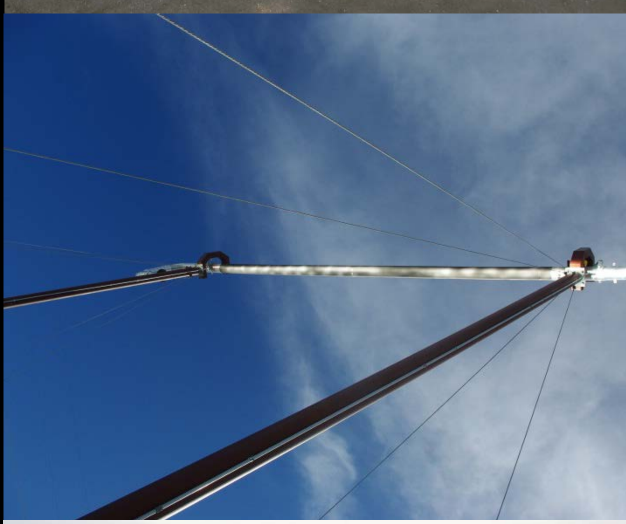
Commercial Development of an Advanced, High-Temperature, Linear-Fresnel Based Concentrating Solar Power Concept



Phase 2 Report

May 28, 2012

Work performed by contract No. DE-FC36-08GO18034.

SkyFuel

Commercial Development of an Advanced, High-Temperature, Linear-Fresnel Based Concentrating Solar Power Concept
Phase 2 Final Report

Nolan Viljoen
Nate Schuknecht

SkyFuel, Inc.
18300 West Highway 72
Arvada, CO 80007

With contributions from:

Randy Brost
Ryan Clark
Adrian Farr
Ryan Thorpe
Guangdong Zhu
David White
Randy Gee

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Executive Summary

This report documents the work performed under the second phase of contract no. DE-FC36-08GO18034 between the Department of Energy (DOE) and SkyFuel.

Included herein is SkyFuel's detailed assessment of the potential for a direct molten salt linear Fresnel collector. Linear Fresnel architecture is of interest because it has features that are well suited for use with molten salt as a heat transfer fluid: the receiver is fixed (only the mirrors track), the receiver diameter is large (reducing risk of freeze events), and the total linear feet of receiver can be reduced due to the large aperture area. Using molten salt as a heat transfer fluid increases the allowable operating temperature of a collector field, and the cost of thermal storage is reduced in proportion to that increase in temperature.

A key element of linear Fresnel architecture is the potential for lower reflector cost. The reflectors in a linear Fresnel system have a relatively flat profile and are located close to the ground, and so have low wind loads compared to other CSP technologies. Wind is the dominant structural design criterion that establishes reflector mass and cost, so reduced wind loads are advantageous to achieving lower cost reflectors. In this contract, wind loads were determined and two linear Fresnel collector designs were engineered and evaluated.

Collector cost is comprised of the sum of the costs of many components: the reflectors, receivers, drives, controls, pylons, etc. The receiver for a high temperature linear Fresnel collector contributes much to the overall cost of the system, so much of the research in Phase 2 was devoted to the development of a baseline design and cost estimate for this component.

At the conclusion of this project, SkyFuel determined that the cost goals set forth in the contract could not be reasonably met. The performance of a Linear Fresnel collector is significantly less than that of a parabolic trough, in particular due to linear Fresnel's large optical cosine losses. On an annual basis, the performance is 20 to 30% below that of a parabolic trough per unit area. The linear Fresnel collector and balance of system costs resulted in an LCOE of approximately 9.9¢/$kWhr_e$. Recent work by SkyFuel has resulted in a large aperture trough design (DSP Trough) with an LCOE value of 8.9 ¢/$kWhr_e$ calculated with comparative financial terms and balance of plant costs (White 2011). Thus, even though the optimized linear Fresnel collector of our design has a lower unit cost than our optimized trough, it cannot overcome the reduction in annual performance.

To verify the design and analysis assumptions, a prototype linear Fresnel collector was fabricated and installed. The test data indicated that the theoretical model used to predict linear Fresnel performance was accurate, that the prototype collector design met performance goals, and that it was a good verification of our assumptions.

It is SkyFuel's conclusion that linear Fresnel technology does not reach parity with parabolic trough technology, and that it is not reasonable to expect that it ever will. SkyFuel recommends against further commercial development of linear Fresnel technology.

Table of Contents

1. Summary

This report documents the work done under the second phase of work performed under contract no. DE-FC36-08GO18034 between the Department of Energy (DOE) and SkyFuel. The first phase of the work was analytical, and resulted in a performance model and optimized design for a linear Fresnel collector. The second phase included detailed design of the linear Fresnel collector with refined cost estimates, and verification of the design and performance models with the fabrication of a prototype collector.

The linear Fresnel solar collector architecture is comprised of a central, fixed linear receiver and rows of mirrors parallel to the receiver. The mirror rows track the sun through the day to focus the reflected light onto the receiver. The receiver absorbs the light, and converts it into thermal energy carried by a heat transfer fluid (HTF).

In this report, the linear Fresnel collector design is referred to as a “Linear Power Tower” or LPT. This nomenclature was adopted because the fundamental concept described in this research is a linear Fresnel collector that operates at high temperatures (550˚C) with molten salt as the heat transfer fluid (HTF), similar to many “Power Tower” collector systems.

The high temperature LPT was pursued based on several observations:

- The higher operating temperature of molten salt substantially reduces storage cost,
- Linear Fresnel collectors use large diameter receivers that freeze slowly – a potential problem with molten salt - than smaller parabolic trough receivers,
- Linear Fresnel collectors incorporate large apertures with low profile mirrors, subject to lower wind loads. Wind loads are a fundamental determinant in collector cost.

Wind tunnel tests for the linear Fresnel architecture were performed. The wind loads for the linear Fresnel system were about ten percent of the corresponding load for parabolic troughs in lift and drag, and forty percent of the corresponding pitching moment. These reduced loads were incorporated in the design of the collectors.

A detailed design of the was undertaken, and full scale structural tests demonstrated the anticipated elastic buckling failure criterion and defined a limit that did not impact optical

performance after a wind event. The optimized design used a structure with 13 cells. The optimum cost occurred with 26 mirror modules per drive string.

Analysis indicated that multiple actuators with a coupled power source had a lower cost than a single actuator driving multiple rows, or multiple actuators and multiple power sources. The drive and control system relies on a common power source for ten actuators, with a rotary actuator at each string of 26 modules.

A prototype linear Fresnel collector was fabricated and installed. This prototype was built to represent a portion of the full collector and was fully functional. The prototype was built in an east-west orientation so that near-normal performance calculations could be made with the low elevation of the sun during winter months.

Data from operation confirmed that:

- The theoretical model to predict linear Fresnel performance was accurate, and
- The prototype collector design met performance goals.

At the outset of this research, the assumption was made that the financial benefit of linear Fresnel over parabolic trough was its compatibility with molten salt as a heat transfer fluid. However, in the time that this research was performed, molten salt receivers for parabolic troughs have become commercially available are in operation in a utility demonstration facility. SkyFuel is actively engaged in developing a large aperture parabolic trough collector design for molten salt operation under separate DOE funding. Parabolic trough design has advanced, is lower in cost, and SkyFuel believes it will offset any potential LPT advantage with molten salt.

Further, the annual performance of a linear Fresnel collector is severely limited by cosine losses; the mirrors do not remain normal to the incident solar radiation. The effective aperture of the collector changes substantially with the time of day and season. This reduces annual performance by twenty to thirty percent compared to line focus collector architectures like the parabolic trough.

It is our conclusion that the linear Fresnel technology does not reach parity with parabolic trough technology, nor is it reasonable to expect further cost reductions will result in that parity. We recommend against further commercial development of linear Fresnel technology.

2. Wind Tunnel Testing (Task 2.1)

SkyFuel contracted Cermak, Peterka, Peterson, Inc. (CPP) Wind Engineering to perform initial wind tunnel studies of a linear Fresnel mirror array. The results of these tests have been previously reported in the Phase 1 report (Brost and Zhu 2009) and the CPP report (Damiani and Peterka October, 2008).

2.1. Method

Figure 1 shows a model of a linear Fresnel collector placed in a wind tunnel at CPP. This was an architectural test wind tunnel, so the wind tunnel floor upstream of the test section contains obstacles placed to simulate ground obstructions causing boundary-layer turbulence. The model was placed on a turntable, allowing simulation of various defined wind directions.

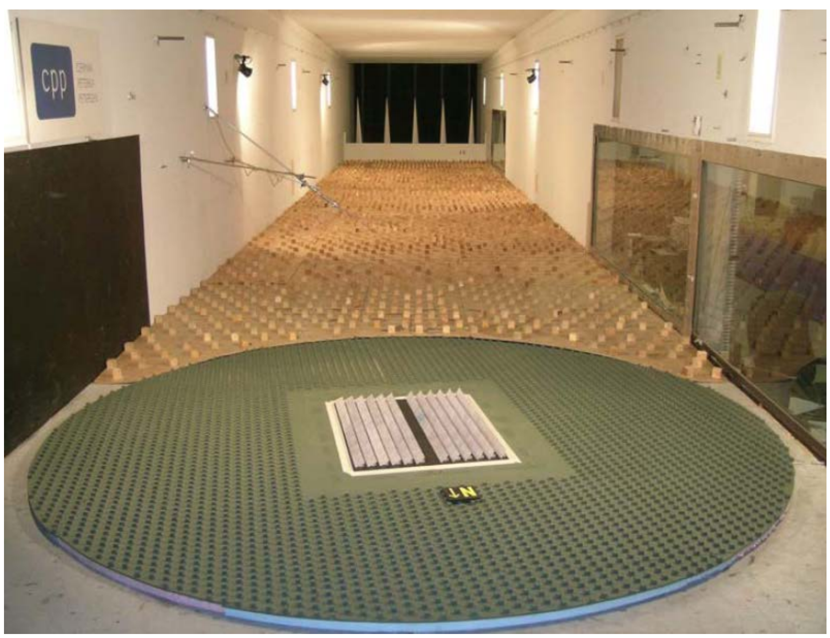


Figure 1 – Wind tunnel at CPP Wind Engineering.

Figure 2 shows one of the wind tunnel test models of a linear Fresnel mirror array. Each mirror panel contained an array of holes which were pressure measurement ports. Each hole was the outlet of an air passage leading to a pressure sensor which measured pressure variations in real time. Each hole seen on the top surface of a mirror was matched by a corresponding hole on the back surface, and each connected to a different pressure sensor. Sensor readings from the front and back surface were then compared to determine the front-to-back pressure difference. Multiplying this net pressure by the surrounding area determined the net load on the mirror. These net loads fluctuated over time, and were tracked to determine the worst-case load.

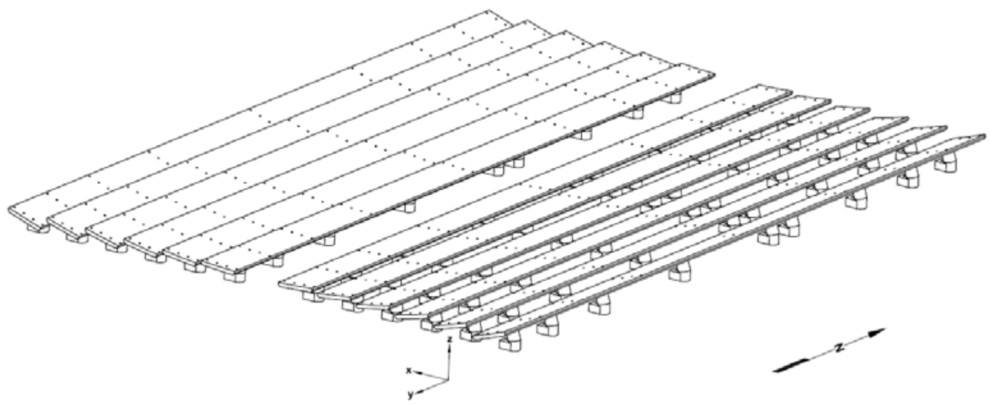
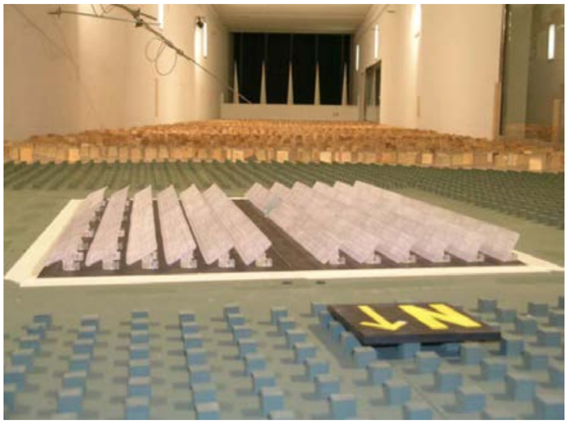
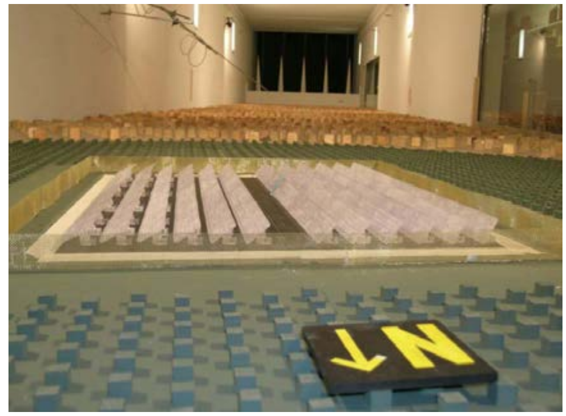


Figure 2 – Example linear Fresnel mirror array model used in testing.

Figure 3 shows a close-up view of the model installed in the wind tunnel, both with and without a wind fence in place. Early tests determined that a wind fence provided a significant decrease in worst-case wind loads, so most tests were performed with a wind fence in place.





(a) (b)

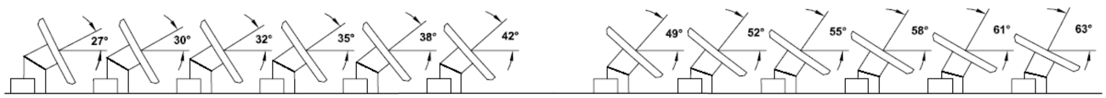
Figure 3 – Model in wind tunnel, (a) without and (b) with wind fence.

Multiple models were fabricated and tested, corresponding to different mirror tilt positions. These configurations are described in Table 1 and shown in Figure 4. Configuration E01 did not include a wind fence around the model. The remaining configurations included a wind fence. The first three “F” configurations correspond to solar tracking configurations for various sun positions; the last two configurations correspond to possible inverted stow configurations. All configurations were subjected to a full battery of wind tests.

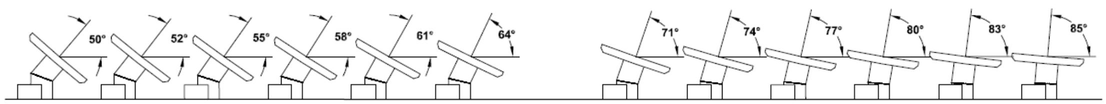
Table 1 – Wind Tunnel Testing Configurations

Configuration	Description
E01	12-reflector array, pivot axis is N-S, Sun Angle 0º (refer to dwg) w/ .5" cube TT
F01	12-reflector array, pivot axis is N-S, Sun Angle 0º (refer to dwg); w/ PERIMETER SCREEN w/ .5" cube TT
F02	12-reflector array, pivot axis is N-S, Sun Angle 45º (refer to dwg) ; w/ PERIMETER SCREEN w/ .5" cube TT
F03	12-reflector array, pivot axis is N-S, Sun Angle 90º (refer to dwg) ; w/ PERIMETER SCREEN w/ .5" cube TT
F04	12-reflector array, pivot axis is N-S, Sun Angle -60º GANGED (refer to dwg) ; w/ PERIMETER SCREEN w/ .5" cube TT
F05	12-reflector array, pivot axis is N-S, Sun Angle -60º SYNCHRONIZED (refer to dwg) ; w/ PERIMETER SCREEN w/ .5" cube TT

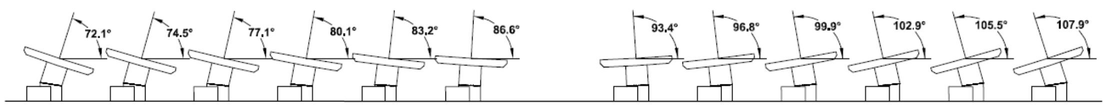
(Damiani and Peterka October, 2008)



F-01



F-02



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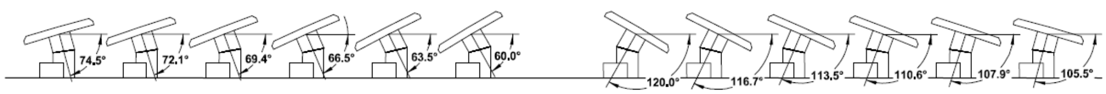

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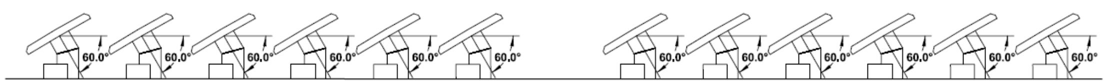

F-05

Figure 4 – Mirror configurations tested.

3. Recommendations

3.1. Comparison with Parabolic Troughs

Recent work by SkyFuel has resulted in a large aperture trough design (DSP Trough) with a significantly reduced installed cost (White 2011). The DSP trough collector costs more than the Fresnel collector on a unit aperture basis, but has higher annual output for the same aperture area. Both of these factors affect the LCOE of the collector designs. Lower specific collector cost, even when coupled with secondary capital cost savings such as reduced land cost, does not overcome the reduction in annual performance.

3.2. Recommendation

The viability of linear Fresnel collector technology hinges upon the reduction of installed system cost overcoming the annual performance reduction compared to parabolic troughs. However, research from this project shows that the LCOE for low-cost linear Fresnel collectors is still ten percent higher than that for troughs.

Linear Fresnel offered some secondary benefits compared to parabolic trough, for example reduced land usage and reduced fluid delivery costs. These benefits were included as a part of the LOCE estimates, however the financial impact was small. High temperature receivers are not commercially available for linear Fresnel projects. Linear Fresnel installations have a greater financial risk due to their low rate of installation; however, debt to equity ratios or interest rates were not adjusted to compensate for these hurdles.

At the outset of this research, SkyFuel noted that a benefit of the linear Fresnel was its inherent compatibility with molten salt as a heat transfer fluid. Operation with molten salt at high temperatures (550°C) substantially reduces the storage cost over operation with conventional fluids such as VP1 at 400°C. A unique feature of the linear Fresnel compared to troughs is the receiver diameter; specifically, a larger diameter receiver takes longer to freeze than the smaller diameter trough receivers. Since this research began, molten salt trough receivers have become commercially available at prices competitive with conventional trough receivers. Also, a molten salt trough demonstration facility is in operation. While the issues related to use of molten salt in parabolic trough collector fields have not been fully resolved, molten salt parabolic trough collectors with small diameter receivers have been fielded and operated with plans to add additional fields.

Taking all of these technology factors into account, the viability of linear Fresnel collector technology hinges upon extraordinarily large and unrealistic reductions in installed system cost in order to overcome the annual performance reduction compared to parabolic troughs. It is our conclusion that linear Fresnel technology cannot reach parity with parabolic trough technology. We recommend against further commercial development of this collector technology.

4. List of Figures

5. List of Tables

6. Bibliography

Brost, Randy, and Guangdong Zhu. *Commercial Development of an Advanced, High Temperature, Linear-Fresnel Based Concentrating Solar Power Concept.* Phase 1 Report, Albuquerque, NM: SkyFuel, Inc, 2009.

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