent design was combined with fixed quotations for similar parts from the commercialized SkyTrough product, and established an installed cost of $130/m$^2$ in 2020.

This project was conducted in two phases. Phase I was a preliminary design, culminating in an optimum trough size and further improvement of an advanced polymeric reflective material. This phase was completed in October of 2011. Phase II has been the detailed engineering design and component testing, which culminated in the fabrication and testing of a single mirror module.

Phase II is complete, and this document presents a summary of the comprehensive work.

# 1. Project Overview

The goal of this project was to develop a parabolic trough collector to enable solar electricity generation in the 2020 marketplace with a levelized cost of energy (LCOE) at or below 9¢/kWh$_e$. Assumptions outside of SkyFuel's scope included a 261 MWe nameplate power block, a capacity factor of 75%, a limit of 15% fossil fuel fraction, a fossil fuel cost of $6.75/MMBtu, and a domestic installation corresponding to Daggett, CA. Increasing trough aperture and operating temperature above the current state-of-the art for parabolic trough collector fields enabled SkyFuel to realize the project goal.

This project was conducted in two phases. Phase I included a preliminary design and optimization, with selection of a trough size and further improvement of an advanced polymer reflective material. Phase II included detailed engineering design and component testing, culminating in fabrication and testing of a single mirror module with molten salt.

SkyFuel concludes that meeting the project goals is practical, and intends to market the baseload parabolic trough collector (SkyTrough ***DSP***) for 2015 markets.

## 1.1. Objectives

The objective of SkyFuel's multi-phased project was to develop and demonstrate an advanced, low-cost concentrating solar power (CSP) collector that uses high-concentration, high-temperature parabolic trough technology in order to substantially reduce the cost of baseload utility-scale solar power generation. At the conclusion of this project, SkyFuel realized two outcomes:

1. The *SkyTrough DSP* (Dispatchable Solar Power) collector is optimized for high temperature service with a maximum temperature more than 100ºC above prior art (500ºC or higher). High temperature design demanded larger apertures and higher concentration ratios.
2. The *SkyTrough DSP* detailed design realized significant reductions in cost due to the larger aperture, while incorporating additional design advancements that substantially lower the installed solar field costs.

# 2. Phase I Conclusions

The result of the Phase I optimization was a trough design of larger aperture and operating temperature than has been fielded in previous utility-scale parabolic trough applications. This trough would have an 8m width x 150m SCA length (1176m$^2$ aperture), with four 4.7m receivers per mirror module and an operating temperature of 500°C or above. A more refined optimization completed in Phase II resulted in a slightly modified design; specifically, the aperture width was optimum at 7.6 rather than 8.0 meters. This change was primarily due to a change in the market price of thermal receivers. The results for an 80mm and a 90mm diameter receiver were nearly identical, and resulted in an LCOE of 8.87¢/kWhe, given standard DOE FOA plant inputs.

The major drivers that led to these conclusions included:

- Reduction in installed cost provided the largest potential for reduction in LCOE
  - An increase in operating temperature, from 400 to 500°C, is secondary to installed cost
  - Cost reductions associated with increased operating temperature were primarily the result of lower storage cost
  - Reflectance increase also offered significant LCOE reductions, but less so than cost or temperature
- The aluminum space frame remained the lowest cost option for trough structures for utility applications, even at larger apertures
  - Aluminum is a more cost-effective choice than steel for space frames

- The space frame has a lower installed cost than torque box or torque tube structures, particularly for troughs with polymer film reflectors

➢ The peak wind load was the primary determinant for parabolic trough design, even for larger apertures:
  - The pitching moment is the critical load, and substantially impacts concentrator cost
  - The torque load increases with the square of aperture width, and aperture area increases only linearly with aperture width. This relationship imposes an upper limit on size

➢ The 70mm diameter by 4.0m long receiver is a poor choice for large aperture troughs
  - The reduction in intercept overwhelms the reductions in thermal loss
  - The short length (4m versus 4.7m for large diameter receivers) increases the installed cost

➢ There is no difference in LCOE for an 80mm or 90mm receiver.

➢ The contour accuracy for large aperture troughs must be high
  - Slope characteristics and magnitude are similar for moderate and large aperture troughs
  - Twist errors are manageable for longer SCA lengths because deeper, alternate geometry space frames provide substantial stiffness with little increase in weight

➢ The advanced DSP mirror film construction will achieve 94% solar weighted hemispherical reflectance, eliminate materials from the polymer stack, and has potential for lower cost

The LCOE for the DOE FOA template with a standardized collector is near 11.6¢/kWhe. SkyFuel optimized the aperture, executed a design, and establised cost and performance for the SAM physical model. The final LCOE was 8.87¢/kWhe and 8.90¢/kWhe for the 80mm and 90mm diameter receiver, respectively. These values are presented schematically in Figure 1.

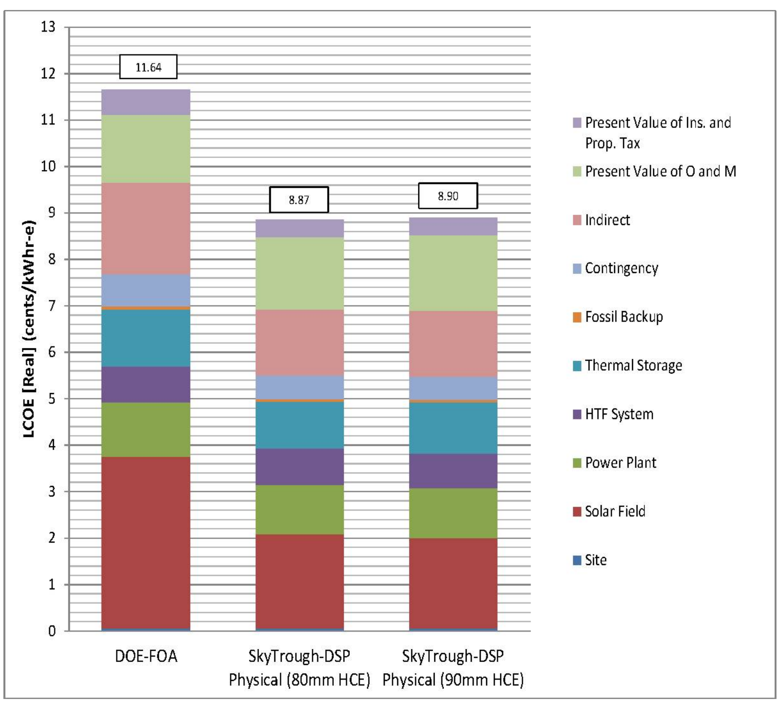


**Figure 1: Phase 1 LCOE Comparisons**

## 2.1. Revisions to Phase I Conclusions

The two phases of this project were separated by a period of 11 months, in which a drastic reduction in worldwide receiver prices occurred. As receiver companies in Europe were joined by those in Asia, prices fell dramatically. During this time, SkyFuel also continued research into component pricing, and found areas for even further reduction in cost. These events led SkyFuel to re-evaluate the Phase I conclusion, focusing on the volatility of receiver prices and other potential market drivers.

The result of this optimization was a trough with an aperture of 7.6m, which was the design carried forward through the balance of the project. While other elements of the design were re-analyzed alongside the aperture, all other Phase I conclusions and preliminary designs remained intact.

## 2.2. ReflecTech® Mirror Film Developments – Phase I

Polymer film development in Phase I was advanced by research to improve the optical performance and durability of ReflecTech Mirror Film. Specific targets were an outdoor lifetime of 20-25 years, and an increase in solar-weighted hemispherical reflectance of one full percentage point. Those targets have been met:

- Pressure sensitive adhesives that increase the durability of the reflector have been incorporated into the production process
- Reflectance has been maximized by improving processes for metallization of the film
- Development has been initiated for an advanced construction with lower costs
- Accelerated exposure tests allow estimates of service lifetime to be made

A solar weighted hemispherical reflectance of 94% has been achieved.

# 3. Phase II Objectives

The second phase of this project included the detailed design of all collector components including advanced ReflecTech mirror film, testing of the laser intercept, optical efficiency, and thermal loss, and operation of a full-scale module with molten salt. Each of these elements is complete.

The Phase II effort maintained the cost goals established during Phase I, improved upon the collector performance, and demonstrated operation and freeze recovery with molten salt as the heat transfer fluid (HTF).

## 3.1. Phase II Testing

The primary goal of this project phase was to demonstrate and quantify performance with a single mirror module while tracking the sun. This test was ultimately successful, demonstrating an optical performance of 76%. To safely and adequately achieve this task, a number of preliminary tests were also required. These included quantification of the contour accuracy of the mirror module, a destructive test in torsion of the space frame, thermal loss testing of the high-temperature receivers, and operational testing of molten salt-compatible receivers.

### 3.1.1. Laser Intercept Testing

A complete SkyTrough DSP module was constructed indoors at SkyFuel's Development and Test Center (DTC), as presented in Figure 2. The local slope error was measured at more than 7,000 locations on the module.

**Figure 2: Optical Test Setup**

Figure 3 presents an example of the data collected for a single mirror panel. The laser spot transverse location is presented along the x-axis, while the axial location is indicated by the data point color. The y-axis in the figure shows the local slope error, in mrad, of each point on the mirror.

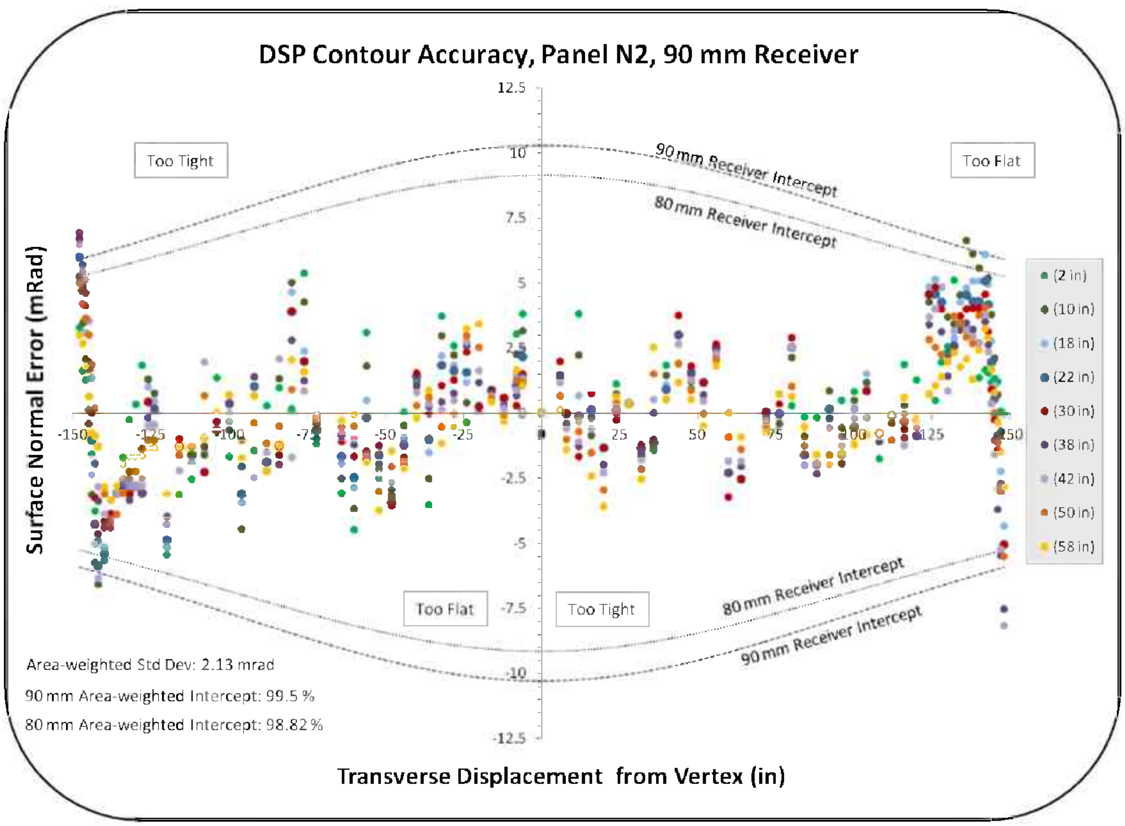


**Figure 3: Contour Accuracy, Single Mirror Module**

Dotted and dashed lines on the chart indicate the allowable range of slope error for laser intercept for each location. The average laser intercept for the trough was 99.1%, and the average standard deviation of slope error was measured at 2.66 mrad.

These results are significantly improved over those modeled in SkyFuel's Phase I optimization, and indicated that there were no significant design, manufacturing, or assembly issues affecting optical performance of the mirror surface.

### 3.1.2. 90mm Receiver Thermal Loss Testing

In order to establish thermal loss of a molten salt-compatible receiver, SkyFuel built a test stand for inductively heating and establishing emittance of receivers at varying temperatures. The test stand was validated against a previously characterized receiver, which was tested at NREL. Conductive and convective end losses were included in the model, to identify only the losses through the receiver wall and glass envelope. Figure 4 presents the heat loss per meter of HCE as a function of absorber temperature. Data is included from the NREL test, SkyFuel's comparative test, and the 90mm molten salt-compatible receiver.

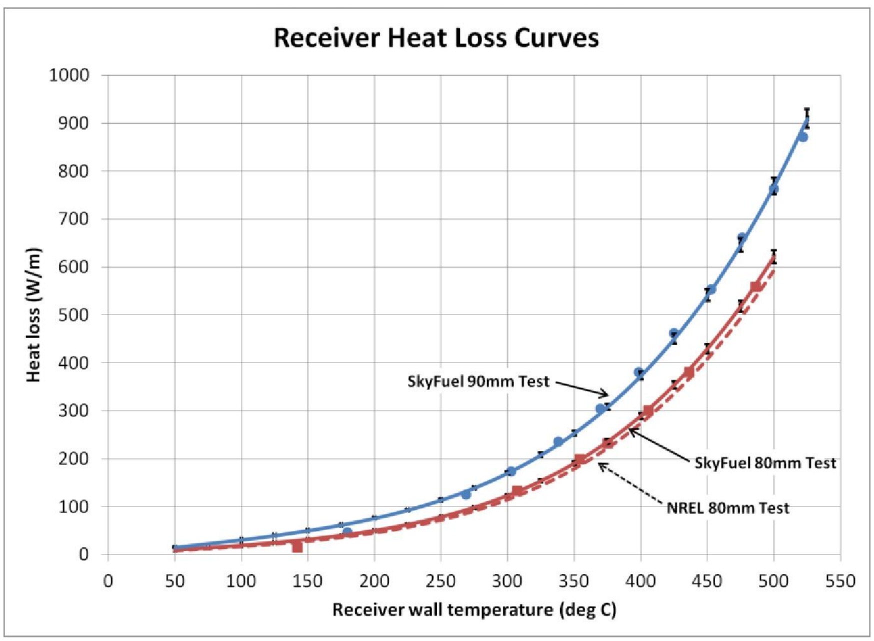


**Figure 4: Receiver Thermal Loss Results**

## 3.2. Phase II Results

A full-scale module was erected outdoors at SkyFuel's hilltop demonstration facility, and tested at near-ambient conditions to mediate the effects of heat loss from the receiver. This demonstration module is presented in Figure 5.

**Figure 5: DSP, Hilltop Demonstration Module**

The optical efficiency of the SkyTrough® DSP was established as 76% +/- 4.8% with a 95% confidence interval. This efficiency is the mean value of a four-hour testing window, which is presented in Figure 6**Error! Reference source not found.**. Similar results were recorded for other testing days, but this particular dataset yielded the longest period of uninterrupted clear skies.

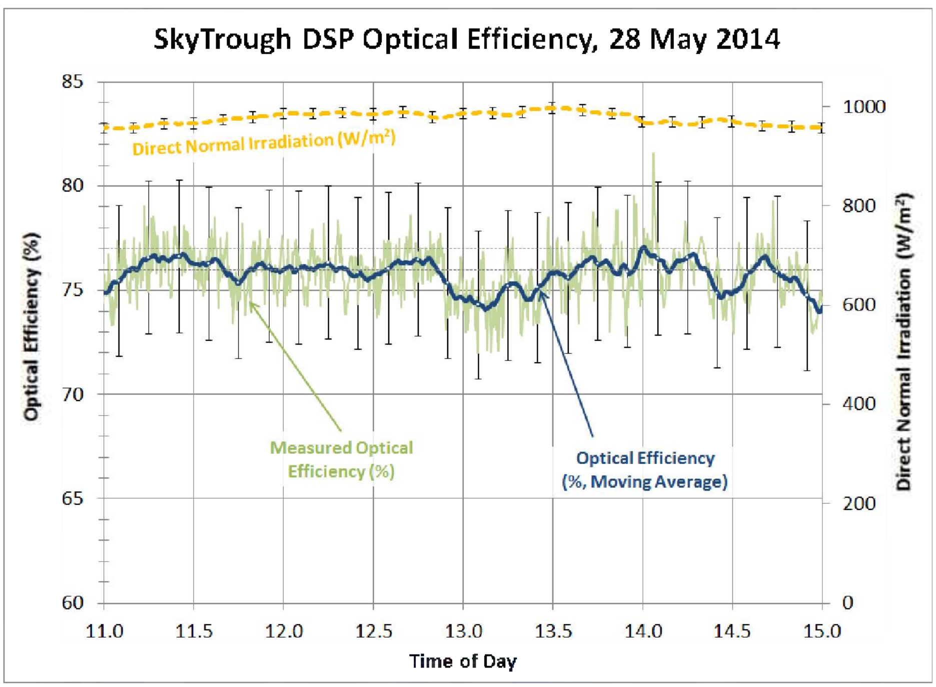


**Figure 6: Optical efficiency test results for the SkyTrough® DSP.**

With optical efficiency and heat loss of the thermal receivers established, a temperature-dependent thermal efficiency was calculated. This data is presented in Figure 7, and assumes a DNI of 1,000 W/m$^2$.

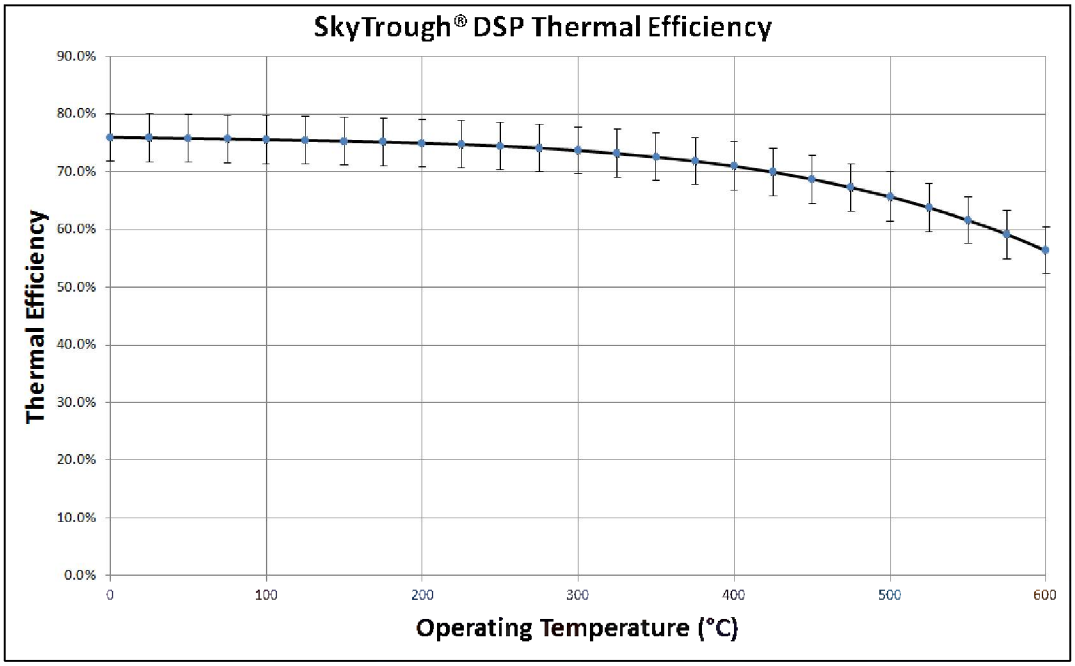


**Figure 7: Thermal efficiency for the SkyTrough® DSP assuming a DNI of 1,000 W/m$^2$.**

Due to the exponential nature of radiative heat transfer, the uncertainty of the data increased with temperature. For an oil-based system operating with an inlet temperature of 300°C and an outlet of 400°C (350°C nominal), the SkyTrough® DSP thermal efficiency is 72.6% +/- 5.6% (95% confidence).

A molten salt field operating with a 300° inlet and 500° outlet (400° nominal) will yield a thermal efficiency of 71% +/- 5.8% (95% confidence). It should be noted that these thermal efficiencies are indicative of a prototype 90mm receiver; smaller diameter receivers may have lower heat losses and yield a higher efficiency, but will increase parasitic demand and reduce intercept factor.

# 4. Molten Salt Operation

Once the optical efficiency tests were complete on the SkyTrough® DSP demonstration loop, molten salt was introduced to the system. The entirety of the field piping loop was fitted with electrically resistive heat trace, insulation, and temperature control equipment. Electrical connection lugs were attached at either end of the thermal receiver string, and on either side of the flexible hose equipment to enable heating via the joule-effect method.

Prior to introduction of molten salt into the fluid loop, salt in the storage tank was kept at a temperature of 300°C for a period of seven days to drive off any intermolecular water. The entire field, including the receivers and flexible hoses, was preheated to an average temperature within 50°C of the molten salt to resist thermal shock during the fluid introduction.

Operational tests proved successful with molten nitrate salt, with no damage to equipment, no safety concerns, and successful delivery through the collector loop using the high-temperature pump.