# Advanced Fresnel Reflector Powerplants - Performance and Generating Costs

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## *ABSTRACT*

This paper describes some of the results of a recent study commissioned by the New South Wales Government on the performance of a new solar array technology called the Compact Linear Fresnel Reflector (CLFR). The performance and cost of this technology are reported for application in large-scale solar thermal electricity generation plants. Comparisons are made of the relative performance and cost compared to parabolic dish and Solel trough solar thermal technologies and future photovoltaic plants. The results suggest that the CLFR is the lowest cost option for large scale solar electricity plant in the foreseeable future.

## 1 INTRODUCTION

Solar thermal electricity has been successfully demonstrated on a large scale in California over the last 15 years, but further cost reductions are needed to establish a place in low cost electricity grids in developed nations. Two approaches have been recently developed in Australia to achieve this goal. The first is the development of large Paraboloidal Dish systems by the Australian National University. A prototype dish has been built in Canberra, and has been supported by the NSW Department of Energy and Australian electricity utilities. The second approach came from a realisation that trough technology (such as the Luz) was near its design limits without some fundamental changes to the absorbing surface. In 1991, Sydney University developed new selective surfaces for solar evacuated tube absorbers (Mills, 1991; Zhang and Mills, 1992). In Mills and Keepin (1993), it was shown that the use of such surfaces in new low concentration designs could dramatically reduce system costs, and increase performance. The Mills and Keepin paper used polar axis trough collectors as the example of a low concentration collector, but there are in fact several low concentration designs that could use advanced evacuated tubes.

In mid-1996, the New South Wales State Government (SERDF, 1997) engaged Solsearch Pty. Ltd. to carry out a feasibility study on which this paper is based. By late 1996, a group of 14 industry and government partners agreed to fund a business plan be for the establishment of a solar thermal test facility and a joint venture for marketing of the technology. At the time of writing, the business plan is being undertaken with the assistance of the original proposers.

The Solsearch feasibility study on which this paper is based provides information for scenario analysis within the business plan. The New South Wales Government, who have supported the feasibility study, have also funded an associated project to establish an advanced evacuated tube production facility for powerplant evacuated tubes in Sydney (SERDF, 1996).

## 2. CLFR TECHNOLOGY

The classical linear Fresnel system uses an array of mirror strips close to the ground to direct solar radiation to a single linear elevated fixed receiver. The first to apply this principle in a real system for solar collection was Francia (1968) who developed both linear and two axis tracking Fresnel reflector systems. One substantial difficulty with the Linear Fresnel Reflector (LFR) technology is that avoidance of shading and blocking leads to increased spacing between reflectors, which in turn leads to large ground utilisation relative to collector area.

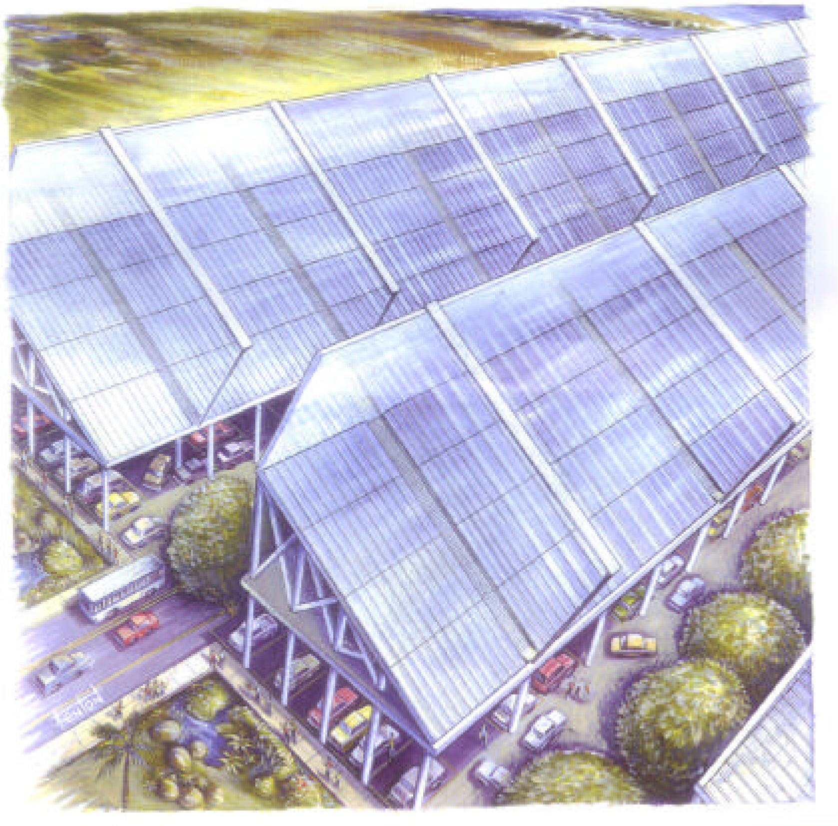

Fig. 1. Artists impression of an inclined CLFR over a parking lot in an urban environment. Inclining the array towards the equator improves the winter performance. Drawing courtesy of Greenpeace

Compact linear Fresnel reflector (CLFR) technology is a new configuration of the Fresnel Reflector field that overcomes the problem of reflector spacing. Traditional LFR technology design is based around one absorber tower. The classical linear Fresnel system has only one linear receiver, and therefore there is no choice about the direction of orientation of a given reflector. However, if one assumes that the size of the field will be large, as it must be in technology supplying electricity in the multi-Megawatt class, it is reasonable to assume that there will be many linear receivers in the system. If they are close enough then individual reflectors have the option of directing reflected solar radiation to at least two receivers. This additional variable in reflector orientation provides the means for much more densely packed arrays and lower absorber tower heights, because patterns of alternating reflector orientation can be set up such that closely packed reflectors can be positioned without shading and blocking. The interleaving of mirrors between two linear receiving towers is shown in fig 2.

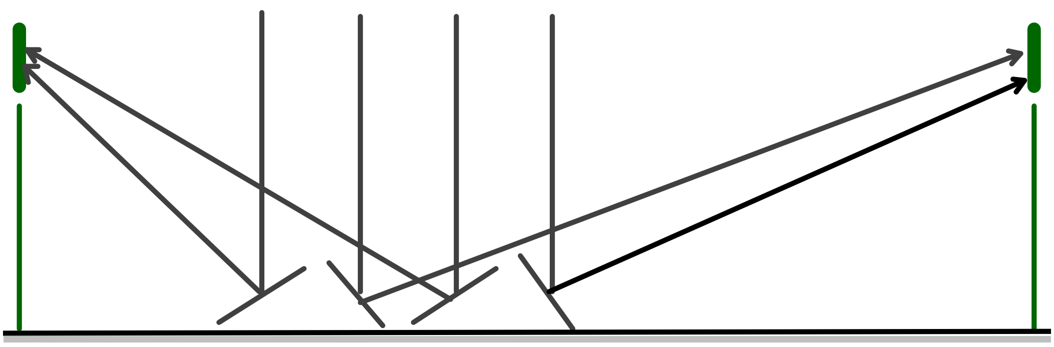

Fig. 2 Schematic diagram showing interleaving of mirrors without shading between mirrors.

The avoidance of large reflector spacings and absorber tower heights is an important issue in determining the cost of ground preparation, array substructure and absorber tower structure costs, steam line thermal losses and steam line cost. The more flexible CLFR still delivers the traditional benefits of a Fresnel reflector system, namely small reflector size, low structural cost, fixed receiver position without moving joints, and the ability to use non-cylindrical receiver geometry.

The CLFR power plant concept is a new optical layout that includes the following additional features which enhance the system cost/performance ratio :

a) The array uses flat or elastically curved reflectors instead of costly sagged glass reflectors. The reflectors are mounted close to the ground, minimising structural requirements.

b) The heat transfer loop is separated from the reflector field and is fixed in space thus avoiding the high cost of flexible high pressure lines or high pressure rotating joints as required in the trough and dish concepts.

c) The heat transfer fluid is water, and passive direct boiling heat transfer could be used to avoid parasitic pumping losses and the use of expensive flow controllers. Steam supply may either be direct to the power plant steam drum, or via a heat exchanger.

d) All glass evacuated tubes very low radiative losses can be used as the core element of the linear absorber array. These tubes are inexpensive, with individual tubes likely to cost US$11 - 15.

e) Maintenance will be lower than in other types of solar concentrators because of nearly flat reflectors and ease of access for cleaning, and because the single ended evacuated tubes can be removed without breaking the heat transfer fluid circuit.

The authors have investigated alternative versions of the basic CLFR concept to determine which are most worthy of development. Aspects of the concept investigated in the Solsearch optimisation study included absorber orientation, absorber structure, the use of auxiliary reflectors adjacent to the absorbers, reflector field configuration, reflector packing densities, and absorber tower heights. Basic CLFR arrangements include analogues of the east-west axis parabolic trough, the north-south axis parabolic trough, and the polar axis parabolic trough. In the latter, the axis is inclined toward the equator at the latitude angle.

In this project most of the early investigation was done on a horizontal east-west axis array using a vertical arrangement of evacuated tubes illuminated from both sides or a horizontal array illuminated from one side. However, North-South arrays were found to deliver greater annual output than East West arrays for all the locations considered in this study.

A North-South array can also be inclined toward the equator to increase winter and annual collection (fig. 1). When the inclination angle is equal to the latitude angle, the array is called a polar axis tracking array. Polar axis arrays yield close to the optimal annual performance. Inclining the array necessitates spacing between the inclined planes of reflector to avoid winter shading, and decreases output per unit ground area compared to a horizontal North South array. Inclined North South arrays have a flatter seasonal output profile compared to horizontal arrays, however, they require a more expensive substructure than horizontal arrays.

## 3 CLFR STUDY RESULTS

The first task in this project was to model alternative versions of the basic CLFR concept to determine the most suitable configuration for further development. Associated with this task was the need to develop models of the paraboloidal dish and parabolic trough systems for comparison. The modelling of the CLFR reflector and absorber required the development of a purpose designed multi-branched raytrace model for the optimisation of the reflector and absorber optics. The results of the feasibility study are as follows:

a) A new absorber tube configuration based on rows of single ended evacuated tubes has been developed. This configuration produces absorption equivalent to a theoretical flat plate vacuum absorber.

b) The best orientation of the rack of evacuated tubes was found to be horizontal rather than vertical as originally proposed.

c) The optimum size of the absorber for vertical and horizontal configurations was determined.

d) Configurations having high reflector field density deliver improved cost/performance. Very dense fields are possible for roof integrated collectors for process heat applications.
e) The North South Polar Field with the array mounted on an inclined structure was evaluated. Polar configurations have a high aperture utilisation and good cost/efficiency but exhibit a poorer ground usage than the horizontal mirror field system because spaces must be left between rows to avoid shading.

f) Linear cavity absorbers with a selective surface were modelled for horizontal field configurations. The cavity absorber cost/performance is good but it is an unproven concept in terms of the long term durability of the selective surface in air.

g) Ganged reflector versions of the CLFR were found to perform very well thus simplifying the tracking system.

## 4 SOLAR SYSTEM PERFORMANCE MODELLING

Solar radiation and thermal simulation models of the collectors were developed in the TRNSYS modelling environment. TRNSYS is a transient system simulation program designed to analyse any transient thermal process. For this project a series of extensions were developed within TRNSYS to simulate parabolic trough and linear Fresnel concentrating collectors. Due to the modular nature of TRNSYS these new routines were integrated with the existing data handling and solar radiation analysis routines that are a feature of TRNSYS.

To model the CLFR, the basic TRNSYS collector routine was modified to include a specification of optical concentration through a biaxial incidence angle modifier map produced by a raytrace. A new routine was designed to accept an incidence angle modifier map with up 50 incidence angles in both the longitudinal and transverse planes.

### 4.1 CLFR Thermal Model

The absorber of the proposed linear Fresnel collector consists of a rack of evacuated tube absorbers mounted in two rows so that the absorber is equivalent to an evacuated flat plate absorber. The heat loss from the evacuated tube rack was determined from the measured characteristics of single evacuated tubes (Harding 1985), with the emittance lowered to the values characteristic of the advanced selective coatings.

The heat loss modes are
- Radiation from the absorber
- Conduction through the insulated header
- Conduction through the glass envelope at the open end of the tube
- Conduction through the metal retainer near the closed end of the absorber tube

The emissivity of advanced stainless steel - copper selective absorber surfaces are shown in fig. 3 together with the emittance of the Luz selective surface. For the stainless steel surface there is a trade-off between absorptance and emittance.

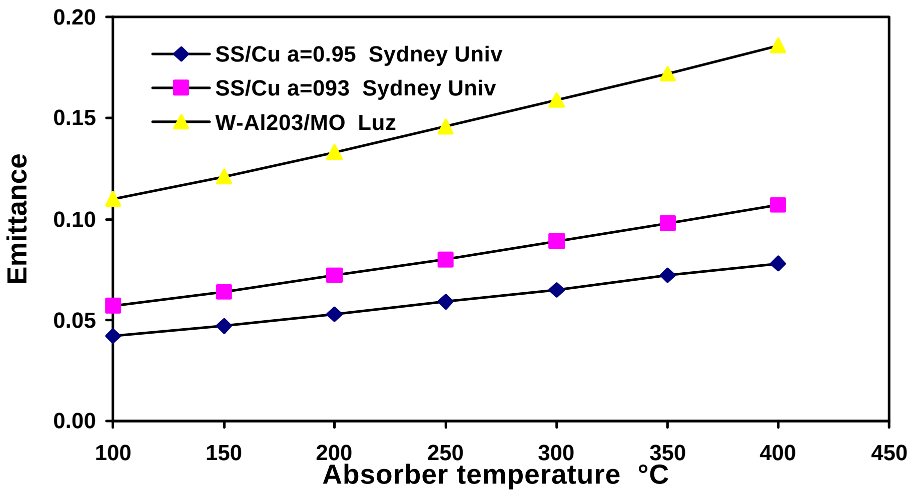

Fig 3.  Emissivity of selective surfaces modelled.

The CLFR assumptions are as follows: a 50 metre wide array is assumed with reflector densities of 24, 36 and 48 reflectors per absorber line.  Each reflector is 1 metre wide with 0.95m actual reflector surface and the rest taken up by edge structure.  Each configuration is calculated for three tower heights, 10m., 12.5 m., and 15 m.  An equal spacing of mirrors is assumed.  A space 1 metre wide is left clear on either side of the tower for access and maintenance.

## 4.2 Parabolic Trough Solar Collector Thermal Model

The parabolic trough concentrator with evacuated tube absorber collector is used in the Luz solar electric power generation (SEGS) plants. A expression for the collector efficiency was developed in terms of absorber wall temperature by computing radiation and convection losses and using test data from SANDIA for the LS2/LS3 collectors, Dudley et al (1994) to determine conduction losses through residual gas and the end bellows.  The model was then combined with Australian weather data to determine the annual performance of the LS3 collector for the locations of interest.

## 4.3 ANU Dish System Thermal Model

The ANU paraboloidal dish is the largest aperture dish system currently operating (395 $m^2$).  Peak thermal loss from an ANU dish operating with direct steam generation has been reported to be 51.3 kW for an operating temperature of 500°C ((Stein, 1996).  The beam radiation for this measurement was 1000 $W/m^2$ which is higher than normal.  For the following analysis a beam intensity of 900 $W/m^2$ is used for peak array sizing purposes.  At the 320°C operating temperature used in this study the thermal loss is estimated in this report to be 51.3kW * (500-20)/(320-20) = 32.1 kW.  Peak input power is $395m^2$*0.9 $kW/m^2$ = 356 kW.  Thus the heat loss at beam intensity of 900 $W/m^2$ is 9%, or a thermal efficiency loss factor of 0.91.  Heat loss from connecting header pipes has been estimated by Lovegrove (1995) to be 8.7% at 500°C, which would be corrected to 5.4% of beam input at 320°C.  A performance simulation with a crude TRNSYS model which includes receiver and steam line capacitance effects suggests that the annual total thermal efficiency loss due to capacitance would be approximately 5%.  The optical and thermal loss factors for the single and array Dish aspects are given in tables 1 and 2.

**Table 1.**
**Paraboloidal dish optical loss factors**

| Loss Factor | Fraction of incident beam radiation | Cumulative effect |
|---|---|---|
| **Input beam radiation** | 1.0 | 1.0 |
| **Single dish optical losses** | 0.92 | 0.92 |
| **Single dish peak thermal losses** | 0.91 | 0.84 |
| **System related thermal losses** | 0.92 | 0.77 |
| **Array shadowing** | 0.90 | 0.70 |

A comparison of the heat loss from the CLFR Fresnel concentrator for three mirror densities, the Luz trough and the ANU parabolic dish is shown in Table 2.  The heat loss per unit aperture of the high-density CLFR reflector configuration is comparable to the Dish and LS3 collectors at temperatures of 300 to 400°C.

## 4.4 Comparison of System Thermal Performance

Table 2 gives comparative heat losses from alternative systems, showing that the CLFR varies from lowest to highest per unit of collection area. In table 3 the modelled aperture performance of the standard CLFR Horizontal and Polar arrays, and the modelled LS3 and Dish arrays are presented for the four locations used in the study.  The aperture performance of the Dish is superior in all cases.  The LS3 system performs in between the two CLFR versions.  The standard CLFR versions are chosen for cost effectiveness not for aperture efficiency. The polar tilted array significantly improves winter performance for higher latitudes (>20°).

**Table 2.**
**Comparison of heat loss from alternative concentrator systems**

| Absorber surface temperature °C | Heat loss per unit area of reflector W/m$^2$ | | | | |
|---|---|---|---|---|---|
| | CLFR 24 | CLFR 36 | CLFR 48 | Luz | Dish |
| **100** | 10.5 | 7.0 | 5.3 | 5.7 | 17.3 |
| **200** | 31.2 | 20.8 | 15.6 | 18.2 | 40.4 |
| **300** | 68.1 | 45.4 | 34.0 | 42.4 | 66.0 |
| **400** | 133.7 | 89.2 | 66.9 | 87.6 | 95.3 |
| **500** | 246.2 | 164.1 | 123.1 | 167.1 | 129.7 |

**Table 3.**
**Annual thermal energy delivery for 300°C saturated steam.**

| System | Annual daily average energy delivery MJ/m$^2$ day | | | |
|---|---|---|---|---|
| | Sydney | Wagga | Dubbo | Longreach |
| **Horizontal CLFR 24 mirror array** | 7.35 | 7.95 | 11.4 | 11.3 |
| **Polar CLFR 24 mirror array** | 9.16 | 9.49 | 14.1 | 12.6 |
| **Horizontal CLFR 48 mirror array** | 6.23 | 6.7 | 9.49 | 9.49 |
| **Polar CLFR 48 mirror array** | 7.88 | 8.12 | 11.9 | 10.7 |
| **LS3 trough** | 7.34 | 8.06 | 10.2 | 11.0 |
| **Dish** | 10.6 | 11.7 | 16.9 | 15.2 |

## 5. Financial Modelling

During the early stages of this project, a German government funded report was published on the LS3 technology by Pilkington Ltd (Pilkington, 1996). This report gives an excellent analysis of the solar trough technology and provides useful information that allowed the authors to present a comparative financial analysis of the alternative technologies. The generating cost for alternative systems was evaluated using the basic Pilkington financial model with the same power block in each system. The estimated annual thermal output from the TRNSYS modelling was used in the spreadsheet in place of the trough output in the original Pilkington spreadsheet. Comparisons included LS3, CLFR, Dish, and a future PV technology. The site of Dubbo in New South Wales was used for the modelling because detailed one minute solar radiation data was available for that site. The electricity generating costs for Dubbo (including solar and power block costs) in Australian cents per kWh(e) are presented in fig 6. Levelised cost parameters used by Pilkington were also adopted for the cost analysis in Australia, these are, 25 year lifetime, 6.7% depreciation rate, 8% annual discount rate, 1% annual insurance rate, 0% annual income tax rate. A PV system based on installed cell costs of A$3 per peak watt was included for comparison, this cell price has been suggested as a selling price for thin film systems in 2001-2005.

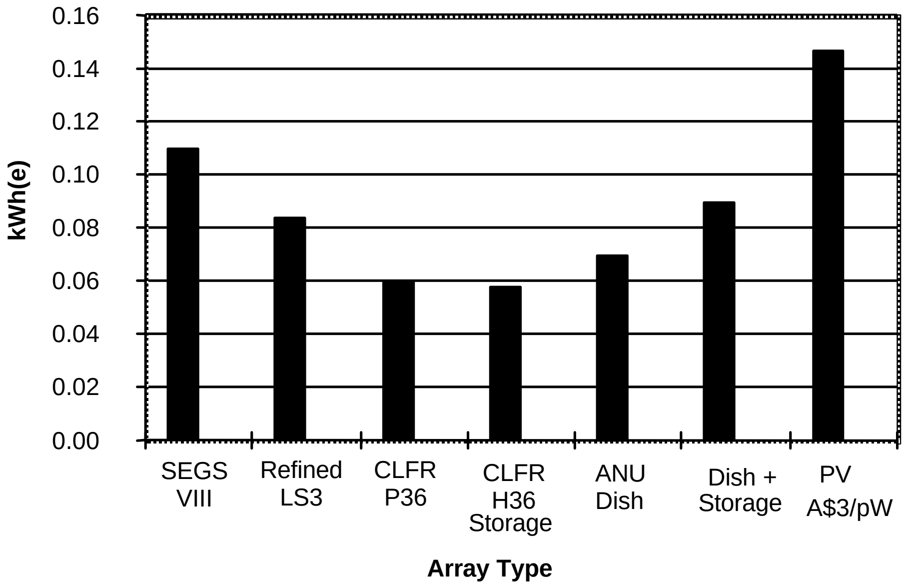


Fig 5. Life cycle generating cost for alternative systems for Dubbo. CLFR P36 has 36 mirrors/absorber in polar configuration, CLFR H36 has 36 horizontal mirrors/absorber. Costs for systems using storage, (rock bed or ammonia) were based on projected costs of US$670 per peak Watt storage capacity, the PV cost is expected between 2001 and 2005.

## 6. CONCLUSIONS

The full project demonstrates that

a) Both the Fresnel and Dish Australian collector options are cheaper than the LS3 or PV options. For PV to compete with the Polar CLFR it's cost must drop to US$1 per peak Watt for an installed system. This includes balance of system costs which are currently US$3-4 per peak Watt on their own. Such a system will still be more intermittent than a solar/gas system, and more polluting if coal is the backup energy form.

b) The ANU parabolic dish complete system was 16% more costly than the cheapest CLFR system, but the CLFR collector was only 26% of the system cost in the latter, so the difference in array cost is substantial.

c) Land occupation was by far the lowest in the case of dense reflector field versions of the horizontal CLFR, followed dense reflector field versions of the Polar CLFR. The CLFR has a clear advantage over other technologies in this respect. For large plant in inland NSW, optimised medium reflector density Polar CLFRs would occupy about the same land area as an optimised Dish system.

Both the CLFR and large parabolic dish solar thermal systems potentially more competitive than LS3 or photovoltaic generation for the foreseeable future. Up to this time, most investment in solar energy has gone toward photovoltaic system development, but for large scale pollution reduction, this is unlikely to be cost efficient in the time frame when pollution reduction is required (2000 - 2020). The CLFR system has important advantages over the Dish, including lower cost, lower maintenance and lower land use related costs. The difference is unlikely to reverse with continued development, and would be increased in storage systems.

In large scale production the CLFR technology can make a major contribution to emissions reduction programs without net societal economic cost because the difference between the cost of solar generated power and gas based power is below environmental pollution offset costs. Used as a replacement for aging coal peaking plant, CLFRs could be introduced on a large scale in a time frame well before similar low cost photovoltaic are available. The conclusion of this study is that the CLFR systems could be developed as a simple and low cost solar technology suited for large-scale implementation in the medium term.

## 7 ACKNOWLEDGMENTS

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## 8 REFERENCES

Cohen G. (1993) *Operation and efficiency of large-scale solar thermal power plants*. Optical Materials Technology for Energy Efficiency and Solar Energy Conversion, SPIE V2017, 332-337.

Cohen, G. and Kearney, D. (1994). *Improved parabolic trough solar electric system based on the SEGS experience*. Proceedings of the 1994 annual conference, ASEC 94, 147-150.

Dudley, V. E., et al (1994) *Test results for SEGS LS-2 solar collector.* SANDIA Report 94-1884.

Francia, G. (1968) *Pilot plants of solar steam generation systems.* Solar Energy 12, 51.

Harding, G.L. et al (1985) *Heat extraction efficiency of a concentric glass tubular collector.* Solar Energy 35, 71-79.

Lovegrove, K, and Banfal, P. (1994) *Optimal design of the heat transport network for a distributed dish solar thermal system.* Proc. 7th International Symposium Solar Concentrating technologies, Moscow, Sept. 26-30.

Mills, D. R. (1991) *High temperature solar evacuated tube for applications above 300°C*. Energy Research and Development Corporation report #1368. Dept. of Primary Industries and Energy, Canberra, ACT 2601.

Mills, D.R. and Keepin, W. (1993). *Baseload Solar Power.* Energy Policy, pp 841-893, August.

Pilkington (1996) *Status report on solar thermal power plants.* ISBN 3-9804901-0-6, Pilkington Solar International, Muhlengasse 7, D-50667 Cologne, Germany.

SERDF (1996) New South Wales State Energy Research and Development Grant to the University of Sydney *Sputtered coatings for solar power plants.* NSW Department of Energy, granted June 1996.Stein, 1996. Personal communication from project participant Mr. Wes Stein, Pacific Power, Park and Elizabeth Streets, GPO Box 5257, NSW 2001, Australia.

Zhang, Q.-C. and Mills, D.R. (1992*) High solar performance selective surface using bi-sublayer cermet film structures*. Solar Energy Mater. and Solar Cells, vol.27, pp.273-290.