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A HYBRID SOLAR CONCENTRATOR PV SYSTEM FOR THE ELECTROLYTIC PRODUCTION OF HYDROGEN

R.D. McConnell,[1] J.B. Lasich,[2] and C. Elam[2]
[1] National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA, email: robert_mccconnell@nrel.gov
[2] Solar Systems Pty Ltd., 6 Luton Lane, Hawthorn, Melbourne VC 3122, Australia, email: jlasich@solarsystems.com.au
[3] U.S. Department of Energy, Golden Field Office, 1617 Cole Blvd., Golden, CO 80401 USA, email: carolyn.elam@go.doe.gov

ABSTRACT: The principal criticisms for considering photovoltaics (PV) for generating hydrogen have been the high cost of PV electricity and low efficiency of PV systems. Recently, however, concentrator PV systems have demonstrated the potential for generating lower-cost electricity, primarily due to the development of solar cells approaching 40% conversion efficiency. Another critical factor for concentrator PV systems is the generation of heat, normally dissipated to the environment, which can enhance the electrolysis of water by using a high-temperature, solid-oxide electrolysis cell. This heat boost—40% measured by one of the authors and confirmed in recent theoretical analyses—provides significant increase in output and economic benefits, thereby creating opportunities for PV to contribute to future transportation markets and even to store PV electricity using lower-cost hydrogen storage.
Keywords: Concentrators, High Efficiency, Hybrid

1 INTRODUCTION

The generation of electrolytic hydrogen from solar energy may be critically important to the world's long-term energy needs for several reasons. The feedstock (water) and solar energy are both carbon free, having no adverse impact on global warming. The solar resource is extensive, with the potential to generate hydrogen near markets, thus minimizing transportation costs. In the past, the principal criticisms for considering PV for generating hydrogen were the high cost of PV electricity and low efficiency of PV system. Recently, however, concentrator PV systems have demonstrated the potential for generating lower-cost electricity, primarily due to the development of solar cells approaching 40% efficiency and reliable concentrators that can use them. Another critical factor favoring concentrator PV systems is the generation of byproduct heat, normally dissipated to the environment, which can augment the electrolysis of water by using a high-temperature solid-oxide electrolysis cell. This heat boost—40% measured by one of the authors at temperatures above 1100°C—in hydrogen production leads to potential solar-to-hydrogen conversion efficiencies of 40% in the near term (i.e., next few years), whereas efficiencies of 50% and higher are realistic targets within 5–10 years. These efficiencies exceed those of any other methods previously considered for producing electrolytic hydrogen from solar electricity.

This paper describes the experiments, presented in two early patents for this approach, that first demonstrated a 40% boost in hydrogen production above that associated with the electrical output alone from the solar cells. We also provide efficiency and cost analyses for generating hydrogen using today's high-efficiency solar cells in the hybrid solar concentrator. These results, based on the long-term potential for concentrator PV (CPV) systems to be mass produced at costs of less than \$1/W, lead to hydrogen production costs comparable with the energy costs of gasoline—recognizing that 1 kg of hydrogen has the energy equivalent of one U.S. gallon of gasoline. Further development and demonstration will be needed to realize the potential of this innovative solar concentrator for generating hydrogen.

2 SYSTEM DESCRIPTION

2.1 Dish concentrator PV system

Solar Systems Pty Ltd. in Australia has developed their dish CPV system over the past 15 years. Figure 1 shows several of their dish concentrators operating on aboriginal lands near Alice Springs, Australia. The visitors at the site indicate the size of the units. Each dish produces about 20 kW using high-efficiency silicon solar cells, but can also accommodate new high-efficiency III-V multijunction solar cells to achieve 30 kW.

Figure 1: Solar Systems' solar farm of dish concentrators on aboriginal lands near Alice Springs, Australia. Each dish is nominally 20 kW. Note the visitors.

2.2 Spectral splitter

The spectral splitter is placed near the focal point of the dish receiver and reflects infrared energy. Visible light is transmitted through to the solar cells and converted into electricity. Figure 2 schematically shows the transmission across the solar spectrum wavelengths.

2.3 Hybrid system

In Solar Systems' patents [1,2], reflected infrared light is gathered in a fiber-optic waveguide and transported to a high-temperature solid-oxide electrolysis cell. See Fig. 3 for a system diagram of the components.

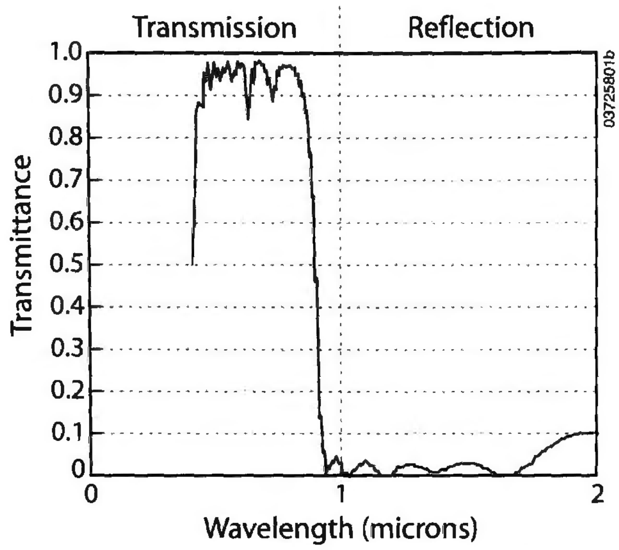

Figure 2: Schematic of a spectral splitter mirror as a function of solar wavelength in microns. Different spectral splitter designs reflect or transmit light across the solar spectrum. For a "hot mirror," light is transmitted in the visible region and reflected in the infrared.

3 SYSTEM TESTS

3.1 Early system tests

The testing of all components shown in Fig. 3 is described in [1,2]. The concentrator was a paraboloidal dish 1.5 m in diameter arranged to track in two axes and capable of producing > 1000-suns concentration. The full dish size was not needed and portions were appropriately shaded. The solar cell was a GaAs PV cell with an output voltage of 1 to 1.1 V at maximum power-point, with a measured efficiency of ~19%. The voltage was an excellent match for direct connection to the electrolysis cell when operating at 1000°C. The electrolysis cell consisted of a 5.8-cm-long by 0.68-cm-diameter yttria-stabilized zirconia (YSZ) closed-end tube coated inside and out with platinum electrodes for the tests. A metal tube surrounding the cell homogenized the solar flux over the surface of the electrolysis cell. The test rig operated above 1000°C for more than 2 hours, with an excess of steam applied to the electrolysis cell. The output stream of unreacted steam and generated hydrogen was bubbled through water, and the hydrogen was collected and measured. Table I shows the following results for 17 minutes of steady-state operation.

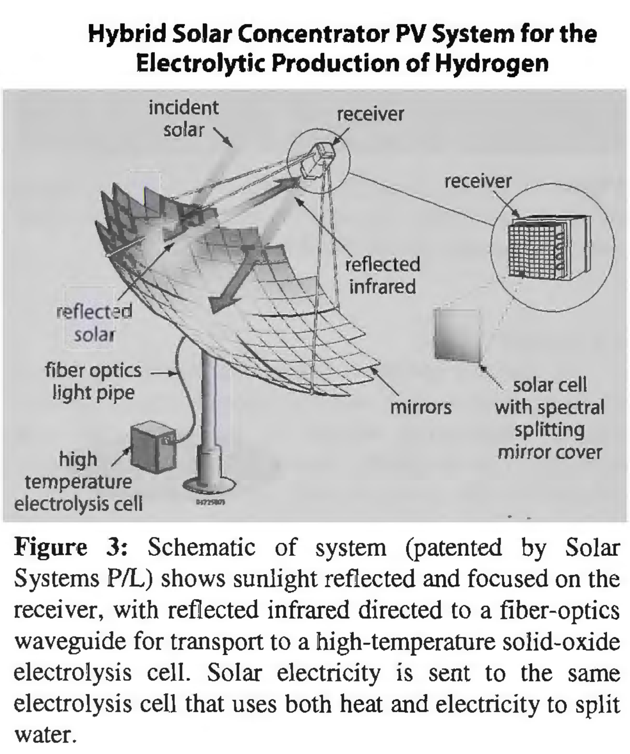

Figure 3: Schematic of system (patented by Solar Systems P/L) shows sunlight reflected and focused on the receiver, with reflected infrared directed to a fiber-optics waveguide for transport to a high-temperature solid-oxide electrolysis cell. Solar electricity is sent to the same electrolysis cell that uses both heat and electricity to split water.

Voltage (V)	Current (A)	Temperature (°C)	H_2 Production (mL)
1.03	0.67	1020	0 (initial)
1.03	0.67	1020	80 (17 min)

Table I: Electrolysis cell measurements at beginning and end of 17 minutes of system operation.

The ratio of the thermoneutral voltage of 1.47 V to the measured electrolysis cell voltage of 1.03 V was 1.43, corresponding to a >40% boost in hydrogen production due to the thermal-energy input. This was also confirmed by energy balance. Combining the optical efficiencies of the concentrator dish (85%), solar cell efficiency (with solar input of 800 W/m^2), and thermal energy boost, the total system efficiency of solar cell, electrolysis cell, and optics was 22% for conversion of solar energy to hydrogen. At the time, this efficiency was almost three times better than that recorded for a working solar plant generating hydrogen.

3.2 Expected results with multijunction solar cells

Since the experiments for these patents were completed, solar cell efficiencies have about doubled from the 19% GaAs cell efficiency used for the system tests and today's world-record efficiency of 37.9% measured at 10 suns for a GaAs-based multijunction solar cell [3]. Similar multijunction cells are commercially available at efficiencies above 30%, being the state-of-the-art power source for today's space satellites. Concentrator companies around the world are working to integrate these high-efficiency multijunction cells into their system designs [3].

Combining the observed thermal enhancement of 40% with a multijunction solar cell efficiency of 35% and an optical efficiency of 85% leads to >40% conversion in the near term. A 40% multijunction solar cell—a result expected in the not-too-distant future—would yield a conversion efficiency of almost 50%. Recent electrochemical theoretical results are consistent with these predictions based on Solar Systems' early experiments [4].

4 COST ANALYSES

4.1 Dish concentrator photovoltaic costs

The largest cost for the hybrid solar concentrator system will be for the dish concentrator and PV receiver. Algora recently completed an extensive cost analysis based on previously collected data for CPV systems [5]. Many of the costs came from installed costs for the 480-kW reflective CPV system in Tenerife. The analysis included a wide range of parameters, including cumulative production of 10 MW for present-day systems to cumulative production of 1000 MW for the mid-term systems where learning is incorporated. Concentrations ranged from 400 suns to 1000 suns, with solar cell efficiencies ranging from 32% to 40%. Whereas module efficiencies ranged from 24.8% to 32.2%, the plant's AC annual efficiency ranged conservatively from 18.2% to 23.6%. Present-day base costs were 2.34 euro/W (almost $3/W with today's exchange rate). The lowest projected costs ranged from 0.5 to 1 euro/W for efficiencies of 40%, 1000-suns concentration, and cumulative production of 1000 MW. We use cost estimates for mature CPV technology to place this cost analysis of hydrogen generated by this hybrid solar concentrator system in a context similar to analyses completed for the electrolytic generation of hydrogen by wind systems (where cumulative production of this highly developed technology is approaching 50 GW) and the conventional production of hydrogen by reforming natural gas. Cost studies for conceptual high-temperature nuclear reactors (projected for mature 600-MW designs) suitable for high-temperature electrolysis cells face similar problems because both the hybrid solar concentrator and high-temperature nuclear reactor are in early stages of exploration for hydrogen generation. Further, high-temperature solid-oxide electrolysis cells will be required in large sizes (500 kW to 500 MW) for integration with nuclear reactors [6]. Units ranging up to 50 kW could be used with dish concentrators and central receivers employed for larger scale.

Using a set of assumptions for a well-developed technology, we acquired costs in $/kW for solid-oxide electrolysis cells from a developer of solid-oxide electrolysis cells [7]. Table II summarizes the cost data for a well-developed technology (1000-MW cumulative production) for the hybrid CPV system and high-temperature solid-oxide electrolysis cell. Table III summarizes the hydrogen production costs for a 10-MW project built with the well-developed technology. We assumed a 20% rate of return per year and did not include operating, storage or delivery costs.

Component costs assuming 1000-MW technology	($/kW)
Concentrator PV	800
Spectral splitter	15
Fiber optics	25
Electrolysis cell	400
TOTAL SYSTEM COST	**1240**

Table II: Component and system costs for 10-MW hybrid CPV project for electrolytic production of hydrogen.

Hydrogen cost data for mature technology	
Plant size (MW)	10
Plant cost ($ million)	12.4
H_2 produced in 1 year (kg)	10^6
Hydrogen cost ($/kg)	2.48

Table III: Hydrogen production data for mature 10-MW plant. The hydrogen cost of $2.48/kg has considerable uncertainty (±25%) related to technology immaturity.

Table IV compares these production costs with those of other hydrogen production technologies.

Process	Hydrogen Production Cost ($/kg)
Gas reformation [8]	1.15
Wind electrolysis [8]	3.10
Hybrid CPV electrolysis	2.48

Table IV: Cost comparison for the hybrid CPV production of electrolytic hydrogen. Note that 1 kg of hydrogen has the energy equivalent of one U.S. gallon of gasoline.

5 DISCUSSION

5.1 Cost analysis uncertainties

There are many cost analyses in the literature for hydrogen production, however, the assumptions behind them vary dramatically. The U.S. Department of Energy and its Hydrogen, Fuel Cells and Infrastructure Technologies Program have established a cost-analysis structure for comparing different hydrogen and fuel cell technologies within a common set of assumptions. The analysis in Table IV is a preliminary study needing additional work to fit within that framework. CPV systems are just beginning to enter the energy market, so cost uncertainties are significant compared with those of highly developed wind systems with a worldwide installed capacity approaching 50 GW. Nevertheless, these preliminary costs are comparable with wind electrolysis costs so that additional cost studies are warranted. Today, wind system costs are in the $800/kW range—as are the estimated costs for highly developed CPV systems—whereas wind electrolysis does not have an opportunity for a heating boost in electrolysis efficiency. Assuming these cost analyses continue to be positive, we will likely plan a larger-scale electrolysis demonstration using the well-developed Solar Systems dish concentrator.

5.2 A hydrogen vision using hybrid solar concentrators

The U.S. National Research Council and Academy of Engineering believes that one of the four most fundamental technological and economic challenges is: "To reduce sharply the costs of hydrogen production from renewable energy sources over a time frame of decades." [9]. Wind electrolysis is a strong renewable energy option, while hybrid CPV electrolysis could be another. Also, the solar energy resource is considered larger and more widely distributed than that of wind energy. And totally new system configurations may be possible with hybrid solar concentrator electrolysis. Small 50-kW systems could be part of hydrogen filling stations, reducing hydrogen distribution costs. Systems could incorporate backup heating sources, probably natural gas in the near term, to improve the electrolysis system capacity factor.

Probably the most dramatic impact of this study has been the realization that this is a possible PV option that could provide transportation fuel on a large scale. In a scenario where hydrogen is used in fuel cell vehicles—which can have double the efficiency of standard internal combustion cars—the "effective cost" of solar hydrogen is half, i.e., $1.24/kg. With European customers presently paying about $2/kg for gasoline, the potential for a very large market clearly exists.

To determine the final price of solar hydrogen to the customer, we would need to factor in the additional costs of operation, distribution, retailing, and taxes versus the reductions due to the "clean and renewable" value of solar hydrogen.

With the imminent market entry of CPV systems for electricity production, the increasing solar cell efficiencies approaching 40% with clearer ideas for 50% solar cells, and the opportunity to use wasted solar heat for augmenting solar electrolysis, this is a potential "leap frog" technology that may rapidly lower the cost of clean hydrogen.

6 CONCLUSION

We have described an innovative hybrid CPV electrolysis technology that offers a cost of hydrogen production lower than wind electrolysis and in the same range as gasoline for much of the world's population. Although the analysis is preliminary, additional cost analysis planned may lead to large-scale demonstrations.

This innovative renewable energy technology could "leap frog" other renewable energy technologies for electrolytic production of hydrogen—a potentially important transportation energy carrier for our future.

7 ACKNOWLEDGEMENTS

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MULTIJUNCTION SOLAR CELLS FOR DENSE-ARRAY CONCENTRATORS

Geoffrey S. Kinsey[1], Raed A. Sherif[1], Hector L. Cotal[1], Peichen Pien[1], Richard R. King[1], Randolph J. Brandt[1], William G. Wise[1], Eduardo L. Labios[1], Kam F. Wan[1], Moran Haddad[1], Jonathon M. Lacey[1], Christopher M. Fetzer[1], Pierre Verlinden[2], John Lasich[2], Nasser H. Karam[1]
[1]Spectrolab, Inc., 12500 Gladstone Avenue, Sylmar, CA 91342, USA
[2]Solar Systems Pty. Ltd., 6 Luton Lane, Hawthorn, Victoria, 3122, Australia

ABSTRACT

A major step forward has been made towards cost reduction of terrestrial PV. World-record multijunction III-V solar cells have been integrated into a commercial Concentrator Photovoltaic (CPV) system.. A dense array of high-efficiency solar cells in the receiver of a high-intensity (~500x) concentrator system has been identified as a viable, cost-effective system. Concentrator Ultra Triple Junction (CUTJ) cells have been developed for use in the Solar Systems CS500 solar electric power generator. The cell is designed for efficient conversion of the specific solar spectrum delivered to the system receiver while minimizing cell cost. Cells are optimized for maximum active area in a Solar Systems dense-array cell module. Solar Systems modules using CUTJ dense-array cells have demonstrated module efficiencies of over 35%. Field testing of CUTJ dense-array cells in a CS500 CPV dish unit at the Hermannsburg solar power plant in Australia was initiated in December 2005. A full multi-junction receiver in a CS500 dish has delivered over 30kW with an efficiency of almost 30%. Following qualification, these systems are slated for entry into the terrestrial market in 2006.

INTRODUCTION

Multijunction solar cells have delivered high efficiencies under the terrestrial spectrum, recently reaching 39% at AM1.5D, low AOD [1]. In order to tap the benefits of this technology in terrestrial applications, economics suggest that these cells be used under high concentration. If the concentration ratio, the optical efficiency, and the cell efficiency are high enough, the potential for a very low system cost exists. In this case, the cost of multijunction cells is a relatively small component of the overall system cost. However, high concentration requires sophisticated management of high fluxes of light, heat, and electricity to achieve maximum power output and to avoid degradation of the cells or the balance of the CPV system. Solar Systems has developed the CS500 solar electric power generator (Fig. 1) using active cooling on a 0.23-m^2 receiver at ~500x [2]. The receiver is composed of 64 modules. Each module is composed of 24 Concentrator Ultra Triple Junction (CUTJ) dense-array solar cells. The CUTJ cells reported in this paper have been optimized specifically for use in a dense array.

CUTJ DESIGN

The CUTJ cell has adapted Spectrolab's UTJ space cell, now in production, to the terrestrial solar spectrum. In order to make these multijunction cells cost effective in a dense array system, the design was modified at every step in the process, from growth to final assembly. The metal-organic vapor-phase epitaxy (MOVPE) growth recipe has been modified in the CUTJ cell to better match the actual spectrum of the concentrated sunlight delivered by the Solar Systems concentrator dish. Cells were designed to deliver maximum current under the specified nominal spectrum in the area of use. These cells were assembled by Solar Systems into modules for on-sun testing. The on-sun testing is providing feedback for further optimization of the growth recipe.

Fig. 1. A Solar Systems CS500 array in Hermannsburg, Australia.

Each of the cells is expected to deliver about 10 A under 500x concentration (50 W/cm^2), so optimization of the front metallization is critical to maintain active area while minimizing resistive power loss. Modeling of the resistive and obscuration losses associated with the frontside metallization was used to determine the optimum design (Fig. 2). A gridline design with less than 10% obscuration and low contact resistance, optimized for ~400x concentration, has been implemented.

The standard cell process is also undergoing streamlining to reduce the cost of the finished cells. Multiple environmental testing programs are ongoing to confirm that the dense-array cells are robust under "real world" highly concentrated sunlight conditions in the field.

The assembly process of the CUTJ cell into modules is a critical step for cells to be used in a dense array. The cell interconnect design has been made compatible with the high-volume pick-and-place machinery used by Solar Systems. CUTJ dense-array cells can be assembled rapidly into modules without introducing electrical shorts or shunts between adjacent cells, and still providing an excellent thermal contact with the heat sink, and a 99% packing density.

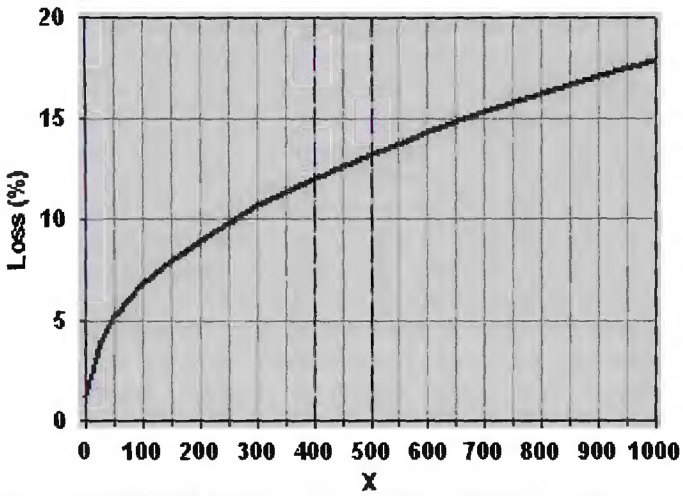

Fig. 2. Modeled losses due to series resistance and obscuration for an optimized gridline pattern.

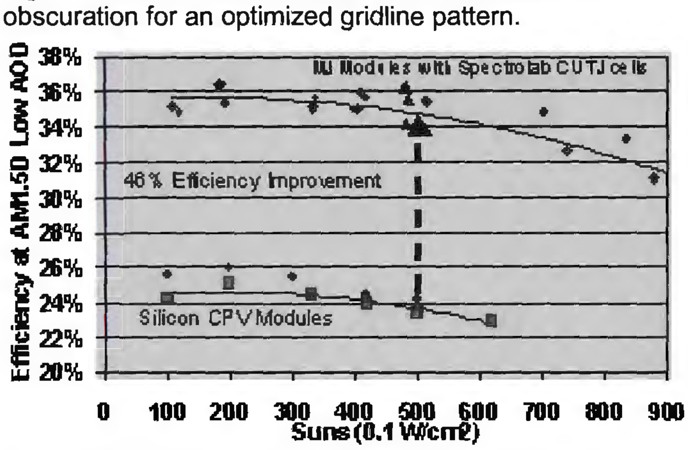

Fig. 3. Solar Systems measurement of efficiency vs. intensity for several multijunction modules compared to silicon modules.

RESULTS

The first set of CUTJ dense array cells shipped to Solar Systems enabled the construction of modules that were calibrated to an outdoor AM1.5D one-sun condition. These modules were then flash tested up to 900x (90 W/cm^2) concentration (Fig. 3). The module efficiency is for an encapsulated module, independent of the rest of the concentrator system. Cell performance peaked near 400x (40 W/cm^2), as expected. For more than 100 modules measured, module efficiency averaged about 34% at 50 W/cm^2. This is a 46% increase with respect to typical commercial point-contact silicon concentrator modules under the same conditions and validates the multijunction approach.

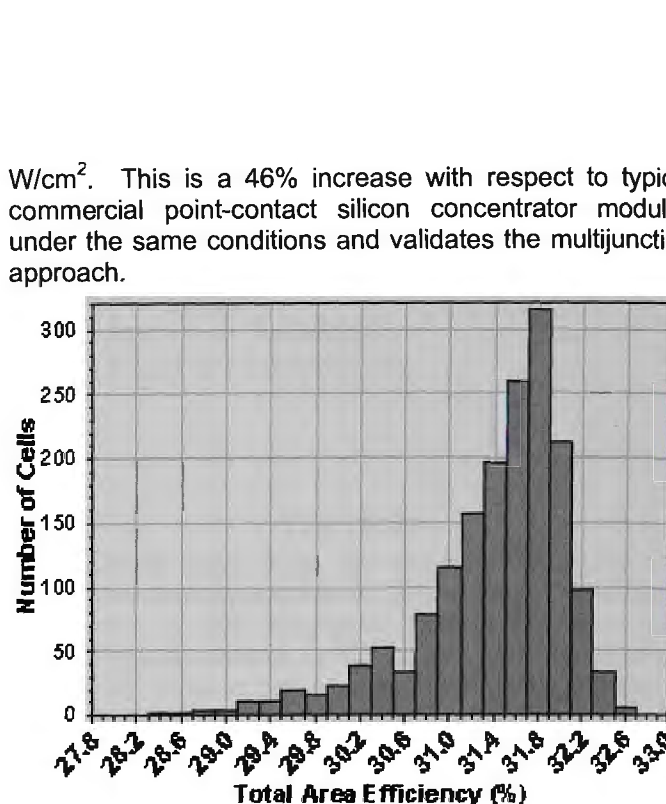

Fig. 4. Total-area efficiency at 500x (50 W/cm^2) of 1684 cells for dense-array assembly.

Solar Systems is currently field testing CUTJ dense array cells in their CS500 generator. Spectrolab provided cells to populate a full 0.23-m^2 receiver. Approximately 1500 cells are required for this receiver area; this results in an output of over 30 kW per generator. The first lot of cells was tested under 500x (50 W/cm^2) concentration (Fig. 4). The 500x concentration level was chosen because it corresponds to the peak intensity at the receiver level in the Solar Systems CS500 dish. The mean efficiency of 31.4% is about 2.6% absolute (7.6% relative) below the 34% mean efficiency of the finished modules. The bare cells were measured at Spectrolab at 25° C. The encapsulated modules were measured at Solar Systems at 21° C. The temperature difference accounts for about 0.7% relative difference. It is believed that the remaining difference is due to the difference in spectrum between the two flash test systems (about 3% relative), the improved anti-reflection characteristics of the encapsulated cells (about 2%) and the light trapping effect of the encapsulation material (about 2%).

The shape of the efficiency histogram is comparable to that of production space cells; this is an indication of a robust cell process. Cell modeling predicts a 0.6% absolute efficiency decrease in cells measured at 500x that were optimized for 400x. To confirm the modeling, a subset of cells was measured at both concentrations (Fig. 5); an offset of 0.7% was observed.

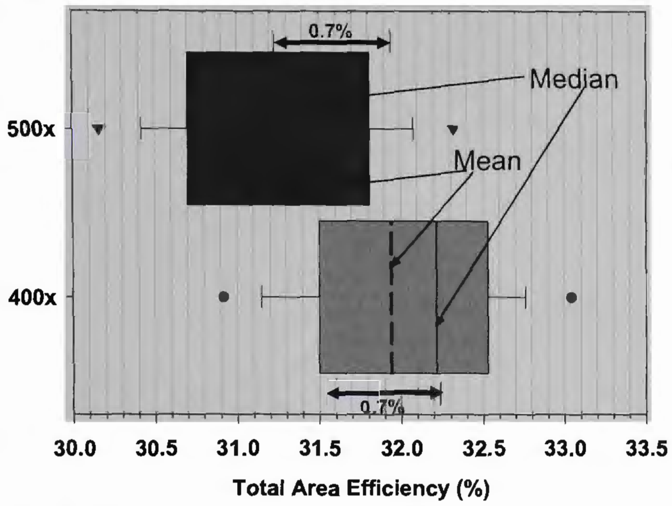

Fig. 5. Performance increase at optimum concentration (400x) measured on 50 cells. The offset in both median and mean is 0.7%.

Analysis of cell performance as a function of concentration was conducted up to a concentration of 1000x. The expected linear increase of current with concentration (with respect to a silicon reference cell) was observed, as was the logarithmic increase of voltage with concentration (Fig. 6). A fit to the voltage vs. concentration data indicates an increase of 169 mV per decade. This corresponds to a lumped ideality factor for all three junctions of 0.94.

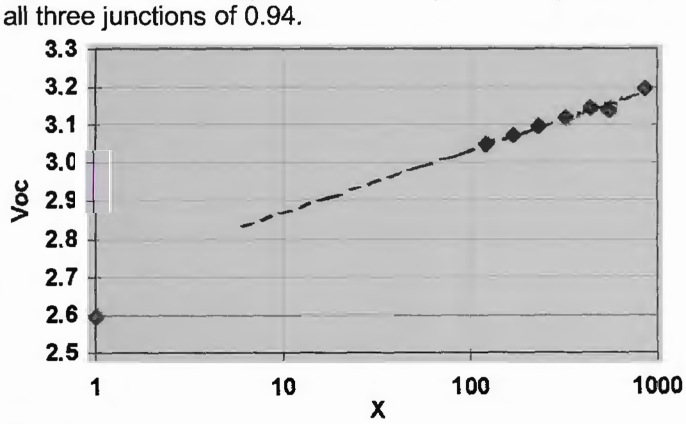

Fig. 6. A fit to the open-circuit voltage as a function of concentration yields a slope of 169 mV per decade.

Accurate flash testing of cells is critical in order to make design changes that result in additional power delivered in the field. The cells were tested at 500x (50 W/cm^2) using a modified Spectrolab large-area pulsed solar simulator (LAPSS). Based on a comparison of the modified LAPSS spectrum to the G173 spectrum (Fig. 7), the current of cells measured on the test setup is expected to be approximately 1% lower than under the standard spectrum. Further enhancements to this test setup are ongoing.

The field testing currently underway will provide feedback for optimization of the cell design. Module performance predicted by flash testing will be verified and any degradation during sustained operation at high concentration will be identified. In parallel with production of cells for modules, development of the MOVPE recipe, cell process, and assembly process continues. Environmental testing leading to qualification of the CUTJ dense-array cell design is also being conducted.

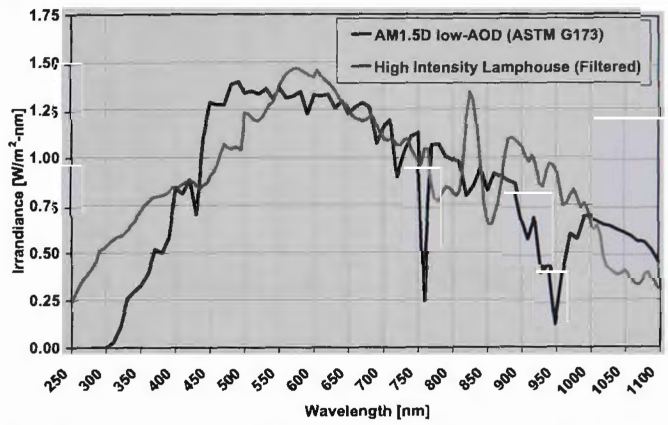

Fig. 7. Comparison of the modified LAPSS spectrum to the ASTM G173 standard.

CONCLUSION

Following the world record efficiency announcement for triple-junction III-V solar cells, a new dense array version of the CUTJ cell has been developed by Spectrolab and Solar Systems for use in high-concentration large power systems. The new cells are designed for high performance, high reliability, and low production cost. A pilot production run of 2000 cells with a mean efficiency of over 31% at 50 W/cm^2 has been delivered. Solar Systems has assembled these cells into modules that have demonstrated over 35% module efficiency under flash testing. Initial field testing of a CS500 solar electric power generator using CUTJ dense-array cells has demonstrated power output over 3 kW and a receiver efficiency of almost 30%. Results from continuing testing will determine if further modifications to the cell design are necessary. Large-scale production is expected to proceed by the end of 2006.

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PERFORMANCE AND RELIABILITY OF MULTIJUNCTION III-V MODULES FOR CONCENTRATOR DISH AND CENTRAL RECEIVER APPLICATIONS

Pierre J. Verlinden[1], Allan Lewandowski[1], Carl Bingham[2], Geoffrey S. Kinsey[3], Raed A. Sherif[3] and John B. Lasich[1]

[1]Solar Systems Pty Ltd, 6 Luton Lane, Hawthorn, Victoria 3122, Australia
[2]NREL, 1617 Cole Blvd., Golden, CO 80401, USA
[3]Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342, USA

ABSTRACT

Over the last 15 years, Solar Systems has developed a dense array receiver PV technology for 500X concentrator reflective dish applications. This concentrator PV technology has been successfully deployed at six different locations in Australia, counting for more than 1 MWp of installed peak power. A new Multijunction III-V receiver to replace the current silicon Point-Contact solar cells has recently been developed. The new receiver technology is based on high-efficiency (> 32%) Concentrator Ultra Triple Junction (CUTJ) solar cells from Spectrolab, resulting in system power and energy performance improvement of more than 50% compared to the silicon cells. The 0.235 m^2 concentrator PV receiver, designed for continuous 500X operation, is composed of 64 dense array modules, and made of series and parallel-connected solar cells, totaling approximately 1,500 cells. The individual dense array modules have been tested under high intensity pulsed light, as well as with concentrated sunlight at the Solar Systems research facility and at the National Renewable Energy Laboratory's High Flux Solar Furnace. The efficiency of the dense array modules ranges from 30% to 36% at 500X (50 W/cm^2, AM1.5D low AOD, 21C). The temperature coefficients for power, voltage and current, as well as the influence of Air Mass on the cell responsivity, were measured. The reliability of the dense array multijunction III-V modules has been studied with accelerated aging tests, such as thermal cycling, damp heat and high-temperature soak, and with real-life high-intensity exposure. The first 33 kWp multijunction III-V receiver was recently installed in a Solar Systems dish and tested in real-life 500X concentrated sunlight conditions. Receiver efficiencies of 30.3% and 29.0% were measured at Standard Operating Conditions and Normal Operating Conditions respectively.

CONCENTRATOR PV TECHNOLOGY

The promise of Concentrator PV (CPV) is to provide high efficiency and low cost solar electricity for utility-scale applications. Over the last ten years, the capacity to produce purified polysilicon feedstock has not grown as fast as the PV market growth of 40% per annum. This situation has contributed to the development in several new research groups of alternative PV technologies to the conventional crystalline silicon flat plate modules. Among these alternative technologies is CPV. The concept is quite simple and the advantages are well known. Using cheap materials such as plastic lenses or glass mirrors to concentrate sunlight onto more expensive solar cells should result in much cheaper solar PV electricity [2]. The idea of concentrating sunlight has existed for hundreds of years, as have some of the concentrator designs, such as Archimedes parabolic mirrors. The idea of using concentrated sunlight for a PV application was proposed in the early 1970's. See for example reference [1]. After 30 years, many of the technical issues have been resolved and Solar Systems dish unit is now one of the few commercially available CPV systems.

The road of CPV development has been long and diverse. Not only is CPV technologically more complex than conventional flat plate PV, but there are also many ways to accomplish the same goal and many avenues to experiment with:

- low (2X to 20X) to high (200X to 1000X) concentration ratio,
- refractive, reflective, or even total internal reflection (TIR) optics,
- linear (1D) or point focus (2D) concentration,
- distributed cells with individual concentrators or dense arrays of solar cells,
- single-junction or multijunction cells,
- passive or active cooling,
- static, seasonal adjustment, 1-axis or 2-axis tracking,
- open or close-loop tracking system.

Additionally, unlike conventional flat plate PV which has many applications, CPV is most suitable to utility-scale applications. This market is now becoming accessible with the projected low cost and demonstrated reliability of large scale CPV systems, as well as the increasing demand for clean energy sources.

DISH CPV SYSTEMS VS. OTHER TECHNOLOGIES

With more than 15 years experience, Solar Systems is one of the most advanced and successful companies commercializing CPV. Solar Systems has made a careful choice of reflective optics and a dense array PV receiver (Fig. 1). This configuration offers the highest performance and excellent maintainability, as well as an unlimited technology development pathway capable of large scale operation in a Central Receiver concept with a projected

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cost of less than US$2/W. Compared to other CPV technologies such as the common Fresnel lens based systems, the large concentrator dish design is indeed more complex because it involves large-scale optics, active cooling and compact array of solar cells. The active cooling also requires corrosion and freeze protection, and involves some pumping power losses (less than 3% of the total DC power, as shown below).

From the solar cell designer's point of view, the dense array option imposes other constraints:

- the active area of the solar cell is the same as the total die area,
- the edge recombination losses become non-negligible,
- the busbars and bonding pads (if they are required) are part of the active area of the cell.

It seems that solar cells for dish or central receiver applications are usually less efficient per active area than solar cells designed for Fresnel lenses, but, in reality, dense array cells make better utilization of the semiconductor and are more efficient per total wafer area.

The concentrator dish design has, however, several advantages: a better optical efficiency, a lower cell operating temperature and a capability to provide co-generation of electricity and heat. A significant advantage of concentrator dish systems compared to other CPV technologies resides in the ability to change a 33 kWp PV receiver in about 30 minutes. The change of receiver could be required for service, cleaning, testing or even repair, but, as solar cell technology improves and as the cost of the cell is small compared to the total system cost, it allows the power station operator to upgrade a concentrator dish PV system to a higher-efficiency receiver at very low cost (Fig. 2).

Finally, the decisive advantage is that a concentrator dish system is also the proof of concept for and the only development path towards large Central Receiver PV technology; potentially the most cost effective way to produce bulk solar electricity [3]. Cost studies at Solar Systems confirm that the total cost, including installation, inverter and balance of system, of a Central Receiver power station would be on the order of US$2/Watt at a production rate of only 100 MW per year.

EXISTING CPV POWER STATIONS

Solar Systems currently operates four CPV power stations and has operated 2 CPV testing facilities in the Australian outback, a total of 1 MWp installed. The power station sites are, in chronological order:

- White Cliffs, New South Wales:
  - o 14 parabolic dishes (1980's solar thermal systems, reconfigured in 1998 for PV generation, retired in 2004)
  - o 250X optical concentration (25 W/cm^2)
  - o Point-Contact Silicon cells
  - o Total DC power: 40 kW
  - o Returned field experience, demonstrated 20% efficiency [4] and gave insight for future developments
- Fosterville, Victoria:
  - o Testing facility of Solar Systems
  - o 2 parabolic dishes of 20 kWp each
  - o Point-Contact Silicon cells at 45 W/cm^2
  - o Used for system development and R&D
- Pitjantjatjara, South Australia:
  - o 10 parabolic dishes installed since 2002,
  - o Total DC power: 220 kWp
- Hermannsburg, Northern Territory (Fig. 1):
  - o 8 parabolic dishes installed since 2005
  - o Total DC power: 190 kWp
- Yuendemu, Northern Territory:
  - o 10 parabolic dishes installed since 2005
  - o Total DC power: 240 kWp
- Lajamanu, Northern Territory:
  - o 12 parabolic dishes installed since 2006
  - o Total DC power: 290 kWp

The four most recent power stations use the same dish design and the same Point-Contact silicon solar cells [4,5] operating at 45 W/cm^2. The dishes are composed of 112 curved mirrors (1.1 x 1.1 m). The projected aperture area of the dish is 129.7 m2 and the receiver area is 0.235 m2. The cell active area is 0.23 m2 and the cell packing density is 98%. The geometrical concentration is 551X and the projected ray-tracing optical efficiency of a dish (with clean mirrors) is 91%, giving an optical concentration of 500X. In reality, the practical optical efficiency of the concentrator is about 85% and, therefore, the optical concentration is about 468X. The optical efficiency of the system was calculated using calorific measurement on existing dishes. Table I shows the main characteristics of the CPV dish (CS500).

Fig.1: Hermannsburg 190 kWp power station

The current CPV systems use Point-Contact Silicon solar cells designed for dense arrays [4-5]. Their efficiency at 45 W/cm^2 (AM1.5D, 25C) is 23% +/- 0.5% as measured by SunPower. The dishes are rated at a DC output peak power of 24kWp at a cell temperature of 21C and 1000 W/m^2 of direct sunlight (SOC). A more realistic power rating is defined at Normal Operating Condition (NOC), i.e. AM1.5D, 850 W/m2, Tc_{ell} 45C, which corresponds to a concentrated irradiation of 39.5 W/cm^2. The power temperature coefficient of the concentrator silicon solar cells at that concentration ratio is –0.35%/C, giving cell efficiency at Normal Operating Condition (NOC, T_{cell} ~ 45C) of about 21% +/- 0.5%. Due to non-uniformity in the concentrated sunlight and due to interconnection losses, the typical performance of a Solar Systems CPV dish at NOC is 15.9 kW, giving a receiver and an overall system efficiency of 17% and 14.4% respectively. The best recorded performance of a silicon CPV system at Solar Systems is 18.7 kW at NOC, corresponding to an overall system efficiency of 17% that includes optical losses.

Table I: Characteristics of CPV dish (CS500)

	Value	Unit
Projected Aperture Area	129.7	m^2
Total Mirror Area	135.5	m^2
Receiver Area	0.2352	m^2
Cell Total Area	0.2304	m^2
Geometr. Concentration	551 X	suns
Optical Efficiency	91%	Simulation limit
Optical Efficiency	85%	Typical (with some dirt)
Optical Concentration	468 X	suns

Fig. 2: Changing a CPV receiver to upgrade to a more efficient PV technology takes only ~30 minutes

SYSTEM UPGRADE WITH MULTIJUNCTION III-V SOLAR CELLS

Because solar cells represent a small part (10% to 20%) of the total cost of the CPV system, it is appropriate to use the most efficient cell available. Due to the high concentration ratio, the cell efficiency has large leverage in reducing the cost of solar electricity. The research team at Spectrolab has demonstrated concentrator Multijunction (MJ) III-V solar cells with record efficiencies of 39%, well above the efficiency of silicon Point-Contact solar cells [6]. Therefore, it was beneficial to upgrade the CPV dish and design a new receiver incorporating the more efficient MJ cells. At the beginning, there were several concerns:

- The robustness of the new Multijunction III-V cells, compared to Silicon cells, has to be established. How would they behave in the harsh environment of a 500X concentrator system?
- What is the efficiency distribution of MJ cells in large volume production?
- What is the total-area efficiency of an MJ cell designed for dense array application?
- How would we maintain the high packing density and still be able to interconnect the cells?

Integrating new cells in a concentrator system is a complex activity requiring considerations of optical, electrical, thermal and material constraints. Due to the complexity of the concentrator PV system, it was decided that the integration of the new cells should be done with minimal change to anything else in the receiver design. There were several challenges:

- designing, with Spectrolab, a new dense array MJ solar cell and testing its total-area efficiency and reliability [9],
- designing and testing a new interconnection scheme between cells without impacting the packing density of the cells in a receiver,
- designing a new module package incorporating bypass diodes, again without impacting the cell packing density,
- modifying the automated assembly process to suit the MJ cells and the interconnection between cells,
- modify the existing package to suit the particular characteristics of the MJ cells (expansion coefficient, optical absorption, sensitivity to moisture),
- designing and demonstrating a production-type flash testing system for qualifying modules,
- modifying the control and data acquisition system to accommodate the higher cell voltage.

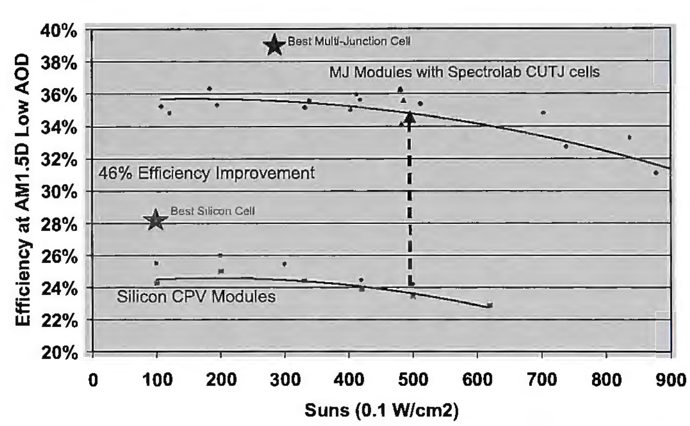

Fig 3: Efficiency at 21°C vs. Intensity for several MJ modules compared to Silicon modules.

PERFORMANCE TESTING

Efficiency measurements

The responsivity of assembled modules was measured using one-sun outdoor calibration. The reference device is a Class 1 pyrheliometer. The modules were mounted behind a collimator with internal optical baffles and black sidewalls. At the same time, the solar spectrum was scanned using a spectrophotometer to determine the ozone, water and aerosol optical thickness.

The efficiency of the MJ modules at intensities between 10 W/cm^2 and 100 W/cm^2 were measured using indoor flash testing with an unfiltered Xenon arc lamp. The efficiencies are reported at 21°C. The intensity during the flash was calibrated using the one-sun outdoor short-circuit current for each individual module. Figure 3 shows the efficiency at 21°C of several MJ modules as a function of intensity. Over more than 100 modules (2,500 cells), the measured efficiency at 500X was between 30% and 36% (AM1.5D low AOD, 50 W/cm^2, 21°C, not independently confirmed). This corresponds to an average 46% improvement compared to silicon modules of identical size and in the same conditions (500X, 21°C).

Temperature Coefficients

The temperature coefficients of MJ III-V solar cells have been reported in the literature [7,8]. However, the temperature coefficients of MJ cells are sensitive to the bandgap of the different semiconductor material composing the MJ solar cell. Using the Concentrator Ultra Triple Junction (CUTJ) cells from Spectrolab, the temperature coefficients of the new MJ modules were measured by several techniques. For the responsivity temperature coefficient, we measured the short-circuit current of the modules when exposed to outdoor direct sunlight (at one sun, AM1.5D). The responsivity temperature coefficient was found to be +0.024%/°C.

For the Voc temperature coefficient measurement, we used our indoor flash tester. The Voc temperature coefficient was found to be between –4.08 mV/°C per cell at 10 W/cm^2 and –3.73 mV/°C per cell at 70 W/cm^2. At the typical incident irradiance of 45 W/cm^2, the voltage temperature coefficient is –3.9 mV/°C per cell.

The power temperature coefficient is much more difficult to measure. We used outdoor concentrated sunlight exposure. At the NREL HFSF facility, the power output of a MJ module made with series-connected MJ cells was measured at an incident irradiance of 50 W/cm^2. The cell temperature was calculated using the Voc (at 50 W/cm^2) vs. temperature data that was obtained in laboratory using a flash tester. The power temperature coefficient was found to be –0.171%/°C.

RELIABILITY TESTING

The modules assembled with MJ solar cells were extensively tested for reliability through thermal cycling, damp heat, high-temperature soak and on-sun long term exposure testing.

Thermal cycling

The MJ modules were submitted to accelerated ageing testing through thermal cycling. A typical CPV system may undergo about 2,000 thermal cycles per year, due to passages of clouds in front of the concentrators. In the Solar Systems CPV system, the cells are typically running at a temperature of 45°C. The expected actual temperature difference during these cycles is from the water inlet temperature (20°C to 35°C) to the Normal Operating Cell Temperature (NOCT) of 45°C.

The test was designed to thermal cycle individual modules between 27°C and 72°C, with 800 cycles per day. In order to make sure that the degradation mechanisms are similar to the actual ones, the set points of temperature were selected to be greater but still similar to the actual temperatures seen by the solar modules. The new MJ modules survived more than 45,000 thermal cycles without any significant degradation. A particular version of the modules survived more than 70,000 cycles without significant degradation (less than 10%).

We believe that the above thermal cycling test demonstrates an expectation of lifetime duration greater than 20 years in a real CPV environment.

Damp heat

The MJ modules were also submitted to a damp heat test of 1,000 hours at 85°C with a relative humidity greater than 85%RH and with a halogen light bias (~ one sun) in order to generate enough voltage and current to enhance any galvanic corrosion. The MJ modules passed the damp heat test with less than 10% degradation in performance.

High-temperature soak

The MJ modules passed without any observable degradation a temperature soak at 100°C for more than 1,000 hours.

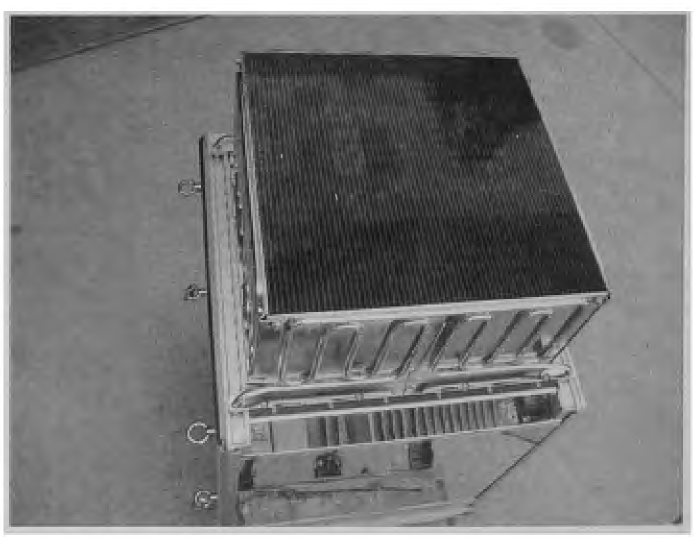

Fig. 4: Multijunction 33 kWp receiver

UV exposure

Intense UV exposure could degrade CPV modules due to yellowing or browning of the encapsulant material, solarization of the cover glass, or degradation of the cell performance. In any case, the observable degradation is expected to be in the current responsivity only. Due to the very high concentration ratio (468X), it was difficult to find a UV source intense enough to be equivalent to an acceleration factor greater than 1. Therefore, it was decided that the best UV exposure test would be on the

CPV dish with real sun. As described below, MJ modules have been placed under concentrated sunlight (concentration ratio greater than 400X) for more than four months during summer without any observable degradation due to intense UV exposure.

ON-SUN TESTING AT THE NREL HFSF

Three individual modules composed of series-connected MJ cells were tested at the NREL High-Flux Solar Furnace (HFSF) in November 2005. The measurement of module efficiency at a standard condition was difficult because the weather was not very good and due to the fact that the air mass number during these testing sessions in Colorado was between 1.9 and 3.8. Nevertheless we were able to demonstrate a lower bound efficiency (see Table II). While the intensity was kept very constant during the measurement via a calibrated louver system in front of the concentrator, the incident power densities were measured by both optical and calorimetric measurements. The two methods gave very similar efficiency results, with a maximum deviation of 1.3% relative in the 10 to 50 W/cm^2 range. The calorimetric measurement also demonstrated the linearity of the MJ solar cell short-circuit current versus intensity (+/- 1.5%) from 100 to 600 suns. Using the typical spectral response of the MJ cells supplied by Spectrolab, the measured solar spectrum at the time of testing and the measured transfer function of the HFSF including the flux uniformizer, we calculated a set of spectrum mismatch coefficients. The mismatch coefficients varied greatly and were not reliable for efficiency correction. We preferred using the ratio of responsivities measured at the NREL HFSF and at Solar Systems using outdoor one-sun AM1.5D calibration (90.06%, 93.16% and 97.7% for the three respective MJ modules). During the experiment, the cell temperature varied from 21°C to 36°C depending on the intensity. The efficiencies in Table II are not corrected for temperature.

ON-SUN AT HERMANNSBURG POWER STATION

Three dishes at the 190 kWp CPV power station of Hermannsburg (Latitude –23.56°, altitude 580 m) were used for on-sun testing of two hybrid receivers and one full 33 kWp MJ receiver. The hybrid receivers were composed of four MJ modules embedded in a standard silicon receiver. They were used mostly for long-term exposure and reliability testing since accurate efficiency measurements were not possible on sun. The first and second hybrid receivers were operated on sun for periods of four and two months respectively during the summer season with only minor operating issues.

In a more significant demonstration, a full 33 kWp receiver (Fig. 4) was installed on dish 1W at the Hermannsburg power station. This particular dish has a projected aperture of 131.9 m^2. It should be noted that the dish was not fully optimized, the mirrors were not previously cleaned and that early results were used for the purpose of this paper. The full 33 kWp MJ receiver is composed of approximately 1,500 MJ solar cells. The parallel and series interconnections between cells and between modules were selected to optimize power output, considering the light non-uniformity at the receiver level, and to accommodate the voltage range of the existing inverters on site. The 33 kWp receiver was installed on March 28, 2006 and has been on sun for more than four weeks at the time of writing this paper (Fig. 5).

Table II: Minimum efficiency of MJ modules measured at NREL HFSF (uncorrected for temperature)

	Intensity W/cm^2	Measured Efficiency (optical method)	Measured Efficiency (calorimetric method)	Spectrum Mismatch Corrected Efficiency
MJ206	10	30.4%	30.2%	33.8%
	20	31.3%	31.1%	34.7%
	30	31.6%	31.3%	35.1%
	40	31.1%	30.8%	34.5%
	43	31.0%	30.3%	34.4%
	50	30.6%	30.2%	33.9%
	60	30.3%	29.6%	33.6%
MJ208	50	30.3%		32.6
MJ209	50	29.0%		29.7%

Table III: Performance of CPV dish 1W (CS500) with MJ receiver at SOC (1000 W/m^2, AM1.5D low AOD, T_{cell} 21°C) and NOC (850 W/m^2, AM1.5D low AOD, T_{cell} 45°C). The dish projected aperture is 131.9 m^2.

	SOC	NOC	Unit
Total P_{in}	131.9	112.1	kW
P_{out}	33.2	27.1	kW
Concent. Irradiance	47.66	40.49	W/cm^2
Receiver I_{sc}	134	114	A
Receiver V_{oc}	301	290	V
Receiver I_{mp}	129	109	A
Receiver V_{mp}	257	248	V
Receiver FF	82.3%	82.0%	%
System Efficiency	25.2%	24.2%	%
Receiver Efficiency	29.6%	28.4%	%
Total Thermal P_{out}	82.87	71.55	kW
Cell Temperature	21	45	°C
Parasitic power	950	950	W

ENERGY AND PERFORMANCE ANALYSIS

It has been possible to collect a large amount of data regarding the performance of the concentrator dish fitted with a MJ receiver under various conditions. Table III shows the performance of the CPV dish at SOC (AM1.5D, 1000 W/m^2 direct, T_{cell} = 21°C) with a projected aperture of 131.9 m^2. A more realistic condition is the Normal Operating Condition (NOC) defined by an incident power density of 850 W/m^2 (AM1.5D low AOD) and a NOC cell temperature of 45°C. Table III also shows the performance of the CPV dish under these conditions.

The numbers in Table III have been obtained by averaging over a large number of data points. We actually recorded an output power of 30.5 kW at a direct incident power density of 937 W/m^2 and a cell temperature of 45.8C. This corresponds to a receiver and an overall system efficiency of 29.0% and 24.7% respectively, and an SOC receiver efficiency of 30.3%. The parasitic power of 950 W per dish is for the cooling system pump, the tracking motors and the control system, corresponding to less than 3% of the rated SOC power output. The parasitic power loss is not included in the efficiency calculation.

Energy output

On a normal clear day, about 45 days after the autumn equinox, the MJ receiver is producing on average daily energy output that is more than 150% of the daily energy produced by the best silicon receiver on the same field during the same period of time. Over the last month (fall equinox), the present rate of energy production during normal operation, in the Australian desert and after deduction of the parasitic energy, is an impressive 2300 kWh/kWp, projected over a one-year period.

Fig. 5: Multijunction 33kWp CPV Receiver on sun

CONCLUSIONS

Concentrator PV for utility-scale application is becoming a reality thanks to the demonstration of several reliable and efficient CPV power stations, the availability of very high-efficiency Multijunction III-V solar cells, and the growth of the global PV market. Solar Systems have designed, build, and tested a new CPV receiver incorporating high-efficiency MJ dense array solar cells developed by Spectrolab and Solar Systems. The performance and reliability results have met the expectations. The CPV system with a Multijunction receiver produces in excess of 50% more power than with a silicon receiver at Normal Operating Conditions (NOC). We demonstrated a PV receiver efficiency of 29.6% at 48 W/cm^2 (AM1.5D low AOD) and 21°C, and a system efficiency of 25.2% under the same conditions (SOC). At NOC, the 33 kWp receiver and system efficiency are 28.4% and 24.2% respectively. The daily energy output is more than 50% greater than the energy output of the best silicon CPV dish on the same field. We believe this is the first time a large scale CPV receiver has been demonstrated at 30.3% efficiency. We have demonstrated a field efficiency of almost 3 times that of silicon flat plate technology, which gives a large advantage over conventional technologies in the effort to reduce cost, particularly when the balance of the system consists of widely available, low-cost glass and steel.

The potential for CPV to hit the projected low cost targets is being proven and the capability of CPV for utility-scale application is being recognized. In particular, the CPV dish design is an excellent proof of concept and development tool for future large scale Central Receiver PV power stations. The CPV technology that has been developed during this project is directly applicable to Central Receiver design and will promote the development of such systems in a near future.

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OPPORTUNITIES FOR WIDESPREAD IMPLEMENTATION OF CONCENTRATOR PHOTOVOLTAIC (CPV) SYSTEMS

J.B. Lasich and P.J. Verlinden
Solar Systems Pty Ltd, 6 Luton Lane, Hawthorn, VIC 3122, Australia

ABSTRACT

Many positive conditions are in place for accelerating the growth of concentrator PV technology. Two of the most important milestones have been the demonstration of a commercial, high-efficiency and reliable CPV system with stable performance and potential low cost. The first two commercial-size 33 kWp multijunction III-V CPV systems have been installed and monitored for almost one year. The receiver DC efficiency is 29.2% +/- 0.5% at Standard Operating Conditions (SOC) and 500X concentration. The overall annualized net AC system efficiency is 19.3%, all losses taken into account. It is believed to be the highest annualized AC system efficiency demonstrated to date for a system of this size and of any commercial continuously running solar-to-electricity technology.

INTRODUCTION

Currently our homes, industries and transport, are pumping every year over 27 billion tons of CO_2 from the consumption and flaring of fossil fuels into our environment [10]. At the same time, industry experts have claimed that the global production of oil has peaked. Although this claim is difficult to verify, it is a general consensus that production of oil will become significantly more expensive over the next decades. These are significant ingredients in a recipe for disaster, which could include global climate disturbance and escalating political or military action over fossil fuels. It is time to find a true long-term solution to these problems. No longer can we justify the "easiest" or the "most profitable" way. We need to find the "best" way that can provide sustainable pollution-free energy, at a cost which can be accommodated by our society.

After more than 30 years of research, development, demonstration and business development, the global market of photovoltaic systems is finally well established. In 2005, the world PV market was over 1,400 MWp and growing faster than 35% per annum over the previous year. The sum of all the PV systems installed worldwide represents a value greatly exceeding US$ 10 billion per year. It is also a market that is largely dominated by one technology (crystalline silicon flat-plate modules) and one market segment (residential and commercial roof-top grid-connected systems). Despite being a very dynamic and aggressive industry, the total installed PV capacity to date represents less than 0.1% of the worldwide electricity generation capacity. In order to achieve a faster growth, it is necessary to see a greater diversity in PV technology, for example concentrators, thin films, and larger sizes of PV power plants, over the next few years.

Fig.1: 190 kWp power station at Hermannsburg

The PV industry is currently under enormous pressure to accelerate its growth and to contribute in a more significant way to the global electricity generation. Concentrator PV (CPV), which has been regarded by many as potentially the cheapest way to produce bulk electricity [1, 6], is at the doorstep of a significant growth due to a series of positive conditions:

- demonstration of high-efficiency (>40%) solar cells [4, 5],
- demonstration of medium volume manufacturing of these high-efficiency (>35%) modules [2, 3],
- demonstration of reliability of CPV systems [2],
- demonstration of system cost competitive to flat-plate PV systems,
- demonstration of improved specific energy production compared to flat-plate PV systems,
- demonstration of stable performance,
- significant growth of the large-scale or utility-scale PV market,
- the cost of large CPV systems currently in development is on a pathway to become competitive to "clean" fossil fuel generation.

Founded in 1991, Solar Systems has become one of the largest and one of the most advanced of the few CPV companies in the world. Among all the different CPV technologies, Solar Systems has, over the years, carefully selected a concentrator design based on a large-scale point-focus reflective optics and dense array receivers. Solar Systems has developed a concentrator dish and a dense-array PV receiver technology suitable for 500X concentration. This technology has been successfully deployed in the Australian outback at several different locations (see Fig. 1 and 2), including four large (> 190 kWp) CPV power stations, and represent a total of about 1 MWp [2]. The frist of these power plants began operation in 1998.

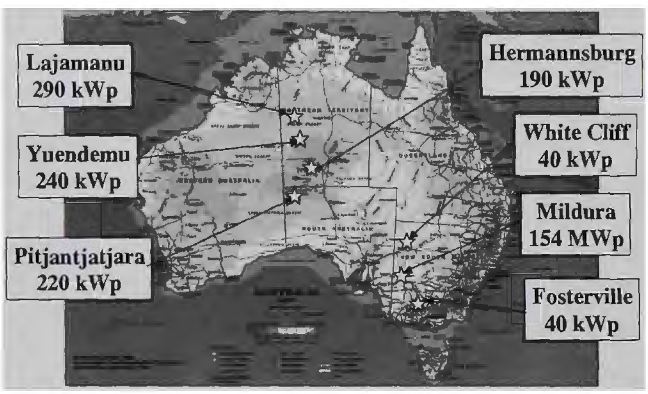

Fig. 2: Location of the different CPV power stations in Australia totaling 1 MWp. The Mildura 154 MWp Central Receiver HCPV power plant will be built in 2013.

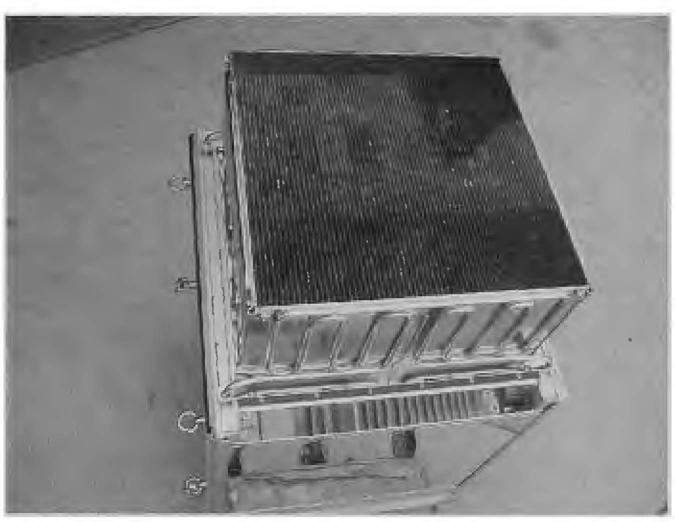

Fig. 3: New 33 kWp receiver using high-efficiency multijunction GaInP/GaInAs/Ge solar cells

Between 1991 and 2005, the dense array receivers have been built using world record-efficiency silicon Point-Contact solar cells [8]. Since 2005, a new dense array receiver composed of Spectrolab's ultra high-efficiency concentrator multijunction GaInP/GaInAs/Ge solar cells has been developed [3] and the world-first 33-kWp multijunction receiver was installed onto one of the dishes at the Hermannsburg power station on March 28th, 2006 [2]. A second multijunction receiver was installed in January 10th, 2007 (see Fig. 3).

The recent development and performance results of the CPV dish systems deployed by Solar Systems in Australia are presented in this paper. The opportunity for widespread implementation of this system in Australia and globally is immense, but it is essential to provide a business development team with a strong platform to launch into new markets. To further reduce cost, Solar Systems is currently developing a Heliostat version of CPV, known as HCPV. The exisiting CPV dish is an excellent proof of performance for the essential components to be used in a large scale and more cost-effective Central Receiver PV system. The future deployment of a 154 MWp central receiver PV system in Mildura, Australia, is announced.

A PLATFORM TO ACHIEVE A FAST GROWING CPV MARKET

Despite many years of research, development and worldwide demonstration of CPV systems totaling more than 2 MWp to date, CPV technology is still in its infancy and far behind the flat-plate PV in terms of market penetration. What do we need to do to achieve faster growth in CPV market development? We see five different areas where we need to concentrate our efforts. Some of the secondary objectives presented below have already been achieved, but we need to continue our efforts to insure a faster and larger development of a utility-scale CPV industry.

Objective 1: to demonstrate reliable CPV system performance through:

- stability of technology,
- demonstration of long-term reliability,
- experience in grid-connected operation,
- establishment of CPV testing methods and standards,
- better understanding of the direct resource,
- establishment of quality, safety and reliability standards suitable to concentrator systems.

Objective 2: to demonstrate cost-effectiveness of annually produced energy ($/kWh and not just $/kWp) compared to conventional PV technology through:

- demonstration of fully installed system cost lower than US$2/Wp,
- demonstration of low O&M cost,
- establishment of an energy-rating system for CPV instead of the power-rating system used by conventional flat-plate PV,
- pursuit of cell and optical efficiency development toward >50% efficient solar cells and >25% AC efficient systems.

Objective 3: to develop a pathway towards GWp-level production through:

- target peak load application (in Australia, peak load market is growing 4-times faster than base load),
- demonstration of high capacity factor,
- demonstration of very large, utility-scale, grid-connected CPV power plants, which benefit from economy of scale on installation and Balance Of System (BOS),
- demonstration of improved ability to dispatch CPV solar electricity.

Objective 4: to develop manufacturing, installation techniques and tools to suit mass production:
- development of tools and techniques particularly suitable to CPV to improve productivity and lower production costs,
- use of existing large scale facilities and processes to produce non-PV components at high-volume and low cost,
- promotion of CPV industry through separate CPV Industry Association,
- continued improvement to attract necessary investment.

Objective 5: to develop a complete grid-connected energy solution:
- development of managed energy production, which may include short-term storage system,
- development of efficient co-generation systems that could include heat and hydrogen [9],
- promote a standard power purchase agreement (PPA) for the CPV industry that is beneficial for both parties,
- provision of long-term energy storage through hydrogen production for transport fuel or electricity generation.

Fig. 4: Replacing a silicon PV receiver by a higher-efficiency multijunction receiver took only 30 minutes

CPV DISH SYSTEMS AND PERFORMANCE OF MULTIJUNCTION RECEIVERS

Solar Systems has focused on and met several of these objectives including:

- demonstration of high peformance, with high potential for continued improvement,
- demonstration of reliability based on 10-years field experience,
- demonstration of cost already competitive to flat-plate PV, even with very low production volume.

A total of 1 MWp of CPV dish systems has been installed in the Australian outback at six different locations, including four large CPV power stations of 190 kWp to 290 kWp (Fig. 1). One of the greatest advantages of the CPV dish system is that every part of it is serviceable. In particular a PV receiver can be changed in less than 30 minutes for maintenance, repair or even upgrade to a newer, more efficient technology (see Fig. 4). The newer generation of CPV dish units has a receiver using the world-record GalnP/GalnAs/Ge triple-junction solar cells [4]. The first multi-junction 33 kWp receiver (Rx46) has been in operation since March 2006 and its performance has been reported in an earlier publication [2]. Corrected for Standard Operating Condition (1 kW/m^2, AM1.5D low AOD and 21°C cell temperature), the multijunction receiver produces 33.2 kW, corresponding to an efficiency of 29.6%. The best uncorrected performance was a power output of 30.5 kW and an efficiency of 29%.

The second 33 kW multijunction receiver (Rx 56) has been in operation since January 2007 and has a very similar performance to the first receiver, as reported in Table I. The best performance of 30.7 kW, as the highest uncorrected power output, was measured on February 1st, 2007 with a direct irradiance of 1029 W/m^2, corresponding to an average concentrated beam of 48.9 W/cm^2. The values corrected for SOC and NOC have been measured and averaged over a two-month period after installation.

Many other very important parameters have been measured in laboratory under flash testing at 50 W/cm^2 and on sun at intensity varying between 40 and 50 W/cm^2 during one year of operation. Several of those are reported in Table II. One important aspect of concentrator PV systems using multijunction III-V solar cells is that the responsivity of the cells significantly varies with the solar spectrum, which itself is dependent on Air Mass, Aerosol Optical Depth (AOD), precipitable water optical thickness, and ozone optical thickness. At the Hermannsburg power station (Latitude –23.6 degree, elevation 565 m) the Air Mass number could be as low as 0.93. The responsivity of the receiver was found to be maximum around AM1.5 and decreasing by about 5% for every Air Mass unit below or above 1.5.

The specific daily energy production (the daily energy production divided by the integrated DSR over a one-day period) was measured over a one-year period (see Fig. 5). The dish produced on average 28 kWh/kWh/m^2. The seasonal variation of the specific daily energy was found to vary by only +/- 10% around the average value, the maximum being 30.3 kWh/kWh/m^2 around the equinox periods and the minimum being 25 kWh/kwh/m^2 around winter and during the cloudy days.

This performance leads to an annualized system DC efficiency of 21.2%, which includes all seasonal variations due to solar spectrum changes. The overall annualized net AC system efficiency is 19.3% including inverter losses and parasitic losses. We believe this the highest annualized AC efficiency reported for a commercial solar system of this size that produces electricity.

Table I: Performance of second CPV dish with MJ receiver (Rx56) at SOC (1000 W/m^2, AM1.5D low AOD, T_{cell} 21°C), NOC (850 W/m^2, AM1.5D low AOD, T_{cell} 45°C) and best observed uncorrected power output at DSR 1029 W/m^2 and concentrated intensity 48.9 W/cm^2.

	SOC	NOC	Best Perform	Unit
P_{out}	32.2	26.2	30.7	kW
Receiver I_{sc}	129	110	131	A
Receiver V_{oc}	301	290	289	V
Receiver I_{mp}	124	105	124	A
Receiver V_{mp}	259	249	247	V
Receiver FF	84%	83%	81%	%
System DC Efficiency	24.4%	23.8%	23.7%	%
Receiver DC Efficiency	28.7%	28.0%	27.9%	%
Cell Temperature	21	45	56.8	°C

Table II: Parameters of Multijunction modules and receivers measured in laboratory under flash testing at 50 W/cm^2 and on-sun

	Min	Typ.	Max	Unit
Voc Temperature Coefficient	-	-4.5	-5.2	mV/°C
Vmp Temperature Coefficient	-	-	-5.8	mV/°C
Power Output Temperature Coefficient	-0.1	-0.15	-0.17	%/°C
Power Output Air Mass Coefficient	-	-5	-	%/AM

MARKETS FOR CPV DISHES AND CENTRAL RECEIVER CPV SYSTEMS

After the demonstration of reliable operation at four large CPV power stations in the Australian outback, the deployment of many more CPV systems is underway. The growth in production rate can be much faster than conventional flat-plate PV since the solar cell area is reduced by a factor of 500X and the bulk of the material composing a CPV system is steel and glass. Just in Australia, there are more than 1,500 MW of installed capacity in diesel generation. Most of these diesel generators are off grid and far away from any large city centers. They power mining, farming and aboriginal communities, and the cost of producing electricity in these remote areas is in the range of AU$0.50/kWh (US$0.39/kWh). Solar Systems CPV dish unit is already competitive with conventional flat-plate PV system and off grid diesel generation. By mid-2007, Solar Systems will have a capacity of production of 5 MWp/year (see Fig. 6) and has government support to install 5 GWp by 2020. Projecting the current growth in production rate into the future (78% growth per year or X10 every 4 years), we can estimate that the annual installation rate of CPV systems by Solar Systems will be:

- Year 2010: 4 MWp
- Year 2015: 150 MWp
- Year 2020: 5 GWp

It is interesting to note that the solar cell efficiency of the solar cell used in Solar Systems units has been growing at an average rate of 1% efficiency point per year, which also is approximately the rate of current and projected performance improvement of Spectrolab's multijunction solar cells [4-5]. It is clear that cell efficiency is crucial to CPV market development. From the curve presented in Fig. 6, every additional percentage point in cell efficiency appears to be correlated to an increase of Solar Systems CPV production by 78%. It would be interesting to see in the future if this prediction is confirmed and if it applies to the entire CPV market.

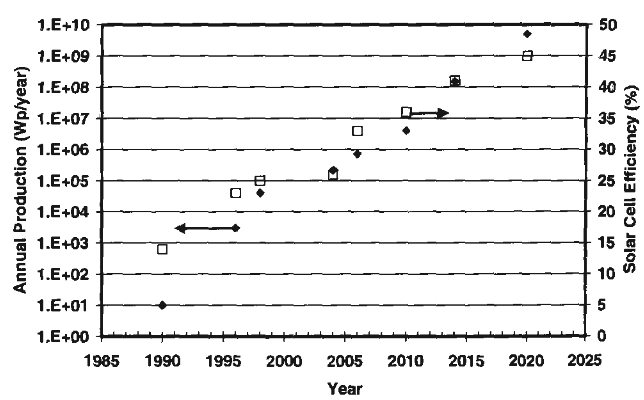

Fig. 6: Past, current and projected future growth of Solar Systems production rate (78% per year) and production solar cell efficiency improvement (1% per year)

For large CPV systems, greater than 2 MWp, Central Receiver or Helisotat Concentrator PV (HCPV) design is expected to have significant savings. Solar Systems is contracting to build a 154 MWp Central Receiver power plant by 2014 near Mildura, Australia. The total estimated cost of the power plant is AU$420 Million (US$325 Million) and is partially funded by the State of Victoria (AU$50 Million) and the Australian Government Low Emission Technology Development Fund (LETDF, AU$75 Million). The Mildura project with LETDF funding will provide a significant support to increase the installation rate of CPV systems above 100 MWp/year and to reduce the cost of solar electricity to around AU$100 per MWh (see Fig. 7).

CONCLUSIONS

Two important milestones have been achieved on the pathway to widespread implementation of CPV systems. High-efficiency and reliable CPV systems have been demonstrated.

A total 1 MWp of installed capacity of CPV dish units has been installed in the Australian outback. The first system began operation in 1998. Two 33 kWp commercial-scale CPV systems using high-efficiency multijunction III-V solar cells have been monitored over the last year and have shown a stable DC efficiency of 29.2% +/- 0.5% at SOC (1,000 W/m^2, 500X, AM1.5D low AOD, 21°C). The average specific daily energy production rate was 28 kW/kWh/m2, corresponding to an overall annualized system efficiency of 21.2% and 19.3%, for DC and net AC respectively (all losses taken into account). We believe this the highest annualized efficiency reported for a commercial PV system of this size and of any commercial, continuously running, solar-to-electricity conversion technology.

A large 154 MWp Central Receiver or HCPV power plant will be built near Mildura, Australia, based on the multijunction CPV technology developed with the dish units. With assistance from the LETDF fund and the State of Victoria, the large HCPV power plants are targeted to bring the cost of solar electricity to AU$100/MWh and below, a level comparable to "clean" bulk power generation.

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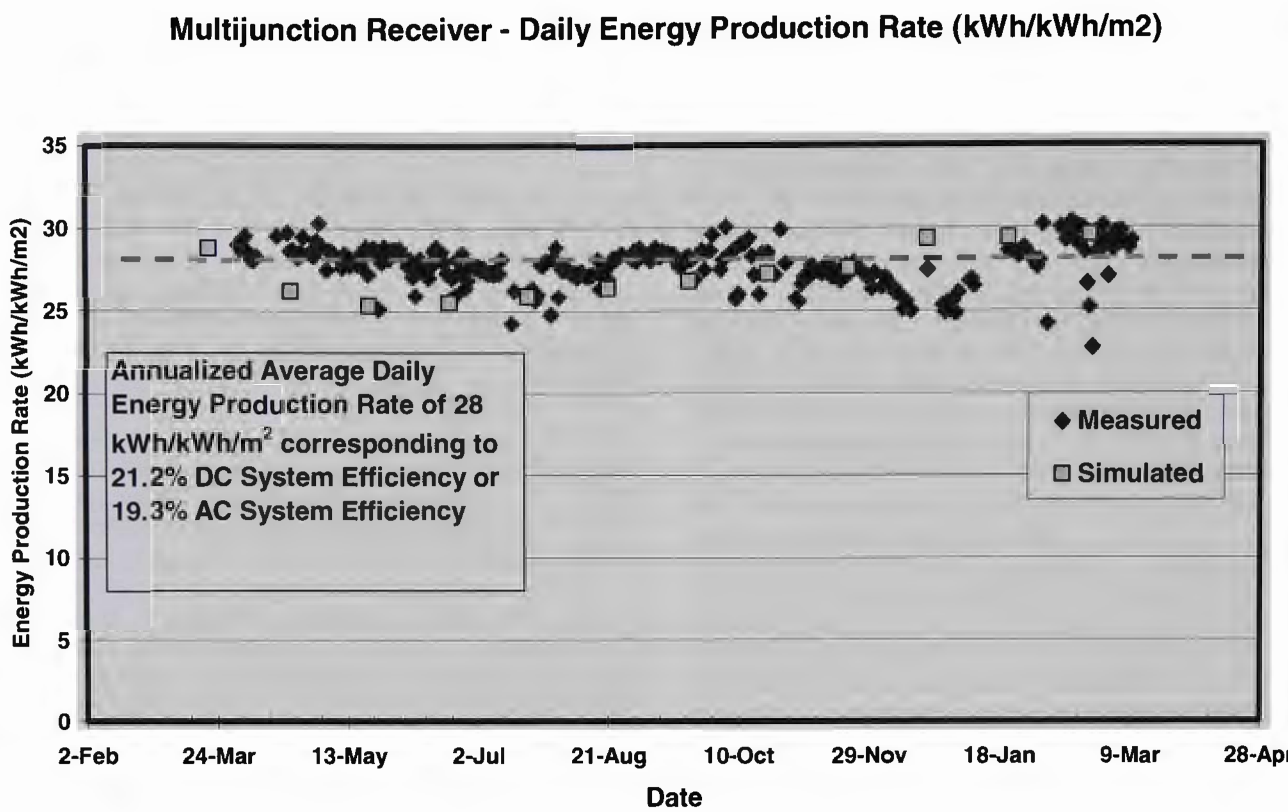

Fig. 5: Specific daily energy production rate of the first 33 kWp multijunction receiver compared to prediction. The average specific energy production is 28 kWh/kWh/m^2.

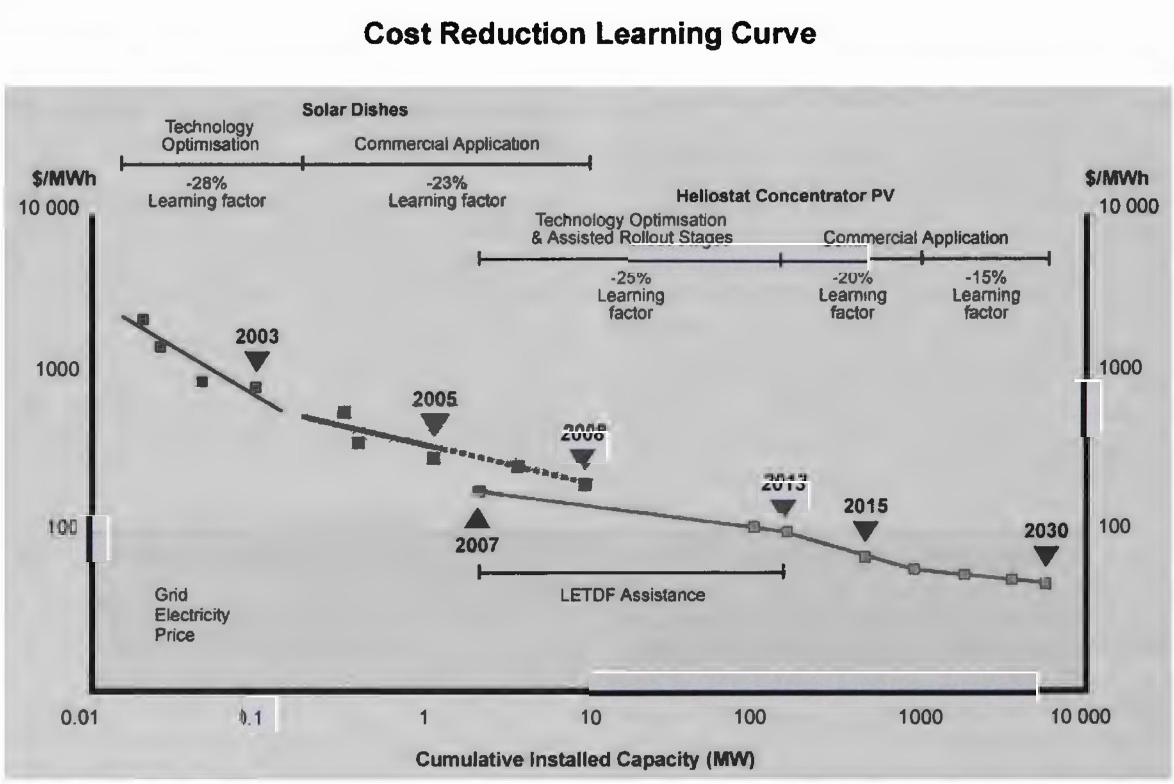

Fig. 7: Cost of solar electricity (in Australian dollars) for CPV dish units and Central Receiver (HCPV) systems

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AUSTRALIAN HYDROGEN TECHNOLOGY FOR SOLAR POWER ON DEMAND AND TRANSPORT

John Lasich[1] Julia Birch[2]

[1,2]Solar Systems, 322 Burwood Rd Hawthorn Victoria Australia 3122,
john.lasich@solarsystems.com.au, julia.birch@solarsystems.com.au

EXTENDED ABSTRACT

Solar Systems is a private company founded 18 years ago to commercialise solar concentrator photovoltaic technology (CPV) and drive CPV power station economics to become favourable for mainstream power generation.

While solar energy is a clean, widespread, free and practically infinite resource, Solar Systems recognises three main challenges associated with solar energy and its CPV technology is designed to overcome these challenges:

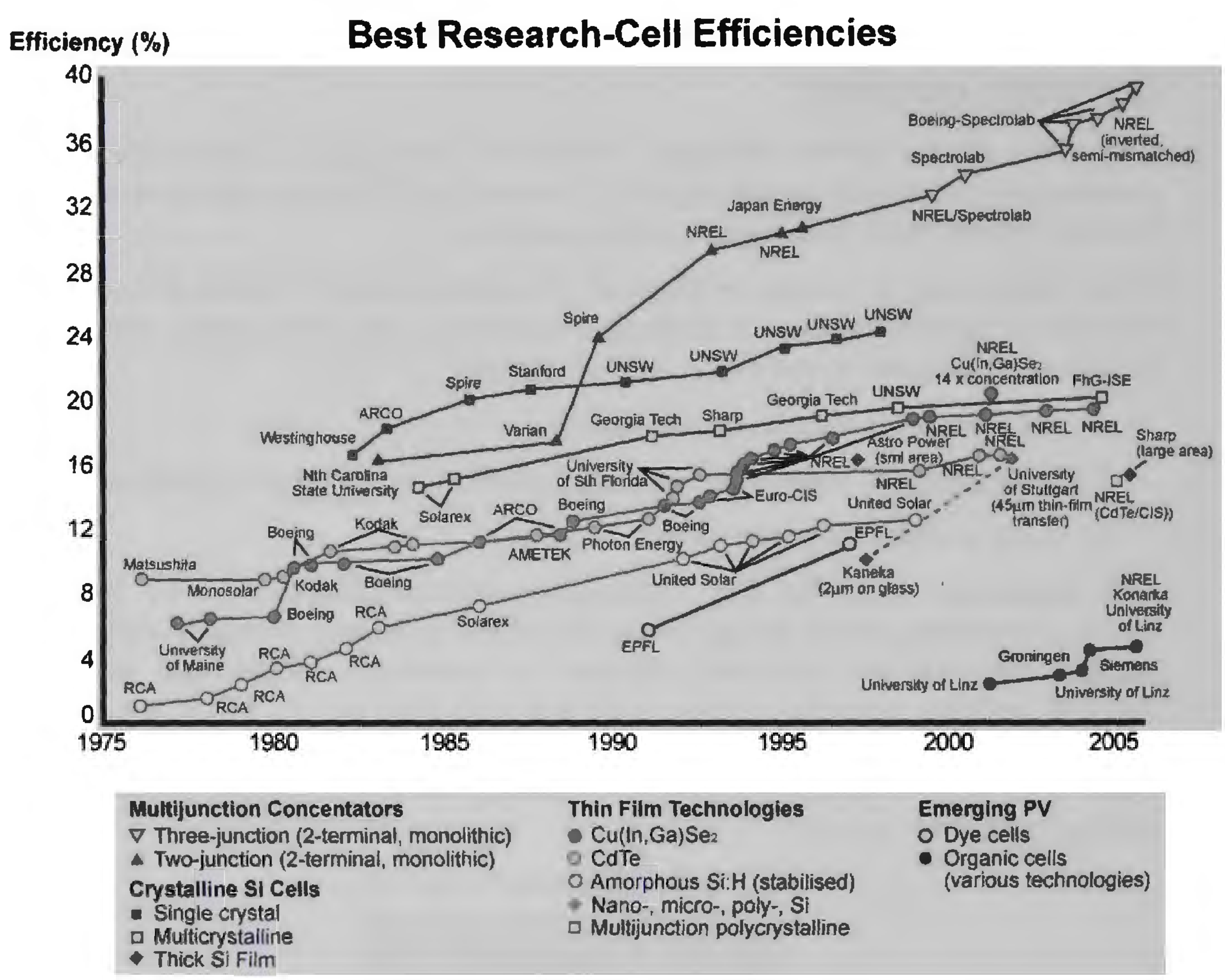
1. Solar energy is a dilute energy source
2. Solar-electrical conversion has been inefficient and therefore expensive
3. Solar availability is intermittent

CPV technology meets the first challenge by concentrating sunlight by 500 times, thereby converting a weak energy source to one that is intense enough to melt steel. In addition, the mirrored structures required to concentrate sunlight are made from standard building materials (glass, steel and concrete) and therefore are relatively inexpensive. Figure 1 shows Solar Systems' commercially available sun-tracking, 14-metre diameter solar dish power station technology, which incorporates patented power, cooling and control systems.

Fig. 1: Solar Systems' solar dish

Concentrating sunlight minimises the area of solar cells required and thus allows the use of (expensive per unit area) high performance photovoltaic (PV) cells. For example, concentrating solar energy to 500 'suns' requires a PV cell area of just 0.2% of the total area of intercepted solar radiation. This allows the use of very high efficient cells which provides a boost in the system's efficiency (NREL, 2005). Solar Systems has collaborated with Boeing company, Spectrolab, to adapt highly efficient space PV cell technology for use in a CPV power station system. Figure 2 shows research cell efficiencies achieved to 2005. Spectrolab's research cell efficiency reached 40.7% in 2007 and commercially available Spectrolab PV cell technology is currently at 35%.

Fig. 2: Best research cell efficiencies (NREL, 2005)



Solar Systems has deployed four CPV power stations in central Australia. Three power stations are located in the Northern Territory and are generating electricity under a long-term power purchase agreement with utility Power and Water.

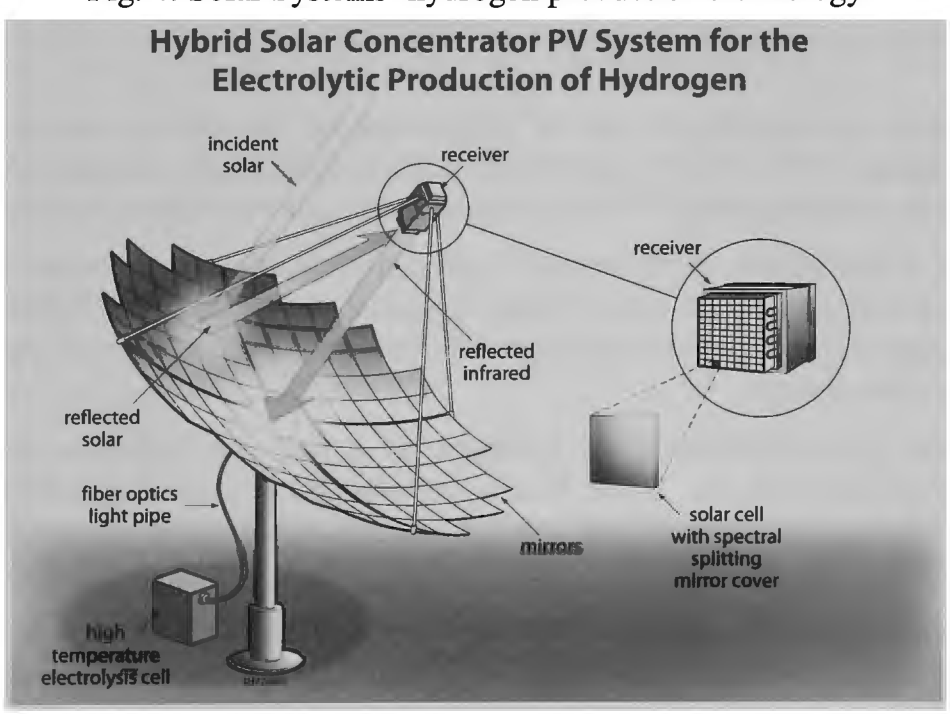
Solar Systems is developing a large-scale CPV configuration for electricity generation to the national electricity market. Figure 3 shows Solar Systems' large scale Heliostat Concentrator Photovoltaic (HCPV) technology that incorporates a central PV tower and a field of heliostats. This configuration enables a reduction in capital cost by incorporating simple structures that can be manufactured in high volumes and by centralising the power plants power and cooling systems. A $420 million, 154MW HCPV project is to be constructed in the north-west region of Victoria. The power station is expected to generate electricity in the range of $100-$120/MWh by 2013 and thereby be competitive with other low emission technologies. Phase One of Solar

Systems' HCPV test facility in Central Victoria near Bendigo will be the first of its kind in the world when complete in 2008.

Fig. 3: Solar Systems' HCPV technology configuration

The third main challenge around solar energy is the intermittency of solar energy supply. Solar Systems' high efficiency hydrogen production technology could enable energy storage for electricity generation on demand and the production of hydrogen for use in hydrogen vehicles. Solar Systems' hydrogen technology works by splitting out the infrared spectrum of sunlight that is normally wasted in the CPV system as heat. The infrared heat energy is added into an electrolyser to assist splitting the water into hydrogen and oxygen at approximately 1000 degrees centigrade. The hydrogen is then stored in order to generate electricity on demand using a fuel cell. The process for hydrogen production is shown in Figure 4. Note that the hydrogen production process is applicable to both the solar dish and HCPV technology.

Fig. 4: Solar Systems' hydrogen production technology



Solar Systems' hydrogen technology has been demonstrated at the scale of a few Watts and is currently at an early R&D phase. The company is seeking to establish a 5-year,

$60 million commercialisation program for its hydrogen production technology this year.

Solar Systems' hydrogen technology is unique because it has potential to have zero losses in the annual electrical output of a solar power station as a result of introducing hydrogen energy storage.

Table 1 provides a comparison of known solar hydrogen production technologies and highlights the superior efficiency of Solar Systems' technology as well as the relative complexity of commercialising the technology.

Tab. 1: Comparison of Solar H2 production methods under investigation by other organisations

Method	Efficiency (approx.)	Op. T (approx.)	Complexity
PV panels and electrolysis, available off the shelf	7%	Ambient	Low – limited potential for improvement
Direct thermal splitting of water, requires 10,000 suns concentration	20%	2500°C	High – serious materials issues
Thermochemical cycles Add elements such as Zn to water	35%	1800°C	High – serious materials and process issues
Biological E.g. slow reacting algae	1%	Ambient	Low – requires large area of water
Solar Systems' hydrogen technology	22% demonstrated, 50% possible	Approx 1000°C	Medium – materials and process issues

A preliminary investigation of cost of adding storage has shown that incorporating hydrogen storage with HCPV solar power station technology increases the upfront capital cost by approximately 35% and roughly doubles power station financial return.

Preliminary investigations of the cost of hydrogen production for transport has shown that the projected production cost of Solar Systems' hydrogen ($0.12-$.19/kWh). The main challenges for development are expected in overcoming the issues of materials and complexity of the system.

The ultimate commercialisation of hydrogen as a fuel also depends on issues of distribution and practical use. These factors are balanced to some degree by the 'clean' renewable value of fuel from the sun and the potential for distributed generation. There is also significant potential for greater utilisation efficiency of hydrogen verses gasoline.

Solar Systems expects commercial hydrogen technology will provide a significant advantage for mainstream power production by removing the intermittency challenge of solar energy. In addition, the technology enables the sale of hydrogen for transport.

BRIEF BIOGRAPHY OF PRESENTER

John Lasich, Founder and Technical Director, Solar Systems

John is the founder of the company and the creator of Solar Systems technology. He has spent the last 18 years working at the leading edge of concentrator photovoltaic systems development and has made significant contribution to the state of the art. He is responsible for establishing the technical strategy for the company and is actively involved in and personally supervises all research and development activities. John has 30 years of practical experience in mainstream energy and renewable energy industry sectors. His experience includes the sale, design, construction, project management, commissioning and operation of significant energy projects in Australia and overseas.

Qualifications

John has a BSc and is currently completing his PhD thesis in the field of concentrator/photovoltaic power generation. John is a member of the International Electrochemical Commission (IEC) standards committee for PV concentrator systems. John is also the inventor of 10 granted and pending patents in the area of solar energy and solar hydrogen production.

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LARGE SCALE CONCENTRATOR PHOTOVOLTAIC SYSTEMS USING MULTIJUNCTION III-V SOLAR CELLS

J.B. Lasich, P.J. Verlinden, A. Lewandowski, D. Edwards, H. Kendall, I. Thomas,
S. Carter, P. Wakeman, I. Varfolomeev, M. Wright, K. Schmidt, W. Hertaeg, R. Metzke, M. Daly and M. Santin

Solar Systems Pty Ltd, 322 Burwood Road, Hawthorn, Victoria 3122, Australia

ABSTRACT

As the size of the worldwide photovoltaic market increases, the size of large scale PV power stations is also increasing. Over the last decade, the PV market growth has been dominated by residential grid-connected applications. During the next decade, the large scale PV power station is thought to become a significant component of the overall PV market. Concentrator PV is well placed to become a major player in this particular segment of the market and poised to be the cheapest method to generate bulk solar electricity. With more than six years of experience with a commercial CPV technology based on large reflective optics and dense array receivers, and with more than 1.2MWp in installed capacity, Solar Systems has developed the world's most efficient CPV technologies to date. We are currently developing a Heliostat Concentrator PV (HCPV), or also called Central Receiver, power station. The first 140-kWp demonstration of this new concept has been built in Australia and is under evaluation. The first large scale deployment of this new technology is a 154-MWp HCPV power station to be built in the northern part of the state of Victoria, Australia, and to be completed by 2013. It is expected to be at that time the largest CPV power station in the world and one of the largest PV systems ever built.

INTRODUCTION

Until recently Concentrator PV (CPV) has not benefited from the dramatic increase in the PV world market. While the overall PV market has grown from about 79MW in 1994 to roughly 4GW in 2007, i.e. almost doubling every two years, CPV still represented last year less than 0.1% of the total PV production. A good reason for this is that the worldwide PV market has been, since 1995, essentially dominated by the residential grid-connected applications, a market segment where CPV has very little to offer. Recently things have changed dramatically. Not only has CPV demonstrated high efficiency and high reliability in large commercial systems [1], the market segment representing medium-to-large size grid-connected power stations is becoming significantly more important. As an example, the sizes of the largest PV power stations are shown in Figure 1 as a function of the year they were or anticipated to be commissioned. Over the last decade, the size of the largest PV power plants have grown exponentially every year, almost multiplying by 10 every 5 years. The world's largest PV power station to date is located in Brandis, Germany. Its current size is 24MW, but will be 40MW when fully commissioned in 2009. There have been several announcements of much larger PV power stations, including a 550-MW thin-film and 250-MW monocrystalline Si PV power stations, both in San Luis Obispo County, California, as well as Solar Systems 154-MW HCPV power station in Victoria, Australia. All three would be completed by 2013. Therefore, it becomes clear that utility-scale application of PV is growing at a fast pace. We expect CPV to play a significant role in this market segment.

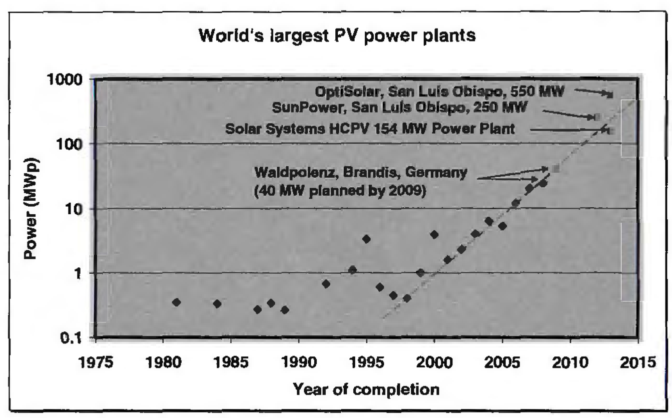

Fig.1: Size of the world's largest PV power plants has a function of the year of completion

EXISTING CPV POWER STATIONS

Recognizing the fact that CPV has the potential to be the most cost-effective PV technology and to play a dominant role in the large scale solar electricity generation, Solar Systems has developed a CPV technology based on large reflective optics (dish) and dense array PV receivers. Its commercial product, CS500, is a 35-kWp dish unit that has been deployed since 2002 in five different power stations in the Australian outback, ranging in power from 175kWp to 350kWp (Fig. 2). The first commercial CPV power station to use the CS500 dish is located in Pitjantjatjara land at Umuwa, South Australia. It is composed of ten 130-m^2 dishes. Originally, when installed in 2002, the dishes were equipped with high-efficiency silicon solar cells and were rated at 22kWp each for a total of 220kWp. One of the great advantages of the dense array technology is that one can upgrade the dish units with more efficient solar cells if the cost benefit is demonstrated. With cells representing about 10% of the overall cost of the dish unit, it was easy to demonstrate the cost benefit of replacing 24%-efficient silicon receivers with 35%-efficient multi-junction III-V receivers. Replacing a receiver with a more efficient one usually takes less than one hour (Fig. 3). This upgrade was carried out in 2008 and the rated power output was increased to 350kWp.

Fig. 2: View of the 350 kWp CPV power station in Umuwa, Australia, newly upgraded to multi-junction III-V cells.

Fig. 3: Upgrade of dish with higher efficiency triple-junction solar cells.

The next generation of CS500 dishes, actually the fourth generation in dish development at Solar Systems was deployed in 2005 and 2006 in three different locations in the Northern Territory, Australia. The original power rating of these three CPV power stations was 190kWp at Hermannsburg, 240kWp at Yuendumu and 290kWp in Lajamanu. In 2005, we then developed our new multi-junction III-V receivers and Hermannsburg became our testing facility for the new technology. We started replacing four receivers at Hermannsburg in March 2006, upgrading the power rating from 190kWp to 230kWp.

In 2008, a fifth CPV power station consisting of five multi-junction dishes with multi-junction solar cells for a total power of 175kWp was built in Windorah, Queensland. The power plant is, at the time of writing this paper, close to commissioning stage. When completed, the total installed capacity of the five CPV power stations would be about 1.2MWp, including 19 dishes or 665kWp with multi-junction III-V solar cells. The company has now more than 10 years of experience with the dense array CPV technology, with dishes of different generations on sun since 2002 and multi-junction III-V solar cells in operation since March 2006. Solar Systems is also the first company in the world to have successfully installed commercial CPV systems with triple-junction solar cells and made the transition from silicon solar cells. Since their installation, the performance data of most dishes has been collected every 15 seconds, including data regarding current, voltage, Direct Normal Irradiance (DNI), cell and coolant fluid temperature, and water flow rate. This vast amount of data is available for analysis and provides a fantastic source of information for improving the performance of the technology [2].

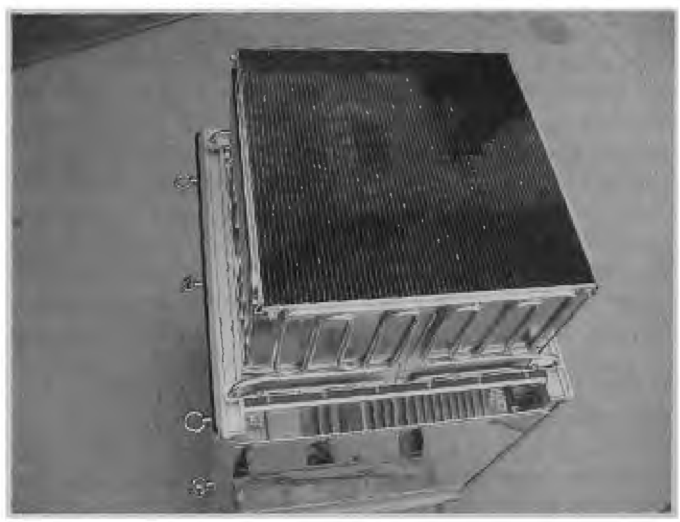

Fig. 4: Multi-junction receiver with a power rating of 35kWp at $50W/cm^2$.

35 kWp DISH UNIT

Our 35 kWp dish unit is composed of a $130\text{-}m^2$ compound parabolic concentrator made of 112 identical mirrors (Fig. 3) concentrating direct sunlight onto a receiver of about $0.25m^2$ (Fig. 4). The design optical concentration ratio is 500X. The average efficiency of the modules in production, measured under flash conditions of $50W/cm^2$ and at 21℃, is greater than 35% (Fig. 5). In 2008, the dish optical design went through a recent revision and a new receiver using modules of a second generation with improved assembly technology was tested. We measured the dish efficiency on a clear day on 31st of May 2008. The dish unit DC efficiency at normal operating temperature reaches 27.8% at an absolute optical air mass index (AM) of 1.5 and a Direct Normal Irradiance (DNI) of $915W/m^2$, corresponding to a concentrated power density of about $43W/cm^2$. The cell temperature at that moment was 37.5℃ and the DC efficiency corrected for 25℃ temperature was 28.4%. The dish DC efficiency actually reached during the day a peak value of 28.2% at AM 1.7 and DNI of 903W/m^2, corresponding to 42W/cm^2 at the receiver level. The cells were running at 37°C and the corrected DC efficiency was 28.8% at 25°C. The maximum output DC power was 33.24kW at AM 1.4 with a DNI of about 965W/m^2 and the cell running at that moment at 39.4°C. The maximum output DC power corrected for a 25°C cell temperature and for a 1kW/m^2 DNI is 35.5kWp. The dish optical efficiency was 85%. The same dish was measured again five months later, in 11/11/2008, giving the same efficiency results, demonstrating the excellent stability in cell efficiency.

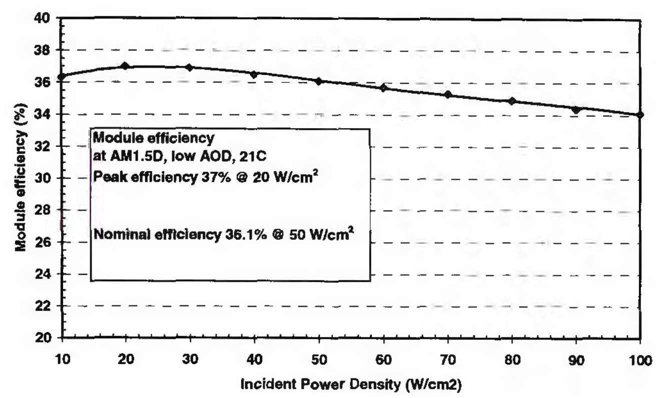

Fig. 5: Typical efficiency of Multi-junction module vs. Incident Power Density at 21°C.

At Solar Systems, we use an Energy Rating system for which we calculate the daily Energy Production Rate (EPR) being the ratio of the daily DC energy output and the daily direct normal insolation [2]. The average EPR of four dishes at Hermannsburg CPV power plant is presented in Fig. 6 over a period of 31 months. The average EPR over this period is 27.4kWh/kWh/m^2 or simply 27.4m^2. It also represents the equivalent area of a 100%-efficient solar-to-electricity converter. This energy rating method allows calculating the annualized DC efficiency by dividing EPR by the projected aperture of the concentrator (130m^2), in this case 21.1%. After changing the dish to the new optics and to the 2nd generation modules, the EPR of that particular dish increased to an average value of 32.3m^2, corresponding to an annualized DC efficiency of 24.8% (Fig. 8).

Accounting for field losses, inverter losses and parasitic power (tracking and cooling), the peak AC efficiency of the new dish is 25.3%. Accounting for the daily and seasonal variations of parameters such as temperature, intensity, Air Mass, Aerosol Optical Depth (AOD) and Water Optical Thickness (WOT), the annualized AC efficiency of the four MJ dishes at the Hermannsburg CPV power station is 19.2%. For the new dish, the annualized AC efficiency increased to 22.5%. The performance improvement due to the new optics and the 2nd generation of modules is clearly shown on Fig. 7 and 8. As far as we know, this is the world's most efficient commercial converter of solar-to-AC-electricity to date in operation. We have recently introduced a new generation of dish which includes the new optimized optics described above and second generation modules, the CS500 Mk V, a large-scale manufacturable unitized dish that is 2.5 tons lighter and has 30% less parts than its predecessor, while increasing wind load capabilities and subsystem modularity. It will become the standard commercial product from January 2009.

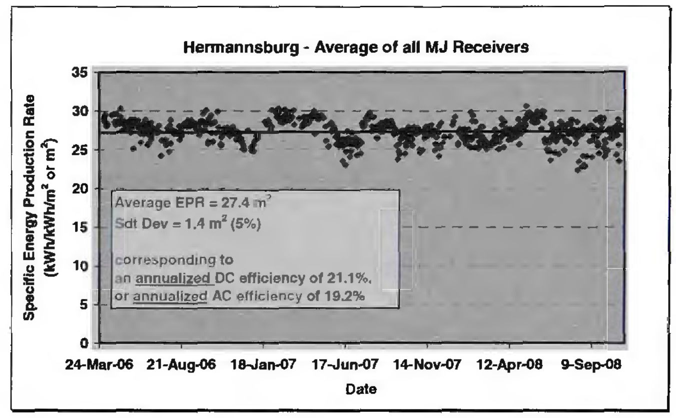

Fig. 6: Energy Production Rate (EPR) in average for 4 dishes in Hermannsburg CPV power station over the last 31 months.

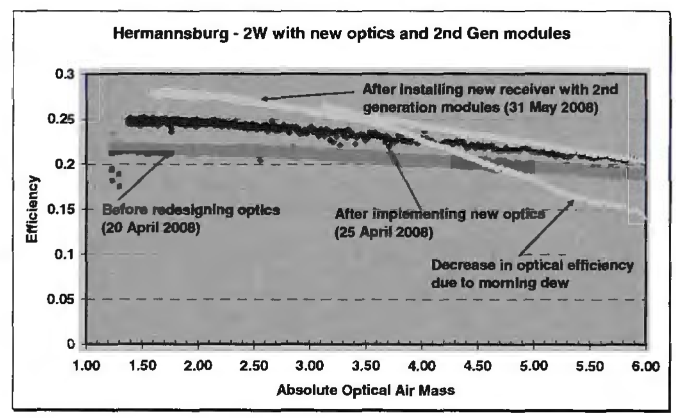

Fig. 7: Dish unit efficiency vs. Absolute Optical Air Mass for three different configurations: a. Old dish optics, b. After installing new optics, c. After installing 2nd generation modules.

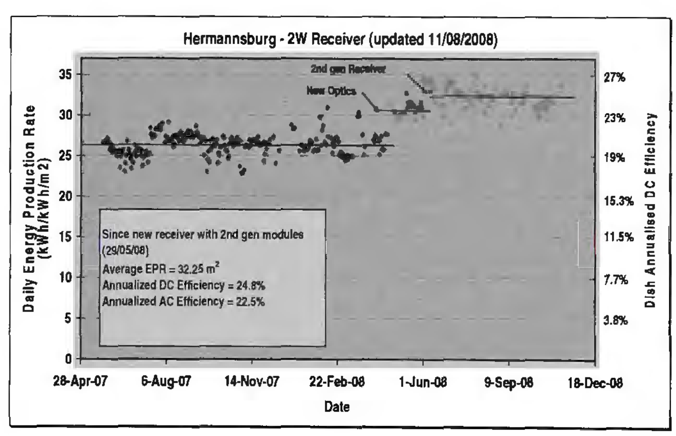

Fig. 8: Improvement in EPR from standard CS500 dish to new dish with new optics and 2nd generation modules.

HELIOSTAT CONCENTRATOR PV (HCPV)

Large CPV power stations using dish technology clearly require a great number of distributed units for utility scale applications. The disadvantage of distributed units is the increased amount of physical infrastructure (wiring, cooling, power conditioning, etc.) and large number of small receivers. The ability to combine many of the components into large central receivers in a Heliostat Concentrator PV (HCPV) configuration takes advantage of economy of scale to potentially significantly reduce system cost. This is exactly analogous to the advantages of central receivers vs. dishes for solar thermal applications. However, like for solar thermal applications, there is a small performance penalty with HCPV due to the nature of heliostat tracking a fixed target (tower located receiver) compared to a dish tracking the sun directly. On the other hand, unlike thermal systems, the efficiency is not dependant on scale and this additional degree of freedom allows much greater flexibility in choosing the size of the 'repeatable optimum field unit'. Performance modeling and cost estimates by Solar Systems indicates significantly lower capital and energy cost potential with HCPV. The experience at Solar Systems with dish technology puts us in a unique position to conduct this scale up to the proof of concept stage. Much of the dish technology experience, including experience with dense array receivers, mirrors, tracking, control and monitoring software, has been either directly applied or easily scaled for the initial demonstration/test facility. In our case, the scaling step has been relatively small to insure high confidence in a successful demonstration and to quickly develop an understanding of the performance, operational and cost differences of any new technology (e.g., heliostat structures and controls).

BRIDGEWATER TESTING FACILITY

We have established at Bridgewater, 80 miles north of our headquarters in Melbourne, a state of the art, 70 acre (28 ha), grid connected R&D test and optimization center for dishes and central receivers. The facility includes mechanical and electrical workshops, training facilities, a control room and, both dish and HCPV test systems. Accommodation is provided on-site for visiting personnel and, the site has been designed to enhance productivity and shorten time to market in the technology advancement process. We currently have on site our latest Mark V generation of the 35kWp dish unit, facilities for a second R&D dish unit to be transported from our previous testing facility in Fosterville, a 140-kWp HCPV systems consisting of a 25-m high tower with a roughly 1m^2 receiver populated with triple-junction cells and a field of 30 heliostats of about 20m^2 (Fig. 9 and 10). The testing facility will also accommodate a second demonstration of the HCPV technology, which will be the first commercial-size prototype, by 2010. As far as we know this is the world's first demonstration of HCPV technology of this size.

To date the 140-kWp HCPV system has been commissioned with operational and performance testing ongoing. A thermal-only receiver was initially installed to assess heliostat tracking/controls, measure power delivery and compare with simulations with an increasing number of targeted heliostats. A fully operational PV receiver has now been installed and is undergoing tests to measure power output in carefully managed steps up to full power. All indications so far point to this system meeting design expectations. Performance results of the 140-kWp HCPV system will be published soon. The next phase will be a first commercial-size prototype of HCPV technology to be completed by 2010.

154-MWp HCPV POWER STATION

Part of the Low Emission Technologies Development Fund (LETDF) of the Australian Government, an AU$420 million large-scale HCPV power station is to be built in the north-west region of the state of Victoria. The rated capacity of the grid-connected plant will be 154MWp and we estimate will produce more than 270GWh per annum. The site latitude will be about 35° South. For the last year, we have been measuring the direct normal solar resource in the area and we estimated that the average direct normal radiation is about 6.5kWh/m^2/day. The total land area required for the CPV power station infrastructure is approximately 500ha. This project will be one of the largest solar power stations in the world and, based on our past results, also one of the most efficient ones. This investment will use as much as possible local suppliers and local industries, creating jobs and new opportunities in an economically depressed region. The project is supported by grant funding from the Australian Government and the Victorian Government. Full commissioning is expected in 2013.

The schedule for the construction of the 154-MWp HCPV power plant is:

- Stage 1: 2MWp by 2010
- Stage 2: 102MWp by 2012
- Stage 3: 154MWp by 2013

Project milestones for the first 12 months are as follows:

- Develop arrangements for grid connection
- Design engineering
- Complete detailed Environmental Management Plant
- Commence construction of 2-MWp pilot plant
- Develop necessary manufacturing facilities

Our utility partner, TRUenergy, a major utility in Australia and a wholly-owned subsidiary of China Light and Power (CLP) is backing the project. Solar Systems is co-developing and exploring projects in Australia with TRUenergy including the 2-MWp HCPV prototype in Victoria with a commitment to expand to 154-MWp power plant subject to certain conditions.

MANUFACTURING FACILITY

Solar Systems is currently building a much larger manufacturing facility in Abbottsford, a suburb of Melbourne, which will have a total capacity of about 500 MWp per annum. The facility will include a fully automated assembly line for dense array modules, as well as a manual assembly line for dense array receivers. It will also include new office and research facilities for optics, reliability, failure analysis, and development of future technologies.

Fig. 9: First 140-kWp HCPV demonstration at Bridgewater testing facility

Fig. 10: 140-kWp HCPV receiver on sun during commissioning at the Bridgewater testing facility

CONCLUSIONS

Solar Systems has installed a total of 1.2MWp of CPV power station in the Australian outback, including 19 dishes or 665kWp with multi-junction III-V solar cells. The first 31 months of experience with the multi-junction solar cells have been successful and all expectations have been met. The cells are very stable over time. The 2nd generation of modules has an efficiency greater than 35% (typically 36%) at 50W/cm^2 and 21°C. At the system level, we measured a peak DC efficiency of the 35kWp dish unit of 28.2%. Corrected to 25°C, the peak efficiency be comes 28.8%. The specific Energy Production Rate is 32.3m^2, corresponding to an annualized DC and AC efficiency of 24.8% and 22.5% respectively. As far as we know, this is the world's most efficient solar-to-AC-electricity converter to date in a commercial power plant.

We have established a new 70-acres R&D testing, optimization and training facility for CPV dishes and HCPV systems in Bridgewater, Victoria. The next generation (Mark V) dish, a large-scale manufacturable unitized dish that is 2.5 tons lighter and has 30% less parts than its predecessor, has been designed and demonstrated. Also, in Bridgewater testing facility, we have built the world's first 140-kWp demonstration of HCPV technology. We currently are designing the first commercial-size prototype of HCPV systems to be completed by 2010, and to be deployed in the contracted 154-MWp HCPV power plants in the north-west region of Victoria to be completed by 2013.

Solar Systems is currently gearing up for large volume production, establishing a new manufacturing facility with a capacity of 500MWp per annum. We expect large scale CPV power stations to become a significant and increasing part of the overall world PV market in the next decade.

ACKNOWLEDGMENTS

The developments presented in this paper have been possible thanks to the hard work of many people at Solar Systems. The authors would like to thank all the employees of Solar Systems who have contributed to the research, design, simulation, manufacturing, construction, installation, commissioning and monitoring of the different CPV power plants and testing facilities, as well as the ongoing commitment and support from our shareholders. The development and the construction of the 154-MWp HCPV power station are supported by the Low Emission Technology Development Fund (LETDF) of the Australian government, by the Victorian Government and by our utility partner TRUenergy.

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ENERGY RATING OF CONCENTRATOR PV SYSTEMS USING MULTI-JUNCTION III-V SOLAR CELLS

P.J. Verlinden and J.B. Lasich
Solar Systems Pty Ltd, Hawthorn, Victoria 3122, Australia

ABSTRACT

An energy rating method is proposed for Concentrator Photovoltaic (CPV) systems. The method allows for easy calculation of the projected annual energy production at any location, which is the most important figure for utility scale PV application. The method consists of recording the daily energy production and the daily solar direct-beam energy. The ratio of these two values is called the Specific Energy Production Rate. It is shown that this figure represents the equivalent area of a 100% efficient energy conversion device. The ratio of the Specific Energy Production rate and the power rating of the CPV system is the well-known Performance Ratio. The influence of temperature, solar spectrum changes, Air Mass (AM), Aerosol Optical Depth (AOD) and precipitable Water Optical Thickness (WOT) is discussed for CPV systems with multi-junction III-V solar cells.

INTRODUCTION

For many years the PV industry has used a power rating system for flat plate PV modules and systems. The most commonly used power rating method is at Standard Rating Conditions (SRC), i.e. at a standard solar spectrum of AM1.5G, corrected for 1000 W/m^2 and with a cell temperature kept at 25°C. These conditions are simulated in laboratory or the measurement results are corrected using appropriate coefficients. Another very common power rating scheme is the PVUSA Testing Condition (PTC), which is closer to real power delivered by the PV system in typical conditions. The PTC reference is based on a solar spectrum of AM1.5G, corrected to 1000 W/cm^2, with an ambient temperature of 20°C and a wind speed of 1 m/sec.

The SRC and PTC power rating systems have existed for many years for flat plate PV modules and, in particular, the SRC rating is the reference for comparing modules, estimating module price or worldwide PV market volume. However, comparing PV systems of different technologies based on their SRC rating is not realistic. Projecting the annual energy production of a PV system at any location, from either SRC or PTC power rating, is somewhat difficult, requires simulation and an accurate knowledge of:

- the cell temperature versus intensity, ambient temperature and wind speed,
- the solar radiation and weather data for that particular site,
- the efficiency temperature coefficient,
- the influence of Air Mass over the responsivity of the considered solar cells,
- and the influence of intensity over the efficiency of the cells.

For the sake of simplicity, and because the efficiency of single junction solar cells, such as crystalline Si, amorphous Si, CdTe and CIGS cells are only weakly dependent on Air Mass and intensity, it is common practice, but not very precise, to assume:

- a constant Normal Operation Cell Temperature (NOCT),
- a constant efficiency temperature coefficient,
- and a constant efficiency with respect to Air Mass and Intensity.

Fig. 1: CPV power station in Hermannsburg, composed of eight dishes, four of which are equipped with multi-junction solar cells, the first being in operation since March 2006.

It has been clear for many years that comparing different PV technologies based on the SRC rating of their modules was not the best method. The issue is even more critical when comparing Concentrator PV (CPV) technologies to flat plate PV technologies. A methodology of energy rating for PV flat plate modules has been proposed for many years [7] but never applied by the PV industry, and it is not applicable to CPV systems.

Solar Systems Pty Ltd has built, operated and monitored CPV power stations for the last decade, including grid-connected CPV systems using multi-junction III-V solar cells for the last 2 years [1] (Fig. 1 and 2). An update on the performance of the concentrator units using multi-junction solar cells over a two-year period is presented in another paper [2]. Recently, an Energy Rating system has been developed by Solar Systems to quantify the performance of these CPV stations and to project the performance of future CPV power stations at other locations.

Fig. 2: 32-kWp CPV dish with multi-junction solar cells at Hermannsburg power station. The dish aperture area is 130m^2.

ENERGY RATING METHOD

The Energy Rating method developed by Solar Systems consists in recording on a daily basis E_{out}, the energy produced by every dish unit (kWh DC), as well as DNR, the integrated direct-beam solar radiation (kWh/m^2). The ratio of these two measured quantities is called the Specific Energy Production Rate:

$$EPR = \frac{E_o}{D^u} \qquad (1)$$

Its unit is in kWh/kWh/m^2 or simply m^2. It corresponds to the equivalent aperture area that would convert the solar energy with 100% efficiency. Although EPR is an energy-based figure of merit of the CPV system, it could also be considered as an effective power rating for a DNI of 1 kW/m^2, which includes all the effects on efficiency due to the changes in AM, intensity, temperature, AOD and other atmospheric parameters. The average Specific Energy Production Rate (EPR) for four 130-m^2 dishes equipped with multi-junction solar cells at Hermannsburg is presented in Figure 3. The direct solar irradiance is measured by a Class 1 pyrheliometer with an acceptance angle of 2.5 degree.

The Specific Energy Production Rate (EPR) of the concentrator dish unit varies from day to day in a range of 23 to 31 m^2 with an average of 27.5 m^2 and a standard deviation of 1.3 m^2 (4.7%), over a two-year period at the Hermannsburg site (Lat. –23.56 degree, elevation 565 m). Since the dishes have an aperture of 130 m^2, it is easy to calculate the annualised DC efficiency, in this case 21.1%, as given by Eq. (2).

$$\text{Annualized Efficiency} = \frac{E}{A} \qquad (2)$$

where A is the total concentrator aperture. The well-known Performance Ratio (PR) of the systems is given by the following equation:

$$PR = \frac{E}{P_S} \qquad (3)$$

where P_{SOC} is the power rating of the CPV system at Standard Operating Conditions. In this case, the P_{SOC} is 32.2 kWp at 1 kW/m^2, AM1.5D, low AOD and 21°C cell temperature. This group of four dishes has an average PR of 85.4%. The annual energy output of the CPV system is calculated by multiplying EPR by the annual DNR, and the capacity factor is given the annual energy output by the rated power and by 8,760 hours/year. In this case, at Hermannsburg which has an annual DNR of 2,464 kWh/m2, the capacity factor is 24.1%.

The day-to-day variations of the EPR, of about +/- 14%, are due to:

- seasonal variation of the sun declination, resulting in change of Air Mass (AM),
- variation of the air turbidity, or Aerosol Optical Depth (AOD),
- variation of the precipitable Water Optical Thickness (WOT),
- variation of temperature of the cooling water and of the cells,
- variation of the optical efficiency of the concentrator due to dust deposit.

The obtained value of EPR also contains secondary effects that are always present in a real life situation, such as shadowing of a dish by another dish and morning dew on the concentrator optics. In order to assess the performance of any CPV system at a reference site (for example at sea level, with a 50-percentile AM of 1.5) or at any site, it is important to understand and to quantify the influence of parameters like AM, AOD, WOT and temperature. From practical experience, we found that the parameters such as AOD and WOT and temperature have a significant influence on EPR

INFLUENCE OF AIR MASS

It is well known that monolithically interconnected multi-junction solar cells are very sensitive to spectrum changes. This is due to the fact that the monolithic stack of cells is optimised for a particular spectrum, for which their photocurrent is balanced. If the spectrum changes from the reference spectrum, one of the cells in the stack will be limiting the overall solar cell current. Figure 4 shows the typical responsivity of a triple-junction GaInP/GaInAs/Ge solar cell as a function of Air Mass. The commercial terrestrial multi-junction solar cells are assumed to be optimised for AM1.5D solar spectrum but in reality, their typical responsivity peaks around AM1.2. This is caused by the difficulty and the cost of growing very thick GaInP top cell [4]. For Air Mass greater than AM1.2, the top cell limits the current of the multi-junction cell. For Air Mass smaller than AM1.2, the middle cell is the limiting one. The Ge cell is usually not limiting in any case because its bandgap is much smaller than the optimum bandgap for the sub-cell of a monolithic triple-junction stack.

The decrease in solar cell responsivity, as the Air Mass differs from the optimum Air Mass, is different for each type of multi-junction cell and was found to be about –0.009 A/W per AM unit for this particular example, or about –6.6% per AM unit. The responsivity of a cell maintained at constant temperature is pretty much linear versus Air Mass, at least in the range from AM0.9 to AM6, and symmetrical around the peak of responsivity at the optimum Air Mass.

In a practical situation, the power output of a CPV system versus Air Mass is more complicated to analyse because of the combined effects of several parameters which are related to Air Mass, i.e. intensity, temperature and spectrum modification by the concentrating optics. Indeed, as the Air Mass increases, the incident power density, as well as the cell temperature, would generally decrease, resulting in two competing effects on the system efficiency. These effects are difficult to demonstrate in a laboratory and must be measured on a real operating CPV system on sun. Figure 5 shows the DC efficiency of one of the 32-kW dish units as a function of Air Mass for a particular day in summer (November 30th, 2007). The top series of data points corresponds to the morning when the cooling water is at a lower temperature, resulting in a higher efficiency than in the afternoon. When comparing Figure 4 and 5, it is obvious that the efficiency curve versus Air Mass is more rounded at the peak and not as steep as the responsivity curve, losing relatively only about 5% per Air Mass unit, due to the opposite effects of intensity and temperature. In particular, it is interesting to note that there is less than 1% relative difference in efficiency in the range of optical Air Mass between 1.35 and 1.65, the peak being at AM1.6. The competing influence of intensity and temperature also are responsible for a shift toward higher optimum optical Air Mass when system efficiency is considered instead of just responsivity (AM1.6 instead of AM1.2).

OPTIMUM AIR MASS

Recently, K. Emery et al. have convincingly proposed that the appropriate reference solar spectrum for characterizing concentrator cells and modules be based on an Air Mass of 1.5 and a Aerosol Optical Depth (AOD) of 0.085 at 500 nm [3]. This study was based on real radiation data from the 1961-1990 US National Solar Radiation Database. This proposal formed the base for the new reference direct-beam solar spectrum ASTM G173. It was shown that, in average over several sites, 50% of the cumulative annual direct-beam solar radiation corresponds to the absolute optical AM1.5. Therefore, it was proposed that the optimum Air Mass to optimise the performance of multi-junction cells for terrestrial CPV application be AM1.5.

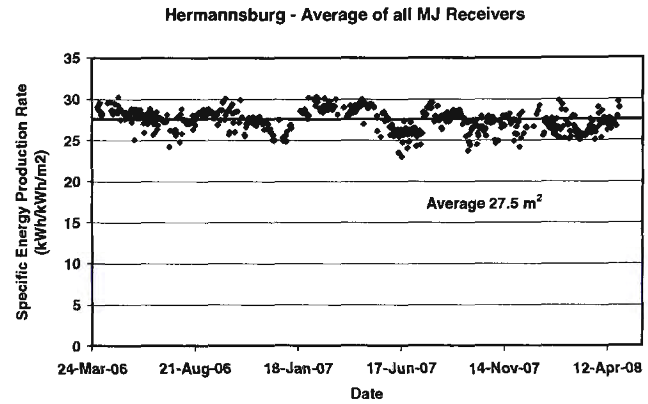

Fig. 3: Specific Energy Production Rate (EPR) per dish averaged over four dishes with multi-junction (MJ) receivers, at Hermannsburg, Australia.

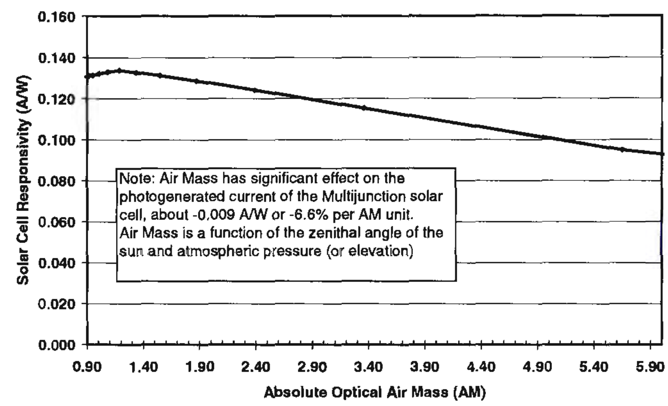

Fig.4: Typical responsivity of a triple-junction GaInP/GaInAs/Ge solar cell vs. absolute optical Air Mass

Using Bird's model of a cloudless sky implemented in the SPCTRAL2 spreadsheet, we calculated the cumulative annual direct-beam solar energy as a function of absolute optical Air Mass for the site of the power station in Hermannsburg (Fig. 6). The 50-percentile indicates that the best AM for optimizing the performance of a CPV system would be AM1.35. Adding a weather pattern and clouds effect does not significantly affect the optimum Air Mass. It was found that the correction is in fact in the range of 0.05 Air Mass unit or less. The cumulative direct-beam energy versus Air Mass for 12 representative days of the year is shown in Figure 7 for Hermannsburg power station. From day to day, the 50-percentile Air Mass varies from AM1.05 to AM 1.60. Based just on the responsivity curve versus Air Mass, the seasonal variations of the declination should be responsible for +/- 2% of the daily EPR. However, considering all the competing effects and considering the efficiency curve versus Air Mass, it is clear that the seasonal variation of the declination is only responsible for variations of EPR in less than +/-1% range. Other effects must be much more significant to explain a +/- 13% range in EPR variation from day to day.

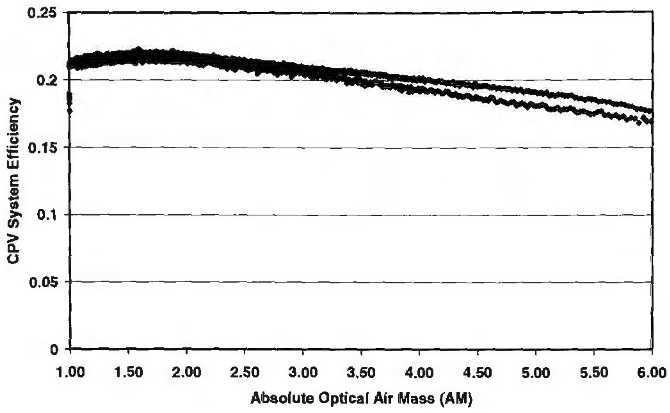

Fig. 5: Typical DC efficiency of a 30 kW dish unit vs. absolute optical Air Mass

We also calculated the best Air Mass to optimize the performance of CPV systems of any site as a function of latitude and elevation (Fig. 8). Since CPV technologies apply only to sites in the sun belt with latitudes between 15 and 35 degrees, we restricted our analysis to latitudes between 0 and 40 degrees. Adding a weather pattern, for example with clouds during the summer rainy season for the tropical sites or during the winter rainy season for the non-tropical sites, results in a minor correction of up to +0.05 AM unit for latitudes between 12 and 25 degrees and in a correction of 0 to –0.1 AM for latitudes between 25 and 40 degrees. The calculated values of the optimum optical AM from the US National Solar Radiation Database for several sites in US [3] are in very good agreement with the simulation results (Fig. 8). The optimum optical Air Mass, at sea level AM_{SL} is very well fitted using the following empirical polynomial equation:

$$AM_{SL} \approx 1.2 - 4.4 \cdot 1^{-3} L + 5.1^{-4} L^2 - 5.1^{-7} L^3 - 2.1^{-8} L^4 \quad (4)$$

where L is the latitude in degrees. Considering that the atmospheric pressure is decreasing by 12.13 mbar per 100 m of elevation, the absolute optical Air Mass becomes:

$$AM \approx \left(1 - \frac{0.1\,.E}{1}\right) AM_{SL} \quad (5)$$

where E is the elevation of the site in meters.

Table I gives the latitude, elevation and the measured 50-percentile absolute optical Air Mass, as well as the calculated optimum Air Mass for 5 sites in US, as well as for Hermannsburg and Mildura power stations in Australia.

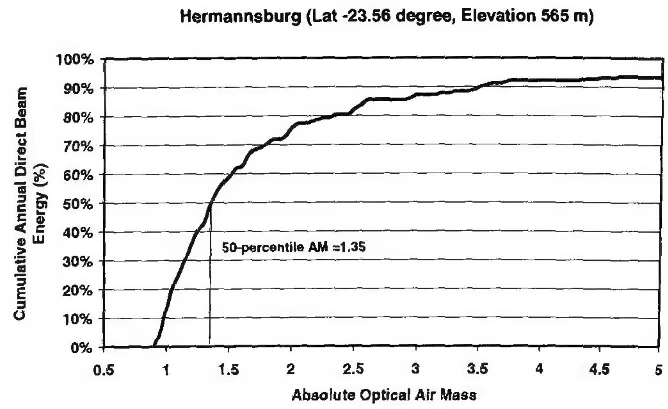

Fig. 6: Cumulative annual direct-beam solar radiation versus absolute optical Air Mass in Hermannsburg, Australia. The 50-percentile Air Mass is AM1.35.

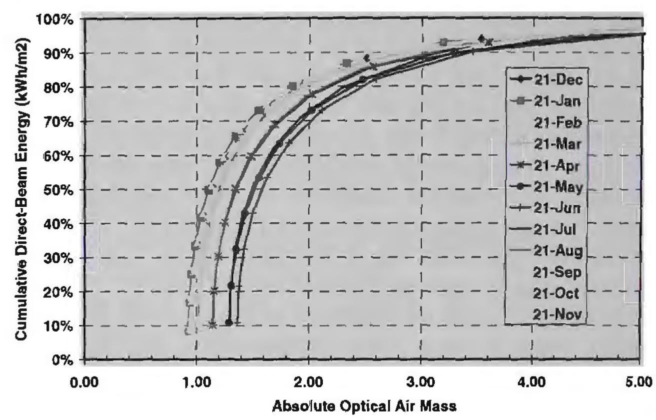

Fig. 7: Cumulative daily direct-beam solar radiation versus absolute optical Air Mass in Hermannsburg, Australia. The 50-percentile Air Mass varies from AM1.05 to AM1.60.

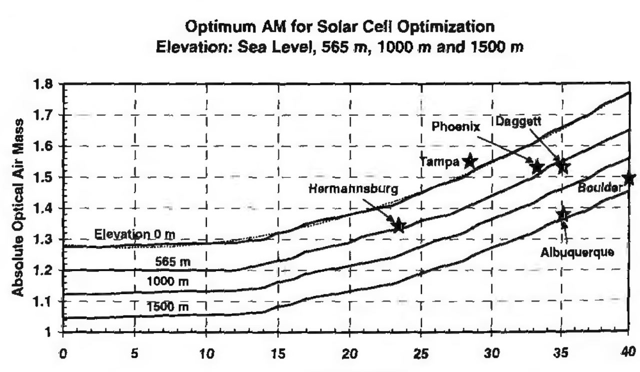

Fig. 8: Optimum Air Mass versus Latitude and elevation. Measured characteristic AM for different sites are noted on the graph.

INFLUENCE OF TEMPERATURE AND OTHER ATMOSPHERIC PARAMETERS

Temperature Coefficient

The temperature coefficient of the multi-junction modules was measured both at the NREL High Flux Solar Furnace (HFSF) using a continuous concentrated beam up to 600 suns [6] and in laboratory using flash testing equipment. At 500X concentration (50 W/cm2), the temperature coefficient for output power or efficiency was found to be –0.17%/°C (relative) by both methods.

In the water-cooled 30-kWp dish unit, the typical cell temperature is 53°C, ranging from 30°C in early morning to a maximum of 60°C around solar noon on very clear days. From day to day, the maximum cell temperature around solar noon varies from 45°C to 60°C. The variations in temperature are responsible for efficiency and EPR variations of about +/- 1.5%.

Aerosol Optical Depth (AOD)

Aerosols are the major scattering and absorbing elements in the sky. They are responsible for decreasing the direct solar irradiance and increasing the diffuse one, mostly in the UV and visible regions of the spectrum. Because the light scattering by the aerosols is not uniform across the spectrum, AOD has a significant effect on the responsivity and the efficiency of a multi-junction solar cell. AOD was measured over a two-year period at the Hermannsburg power station and was found to be between 0.04 and 0.20 cm when no clouds are present. The typical values of AOD are between 0.08 and 0.11 cm.

Using Bird's model and SPTRAL2 spreadsheet, we calculated the impact of AOD on the responsivity of a triple-junction solar cell (Fig. 9). The AOD coefficient for responsivity was found to be –0.056 A/W/cm, which could result in efficiency variation in the order of +/- 3% for the range of observed values of AOD.

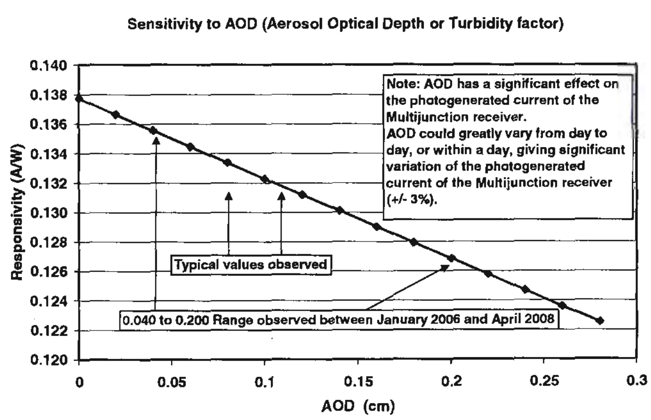

Fig. 9: Responsivity of a triple-junction solar cell versus AOD for AM1.5D

Precipitable Water Optical Thickness (WOT)

Water in the atmosphere has a very interesting effect on the responsivity of multi-junction solar cells. Water is responsible for sunlight absorption in many different regions of the solar spectrum, but the most important absorption bands are 925-1000 nm, 1070-1180 nm, 1320-1520 nm and 1740-1980 nm. The first two bands of absorption are within the absorption region of the Ge sub-cell. Therefore, as the water optical thickness decreases, the DNI reading increases and the Ge sub-cell generation increases. However, the cell photocurrent does not increase because it is already limited by the top or middle cell, and the power output remains unchanged. In consequence, a decrease in WOT results in a decrease of the cell responsivity and system efficiency (Fig. 10).

Values for WOT in Hermannsburg over the last two years were typically in the range of 1.25 to 2.25 cm, but some extremely low values were as low as 0.25 cm. By simulation, using SPCTRAL2, the effect of WOT on the multi-junction receiver efficiency was found be +/- 8%. We concluded that variations in the Water Optical Thickness was the main cause of variations in daily EPR.

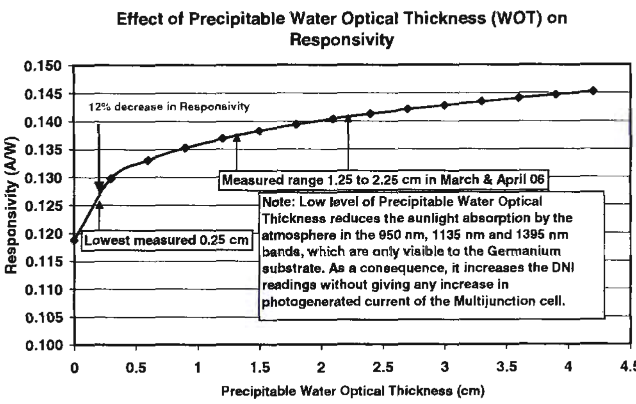

Fig. 10: Responsivity of a triple-junction solar cell versus precipitable Water Optical Thickness (WOT)

ENERGY OUTPUT CALCULATION

In order to implement an energy rating method for CPV systems with multi-junction solar cells, it is important to decide:

- what is the requirement for the acceptance angle of the pyrheliometer,
- how long do we want to gather daily EPR data to calculate the average value,
- and how do we apply corrections in order to extrapolate the energy rating for another site.

First, it appears that the pyrheliometer for DNI measurement must have an acceptance angle as close as possible to the acceptance angle of the concentrator. A large acceptance angle of the pyrheliometer would under-estimate the EPR for cloudy or hazy days.

Second, the length of the EPR averaging period should ideally be one year, but a six-month period from solstice to solstice would be acceptable if it encompass all the different weather patterns for the considered site.

Finally, as far as latitude and elevation are concerned, it appears that there is no need to apply significant corrections to the average EPR. For latitude between 15 and 35 degrees, and elevation between 0 and 1500 m, the 50-percentile optical Air Mass varies from AM1.1 to AM1.65, resulting in less than 1% possible correction to the EPR. The most important corrections to apply to the average EPR for extrapolating to a different locations would be based on the average values of AOD and WOT, which are usually not well known. Therefore, to be able to extrapolate EPR to other locations and to be able to calculate annual energy production at these locations, it is paramount to have a correct solar resource assessment that includes daily AOD and WOT measurements.

In practical terms, estimating the power output of a given CPV system at any location consists of:

- Measuring the daily energy output and the DNR at a known site, and extracting EPR, over a 6-month to one-year period,
- Assessing the solar resource and weather pattern at the future site, measuring not only DNR with a pyrheliometer but also AOD and WOT with a spectrophotometer, as well as ambient temperature,
- Calculating the 50-percentile AM at the known site as well as at future site,
- Calculating the estimated energy output of the CPV system at the future site by multiplying EPR by the measured DNR,
- Applying corrections for AM, temperature, AOD and WOT, which are anticipated to be relatively small considering that most suitable sites for CPV are located within a range of latitudes between 15 and 40 degrees.

The energy output can be estimated by this method with accuracy better than +/- 10%.

CONCLUSIONS

An energy rating method is proposed for CPV systems. It consists in measuring Specific Energy Production Rate (EPR) over a period of time long enough to represents the typical weather at a particular location. The average value of the EPR represents the equivalent aperture area of a PV system with 100% efficiency. The annualised DC efficiency is the EPR divided by the total aperture area. The 50-percentile Air Mass or optimum Air Mass for optimising the performance of CPV systems was calculated as a function of latitude and elevation, and an empirical formula was given. For practical locations for CPV (between 15 and 40 degrees of latitude), very small corrections may be applied to the measured EPR value for the purpose of estimating the energy output of the same CPV system in a different location. The temperature coefficient of CPV systems with multi-junction solar cells was reported, as well as the influence of other atmospheric parameters such as AOD and the water optical thickness (WOT). The AOT and WOT seem to be the most significant parameters to influence the efficiency or the energy output of a CPV system, and must be appropriately assessed before estimating the energy output of a CPV system with multi-junction cells.

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Table I: Latitude, Elevation, Measured 50-percentile optical Air Mass, and Calculated optimum Air Mass for 6 different sites in USA and in Australia.

Sites	Latitude (degree)	Elevation (m)	Measured 50-percentile Optical AM	Calculated optimum AM (no clouds)
Albuquerque	35.08	1768	1.375	1.30
Boulder	40.02	1655	1.49	1.40
Daggett	35.00	587	1.52	1.50
Phoenix	33.45	447	1.52	1.55
Tampa	27.95	36	1.55	1.50
Hermannsburg	-23.56	565	-	1.35
Mildura	-34.23	50	-	1.65

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UPDATE ON TWO-YEAR PERFORMANCE OF 120 KWp CONCENTRATOR PV SYSTEMS USING MULTI-JUNCTION III-V SOLAR CELLS AND PARABOLIC DISH REFLECTIVE OPTICS

P.J. Verlinden, A. Lewandowski, H. Kendall, S. Carter, K. Cheah, I. Varfolomeev,
D. Watts, M. Volk, I. Thomas, P. Wakeman, A. Neumann, P. Gizinski, D. Modra, D. Turner and J.B. Lasich
Solar Systems Pty Ltd, Hawthorn, Victoria 3122, Australia

ABSTRACT

Multi-junction III-V solar cells have been in operation for the last two years in several 500X dish concentrator PV systems using reflective optics. The performance monitoring of these CPV systems on a 15-second basis has accumulated a very large amount of data and allowed for analysis of the influence of atmospheric parameters to the system efficiency. Dense array modules are assembled into large receivers of approximately a quarter of square meter in size and with a typical efficiency of 31.7% and power output of 36.5kWp under Standard Operating Conditions (SOC, 1000W/m^2, AM1.5D, low AOD and 21°C cell temperature). At Normal Operating Cell Temperature (NOCT 53°C), the receiver efficiency and power output become 30% and 35.4kW. The DC efficiency of the dish unit is 24.5% at SOC. More interestingly, the specific Energy Production Rate (EPR) of each dish, being the ratio of the daily energy output and the daily incident direct-beam energy (DNR), was measured. In average, over a two-year period and over four dishes, the EPR was 27.5 m^2, corresponding to the equivalent aperture of a 100%-efficient solar energy converter. The annualised efficiency of these CPV systems is 21.1%. A new generation of dense array modules have demonstrated efficiency of 36.1% at 50W/cm^2 and 21°C. Also, a new redesigned optics has recently been implemented on one of the dishes and has demonstrated a significant boost in efficiency, bringing the SOC efficiency to 26.2% and an expected EPR of 30 m^2. We expect that combining the 2nd generation modules with the redesigned optics would improve the DC efficiency to 28% at SOC.

INTRODUCTION

Over the last decade, Solar Systems Pty Ltd has built, managed and monitored Concentrator PV (CPV) power stations, with currently over 1 MWp of installed capacity in the Australian outback. The CPV power stations are composed of individual 130 m^2 reflective dishes concentrating 500-times the sunlight onto a dense array receiver. While the first dishes used mono-crystalline high-efficiency silicon solar cells, the latest generation uses multi-junction III-V solar cells, specially designed for dense array application. Currently, Solar Systems has installed four dishes with multi-junction III-V solar cells for a total of over 120kWp (Fig. 1), the earliest one being installed in March 2006 at the Hermannsburg power station (Latitude – 23.6 degrees and 565 m elevation). Since their installation, the performance of these CPV units has been continuously monitored and data have been gathered every 15 seconds. As reported previously [1-2], early modules were successfully tested at the NREL High Flux Solar Furnace (HFSF) under continuous concentrated sunlight up to 60 W/cm^2. The next demonstration step consisted in building two first hybrid receivers composed of modules with silicon cells and modules with triple-junction solar cells. One of these receivers has been on sun since December 2005. The third step in demonstration was to upgrade several CPV dishes by replacing their silicon receivers with multi-junction ones, an operation that takes only about 30 minutes. The first multi-junction receiver went on sun in March 2006, followed by three other ones during 2006 and 2007. We have monitored their performance and acquired enough confidence that the multi-junction technology is reliable, cost effective and could be deployed in very large-scale utility applications. Based on its long experience with concentrator silicon solar cells, Solar Systems is the first company to demonstrate and promote commercial CPV systems with multi-junction solar cells, and also the first company that has made a successful transition from silicon with a proven commercial CPV system. In this paper, we report on the performance analysis of these four dishes with multi-junction receivers.

MODULE AND RECEIVER EFFICIENCY

Each CPV dish is composed of 112 identical curved mirrors (Fig. 2). The total aperture area is 130 m^2. Dense array CPV modules are assembled with triple-junction solar cells from Spectrolab [3], with integrated bypass diodes, cooling system and temperature sensor (Fig. 3). Each module is individuality flash tested and sorted before assembly into the receivers (Fig. 4). The overall packing density at the dense array receiver level, i.e. the area of the receiver divided by the cell area, is greater than 97%. We are presenting below historical data on modules, receivers and dish units, the early ones containing the first generation of modules exhibiting efficiency in the 32% to 34% range.

Fig. 1: Partial view of the Hermannsburg 220 kWp power station in the Australian outback. The four 32-kWp dishes on the picture are equipped with multi-junction solar cells.

The typical efficiency of a recent module versus incident power density is presented in Figure 5. The maximum efficiency of 37% is obtained at about 200X (20 W/cm^2, AM1.5D, low AOD, and 21°C). At the nominal incident power density of 50 W/cm^2, the module efficiency is 36.1% (Table 1). The modules are rated 650Wp at Standard Operating Conditions (SOC), nominally 50W/cm^2, AM1.5D, low AOD, and 21°C cell temperature. After assembly, each receiver is flash tested before installation onto a dish. Under flash testing the uniformity across the quarter-square-meter receiver area is within +/- 5%. The typical receiver performance is presented in Table 1. At an incident power density of 50W/cm^2 and at a cell temperature of 21°C, the efficiency of the ent ire receiver is 31.7%. The difference between the module and receiver efficiency is due to the packing density, the current mismatch between modules, the uniformity of the receiver flash tester (better than +/- 5%) and the protective diodes within the receiver. The receivers are rated 36.5 kWp at a uniform intensity of 50W/cm^2, AM1.5D, low AOD, at 21°C cell temperature, and 35.4kW at Normal Oper ating Cell Temperature (NOCT).

The receivers are actively cooled with water, the heat being rejected in a large solar pond. In normal operation, the cells are running at a temperature varying between 30°C in early morning in winter and a maximum of 60°C around solar noon on warm sunny days in summer (ambient temperature of 45°C). The Normal Operating Cell Temperature (NOCT) is 53°C, when the incident power density is 1kW/m^2 and the ambient temperature is 32°C. The temperature coefficient of the multi-junction modules was measured both at the NREL HFSF using a continuous concentrated beam up to 600 suns [2] and in laboratory using flash testing equipment. At 500X concentration (50W/cm2), the temperature coefficient for output power or efficiency was found to be –0.17%/°C (relative) by both methods. The flash testing performance results for a typical module and a typical receiver are presented in Table 1. At NOCT, the corrected module efficiency is 34.1%.

Fig. 2: CPV dish unit with 130-m^2 total aperture and 500X concentration ratio. The dish unit is rated 32kWp, with a EPR of 27.5kWh/kWh/m^2.

Fig. 3: 650-Wp multi-junction module with integrated cooling.

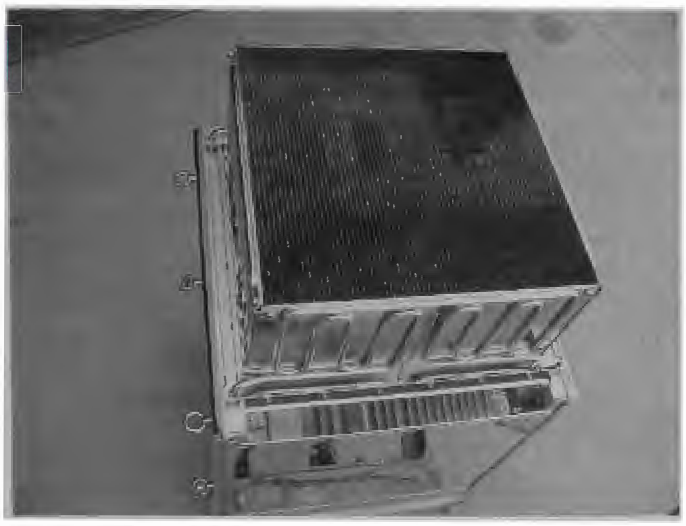

Fig. 4: 35-kWp Receiver with multi-junction solar cells

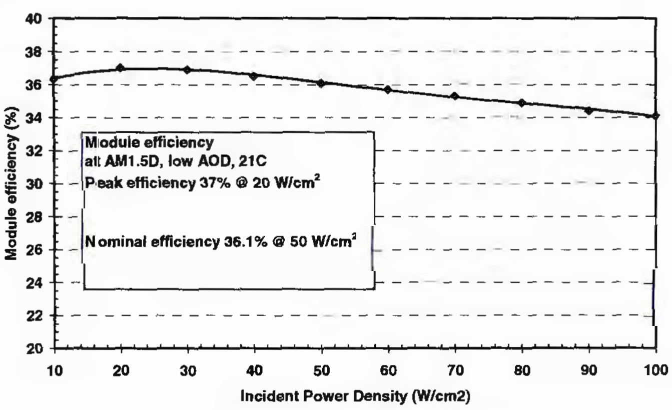

Fig. 5: Efficiency of a recent typical multi-junction module versus incident power density.

DATA COLLECTION AND SYSTEM EFFICIENCY

Over the last two years, data was collected every 15 seconds, which allows for extensive study of real-life performance and analysis of influence on the system efficiency of parameters such as optical Air Mass, temperature, and intensity. Figures 6 and 7 show, as a function of the absolute optical Air Mass, the efficiency of the dish unit "1W" at the Hermannsburg power station, for two representative days.

The first series of data points (Fig. 6) was collected on 28 July 2007, in the middle of the Australian winter. The day was relatively cool with a maximum ambient temperature of 28℃. The Direct Normal Irradiance (DNI) reached a maximum of 897 W/cm^2 and the cell temperature a maximum of 46.3℃. As shown on the graph, the efficiency of the dish unit increased with decreasing Air Mass, until reaching a peak efficiency of 23.5% at AM1.27. As discussed in another paper [4], the influence of Air Mass on the system efficiency is not as strong as expected because of opposite influence of intensity and temperature.

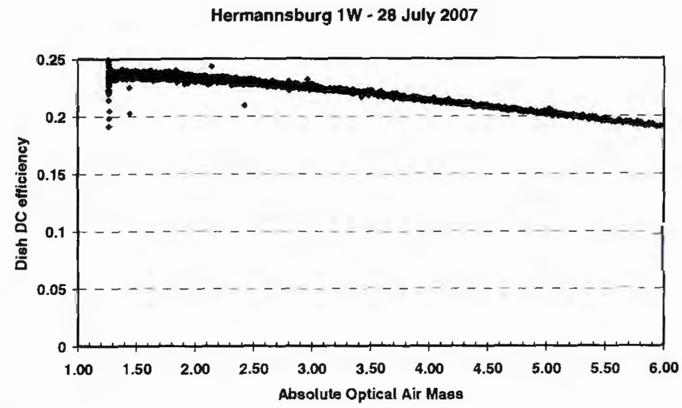

Fig. 6: DC Dish efficiency versus Absolute Optical Air Mass for dish "1W" at Hermannsburg power station on a cool clear day of winter (28 July 2007). The peak cell temperature was 46.3°C.

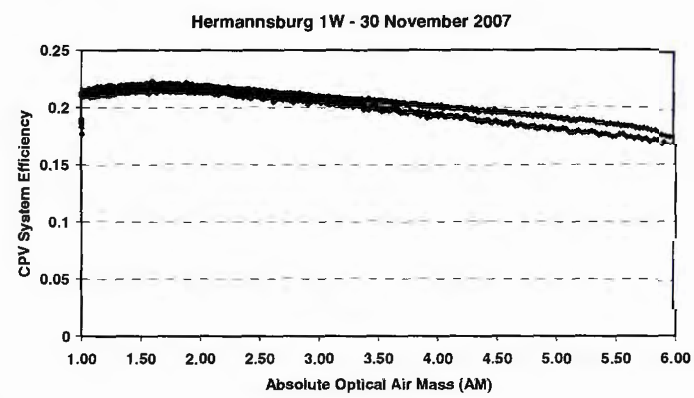

Fig. 7: DC efficiency of same dish as Fig. 6 but on a warm day of summer (30 November 2007). The peak cell temperature was 58.6°C.

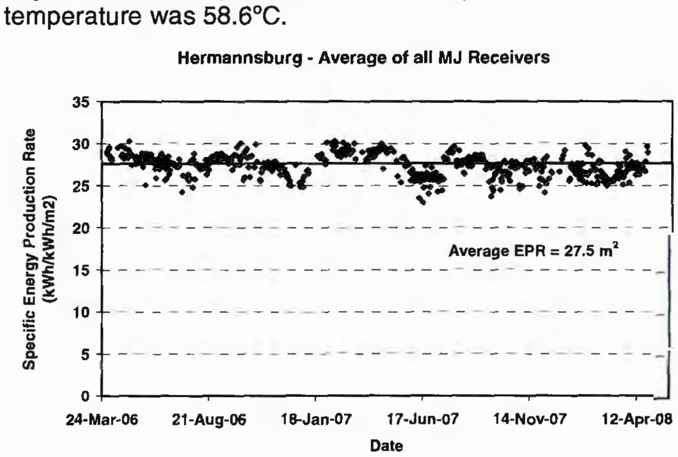

Fig. 8: Specific Energy Production Rate (EPR), averaged over 4 dishes, from March 2006 until April 2008. Average EPR is 27.5 m^2, corresponding to an annualised DC system efficiency of 21.2%.

The second series of data (Fig. 7) was collected on 30 November 2007, on a clear day in the beginning of the Australian summer, which is usually the beginning of the rainy season at this latitude. The cells reached a maximum temperature of 58.6°C, while the ambient temperature reached 42.8°C. The dish efficiency peaked at 22.0% while the optical Air Mass was AM1.6, DNI was 895.5W/m^2 and the cell temperature was 50.9°C. It is interesting to note that, even the multi-junction cells have a maximum responsivity for approximately AM1.2, the efficiency reaches a maximum at higher Air Mass because of the opposite effect of temperature and intensity [4]. The efficiency and power data is summarized in Table 1, as well as the SOC corrected values.

ANNUALISED PERFORMANCE

The Specific Energy Production Rate (EPR) is calculated on a daily basis as the ratio of the daily energy output and the daily DNR. The average EPR of the four multi-junction dishes at Hermannsburg is presented in Figure 8. The unit of EPR is kWh/kWh/m^2, or simply m^2. It represents the area of an equivalent 100%-efficient solar energy converter. It varies from day to day between 23 m^2 and 30 m^2, due to seasonal variations of the sun declination, the temperature, the Aerosol Optical Depth (AOD) and the Water Optical Thickness (WOT) [4]. During the two years of observation, EPR averaged to 27.5 m^2 with a standard deviation of 1.3 m^2 or 4.7%.

The annualised efficiency of the CPV dish unit can easily be calculated by dividing the EPR value by the aperture area of the concentrator (130 m^2). The annualised efficiency is 21.1%. The Performance Ratio (PR) is obtained by dividing the EPR by the SOC rated power of the dish unit (32.2kWp). We obtained a PR of 85.4%. In Hermannsburg, which has a daily average DNI of 6.75kWh/m2, the annual energy output is 67,753 kWh per dish or 2,104kWh/kWp. This corresponds to a capacity factor of 24%.

RELIABILITY

The reliability of the multi-junction receivers has been excellent over the two years of monitoring. In particular the efficiency of the multi-junction cells has shown to be very stable over time, as we can see on Figure 8. In addition, modules have been tested under thermal cycling and high-temperature soak, and have a projected lifetime greater than 25 years.

NEW DISH OPTICS

Recently the optics of the dish unit has been redesigned and optimised for higher efficiency. The new optics has been implemented on dish "2W" of the Hermannsburg power station on 24 April 2008. Although we only have limited data with the new dish optics, the benefit was obvious and demonstrated a significant increase in the dish efficiency (Fig. 9). The peak efficiency of dish "2W" around solar noon achieved 24.90% on 25 April 2008 after the redesign of the dish optics was implemented. The benefit of the new optics could also be observed on the EPR graph of dish "2W". EPR increased from an average 26.4 m^2 before the optics change to an average 30.1 m^2 over six days after the implementation of the redesigned optics. At SOC, the corrected dish efficiency reaches 26.2% and the power output is 33.9 kWp.

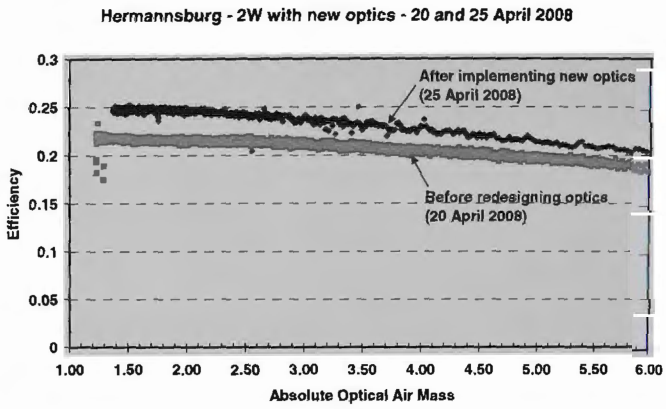

Fig. 9: Dish unit efficiency versus Absolute Optical Air Mass for dish 2W at Hermannsburg after redesigning optics.

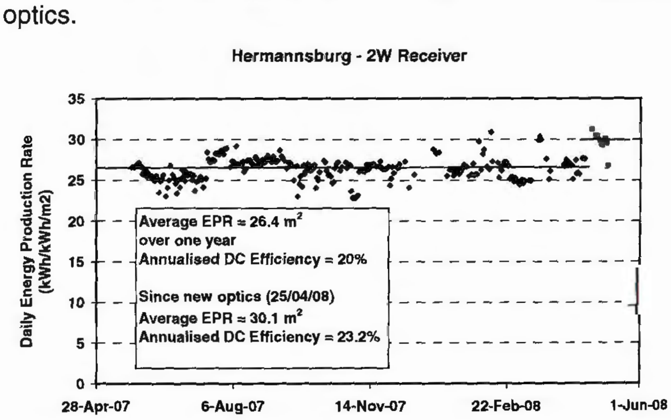

Fig. 10: Specific Energy Production Rate (EPR) of Dish 2W at Hermannsburg power station over one-year period, before (average EPR 26.4m^2) and after (average EPR 30.1m^2) optics redesign.

Table 1: Typical Module and Receiver flash testing performance at SOC (50 W/cm^2, AM1.5D, low AOD and 21°C cell temperature) and at NOCT (53°C). The dish unit efficiency is presented for two different days (winter and summer) and at SOC. The efficiency of dish unit "2W" after implementing the redesigned optics is also presented.

		FF (%)	P_{out} (W or kW)	η (%)	Conditions
Module	**Module Measured at SOC**	84.2	650 W	36.1	SOC Tcell = 21°C AM1.5D P_{in} = 50 W/cm^2
	Module Corrected for NOCT	82.7	615 W	34.1	NOCT Tcell = 53°C AM1.5D P_{in} = 50 W/cm^2
Receiver	**Receiver Measured at SOC**	78.4	36.5 kW	31.7	SOC Tcell = 21°C AM1.5D P_{in} = 50 W/cm^2
	Receiver Corrected for NOCT	78.3	35.4 kW	30.0	NOCT Tcell = 53°C AM1.5D P_{in} = 50 W/cm^2
Dish Unit	**Dish Unit**	-	27.7 kW	23.5%	Tcell = 46.3°C AM1.27D P_{in} = 893 W/m^2
	Dish Unit	-	25.0 kW	22%	Tcell = 50.9°C AM1.60D P_{in} = 895.5 W/m^2
	Dish Unit Corrected for SOC	-	32.2 kWp	24.5%	SOC Tcell = 21°C AM1.5D P_{in} = 1000 W/m^2
	Dish 2W Redesigned optics	-	29.1 kW	25.0%	Tcell = 48.9°C AM1.50D P_{in} = 900 W/m^2
	Dish 2W Redesigned optics, Corrected for SOC	-	33.9 kWp	26.2%	SOC Tcell = 21°C AM1.5D P_{in} = 1000 W/m^2

CONCLUSIONS

Four dishes of the Hermannsburg power station have been upgraded with multi-junction receivers, the first one being installed in March 2006. Flash testing efficiency of typical dense array modules is 36.1% at 500X (50W/cm^2, AM1.5D, low AOD, and at 21°C). At the receiver level, the efficiency is 31.7% also measured by flash testing and under the same conditions. The overall efficiency of a 130-m^2 dish unit is 24.5% at SOC (1000W/m^2, AM1.5D, low AOD, 21°C cell temperature). New dish optics has been designed for efficiency improvement and we demonstrated a significant boost in efficiency for one particular dish. This particular dish has an overall efficiency of 26.2% at SOC. More interestingly for annual energy calculation, we proposed to use the specific Energy Production Rate (EPR) has a new energy rating scheme for CPV system with multi-junction solar cells. In average over a two-year period and over four CPV dish units, the EPR value is 27.5m^2, which means that each 130-m^2 dish is equivalent to a 100%-efficient solar energy converter with an aperture of 27.5m^2. The annualised efficiency can easily be obtained and is 21.1% in this case. We expect EPR to increase significantly with the new redesigned dish optics to a value around 30m^2, which would bring the annualised efficiency around 23.1%. Soon, we plan to deploy the next generation of modules with the new optics design, which is expected to reach a peak DC efficiency of 28% at SOC and an annualised DC efficiency of 24.7%. The annualised AC efficiency would in this case be about 22.4% This value is approaching the thermal efficiency of 25.2% of brown coal power plants in Victoria, Australia [5]

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WORLD'S FIRST DEMONSTRATION OF A 140kWp HELIOSTAT CONCENTRATOR PV (HCPV) SYSTEM

J.B. Lasich, P.J. Verlinden, A. Lewandowski, D. Edwards, H. Kendall, S. Carter, I. Thomas, P. Wakeman, M. Wright, W. Hertaeg, R. Metzke, M. Daly, M. Santin, A. Neumann, A. Wilson, A. Caprihan and M. Stedwell

Solar Systems Pty Ltd, 45 Grosvenor Street, Abbotsford, Victoria 3067, Australia
Solar Systems USA, 8401 N. Central Expressway, Suite 225, Dallas, TX 75225

ABSTRACT

Solar Systems has more than 10 years experience with grid-connected CPV systems using large reflective optics. Over the last 7 years, Solar Systems has deployed 47 dish units, of which 23 are with multijunction solar cells, in five different commercial CPV power plants and two testing facilities, for a total installed capacity of 1.5 MWp. Recently, Solar Systems has designed and built a 140kWp Heliostat Concentrator PV (HCPV) system at its new Testing and Training Facility in Bridgewater, Victoria. The demonstration of the performance of the HCPV system met all the specification targets. The system reached a power output of 140kW with a DC efficiency of 24% to 26% and an optical efficiency of 84%, measured on two different days, four months apart, around solar noon. This is the first utility-scale Heliostat CPV system ever built. It is also for Solar Systems the first demonstration of a new technology to be deployed in a large 154-MWp power plant in Northern Victoria.

INTRODUCTION

During the design phase and technology selection for a utility-scale PV power station, the Levelized Cost of Electricity (LCOE) is one of the primary criteria used in the decision process. Parameters that greatly influence LCOE are system efficiency, cost of the components, cost of on-site build and installation, cost of Operation and Maintenance (O&M), location and capacity factor. The cost of installation, and in particular the cost of power reticulation, is greatly influenced by the physical size of the power plant and therefore the system efficiency. On the other hand, the capacity factor of the power plant is mostly determined by the type of tracking (fixed angle, one-axis or 2-axis tracking), the location of the power plant, the climate at that location and the temperature coefficient of the solar cells. For these reasons, Concentrator PV (CPV) technology is of great interest for utility-scale solar power stations. With high-efficiency multi-junction solar cells, it features what we believe to be the highest system efficiency ever demonstrated for solar-to-AC-electrical energy conversion, and high capacity factor due to 2-axis tracking and low temperature coefficient [1].

The concept of a PV central receiver system was originally presented by R. Swanson [2]. Photovoltaic central receiver systems or Heliostat CPV (HCPV) have the potential to be the optimum solar energy generation system for utility scale because it combines all the advantages of CPV (high-efficiency, high capacity factor, low cost). It centralizes the electric generation in a high-power central receiver, avoiding the cost of power and cooling fluid reticulation over a large field, and can have a collector field of heliostat chosen for minimum cost per area. Since the efficiency of HCPV is substantially independent of scale, this technology has considerable scope to minimise the cost by selecting the appropriate power blocks and subsystems with the lowest cost of fabrication, installation and O&M. In general, the total installed cost of a solar power station can be minimised by:

- Minimizing the amount of equipment to be deployed per MWp. This is substantially driven by efficiency and concentration ratio. Our 36cm^2 dense array module with an efficiency of 37% at 500X [1] is emerging as the most efficient solar energy converter available.
- Maximizing the proportion of pre-fabricated sub-systems, for example an appropriately sized heliostat can be factory assembled, pre-commissioned and shipped to site as a complete unit. As another example, 1MW-scale HCPV receiver can be pre-assembled in factory and shipped to site in one piece.
- Rationalizing the infrastructure to reduce cost by minimizing field reticulation and cooling. For HCPV, concentrated light is used as the actual transfer medium to bring a large amount of power to a central point. A smaller number of large sub-system blocks are used to convert light to AC electricity. Typically larger components have a lower specific cost per MWp and greater efficiency.

This paper describes the pathway to the development of a heliostat CPV system and reports on the results from testing of the world's first utility scale Heliostat CPV system using multijunction solar cells.

SOLAR SYSTEMS TECHNOLOGY

Over the last two decades, Solar Systems Pty Ltd has developed a PV technology based on a unique concentrator with reflective optics and dense array PV receivers. Since 1996, Solar Systems has built, managed and monitored Concentrator PV (CPV) power stations, with currently over 1.5 MWp of installed capacity in the Australian outback, distributed over five power stations, ranging from 175kWp to 350kWp, and two testing facilities. The CPV power stations are composed of individual 130-m^2 reflective dishes concentrating 500 times the sunlight onto a dense array receiver of about 0.25 m^2. While the first dishes used mono-crystalline high-efficiency silicon solar cells, the latest generation uses multi-junction III-V solar cells, specially designed for dense array application [6]. Currently, Solar Systems has installed 23 dishes with multi-junction III-V solar cells for a total of over 805kWp in grid-connected capacity (Fig. 1), the earliest one being in operation since March 2006.

Fig. 1: Hermannsburg 240 kWp power station. The four dishes on the right are fitted with multijunction receivers.

Since their installation, the performance of these CPV units has been continuously monitored and data have been gathered every 15 seconds. Among these 23 dishes, 16 were originally fitted with high-efficiency silicon solar cells and were progressively upgraded with receivers containing multijunction solar cells, boosting the efficiency by more than 56% [3]. The exchange of an existing silicon receiver by a multijunction receiver is an easy operation that can be performed with one single person within about 1 hour of time, resulting in a significant boost of performance that clearly justifies the cost of the upgrade.

We have reported earlier the performance of the 35 kWp CPV dish unit [1, 3-5], as well as its energy rating [7, 8]. Each CPV dish unit, CS500, is composed of 112 identical mirrors forming a compound parabolic concentrator with an aperture area of 130m^2, concentrating sunlight onto a receiver of about 0.25m^2, populated with about 1600 multijunction solar cells in a series-parallel interconnection scheme to optimise the AC power output (Fig. 2). As measured at the beginning of life of this particular dish configuration, on 31st of May 2008, the CS500 dish unit had a DC power efficiency of 28.4%, corrected to 1000W/m^2, 25℃ cell temperature and AM1.5D. At Normal Operating Conditions (NOC), the cell temperature is 50℃ and the CS500 dish unit efficiency is 27.2%. The same dish measured almost one year later, on 19th of May 2009, had similar performance. Particular atmospheric conditions, spectrum changes, dirt on the mirror surface, cell temperature, and intensity differences make it difficult to obtain an efficiency number with accuracy better than +/- 10% relative, particularly for CPV systems using multijunction solar cells. Figure 3 shows the DC power efficiency of the same dish after one year of operation, uncorrected and corrected to 25℃ cell temperature, but not adjusted for spectrum variations and other dish conditions. The uncorrected and 25℃-corrected DC efficiency is 26.8% and 27.6% respectively. On this graph, the measurement noise is about +/- 2% relative. While variability in measurement conditions, such as Air Mass, turbidity and water optical thickness, may influence the results by up to +/-10% relative, the raw data indicates that there is no significant change in performance. When including Balance of System (BOS) losses, such as power reticulation losses, cooling fluid pumping losses, tracking, and inverter losses, the peak AC power efficiency is 24.4% at NOC.

Fig. 2: 35-kWp dish unit. The dish aperture is 130 m^2 and the receiver area 0.25m^2.

We recently proposed a better way to look at the performance of a CPV system by measuring the daily produced energy and the daily solar direct-normal energy [7, 8]. The ratio of these two values is the Specific Energy Production Rate (EPR) and has the unit of kWh/kWh/m^2 or simply m^2. It also represents the area of an equivalent 100%-efficient solar energy converter. The ratio of EPR and the aperture of the dish is the energy efficiency. When integrated over a one-year period, this method allows for calculating the annualised energy efficiency, which includes all effects that can impact the annual energy production, i.e. daily and seasonal spectrum changes, intensity variations, temperature variations, shading between dish units, morning dew on the mirrors, and dirt deposits on the mirrors. Figure 4 shows the improvement in EPR of one of the dish units at the Hermannsburg power station, over a two-year period. After re-designing the optics of the dish and after installing a receiver with modules from the 2^{nd} generation, we were able to increase the EPR of the dish from an average 26.5m^2 to an average 32.5m^2, which corresponds to an annualised DC and AC energy efficiency of 24.8% and 22.5% respectively. As far as we know, this is the highest annualised energy efficiency reported to date for conversion of solar energy to AC electricity.

Over the years, we have acquired enough confidence that the multi-junction technology is reliable, cost effective and could be deployed in very large-scale utility applications. We have developed a reliable and quantifiable solar power system which is supported by established maintenance procedures, integrated monitoring and readily exchanged components. This experience has allowed Solar Systems to progress to large scale HCPV systems with multi-junction solar cells. With the deployment of the new HCPV technology, Solar Systems makes another step forward to potentially lower installed system cost and thus lowering LCOE.

HELIOSTAT CONCENTRATOR PV

Large CPV power stations using dish technology clearly require a great number of distributed units for utility scale applications. The disadvantage of distributed units is the increased amount of physical infrastructure (wiring, cooling, power conditioning, etc.) and large number of small receivers. The ability to combine many of the active components into large central receivers in a Heliostat Concentrator PV (HCPV) configuration takes advantage of economies of scale, giving potential to significantly reduce system cost, as well as operation and maintenance cost. This is analogous to the advantages of central receivers vs. dishes for solar thermal applications. However, like for solar thermal applications, there is a performance penalty with HCPV due to the nature of heliostat tracking a fixed target (tower located receiver) compared to a dish tracking the sun directly. On the other hand, unlike thermal systems, the efficiency is not dependant on scale and this additional degree of freedom allows much greater flexibility in choosing the size of the 'repeatable optimum field unit'. Performance modelling, correlated by actual test results, and cost estimates by Solar Systems indicate significantly lower capital and energy cost potential with HCPV. The experience at Solar Systems with dish technology puts us in a unique position to conduct this scale up to the proof of concept stage. The transfer of the essential technology into the heliostat format was successful and achieved the target performance as designed. Much of the dish technology experience, including experience with dense array receivers, mirrors, tracking, control, cooling and management system, has been either directly applied or easily scaled up for the initial demonstration of 140 kWp.

In our case, the scaling step has been relatively small to ensure high confidence in a successful demonstration and to quickly develop an understanding of the performance, operational and cost differences of any new technology, e.g. heliostat structures, controls and CPV receiver response.

BRIDGEWATER TESTING FACILITY

We have established at Bridgewater, near our headquarters in Melbourne, a state of the art, 70 acre (28 ha), grid connected R&D test and optimization centre for dishes and central receivers (Fig.5). The facility includes mechanical and electrical workshops, training facilities, a control room and, both dish and HCPV test systems. Accommodation is provided on-site for visiting personnel and, the site has been designed to enhance productivity and shorten time to market in the technology advancement process. We currently have on site our latest 5^{th} generation of the 35kWp dish unit, facilities for a second R&D dish unit to be transported from our previous testing facility in Fosterville, a 140-kWp HCPV systems consisting of a 30m high test bed tower with an approximate 1m^2 receiver populated with triple-junction cells and a field of 32 heliostats of about 20m^2 in mirror area (Fig. 6 and 7). The testing facility will also accommodate a second demonstration of the HCPV technology, which is planned to be the first pre-production commercial-size prototype, by 2010.

Fig. 5: 70-acre (28 ha) Solar Systems Testing and Training Facility in Bridgewater, Victoria, Australia.

To date the 140-kWp HCPV system has been commissioned with operational and performance testing ongoing since November 2008. A thermal-only receiver was initially installed to assess heliostat tracking and controls, to measure power delivery and to compare with simulations with an increasing number of targeted heliostats. A fully operational CPV receiver was installed in November 2008 and has been undergoing tests to measure power output under a wide range of conditions since that time (Fig. 8).

Fig. 6: 140kWp HCPV system with 5th generation 35kWp dish unit at Bridgewater Testing Facility.

Fig. 7: Field of heliostats of 140kWp HCPV system. Each heliostat has a mirror area of about $20m^2$.

Fig. 8: View of the test bed tower with $1m^2$ receiver of 140kWp HCPV system on sun (500X concentration ratio).

PERFORMANCE OF HCPV SYSTEM

At the moment of writing of this paper, we have had more than six months of experimental time during summer and autumn with our first HCPV system. The system was built for R&D purposes, with a design that ensures safety for workers and environment, and flexibility for future experiments. The field is composed of 32 heliostats. Although 28 heliostats are by design sufficient to achieve the target of 140kW, we installed an additional 4 heliostats for research purposes. Each heliostat has a mirror area of about $20m^2$. The $1m^2$ receiver, installed at the top of the test bed tower, is equivalent in size to four dish receivers, but could be expanded up to more than half a MW. The geometrical concentration ratio varies with the number of heliostats tracking the sun and could be as high as 620X. The receiver and secondary optics are actively cooled.

On a typical summer day around solar noon, 11th of December 2008 at 1PM, with 28 heliostats tracking the sun, the HCPV system delivered 139.5kW, with the following parameters:

- DNI = 1068 W/m^2
- Cell Temperature = 51.3℃
- 28 heliostats
- Total mirror area = $542m^2$
- DC Power Output = 139.5 kW
- DC Power efficiency = 24.1%
- DC Power efficiency corrected to 25℃ Cell Temperature = 25.2%
- DC Power Output normalised to $1kW/m^2$ and 25℃ Cell Temperature = 136.7 kW

About four months later, on 20th of April 2009 at 1:22PM, we performed a similar testing with 28 heliostats. The HCPV system delivered 123.7kW, with the following parameters:

- DNI = 878.3 W/m^2
- Cell Temperature = 38℃
- 28 heliostats
- Total mirror area = $542m^2$
- DC Power Output = 123.7 kW
- DC Power efficiency = 26%
- DC Power efficiency corrected to 25℃ Cell Temperature = 26.6%
- DC Power Output normalised to $1kW/m^2$ and 25℃ Cell Temperature = 144 kW

During that measurement, the thermal power sunk by the cooling circuit was approximately 230kW. Assuming an 11% reflectivity at the cell surface, we calculated an optical efficiency of 84%.The modelled performance in optical efficiency at this time was 89% and, when corrected for known losses, was 86%. The incident power density at the cell surface was $42.5W/cm^2$.

Of course instantaneous power efficiency is not sufficient to judge the cost effectiveness of a solar converter. In order to be able to calculate LCOE, we need to measure produced energy and to evaluate the annualised energy efficiency of the HCPV system. Analysis of produced energy over a representative period of time is ongoing and will be complete in about one year. Finally, the current HCPV demonstration was build for R&D purposes. Its cost is not representative of the cost of a commercial system. In order to finish the LCOE evaluation, we need to demonstrate the real cost of building a commercial prototype. This is also ongoing and will be complete by 2010.

COMPARISON OF HCPV WITH DISHES

Traditional wisdom has been to think of heliostat fields as being optically less efficient than dishes, by 15% to 30% depending upon the configuration and location. If we consider just the simple optical efficiency, this is generally true. For example, our typical dish optical efficiency is modelled to be 90%, whereas the energy weighted optical efficiency of HCPV for a favourable location over a one-year period is about 79%, or about 12% relatively less efficient than a dish. This raises the further question of whether there are other compensating factors that can enhance system efficiency for HCPV vs. a field of dishes. These may include the following considerations:

1. The power generated by a field of dishes must be reticulated back to a central point. There is power loss associated to power reticulation of a field of dishes that does not exist in the case of HCPV, and equates to a gain of about 1.5%.
2. Whereas shading between heliostats and by the tower is already taken into account in the calculation of the optical efficiency of HCPV, shading between dishes is not included in the calculation of the dish optical efficiency. Energy loss due to shading is a function of the distance between dishes, and about 3% in typical power plants.
3. A larger HCPV receiver allows for more parallel interconnections between modules, resulting in an estimated 2% power gain compared to dish CPV systems. However, this is not so true in early morning and late afternoon. We are currently assuming that the two designs are more or less equivalent for that matter.
4. Other economies of scale are also possible with HCPV, for example:
    - bigger and more efficient pump: +1%
    - more efficient fluid cooling: +1%
    - higher voltage, more efficient inverter: +1%
    - easier cleaning of mirrors: +1% for same cost of washing

In summary, the penalty in optical efficiency of HCPV compared to Dish CPV can be partially compensated by the gain in power reticulation, shading effect, parallel interconnections between modules, more efficient pump, cooling and inverter and lower cleaning costs. Our current estimate is that the difference in performance between HCPV and Dish CPV is of the order of 5% for a good design in an appropriate location. This important conclusion makes the HCPV concept very attractive to lower LCOE, due to significant cost savings in infrastructure, compared to CPV, which is already considered by many as the cheapest way to produce solar electricity at a utility scale.

CONCLUSIONS

We have established a new state-of-the-art Testing and Training Facility in Bridgewater, Victoria, that includes the latest generation of our 35kWp Dish CPV unit, as well as a newly constructed 140kWp Heliostat CPV system.

The HCPV system has been tested over a six-month period and has met all the design specifications. With a field of 28 heliostats of 20m^2 each, the 1m^2 receiver produced the target peak power output of 140kW with an efficiency of 24% to 26%. The optical efficiency of the field of heliostat and secondary optics is 84%. We believe this is the world's first demonstration of an HCPV system of this size.

Our CS500 dish CPV system still has the best optical efficiency and has demonstrated excellent annualised energy efficiency. Although it is too early to make any firm conclusions, the combination of confirmed and predictable performance, better than expected system efficiency for HCPV vs. dish and inferred lower cost per square metre for collector and infrastructure indicate that HCPV has strong potential to lowering LCOE for utility scale solar power generation.

ACKNOWLEDGEMENTS

The authors would like to thank everyone at Solar Systems involved with the HCPV project, the fabrication of the dense array modules and receivers, site construction, optical modelling, heliostat design, control software and monitoring.

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Hermannsburg - 2W - 19 May 2009

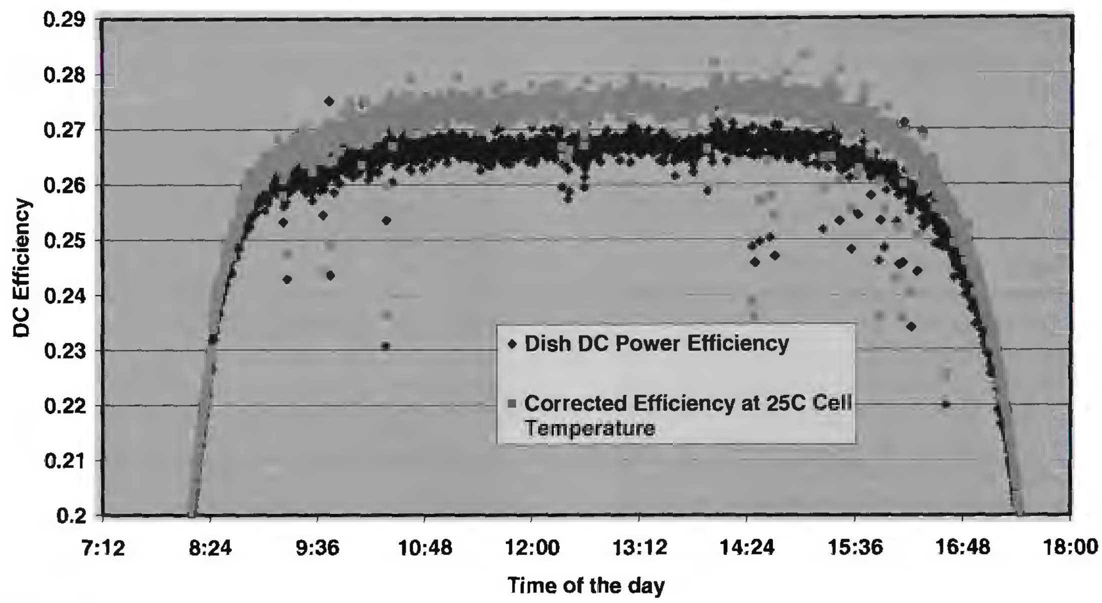

Fig. 3: DC Power efficiency of CS500 dish unit after one year of operation, uncorrected and corrected for 25°C cell temperature.

Hermannsburg - 2W Receiver

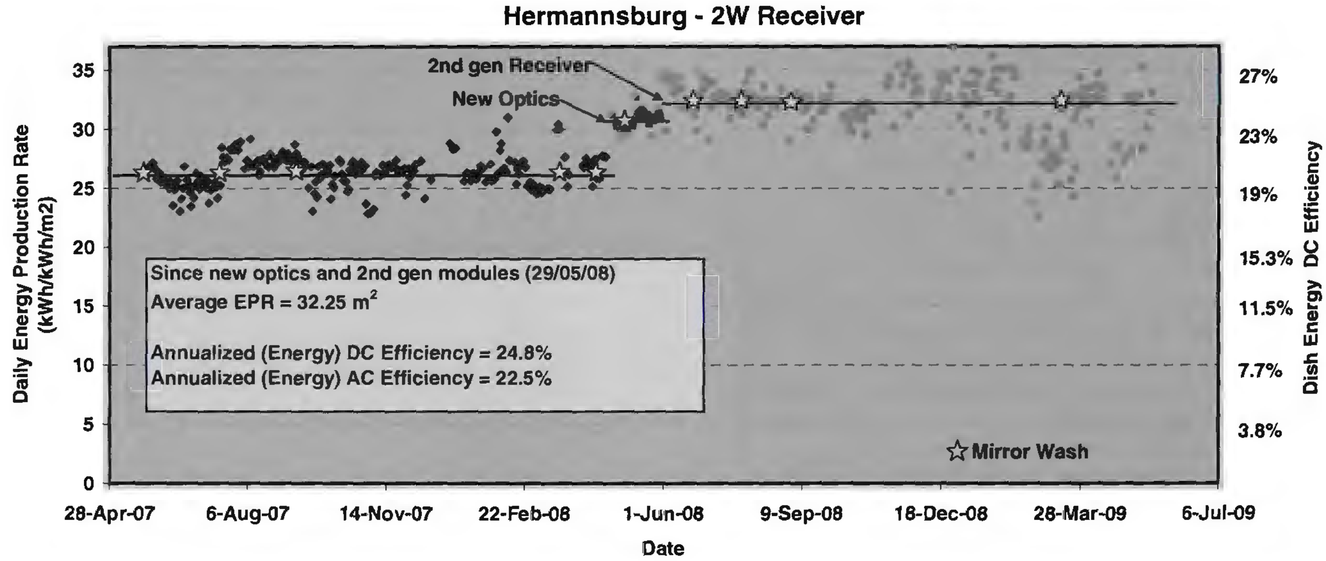

Fig.4: Specific Energy Production Rate (EPR) of one dish unit over a two-year period and improvements due to optic re-design and installation of 2nd generation modules. Yellow stars indicate the dates of mirror wash.

2. Patents

2.1 Lasich J.B., 1993, "Apparatus for Separating Solar Radiation into Longer and Shorter Wavelength Components", Patent No. 731495, Australia

AUSTRALIA

Commonwealth
of Australia

Letters patent

Patents Act 1990

**No.
731495**

STANDARD PATENT

I, Leo John O'Keeffe, Acting Commissioner of Patents, grant a Standard Patent with the following particulars:

Name and Address of Patentee:
John Beavis Lasich, 171 Latrobe Street Melbourne Victoria 3000 Australia

Name of Actual Inventor: John Beavis Lasich

Title of Invention: Apparatus for separating solar radiation into longer and shorter wavelength components

Application Number: 71938/98

Term of Letters Patent: Twenty years commencing on 25 November 1993

Divisional of: 691792

Dated this 12 day of July 2001

COMMONWEALTH OF AUSTRALIA
AUSTRALIA
PATENT OFFICE

**L.J.O'KEEFFE
ACTING COMMISSIONER OF PATENTS**

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(54) Title
Apparatus for separating solar radiation into longer and shorter wavelength components

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199455539

(71) Applicant(s)
John Beavis Lasich

(72) Inventor(s)
John Beavis Lasich

(74) Agent/Attorney
GRIFFITH HACK,GPO Box 1285K,MELBOURNE VIC 3001

(56) Related Art
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AU 59853/90

AUSTRALIA

Patents Act 1990

COMPLETE SPECIFICATION

STANDARD PATENT

Applicant(s):

JOHN BEAVIS LASICH

Invention Title:

APPARATUS FOR SEPARATING SOLAR RADIATION INTO LONGER AND SHORTER WAVELENGTH COMPONENTS

The following statement is a full description of this invention, including the best method of performing it known to me/us:

APPARATUS FOR SEPARATING SOLAR RADIATION INTO LONGER AND SHORTER WAVELENGTH COMPONENTS

The present invention relates to an apparatus for separating longer and shorter wavelength solar radiation so that the separated components of the solar radiation spectrum can be used as required in selected end-use applications, such as the production of hydrogen.

The present invention has been divided from Australian application 55539/94 for a standard patent and the disclosure in the patent specification of that patent application is incorporated herein by cross-reference.

The use of hydrogen as a carrier of energy, particularly in the context as a fuel, has the following significant technical advantages over other energy sources.

1. Supply side considerations - hydrogen is inexhaustible, storable, transportable, and has a high energy density compared with other chemical fuels.

2. Demand side considerations - hydrogen is non-polluting, more versatile than electricity, more efficient than petrol, and convertible directly to heat and electricity for both mobile and stationary applications.

By way of particular comparison, the large scale use of solar energy as an energy source has been limited for technical reasons and cost by a lack of a suitable short and long term storage medium for solar energy.

However, notwithstanding the above technical advantages of hydrogen as an energy source, the cost of production of hydrogen has been too high hitherto for widespread use as a fuel.

In the case of the production of hydrogen by electrolysis of water, a major factor in the high cost of production has been the cost of electricity to operate electrolysis cells.

In the specific case of solar radiation-generated electricity, the high cost of electricity is due in large part to the relatively low efficiency of photovoltaic (or thermal) conversion of solar energy into electricity which means that a relatively large number of photovoltaic cells (or, in the case of thermal conversion, a large collection area) is required to generate a unit output of electricity.

An object of the present invention is to provide an apparatus for separating longer and shorter wavelength components of the solar radiation spectrum such that the separated components can be used efficiently in a solar radiation based method and apparatus for producing hydrogen in an electrolysis cell.

According to the present invention there is provided an apparatus for separating solar radiation into a longer wavelength component and a shorter wavelength component, the apparatus comprising: a means for concentrating solar radiation, a mirror for selectively reflecting either the longer wavelength component or the shorter wavelength component of the solar radiation spectrum, the mirror being positioned in the light path of the solar radiation from the concentrating means, the mirror comprising a spectrally selective filter to make the mirror transparent to the non-reflected component of the solar radiation spectrum to allow the non-reflected component to pass through the mirror to a first receiver, and the mirror being appropriately curved in order to selectively concentrate and direct the longer or shorter wavelength component towards a receiver that is external to the apparatus.

It is preferred that the mirror be appropriately curved so that it can concentrate and direct the reflected longer wavelength component or the shorter wavelength component to a distant point for collection by a receiver.

It is preferred that the apparatus further comprises, a non-imaging concentrator for concentrating the reflected longer or shorter wavelength component.

It is preferred that the apparatus further comprises, an optical fibre of light guide for transferring the concentrated reflected longer or shorter wavelength component for use in an end use application.

It is preferred particularly that the end use application be the generation of hydrogen by electrolysis of water. In this end use application the longer wavelength component is suitable for use as a source of thermal energy and the shorter wavelength component is suitable for use as a source of electrical energy. In particular in this end use application there is provided:

(a) an electrolysis cell having an inlet for steam and outlets for hydrogen, oxygen, and excess steam;

(b) the above-described apparatus for separating solar radiation into a longer wavelength component and a shorter wavelength component;

(c) a means for separately converting the longer wavelength component into thermal energy and the shorter wavelength component into electrical energy arranged in series or in parallel relationship for providing the energy required for converting water into steam and/or heating steam for operating the electrolysis cell to decompose the steam into hydrogen and oxygen at high temperatures of at least 700°C, more preferably at least 1000°C.

The present invention is described further by way of example with reference to the accompanying drawings, in which:

Figure 1 illustrates schematically an apparatus for producing hydrogen which incorporates a conventional array of solar cells and thermal energy receiver;

Figure 2 illustrates schematically another apparatus for producing hydrogen which incorporates an embodiment of an apparatus for separating solar radiation into longer and shorter wavelength components in accordance with the present invention;

Figure 3 illustrates schematically an apparatus for producing hydrogen which incorporates another embodiment of the apparatus in accordance with the present invention;

Figure 4 illustrates schematically an apparatus for producing hydrogen which incorporates another embodiment of the apparatus in accordance with the present invention;

Figure 5 is a diagram which shows the major components of an experimental test rig based on the apparatus shown in Figure 1; and

Figure 6 is a detailed view of the electrolysis cell of the experimental test rig shown in Figure 4.

As is indicated above, the present invention has been divided from application 55539/94. The invention disclosed and claimed in application 55539/94 relates to using solar energy to provide the total energy requirements, in the form of a thermal energy component and an electrical energy component, to form hydrogen and oxygen by the electrolysis of water. In this connection, the applicant found that the combined effect of solar-generated thermal energy and solar-generated electrical energy results in a significant improvement in the efficiency of the electrolysis of water in terms of energy utilisation, particularly when the thermal component is provided as a by-product of solar-generated electricity production.

The following description of the present invention is in the context of the production of hydrogen.

The apparatus shown schematically in Figure 1 comprises, a suitable form of solar concentrator 3 which focuses a part of the incident solar radiation onto an array of solar cells 5 for generating electricity and the remainder of the incident solar radiation onto a suitable form of receiver 7 for generating thermal energy.

The electricity and the thermal energy generated by the incident solar radiation are transferred to a suitable form of electrolysis cell 9 so that:

(a) a part of the thermal energy converts an inlet stream of water for the electrolysis cell 9 into steam and heats the steam to a temperature of about 1000°C; and

(b) the electrical energy and the remainder of the thermal energy operate the electrolysis cell 9 to decompose the high temperature steam into hydrogen and oxygen.

The hydrogen is transferred from the electrolysis cell 9 into a suitable form of storage tank 11.

The receiver 7 may be any suitable form of apparatus, such as a heat exchanger, which allows solar radiation to be converted into thermal energy.

The apparatus shown in Figure 1 further comprises a heat exchanger means (not shown) for extracting thermal energy from the hydrogen and oxygen (and any exhaust steam) produced in the electrolysis cell 9 and thereafter using the recovered thermal energy in the step of converting the inlet stream of water into steam for consumption in the electrolysis cell 9. It is noted that the recovered thermal energy is at a relatively lower temperature than the thermal energy generated by solar radiation. As a consequence, preferably, the recovered thermal energy is used to preheat the inlet water, and the solar radiation generated thermal energy is used to provide the balance of the heat component required to convert the feed water or steam to steam at 1000°C and to contribute to the operation of the electrolysis cell 9.

It is noted that the component of the thermal energy which is used endothermically at high temperature in the electrolysis cell 9 is consumed at nearly 100% efficiency. This high thermal energy utilisation is a major factor in the high overall efficiency of the system. It is also noted that high temperatures are required to achieve the high thermal energy efficiency and as a consequence only systems which can collect and deliver thermal energy at high temperatures (700°C+) can achieve the high efficiency.

The apparatus shown in Figure 1 is an example of a parallel arrangement of solar cells 5 and thermal energy receiver 7. The apparatus shown schematically in Figures 2 to 4 are examples of series arrangements.

In addition, the apparatus shown schematically in Figures 2 to 4 incorporate examples of apparatus in accordance with the present invention for separating solar radiation into longer and shorter wavelength components.

The apparatus shown schematically in Figures 2 to 4 take advantage of the fact that solar cells selectively absorb shorter wavelengths and may be transparent to longer wavelengths of the solar radiation spectrum. In this connection, the threshold is in the order of 1.1 micron for silicon solar cells and 0.89 micron for GaAs cells leaving 25% to 35% of the incoming energy of the solar radiation, which is normally wasted, for use as thermal energy.

In each case, the apparatus shown in Figures 2 to 4 are arranged so that, in use, solar radiation is reflected from a solar concentrator 3 onto a first receiver in the form of a solar cell 15 to generate electricity from the shorter wavelength component of the solar radiation and the solar radiation that is not used for electricity generation, i.e. the longer wavelength component, is directed to a second receiver in the form of thermal energy receiver (not shown) of an electrolysis cell 17 to convert the solar radiation into thermal energy. More particularly, in each case the apparatus shown in Figures 2 to 4 comprises a means which, in use, separates the longer and shorter wavelength components of the solar radiation spectrum so that the components can be used separately for thermal energy and electricity generation, respectively.

The solar radiation separating means comprises a mirror 27 (not shown in Figure 2 but shown in Figures 3 and 4) positioned in front of or behind the solar cells 15.

In situations where the mirror 27 is positioned in front of the solar cells 15, as shown in Figures 3 and 4, the mirror 27 comprises an interference filter or edge filter (not shown) which makes the mirror 27 transparent to the shorter wavelength component of the solar radiation spectrum.

The mirror 27 may be of any suitable shape to reflect and selectively direct the longer wavelength component of the solar radiation spectrum. For example, in situations where the mirror 27 is positioned in front of the solar cells 15 and the focal point of the solar concentrator 3, as shown in Figures 3 and 4, the mirror 27 may take the form of a Cassigranian mirror, and in situations where the mirror 27 is positioned behind the focal point of the solar concentrator 3, the mirror may take the form of a Gregorian mirror.

The longer wavelength radiation reflected by the mirror 27 may be transferred to the electrolysis cell 17 by any suitable transfer means 21 such as a heat pipe (not shown) or an optical fibre (or light guide), as shown in Figures 2 and 4, or directly as radiation, as shown in Figure 3.

With particular regard to the apparatus shown in Figure 4, the electrolysis cell 17 is positioned remote from the solar cells 15, and the apparatus further comprises a non-imaging concentrator 33 for concentrating the reflected longer wavelength component of the solar radiation prior to transferring the concentrated component to the optical fibre or light guide 21.

It is also noted that the present invention is not limited to use of the reflected longer wavelength component of the solar radiation spectrum to provide thermal energy to an electrolysis cell and may be used to provide thermal energy in any end use application.

The electrolysis cells 9,17 shown in the figures may be of any suitable configuration. Typically, the electrolysis cells 9,17 are formed from a material, such as yttria stabilised zirconia (YSZ), which is porous to oxygen and impermeable to other gases, and the accessories, such as membranes and electrodes (not shown), are formed from materials, such as alloys and cermets.

The apparatus described above take advantage of the facts that:

(a) the electrical potential and the electrical energy necessary to produce hydrogen in an electrolysis cell decreases as the temperature increases and the balance of the energy requirements to operate the electrolysis cell can be provided in the form of thermal energy;

(b) the efficiency of generation of thermal energy from solar radiation is significantly higher (in the order of 3 to 4 times) than the efficiency of generation of electricity from solar radiation; and

(c) the efficiency of consumption of the thermal energy endothermically in the electrolysis cell approaches 100%.

It is noted that it is believed by the applicant that the use of the by-product thermal energy can only be practically executed by the means described herein since other currently known methods are not capable of transferring energy to produce a temperature in excess of 1000°C.

In other words, a particular advantage of the present invention is that, as a consequence of being able to separate the longer and shorter wavelength components of the solar radiation spectrum, it is possible to recover and convey and use that longer wavelength component in high temperature applications where otherwise that longer wavelength component would have been converted into low temperature heat (typically less than 45°C) and being unusable.

Further advantages of the present invention in the context of hydrogen production are as follows:

1. The efficiency of hydrogen production is greater than any other known method of solar radiation generated hydrogen production.

2. The present invention increases the overall efficiency of the system, i.e. the efficiency of producing hydrogen by this method is greater than the efficiency of just producing electricity.

3. The present invention provides a medium, namely hydrogen, for the efficient storage of solar energy hitherto not available economically and thus overcomes the major technological restriction to large scale use of solar energy.

It should be noted that the performance of the present invention in the context of hydrogen production is expected to exceed 50% efficiency. The theoretical performance is in the order of 60%, whereas the existing technology is not expected to practically exceed 14% efficiency and has a threshold limit of 18%.

In order to illustrate the performance of the invention disclosed and claimed in application 55539/94 the applicant carried out experimental work, as described below, on an experimental test rig shown in Figures 5 and 6 which is based on the embodiment of the apparatus shown in Figure 1.

With reference to Figures 5 and 6, the experimental test rig comprised a 1.5m diameter paraboloidal solar concentrating dish 29 arranged to track in two axes and capable of producing a solar radiation flux of approximately 1160 suns and a maximum temperature of approximately 2600°C. It is noted that less than the full capacity of power and concentration of the concentrating dish 29 was necessary for the experimental work and thus the receiving components (not shown) were appropriately positioned in relation to the focal plane and/or shielded to produce the desired temperatures and power densities.

The experimental rig further comprised, at the focal zone of the solar concentrating dish 29, an assembly of an electrolysis cell 31, a tubular heat shield/distributor 45 enclosing the electrolysis cell 31, a solar cell 51, and a length of tubing 41 coiled around the heat shield/distributor 45 with one end extending into the electrolysis cell 31 and the other end connected to a source of water.

The solar cell 51 comprised a GaAs photovoltaic (19.6mm active area) concentrator cell for converting solar radiation deflected from the concentrator dish 31 into electrical energy. The GaAs photovoltaic cell was selected because of a high conversion efficiency (up to 29% at present) and a capacity to handle high flux density (1160 suns) at elevated temperatures (100°C). In addition, the output voltage of approximately 1 to 1.1 volts at maximum power point made an ideal match for direct connection to the electrolysis cell 33 for operation at 1000°C.

With particular reference to Figure 6, the electrolysis cell 31 was in the form of a 5.8cm long by 0.68cm diameter YSZ closed end tube 33 coated inside and outside with platinum electrodes 35, 37 that formed cathodes and anodes, respectively, of the electrolysis cell 31 having an external surface area of 8.3cm^2 and an internal surface area of 7.6cm^2.

The metal tube 45 was positioned around the electrolysis cell 31 to reduce, average and transfer the solar flux over the surface of the exterior surface of the electrolysis cell 31.

The experimental text rig further comprised, thermocouples 47 (Figure 5) connected to the cathode 35 and the anode 37 to continually measure the temperatures inside and outside, respectively, the electrolysis cell 31, a 1mm^2 platinum wire 32 connecting the cathode 35 to the solar cell 51, a voltage drop resistor (0.01Ω) (not shown) in the circuit connecting the cathode 35 and the solar cell 51 to measure the current in the circuit, and a Yokogawa HR-1300 Data Logger (not shown).

The experimental test rig was operated with the electrolysis cell 31 above 1000°C for approximately two and a half hours with an excess of steam applied to the electrolysis cell 31. The output stream of unreacted steam and the hydrogen generated in the electrolysis cell 31 was bubbled through water and the hydrogen was collected and measured in a gas jar.

When a steady state was reached, readings of temperature, voltage, current and gas production were recorded and the results are summarised in Table 1 below.

Time	Electrolysis Cell Voltage	Electrolysis Cell Current	Electrolysis Cell Temperature	Gas Production
	V	Amps	°C	ml
2.22	1.03	.67	1020	0
2.39	1.03	.67	1020	80
net 17 minutes				net 80ml

On the basis of the measured electrolysis cell voltage of 1.03 V recorded in Table 1 and a determined thermoneutral voltage of 1.47, the electrical efficiency of the electrolysis cell 31, calculated as the ratio of the thermoneutral and measured voltages, was $\frac{1.47}{1.03} = 1.43$

In terms of the solar cell efficiency, with the solar cell 31 positioned to receive a concentration ratio of 230 suns and assuming:

(a) an output voltage = 1.03 (=voltage across electrolysis cell and allows for connection losses);

(b) a current of 0.67 Amps;

(c) direct solar input is 800 w/m' ^{2}; and

(d) an active solar cell area = 19.6 x $10^{-6}m^2$.

the efficiency of the solar cell 51 (η_{pv}) was

$$\eta pv = \frac{\text{output}}{\text{input}} = \frac{1.03 \times .67}{\frac{19.6}{10^6} \times 230 \times 800} = \frac{.69}{3.6} = .19$$

With a spectral reflectivity of 0.9 for the mirror surface of the solar concentrating dish 29, the efficiency of the solar concentrator dish 29 was 0.85.

Thus, the total system efficiency of the solar cell 51 and the electrolysis cell 31 and optics (η_{total}) was

$$\eta total = 0.85x.19x1.43=.22 \quad (22\%)$$

The above figures of 22% is approximately twice the best previous proposed systems and more than three times the best recorded figure for a working plant.

The results of the experimental work on the experimental test rig establish that:

(a) it is possible to produce hydrogen by high temperature electrolysis of water driven totally by solar radiation,

(b) the efficiency of production is greatly improved over known systems, and

(c) a significant portion of the heat of solar radiation can be used directly in the electrolysis reaction thus reducing greatly expensive electrical input by almost half.

Many modifications may be made to the preferred embodiments of the present invention as described above without departing from the spirit and scope of the present invention.

By way of example, whilst the preferred embodiments describe that the present invention separates the longer and shorter wavelength components of the solar radiation spectrum by reflecting the longer wavelength component, it can readily be appreciated that the present invention is not limited to such an arrangement and extends to arrangements in which the shorter wavelength component is reflected.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. An apparatus for separating solar radiation into a longer wavelength component and a shorter wavelength component, the apparatus comprising: a means for concentrating solar radiation, a mirror for selectively reflecting either the longer wavelength component or the shorter wavelength component of the solar radiation spectrum, the mirror being positioned in the light path of the solar radiation from the concentrating means, the mirror comprising a spectrally selective filter to make the mirror transparent to the non-reflected component of the solar radiation spectrum to allow the non-reflected component to pass through the mirror to a first receiver, and the mirror being appropriately curved in order to selectively concentrate and direct the longer or shorter wavelength component towards a receiver that is external to the apparatus.

2. The apparatus defined in claim 1, wherein the spectrally selective filter comprises an interference or edge filter.

3. The apparatus defined claim 1 or claim 2 further comprising, a non-imaging concentrator for further concentrating the reflected longer or shorter wavelength component from the mirror.

4. The apparatus defined in claim 3 further comprising, a means for conveying the concentrated reflected longer or shorter wavelength component for use in an end use application.

5. The apparatus defined in claim 4, wherein the conveying means is an optical fibre or a light guide.

6. The apparatus defined in claim 4 or claim 5

wherein, the end use application comprises any one of the following, the generation of hydrogen by electrolysis of water, the generation of electricity for shaft power by the use of a Stirling engine, a steam heater, or a super heater.

7. The apparatus defined in any one of the preceding claims wherein the second receiver is remote from the first receiver.

8. A apparatus for separating solar radiation into a longer wavelength component with a shorter wavelength component substantially as hereinbefore described with reference to the accompanying drawings.

Dated this 29th day of January 2001
JOHN BEAVIS LASICH
By their Patent Attorneys
GRIFFITH HACK
Fellows Institute of Patent
Attorneys of Australia

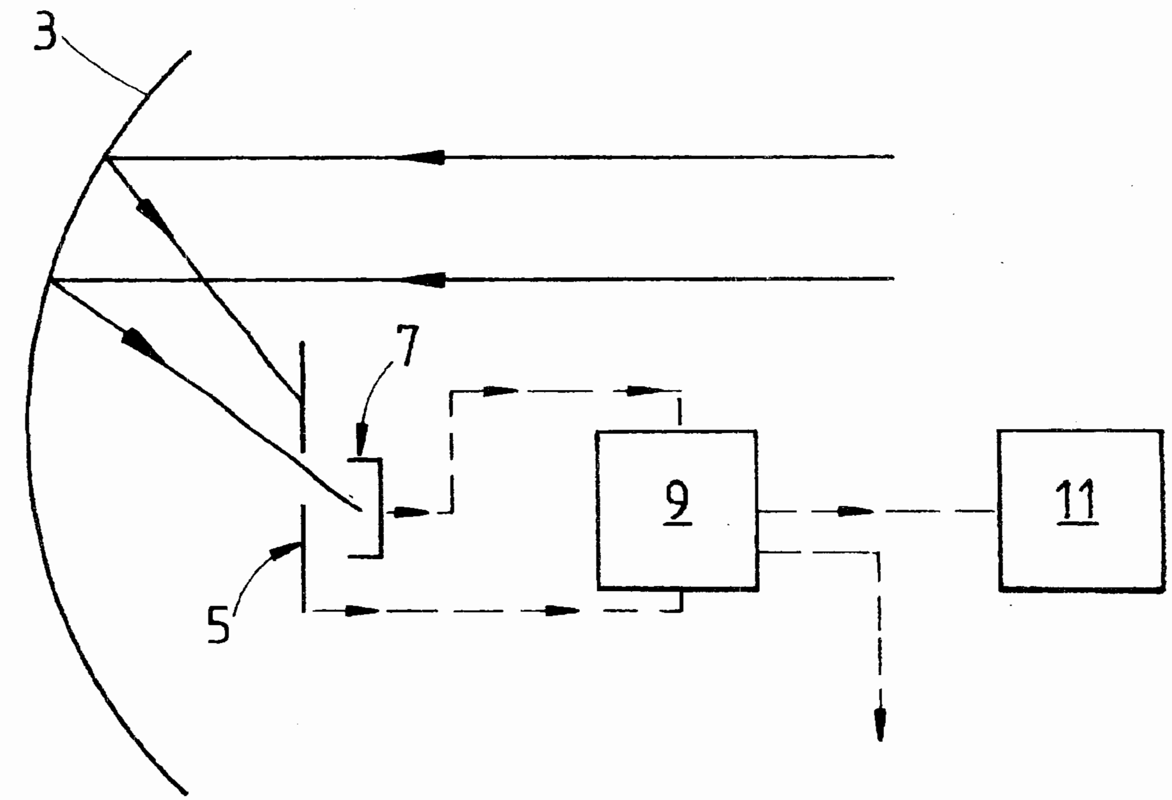


FIGURE 1

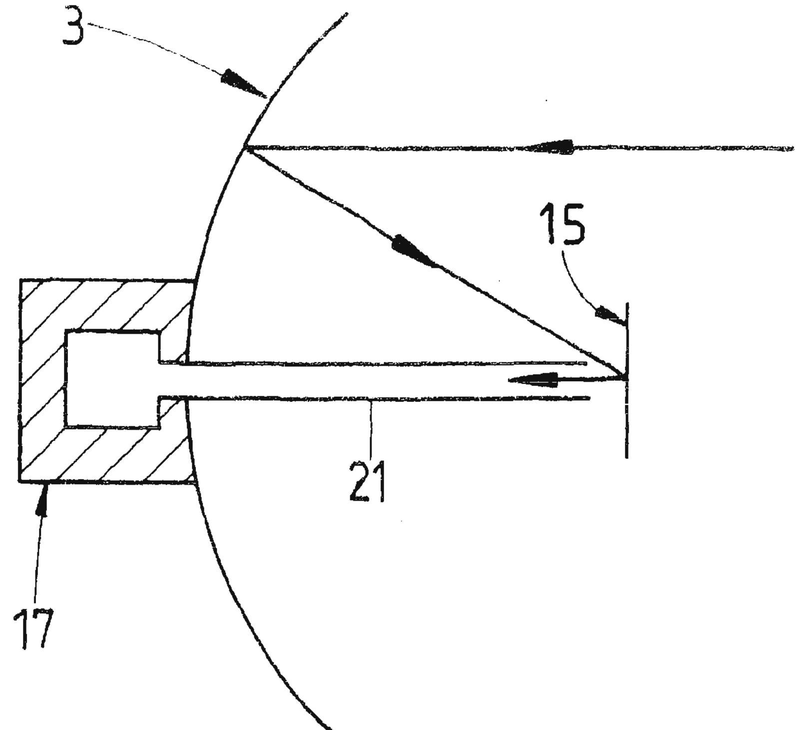


FIGURE 2

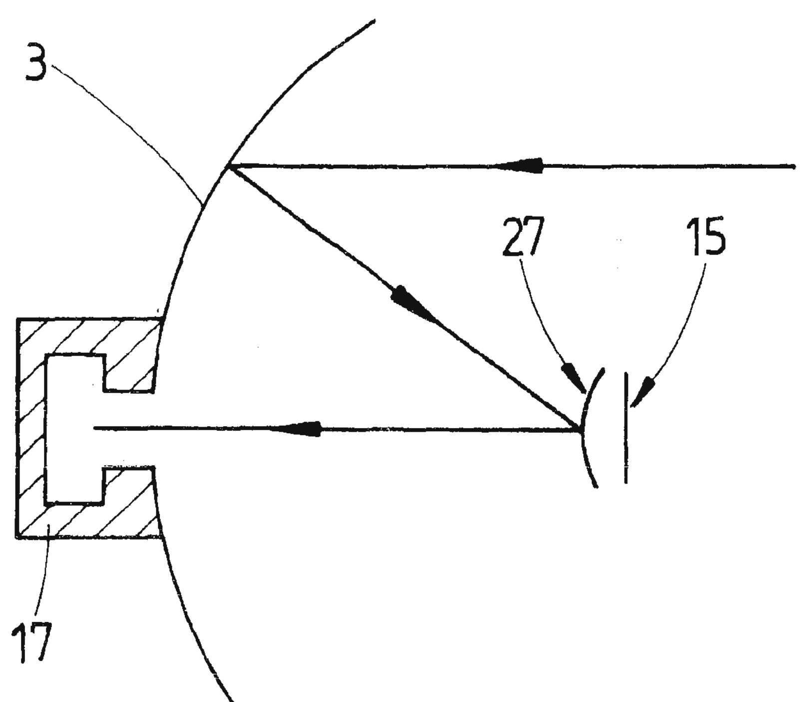


FIGURE 3

FIGURE 4

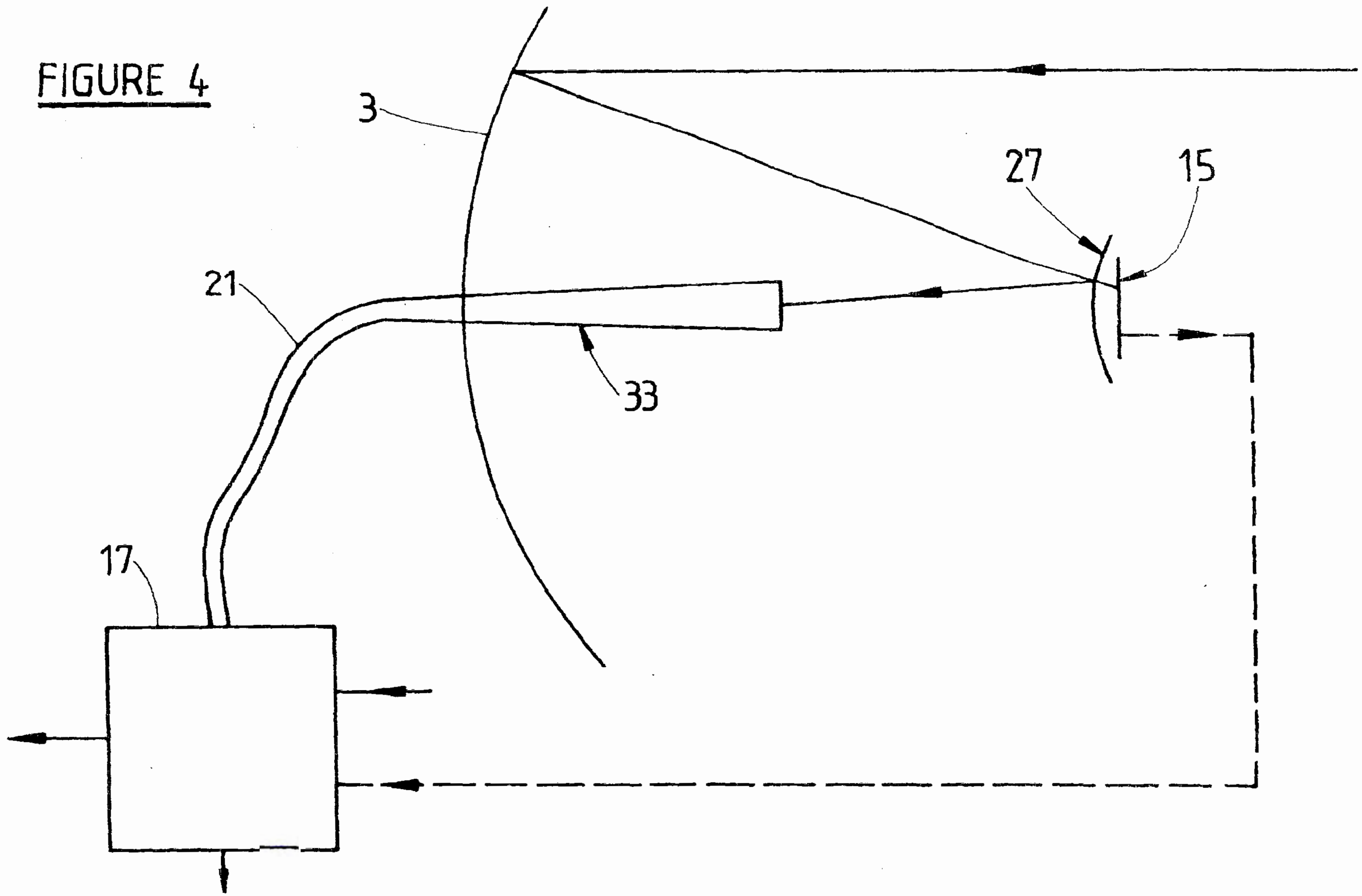
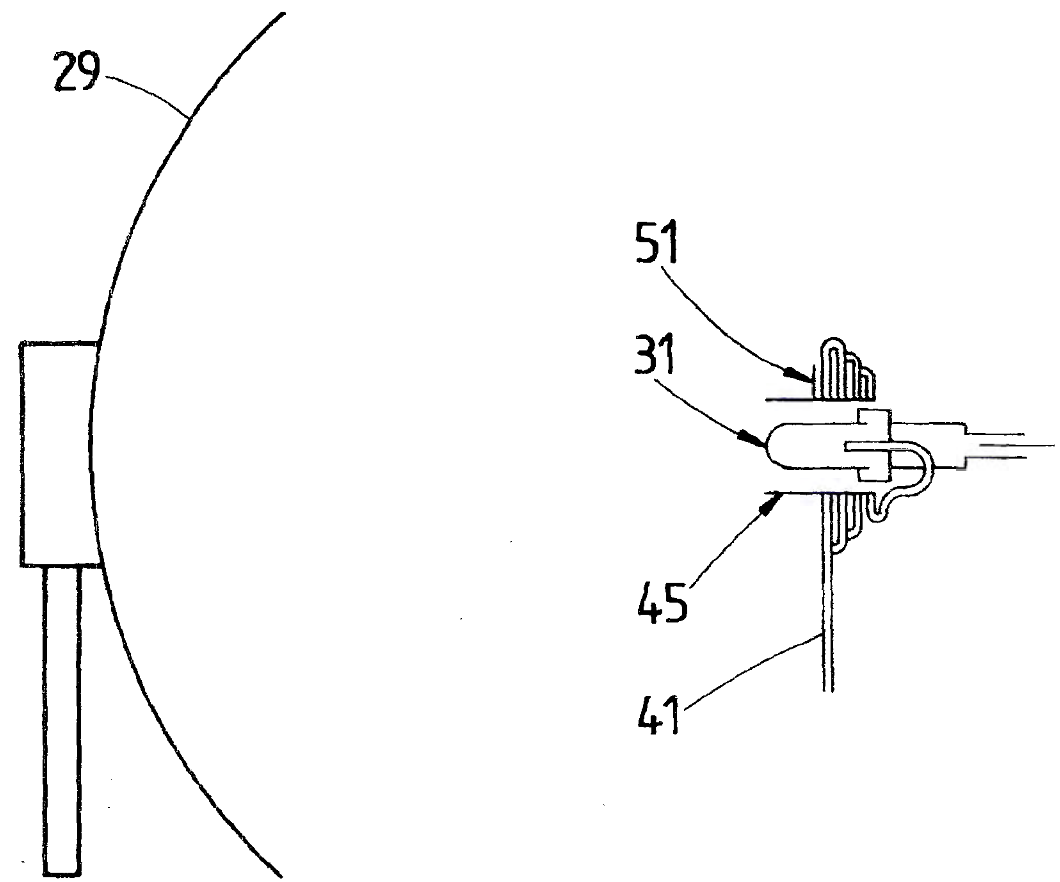


FIGURE 5



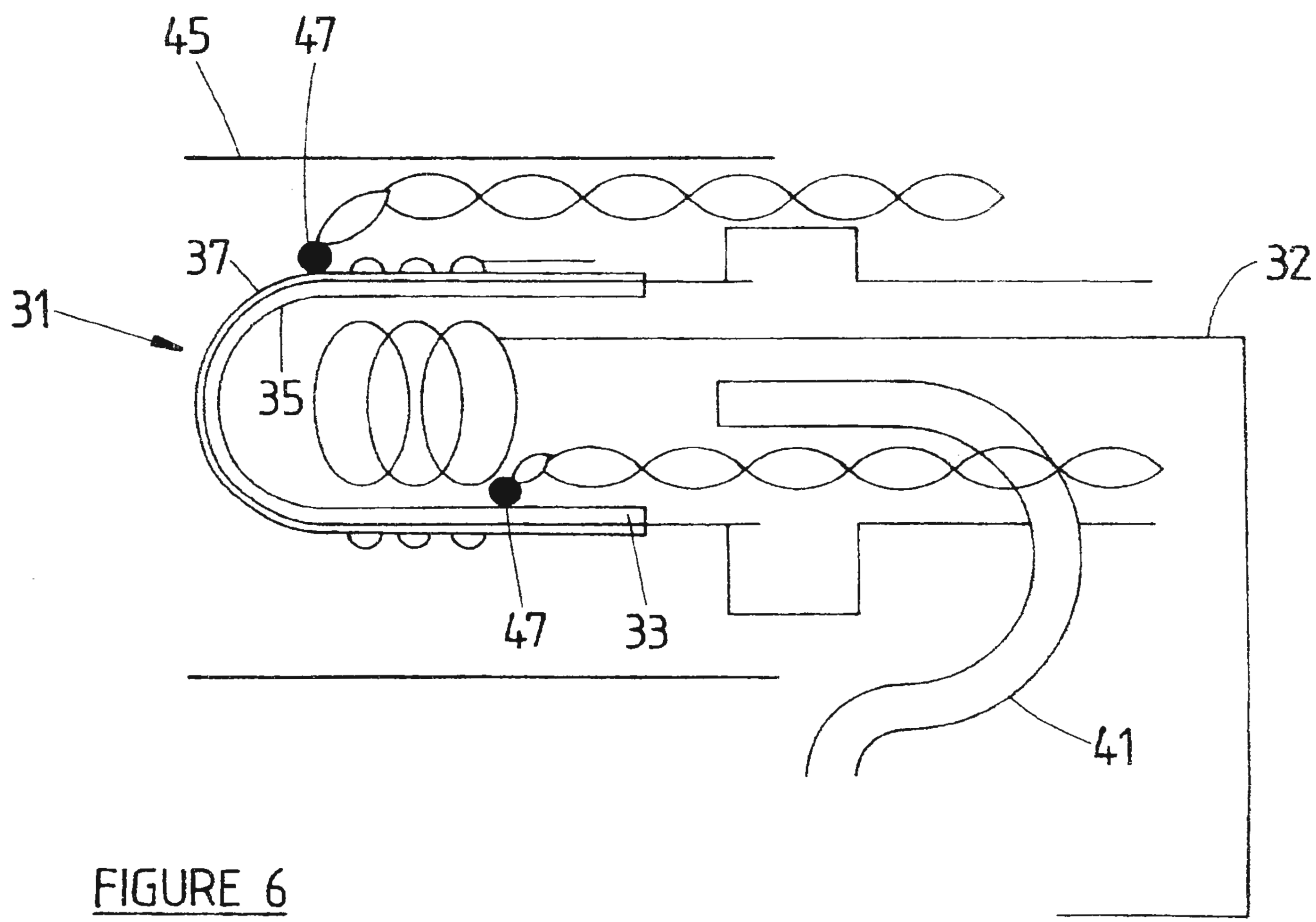


FIGURE 6

2.2 Lasich J.B., 1993, "Production of Hydrogen from Solar Radiation at High Efficiency", Patent No. 5658448, USA

The United States of America

The Commissioner of Patents and Trademarks

Has received an application for a patent for a new and useful invention. The title and description of the invention are enclosed. The requirements of law have been complied with, and it has been determined that a patent on the invention shall be granted under the law.

Therefore, this

United States Patent

Grants to the person(s) having title to this patent the right to exclude others from making, using, offering for sale, or selling the invention throughout the United States of America or importing the invention into the United States of America for the term set forth below, subject to the payment of maintenance fees as provided by law.

If this application was filed prior to June 8, 1995, the term of this patent is the longer of seventeen years from the date of grant of this patent or twenty years from the earliest effective U.S. filing date of the application, subject to any statutory extension.

If this application was filed on or after June 8, 1995, the term of this patent is twenty years from the U.S. filing date, subject to any statutory extension. If the application contains a specific reference to an earlier filed application or applications under 35 U.S.C. 120, 121 or 365(c), the term of the patent is twenty years from the date on which the earliest application was filed, subject to any statutory extension.

Commissioner of Patents and Trademarks

Attest

US005658448A

United States Patent [19]

Lasich

[11] Patent Number: 5,658,448

[45] Date of Patent: Aug. 19, 1997

[54] **PRODUCTION OF HYDROGEN FROM SOLAR RADIATION AT HIGH EFFICIENCY**

[76] Inventor: **John Beavis Lasich**, 171 Latrobe Street, Melbourne, Victoria, Australia, 3000

[21] Appl. No.: **446,582**

[22] PCT Filed: **Nov. 25, 1993**

[86] PCT No.: **PCT/AU93/00600**

§ 371 Date: **May 24, 1995**

§ 102(e) Date: **May 24, 1995**

[87] PCT Pub. No.: **WO94/12690**

PCT Pub. Date: **Jun. 9, 1994**

[30] **Foreign Application Priority Data**

Nov. 25, 1992 [AU] Australia PL6021

[51] **Int. Cl.**^{6} **C25B 1/02**; C25B 1/04; H02N 6/00

[52] **U.S. Cl.** **205/628**; 205/637; 204/275; 136/246; 136/206; 429/111

[58] **Field of Search** 205/628, 637; 136/246, 206; 204/275; 429/111

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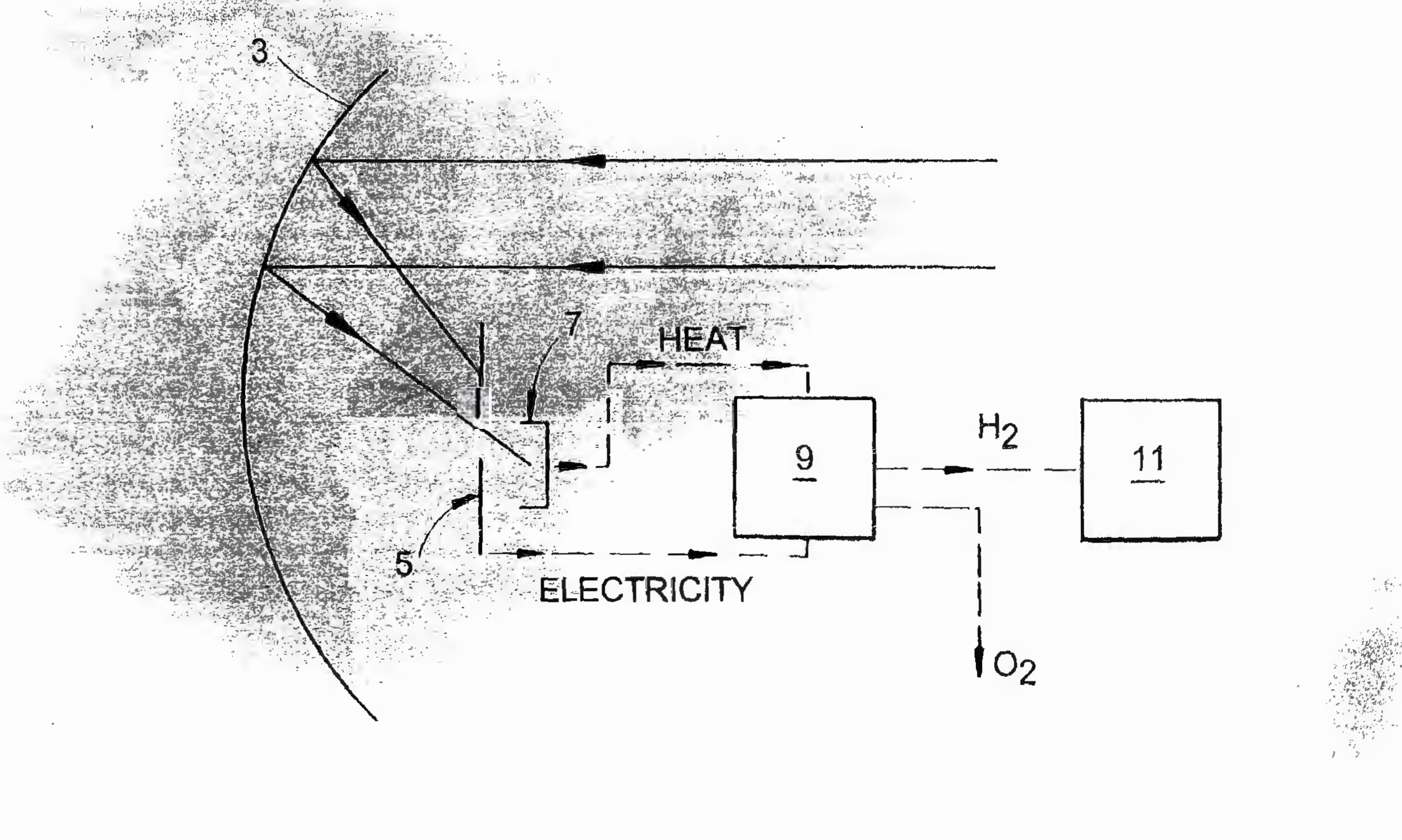
Primary Examiner—Kathryn L. Gorgos
Assistant Examiner—Alex Noguerola
Attorney, Agent, or Firm—Fish & Richardson P.C.

[57] **ABSTRACT**

Method and apparatus for producing hydrogen by conversion of solar energy into thermal and electrical energy for electrolysis of steam.

18 Claims, 5 Drawing Sheets



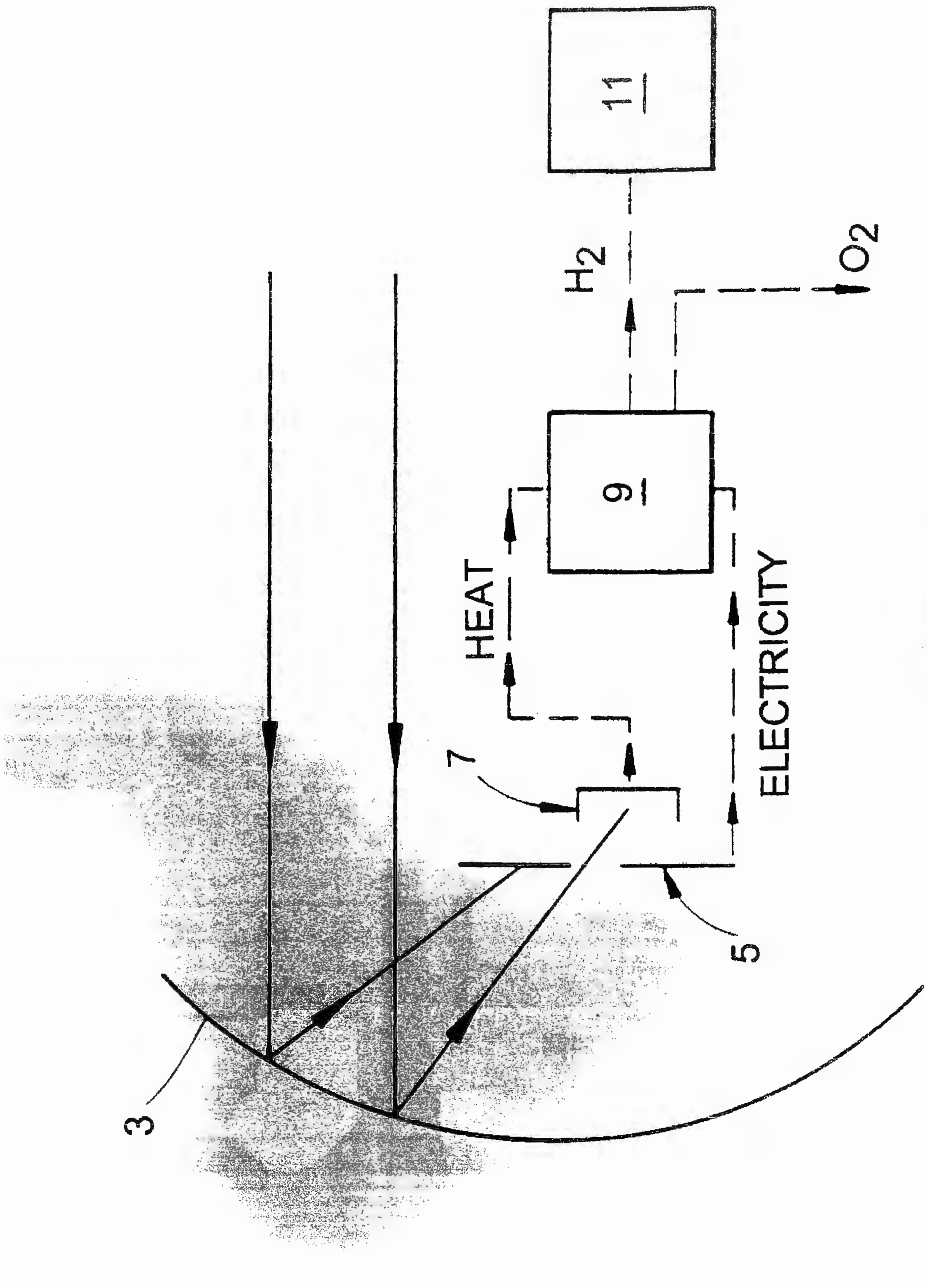


FIG. 1

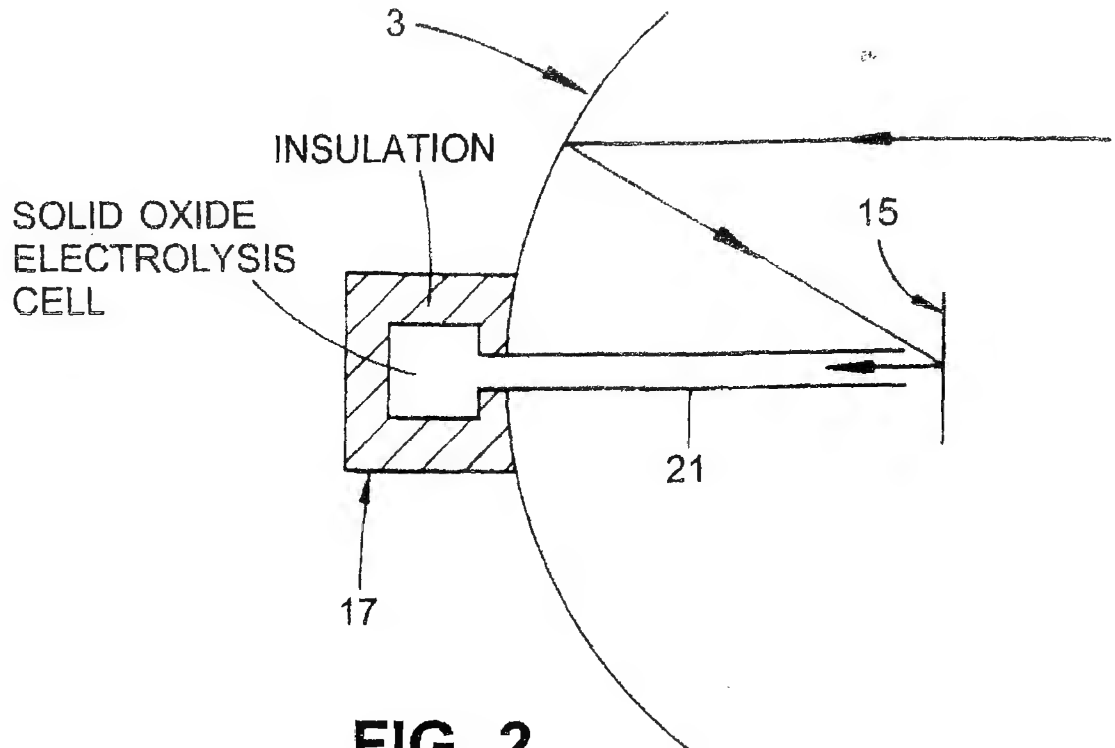

3
INSULATION
SOLID OXIDE
ELECTROLYSIS
CELL
15
21
17

FIG. 2

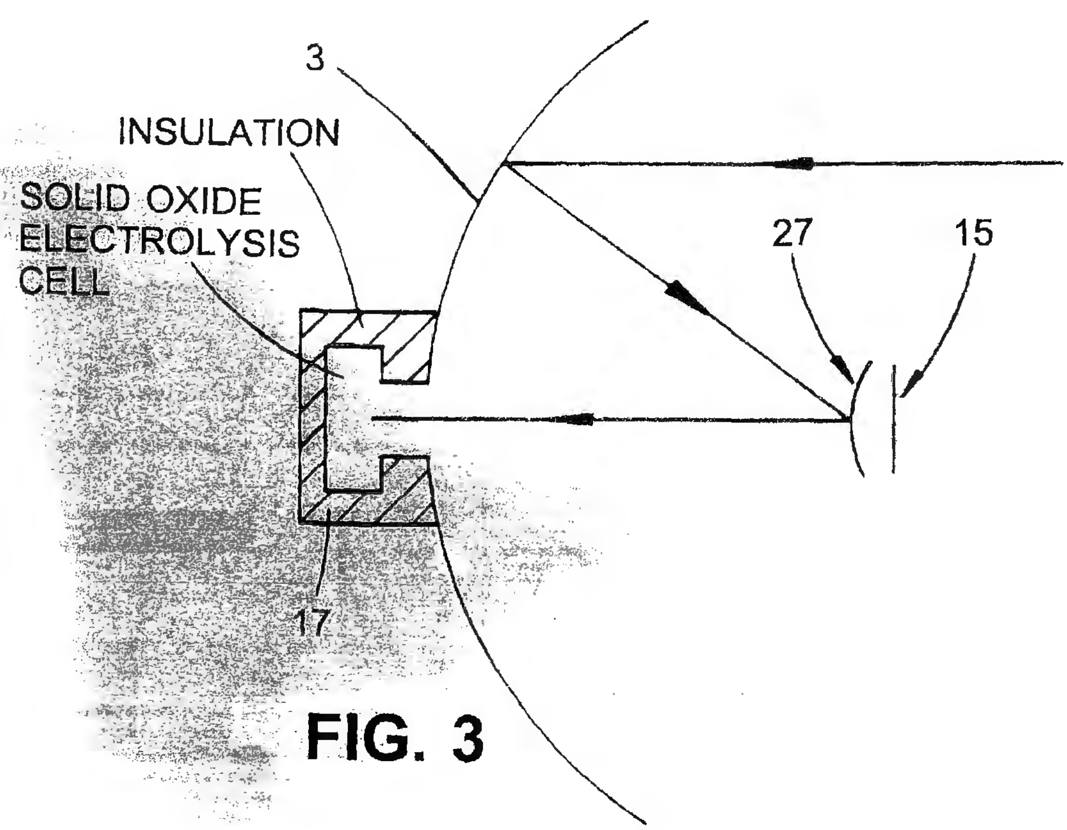

3
INSULATION
SOLID OXIDE
ELECTROLYSIS
CELL
27
15
17

FIG. 3

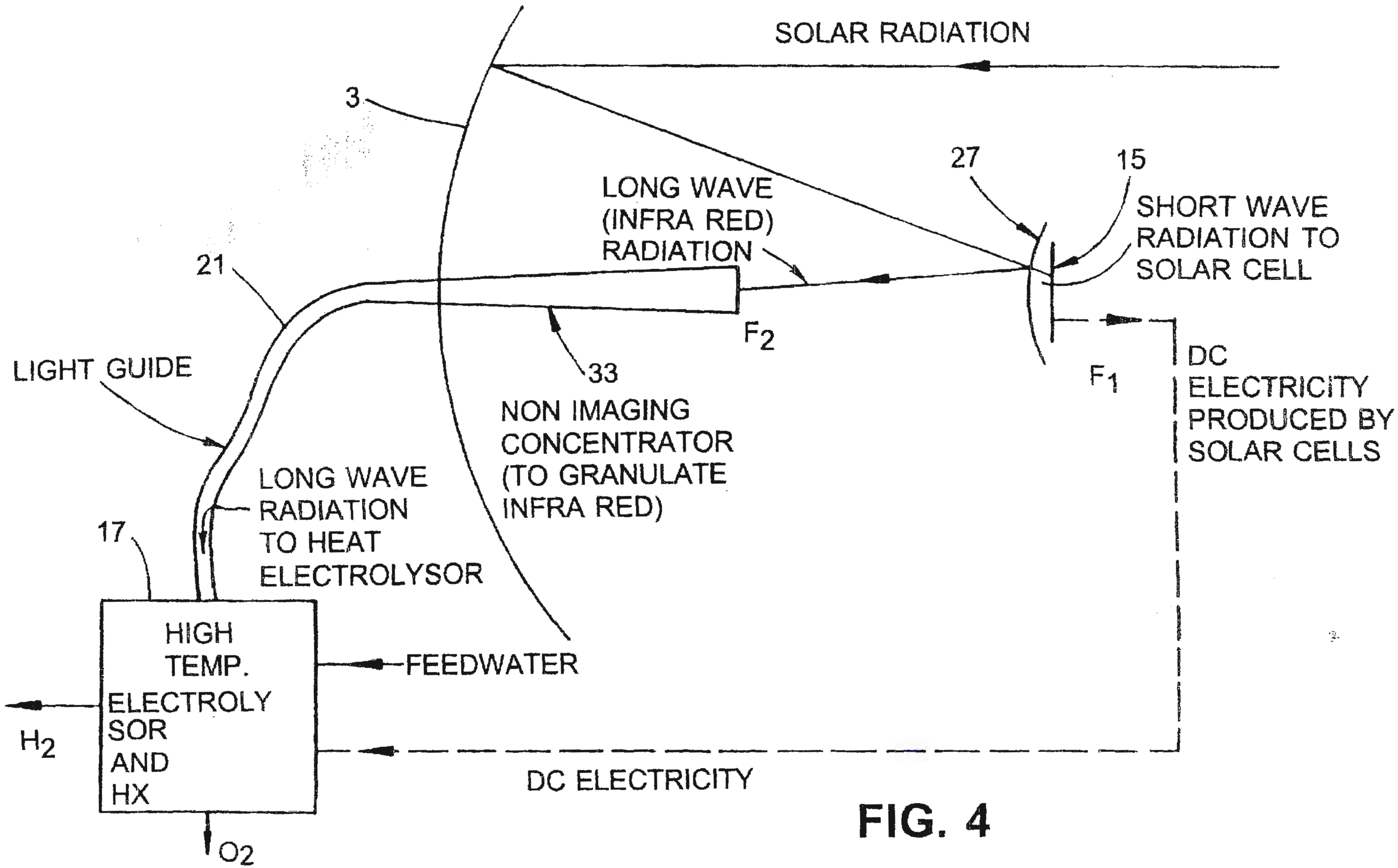
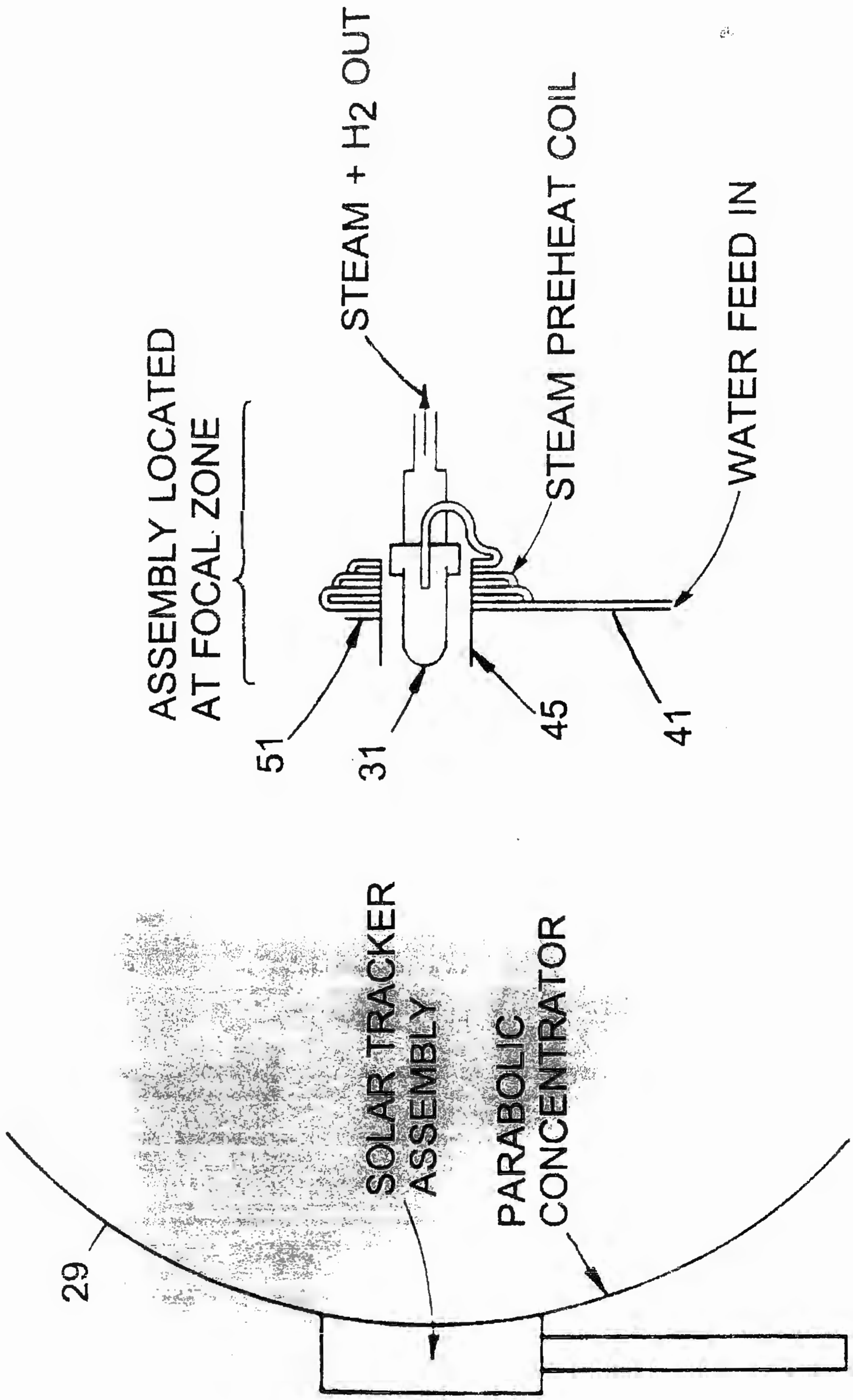

SOLAR RADIATION
3
27
15
LONG WAVE
(INFRA RED)
RADIATION
SHORT WAVE
RADIATION TO
SOLAR CELL
21
F_2
F_1
LIGHT GUIDE
33
DC
ELECTRICITY
PRODUCED BY
SOLAR CELLS
NON IMAGING
CONCENTRATOR
(TO GRANULATE
INFRA RED)
LONG WAVE
RADIATION
TO HEAT
ELECTROLYSOR
17
HIGH
TEMP.
ELECTROLY
SOR
AND
HX
FEEDWATER
H_2
O_2
DC ELECTRICITY

FIG. 4


ASSEMBLY LOCATED
AT FOCAL ZONE
STEAM + H2 OUT
STEAM PREHEAT COIL
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51
31
45
41
SOLAR TRACKER
ASSEMBLY
PARABOLIC
CONCENTRATOR
29

FIG. 5

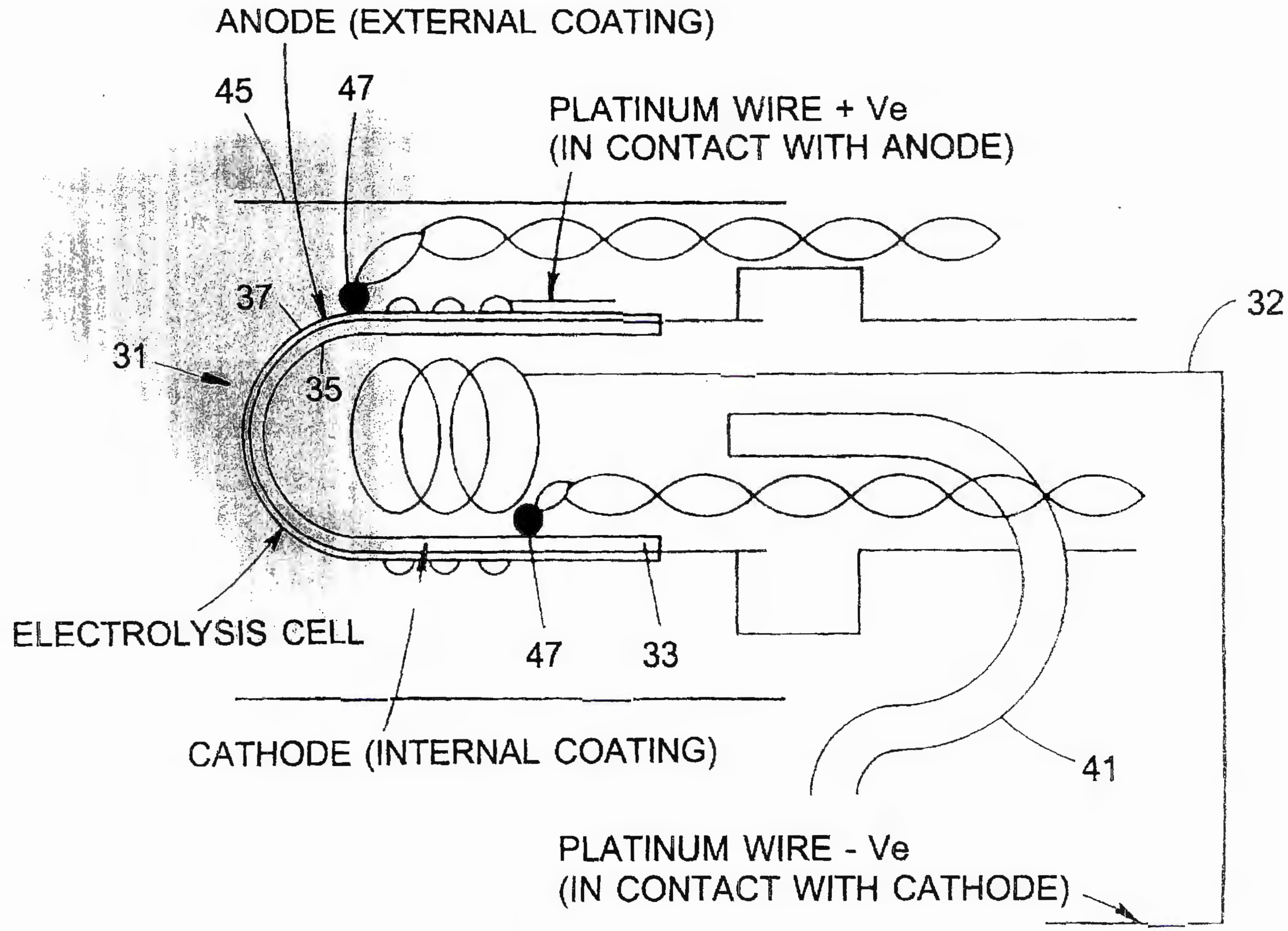
ANODE (EXTERNAL COATING)
45
47
PLATINUM WIRE + Ve
(IN CONTACT WITH ANODE)
37
32
31
35
ELECTROLYSIS CELL
47
33
CATHODE (INTERNAL COATING)
41
PLATINUM WIRE - Ve
(IN CONTACT WITH CATHODE)

FIG. 6

PRODUCTION OF HYDROGEN FROM SOLAR RADIATION AT HIGH EFFICIENCY

The present invention relates to a method and an apparatus for the production of hydrogen and in particular for the production of hydrogen in an electrolysis cell using solar radiation as a source of energy for the cell.

A present invention also relates to an apparatus for separating longer and shorter wavelength solar radiation so that the separated components of the solar radiation spectrum can be used as required in selected end-use applications, such as the production of hydrogen.

The use of hydrogen as a carrier of energy, particularly in the context as a fuel, has the following significant technical advantages over other energy sources.

1. Supply side considerations—hydrogen is inexhaustible, storable, transportable, and has a high energy density compared with other chemical fuels.
2. Demand side considerations—hydrogen is non-polluting, more versatile than electricity, more efficient then petrol, and convertible directly to heat and electricity for both mobile and stationary applications.

By way of particular comparison, the large scale use of solar energy as an energy source has been limited for technical reasons and cost by a lack of a suitable short and long term storage medium or solar energy.

However, notwithstanding the above technical advantages of hydrogen as an energy source, the cost of production of hydrogen has been too high hitherto for widespread use as a fuel.

In the case of the production of hydrogen by electrolysis of water, a major factor in the high cost of production has been the cost of electricity to operate electrolysis cells.

In the specific case of solar radiation-generated electricity, the high cost of electricity is due in large part to the relatively low efficiency of photovoltaic (or thermal) conversion of solar energy into electricity which means that a relatively large number of photovoltaic cells (or, in the case of thermal conversion, a large collection area) is required to generate a unit output of electricity.

An object of the present invention is to provide a solar radiation based method and apparatus for producing hydrogen in an electrolysis cell which has a significantly higher efficiency and thus lower cost per unit energy produced than the known technology.

Another object of the present invention is to provide an apparatus for separating longer and shorter wavelength components of the solar radiation spectrum such that the separated components can be used efficiently.

According to a first aspect of the present invention there is provided a method of producing hydrogen comprising, converting solar radiation into thermal energy and electrical energy, and using the thermal energy and the electrical energy for producing hydrogen and oxygen by electrolysis of water.

The above first aspect of the present invention is based on the realisation that when the electrolysis process is run at high temperature (1000°C) the electrical voltage required to maintain a given output of hydrogen can be reduced provided there is a complementary increase in thermal energy input.

The above first aspect of the present invention is based on the realisation that a significant improvement in efficiency of energy utilisation over and above a conventional electrolysis cell that is operated solely by electrical energy generated from solar radiation by a photovoltaic cell (or by thermal electrical generation methods) can be achieved by using the thermal energy produced in the generation of electrical energy, which otherwise would be regarded as a waste low temperature heat (with a cost of disposal), with the solar generated electrical energy to operate the electrolysis cell.

The above first aspect of the present invention is also based on the realisation that such waste thermal energy can only be used to advantage, in terms of efficiency of energy utilisation, if that thermal energy can be transferred to the electrolysis cell and produce the high temperatures necessary to operate the electrolysis cell.

It is preferred that the method comprises separating the solar radiation into a shorter wavelength component and a longer wavelength component, and converting the shorter wavelength component into electrical energy and converting the longer wavelength component into thermal energy.

It is preferred that the method comprises, producing hydrogen and oxygen by electrolysis of water by converting water into steam and heating the steam to a temperature of at least 700° C., more preferably 1000° C., and decomposing the steam into hydrogen and oxygen in an electrolysis cell.

It is preferred that the method comprises using solar radiation generated thermal energy for converting water into steam and/or pre-heating steam and for operating the electrolysis cell and using solar radiation generated electrical energy for operating the electrolysis cell.

It is preferred particularly that the method comprises extracting thermal energy from hydrogen, oxygen, and exhaust steam produced in the electrolysis cell and using the extracted thermal energy as part of the energy component required for converting water into steam or for pre-heating steam for consumption in the electrolysis cell.

According to the first aspect of the present invention there is also provided an apparatus for producing hydrogen by electrolysis comprising, an electrolysis cell having an inlet for steam and outlets for hydrogen, oxygen, and excess steam, a means for separately converting solar radiation into thermal energy and into electrical energy arranged in series or in parallel relationship for providing the energy required for converting water into steam and/or heating steam for operating the electrolysis cell to decompose the steam into hydrogen and oxygen at high temperatures of at least 700° C., more preferably at least 1000° C.

It is preferred that the electrolysis cell be at least partially formed from materials that allow oxygen to be separated from hydrogen in and/or adjacent to the electrolysis cell.

It is preferred that the apparatus further comprises, a means for concentrating solar radiation on the thermal energy conversion means and on the electrical energy conversion means in the appropriate proportions and wavelengths.

In one embodiment, it is preferred that the electrical energy conversion means and the thermal energy conversation means be adapted for separately receiving solar radiation.

In another embodiment it is preferred that the apparatus further comprises a means for separating solar radiation into a shorter wavelength component and a longer wavelength component, wherein:

(a) the electrical energy conversion means is adapted for receiving end for converting the shorter wavelength component into electrical energy; and

(b) the thermal energy conversion means is adapted for receiving and converting the longer wavelength component into thermal energy.

It is preferred that the solar radiation separating meats comprises a mirror for selectively reflecting either the longer wavelength component or the shorter wavelength component of the solar radiation spectrum.

It is preferred particularly that the mirror be positioned between the solar radiation concentrating means and the electrical energy conversion means and that the mirror comprise a spectrally selective filter to make the mirror transparent to the non-reflected component of the solar radiation spectrum.

It is preferred more particularly that the mirror be adapted for selectively reflecting the longer wavelength component of the solar radiation spectrum and that the spectrally selective filter be an interference or edge filter to make the mirror transparent to the shorter wavelength component of the solar radiation spectrum.

It is preferred that the apparatus further comprises a non-imaging concentrator for concentrating the reflected longer wavelength component of the solar radiation spectrum.

It is preferred that the apparatus further comprises an optical fibre or a light guide for transferring the reflected longer wavelength component of the solar radiation spectrum to the thermal conversion means.

It is preferred that the apparatus further comprises, a heat exchange means for extracting thermal energy from hydrogen, oxygen, and exhaust steam produced in the electrolysis cell and using the extracted thermal energy as part of the energy component required for converting feed water into steam or for pre-heating steam for consumption in the electrolysis cell.

According to a second aspect of the present invention there is provided an apparatus for separating solar radiation into a longer wavelength component and a shorter wavelength component comprising, a mirror for selectively reflecting either the longer wavelength component or the shorter wavelength components of the solar radiation spectrum.

It is preferred that the mirror comprise, a spectrally selective filter to make the mirror transparent to the non-reflected component of the solar radiation spectrum.

It is preferred that the mirror be appropriately curved so that it can concentrate and direct the reflected longer wavelength component or the shorter wavelength component to a distant point for collection by a receiver.

It is preferred that the apparatus further comprises, a non-imaging concentrator for concentrating the reflected longer or shorter wavelength component.

It is preferred that the apparatus further comprises, an optical fibre of light guide for transferring the concentrated reflected longer or shorter wavelength component for use in an end use application.

It is preferred particularly that the end use application be the generation of hydrogen by electrolysis of water.

The present invention is described further by way of example with reference to the accompanying drawings, in which:

FIG. 1 illustrates schematically one embodiment of an apparatus for producing hydrogen in accordance with the present invention;

FIG. 2 illustrates schematically another embodiment of an apparatus for producing hydrogen in accordance with the present invention;

FIG. 3 illustrates schematically a further embodiment of an apparatus for producing hydrogen in accordance with the present invention;

FIG. 4 illustrates schematically a further embodiment of an apparatus for producing hydrogen in accordance with the present invention;

FIG. 5 is a diagram which shows the major components of an experimental test rig based on the preferred embodiment of the apparatus shown in FIG. 1; and

FIG. 6 is a detailed view of the electrolysis cell of the experimental test rig shown in FIG. 4.

The basis of the first aspect of the present invention is to use solar energy to provide the total energy requirements, in the form of a thermal energy component and an electrical energy component, to form hydrogen and oxygen by the electrolysis of water. In this connection, the applicant has found that the combined effect of solar-generated thermal energy and electrical energy results in a significant improvement in the efficiency of the electrolysis of water in terms of energy utilisation, particularly when the thermal component is provided as a by-product of solar-generated electricity production.

The apparatus shown schematically in FIG. 1 is in accordance with the first aspect of the present invention and comprises, a suitable form of solar concentrator 3 which focuses a part of the incident solar radiation onto an array of solar cells 5 for generating electricity and the remainder of the incident solar radiation onto a suitable form of receiver 7 for generating thermal energy.

The electricity and the thermal energy generated by the incident solar radiation are transferred to a suitable form of electrolysis cell 9 so that:

(a) a part of the thermal energy converts an inlet stream of water for the electrolysis cell 9 into steam and heats the steam to a temperature of about 1000° C.; and

(b) the electrical energy and the remainder of the thermal energy operate the electrolysis cell 9 to decompose the high-temperature steam into hydrogen and oxygen.

The hydrogen is transferred from the electrolysis cell 9 into a suitable form of storage tank 11.

The receiver 7 may be any suitable form of apparatus, such as a heat exchanger, which allows solar radiation to be converted into thermal energy.

The apparatus shown in FIG. 1 further comprises a heat exchanger means (not shown) for extracting thermal energy from the hydrogen end oxygen (and any exhaust steam) produced in the electrolysis cell 9 and thereafter using the recovered thermal energy in the step of converting the inlet stream of water into steam for consumption in the electrolysis cell 9. It is noted that the recovered thermal energy is at a relatively lower temperature than the thermal energy generated by solar radiation. As a consequence, preferably, the recovered thermal energy is used to preheat the inlet water, and the solar radiation generated thermal energy is used to provide the balance of the heat component required to convert the feed water or steam to steam at 1000° C. and to contribute to the operation of the electrolysis cell 9.

It is noted that the component of the thermal energy which is used endothermically at high temperature in the electrolysis cell 9 is Consumed at nearly 100% efficiency. This high thermal energy utilisation is a major factor in the high overall efficiency of the system. It is also noted that high temperatures are required to achieve the high thermal energy efficiency and as a consequence only systems which can collect and deliver thermal energy at high temperatures (700° C.+) can achieve the high efficiency.

The apparatus shown in FIG. 1 is an example of a parallel arrangement of solar cells 5 and thermal energy receiver 7 in accordance with the first aspect of the present invention. The first aspect of the present invention is not restricted to such arrangements and extends to series arrangements of solar cells 5 and thermal energy receiver 7. The apparatus shown schematically in FIGS. 2 to 4 are examples of such series arrangements. In addition, the apparatus shown schematically in FIGS. 2 to 4 incorporate examples of apparatus in accordance with the second aspect of the present invention.

The apparatus shown schematically in FIGS. 2 to 4 take advantage of the fact that solar cells selectively absorb shorter wavelengths and may be transparent to longer wavelengths of the solar radiation spectrum. In this connection, the threshold is in the order of 1.1 micron for silicon solar cells and 0.89 micron for GaAs cells leaving 25% to 35% of the incoming energy of the solar radiation, which is normally wasted, for use as thermal energy.

The apparatus shown in FIGS. 2 to 4, in terms of the first aspect of the present invention, in each case, is arranged so that, in use, solar radiation is reflected from a solar concentrator 3 onto a solar cell 15 to generate electricity from the shorter wavelength component of the solar radiation and the solar radiation that is not used for electricity generation, i.e. the longer wavelength component, is directed to a thermal energy receiver (not shown) of an electrolysis cell 17 to convert the solar radiation into thermal energy. The apparatus shown in FIGS. 2 to 4, in terms of the second aspect of the present invention, in each case, comprises a means which, in use, separates the longer and shorter wavelength components of the solar radiation spectrum so that the components can be used separately for thermal energy and electricity generation, respectively.

The solar radiation separating means comprises a mirror **27** (not shown in FIG. 2 but shown in FIGS. 3 and 4) positioned in front of or behind the solar cells **15**.

In situations where the mirror **27** is positioned in front of the solar cells **15**, as shown in FIGS. 3 and 4, the mirror **27** comprises an interference filter or edge filter (not shown) which makes the mirror **27** transparent to the shorter wavelength component of the solar radiation spectrum.

The mirror **27** may be of any suitable shape to reflect and selectively direct the longer wavelength component of the solar radiation spectrum. For example, in situations where the mirror **27** is positioned in front of the solar cells **15** and the focal point of the solar concentrator **3**, as shown in. FIGS. 3 and 4, the mirror **27** may take the form of a Cassigranian mirror, and in situations where the mirror **27** is positioned behind the focal point of the solar concentrator **3**, the mirror may take the form of a Gregorian mirror.

The longer wavelength radiation reflected by the solar cells **15** may be transferred to the electrolysis cell **17** by any suitable transfer means **21** such as a heat pipe (not shown) or an optical fibre (or light guide), as shown in FIGS. 2 and 4, or directly as radiation, as shown in FIG. 3.

With particular regard to the apparatus shown in FIG. 4, the electrolysis cell **17** is positioned remote from the solar cells **15**, and the apparatus further comprises a non-imaging concentrator **33** for concentrating the reflected longer wavelength component of the solar radiation prior to transferring the concentrated component to the optical fibre or light guide **21**.

It is also noted that the second aspect of the present invention is not limited to use of the reflected longer wavelength component of the solar radiation spectrum to provide thermal energy to an electrolysis cell and may be used to provide thermal energy in any end use application.

The electrolysis cells **9**,**17** shown in the figures may be of any suitable configuration. Typically, the electrolysis cells **9**,**17** are formed from a material, such as yttria stabilised zirconia (YSZ), which is porous to oxygen and impermeable to other gases, and the accessories, such as membranes and electrodes (not shown), are formed from materials, such as alloys and cermets.

The apparatus of the present invention as described above take advantage of the facts that:

(a) the electrical potential and the electrical energy necessary to produce hydrogen in an electrolysis cell decreases as the temperature increases and the balance of the energy requirements to operate the electrolysis cell can be provided in the form of thermal energy;

(b) the efficiency of generation of thermal energy from solar radiation is significantly higher (in the order of 3 to 4 times) than the efficiency of generation of electricity from solar radiation; and

(c) the efficiency of consumption of the thermal energy endothermically in the electrolysis cell approaches 100%.

It is noted that it is believed by the applicant that the use of the by-product thermal energy can only be practically executed by the means described herein since other currently known methods are not capable of transferring energy to produce a temperature in excess of 1000° C.

In other words, a particular advantage of the present invention is that, as a consequence of being able to separate the longer a shorter wavelength components of the solar radiation spectrum, it is possible to recover and convey and use that longer wavelength component in high temperature application where otherwise that longer wavelength component would have been converted into low temperature heat (typically less than 45° C.) and being unusable.

Further advantages of the present invention are as follows:

1. The efficiency of hydrogen production is greater than any other known method of solar radiation generated hydrogen production.
2. The present invention increases the overall efficiency of the system, i.e. the efficiency of producing hydrogen by this method is greater than the efficiency of just producing electricity.
3. The present invention provides a medium, namely hydrogen, for the efficient storage of solar energy hitherto not available economically and thus overcomes the major technological restriction to large scale use of solar energy.

It should be noted that the performance of the present invention is expected to exceed 50% efficiency. The theoretical performance is in the order of 60%, whereas the existing technology is not expected to practically exceed 14% efficiency and has a threshold limit of 18%.

In order to illustrate the performance of the present invention the applicant carried out experimental work, as described below, on an experimental test rig shown in FIGS. 5 and 6 which is based on the embodiment of the apparatus shown in FIG. 1.

With reference to FIGS. 5 and 6, the experimental test rig comprised a 1.5 m diameter paraboloidal solar concentrating dish **29** arranged to track in two axes and capable of producing a solar radiation flux of approximately 1160 suns and a maxim temperature of approximately 2600° C. It is noted that less than the full capacity of power and concentration of the concentrating dish **29** was necessary for the experimental work and thus the receiving components (not shown) were appropriately positioned in relation to the focal plane and/or shielded to produce the desired temperatures and power densities.

The experimental rig further comprised, at the focal zone of the solar concentrating dish **29**, an assembly of an electrolysis cell **31**, a tubular heat shield/distributor **45** enclosing the electrolysis cell **31**, a solar cell **51**, and a length of tubing **41** coiled around the heat shield/distributor **45** with one end extending into the electrolysis cell **31** and the other end connected to a source of water.

The solar cell **51** comprised a GaAs photovoltaic (19.6 mm active area) concentrator cell for converting solar radiation deflected from the concentrator dish **31** into electrical energy. The GaAs photovoltaic cell was selected because of a high conversion efficiency (up to 29% at present) and a capacity to handle high flux density (1160 suns) at elevated temperatures (100° C.). In addition, the output voltage of approximately 1 to 1.1 volts at maximum power point made an ideal match for direct connection to the electrolysis cell **33** for operation at 1000° C.

With particular reference to FIG. **6**, the electrolysis cell **31** was in the form of a 5.8 cm long by 0.68 cm diameter YSZ closed end tube **33** coated inside and outside with platinum electrodes **35**, **37** that formed cathodes and anodes, respectively, of the electrolysis cell **31** having an external surface area of 8.3 cm^2 and an internal surface area of 7.6 cm^2.

The metal tube **45** was positioned around the electrolysis cell **31** to reduce, average and transfer the solar flux over the surface of the exterior surface of the electrolysis cell **31**.

The experimental text rig further comprised, thermocouples **47** (FIG. **5**) connected to the cathode **35** and the anode **37** to continually measure the temperatures inside and outside, respectively, the electrolysis cell **31**, a 1 mm^2 platinum wire **32** connecting the cathode **35** to the solar cell **51**, a voltage drop resistor (0.01Ω) (not shown) in the circuit connecting the cathode **35** and the solar cell **51** to measure the current in the circuit, and a Yokogawa HR-1300 Data Logger (not shown).

The experimental test rig was operated with the electrolysis cell **31** above 1000° C. for approximately two and a half hours with an excess of steam applied to the electrolysis cell **31**. The output stream of unreacted steam and the hydrogen generated in the electrolysis cell **31** was bubbled through water and the hydrogen was collected And measured in a gas jar.

When a steady state was reached, readings of temperature, voltage, current and gas production were recorded and the results are summarised in Table 1 below.

Time	Electrolysis Cell Voltage	Electrolysis Cell Current	Electrolysis Cell Temperature	Gas Production
	V	Amps	°C.	ml
2.22	1.03	.67	1020	0
2.39	1.03	.67	1020	80
net 17 minutes				net 80 ml

On the basis of the measured electrolysis cell voltage of 1.03 V recorded in Table 1 and a determined thermoneutral voltage of 1.47, the electrical efficiency of the electrolysis cell **31**, calculated as the ratio of the thermoneutral and measured voltages, was

$$\frac{1.47}{1.03} = 1.43$$

In terms of the solar cell efficiency, with the solar cell **31** positioned to receive a concentration ratio of 230 suns and assuming:

(a) an output voltage=1.03 (=voltage across electrolysis cell and allows for connection losses);

(b) a current of 0.67 Amps;

(c) direct solar input is 800 w/m^2; and

(d) an active solar cell area=19.6×10^{-6} m^2, the efficiency of the solar cell **51** (ηpv) was

$$\eta_{pv} = \frac{\text{output}}{\text{input}} = \frac{1.03 \times .67}{\frac{19.6}{10^6} \times 230 \times 800} = \frac{.69}{3.6} = .19$$

With a spectral reflectivity of 0.9 for the mirror surface of the solar concentrating dish **29**, the efficiency of the solar concentrator dish **29** was 0.85.

Thus, the total system efficiency of the solar cell **51** and the electrolysis cell **31** and optics (ηtotal) was

$$\eta\text{total}=0.85\times0.19\times1.43=0.22 \qquad (22\%)$$

The above figures of 22% is approximately twice the best previous proposed systems and more than three times the best recorded figure for a working plant.

The results of the experimental work on the experimental test rig establish that:

(a) it is possible to produce hydrogen by high temperature electrolysis of water driven totally by solar radiation,

(b) the efficiency of production is greatly improved over known systems, and

(c) a significant portion of the heat of solar radiation can be used directly in the electrolysis reaction this reducing greatly expensive electrical input by almost half.

Many modifications may be made to the preferred embodiments of the present invention as described above without departing from the spirit and scope of the present invention.

By way of example, it is noted that, whilst the preferred embodiments describe methods which convert water into hydrogen and oxygen, it can readily be appreciated that the present invention is not so limited and extends to operating the methods in reverse to consume hydrogen and oxygen to produce thermal energy and electricity. In this regard, it has been found by the applicant that under certain conditions the electrical input required to produce a unit of hydrogen in accordance with the preferred embodiments of the method is less than the electrical output produced when the hydrogen is used in the methods arranged to operate in reverse and thus as well as the system producing hydrogen the overall electrical efficiency of the plant can also be enhanced.

Furthermore, whilst the preferred embodiments describe the use of solar cells to convert solar energy into electricity, it can readily be appreciated that the present invention is not so limited and extends to any suitable solar radiation to electricity converters.

Furthermore, whilst the preferred embodiments describe that the second aspect of the present invention separates the longer and shorter wavelength components of the solar radiation spectrum by reflecting the longer wavelength component, it can readily be appreciated that the second aspect of the present invention is not limited to such an arrangement and extends to arrangements in which the shorter wavelength component is reflected.

I claim:

1. A method of producing hydrogen by the electrolysis of steam, the method comprising, converting solar radiation into thermal energy and electrical energy, and using a part of the thermal energy to convert water into steam and to heat the steam to a temperature of at least 700° C., and using the electrical energy and the remaining part of the thermal energy to operate an electrolysis cell to decompose the steam and to produce hydrogen and oxygen, with the thermal energy providing at least a part of the endothermic component of the electrolysis reaction and to significantly reduce the additional external electrical energy required to operate the electrolytic cell and increasing the efficiency of hydrogen production.

2. The method defined in claim 1 comprising, separating the solar radiation into a shorter wavelength component and a longer wavelength component, and converting the shorter wavelength component into electrical energy and converting the longer wavelength component into thermal energy.

3. The method defined in claim 1 or claim 2 further comprising, using solar radiation generated thermal energy for converting water into steam and for operating the electrolysis cell and using solar radiation generated electrical energy for operating the electrolysis cell.

4. The method defined in claim 3 further comprising, extracting thermal energy from hydrogen, oxygen, and exhaust steam produced in the electrolysis cell and using the extracted thermal energy as part of the energy component required for converting water into steam and for pre-heating steam for consumption in the electrolysis cell.

5. An apparatus for producing hydrogen by electrolysis comprising:

an electrolysis cell having an inlet for steam and outlets for hydrogen, oxygen, and excess steam,

means for separating solar radiation, by wavelength, into a first wavelength component and a second wavelength component, said first wavelength component being relatively shorter than said second wavelength component,

electrical energy conversion means for receiving and converting said first (shorter) wavelength component into electrical energy, and

thermal energy conversion means for receiving and converting said second (relatively longer) wavelength component into thermal energy,

said electrical energy conversion means and said thermal energy conversion means being arranged in series or in parallel relationship for providing energy required for converting water into steam and for operating the electrolysis cell to decompose the steam into hydrogen and oxygen at high temperature of at least 700°C.

6. The apparatus defined in claim 5 wherein, the electrolysis cell is at least partially formed from materials that allow oxygen to be separated from hydrogen in or adjacent to the electrolysis cell.

7. The apparatus defined in claim 5 or claim 6, further comprising, a means for concentrating solar radiation on the thermal energy conversion means and on the electrical energy conversion means.

8. The apparatus defined in claim 7 wherein, the electrical energy conversion means and the thermal energy conversion means are adapted for separately receiving solar radiation.

9. The apparatus defined in claim 5, wherein the solar radiation separating means comprises, a mirror for selectively reflecting either said second (relatively longer) wavelength component or said first (shorter) wavelength component of the solar radiation spectrum.

10. The apparatus defined in claim 9, wherein the mirror is positioned between the solar radiation concentrating means and the electrical energy conversion means and the mirror comprises a spectrally selective filter to make the mirror transparent to the non-reflected component of the solar radiation spectrum.

11. The apparatus defined in claim 9, wherein the mirror is adapted for selectively reflecting said second (relatively longer) wavelength component of the solar radiation spectrum.

12. The apparatus defined in claim 11, wherein the spectrally selective filter comprises an interference or edge filter.

13. The apparatus defined in claim 9 further comprising, a non-imaging concentrator for receiving and further concentrating the reflected component of the solar radiation spectrum.

14. The apparatus defined in any one of claim 9 to 13 further comprising, a means for conveying the reflected component of the solar radiation spectrum to the thermal energy conversion means.

15. The apparatus defined in claim 14, wherein the conveying means comprises an optical fibre or a light guide.

16. The apparatus defined in claim 5 wherein the electrical energy conversion means is a solar cell.

17. The apparatus defined in claim 5 further comprising, a heat exchange means for extracting thermal energy from hydrogen, oxygen, and exhaust steam produced in the electrolysis cell and using the extracted thermal energy to form steam for consumption in the electrolysis cell.

18. The apparatus defined in claim 5, wherein the apparatus is reversible so that hydrogen and oxygen can be reacted together to produce heat and electricity.

* * * * *

2.3 Lasich J.B., 2001, "Cooling Circuit for Receiver of Solar Radiation", Patent No. 7076965B2, USA

US007076965B2

(12) United States Patent
Lasich

(10) **Patent No.: US 7,076,965 B2**
(45) **Date of Patent: Jul. 18, 2006**

(54) **COOLING CIRCUIT FOR RECEIVER OF SOLAR RADIATION**

(76) Inventor: **John Beavis Lasich**, 11 Pretoria St., Balwyn (AU) VIC 3103

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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PCT Pub. Date: **Oct. 10, 2002**

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H01L 25/00 (2006.01)
H02N 6/00 (2006.01)
(52) **U.S. Cl.** **62/259.2**; 136/246; 136/244
(58) **Field of Classification Search** 62/259.2; 136/246, 244, 248, 251
See application file for complete search history.

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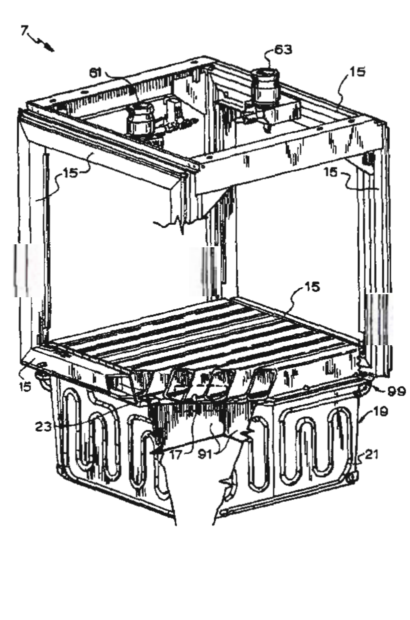
Primary Examiner—Chen Wen Jiang
(74) *Attorney, Agent, or Firm*—Klarquist Sparkman LLP

(57) **ABSTRACT**

A receiver for a system for generating electrical power from solar radiation is disclosed. The systems includes the receiver and a means (**3**) for concentrating solar radiation onto the receiver. The receiver includes a plurality of photovoltaic cell modules. Each module includes a plurality of photovoltaic cells (**5**), and includes an electrical connection that forms part of the receiver electrical circuit. The receiver includes a coolant circuit for cooling the photovoltaic cells with a coolant. The coolant circuit includes a coolant flow path in each module that is in thermal contact with the photovoltaic cells so that in use coolant flowing through the flow path extracts heat from the photovoltaic cells and thereby cools the cells.

39 Claims, 5 Drawing Sheets



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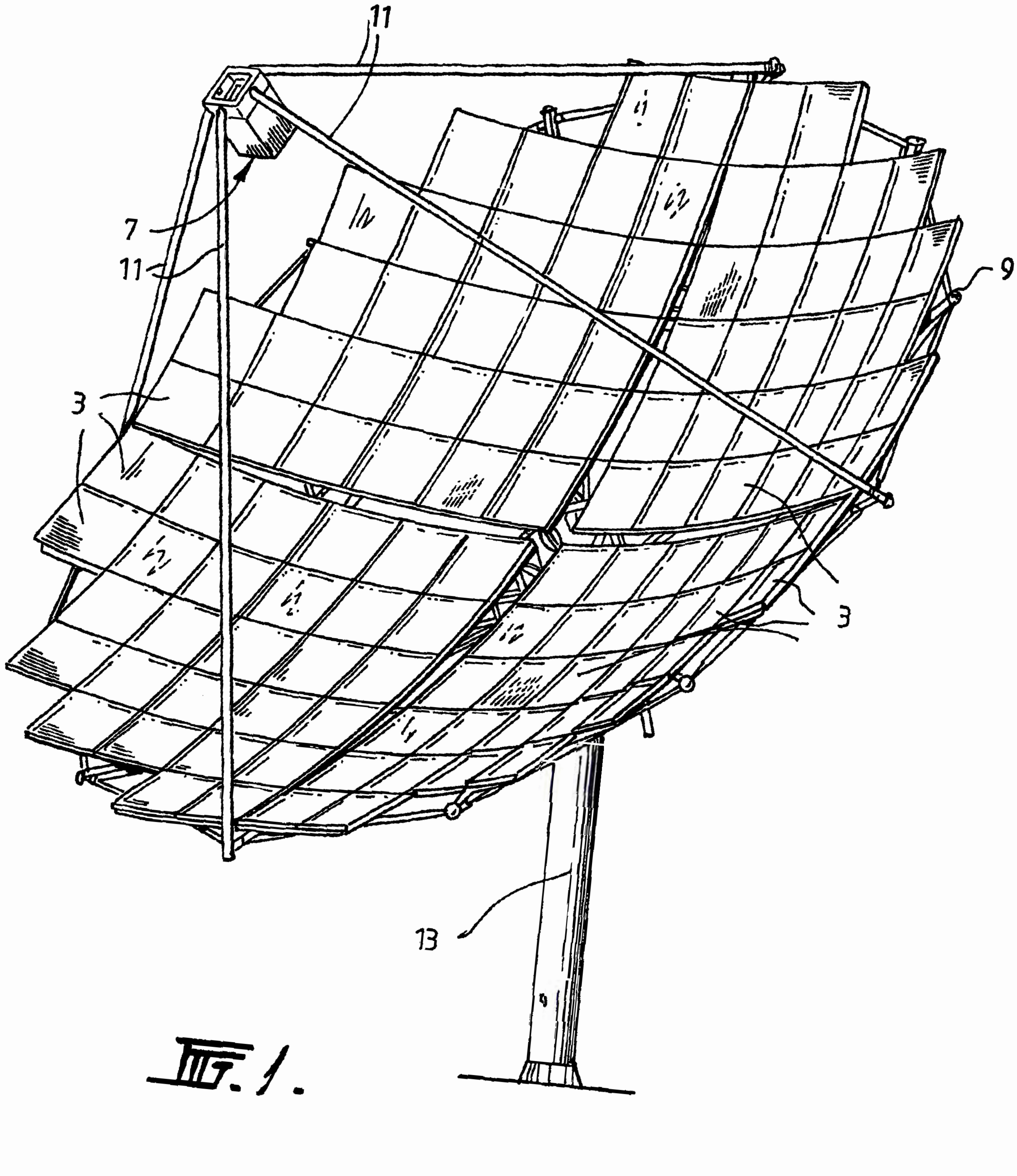

FIG. 1.

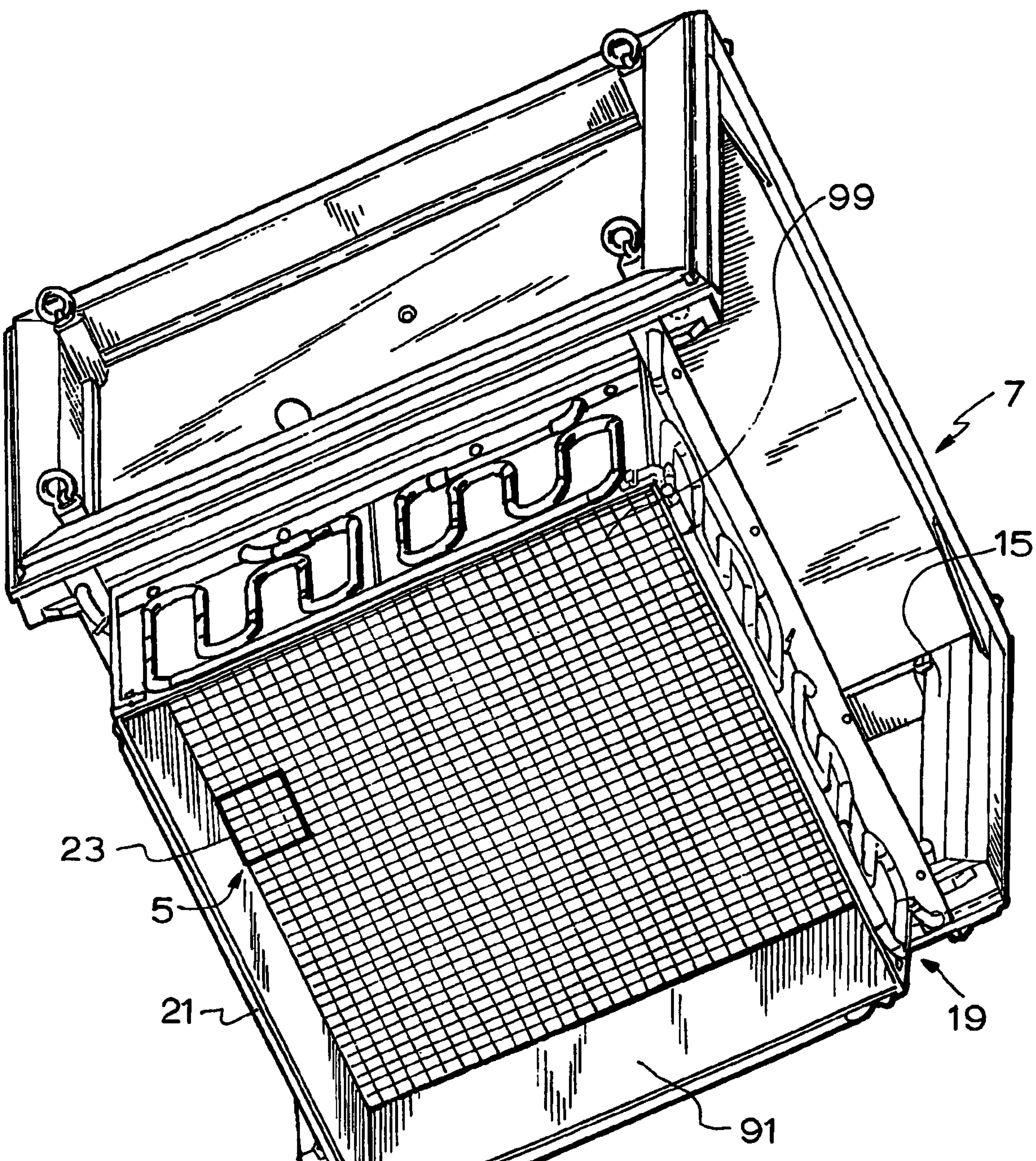

FIG. 2.

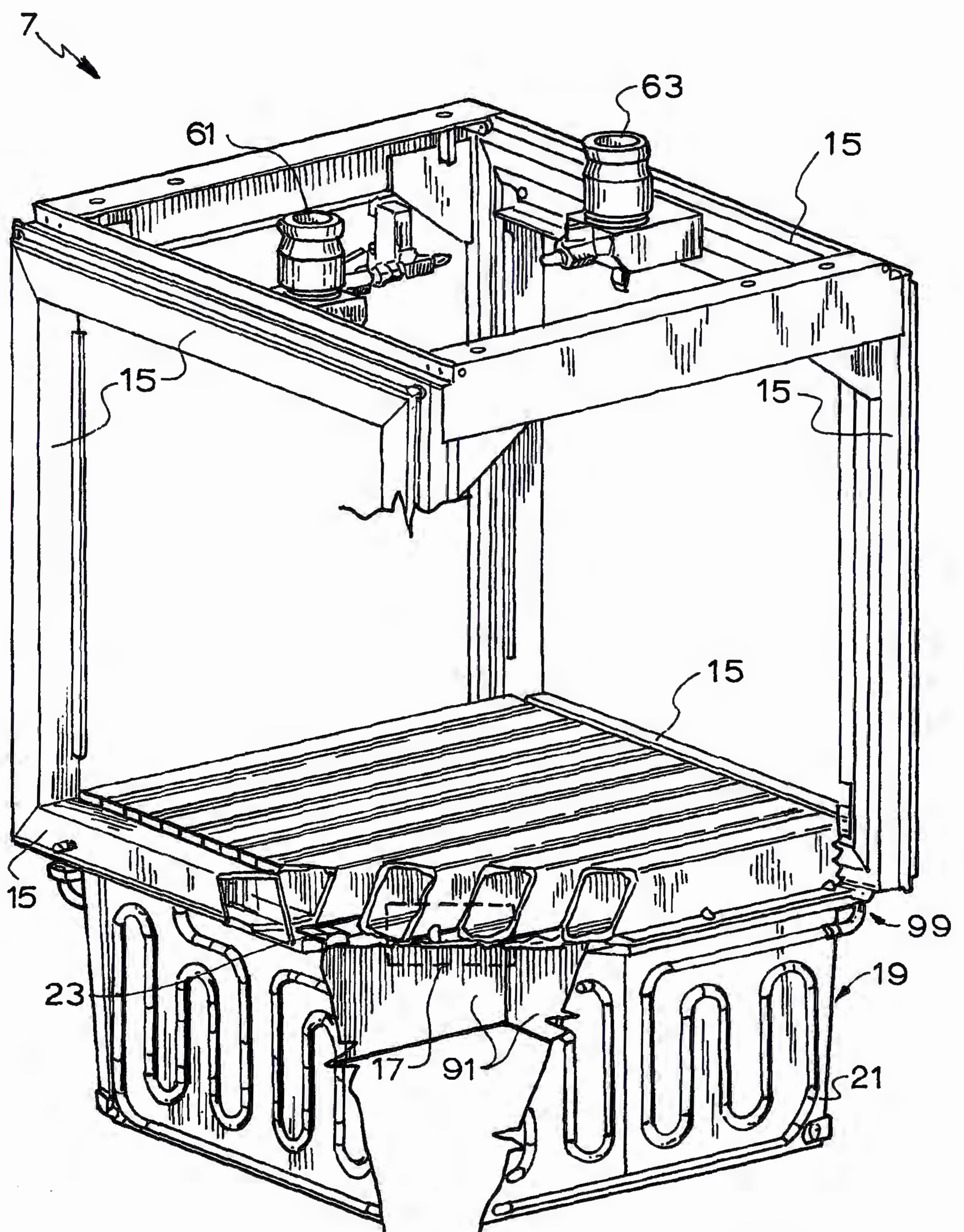

FIG. 3.

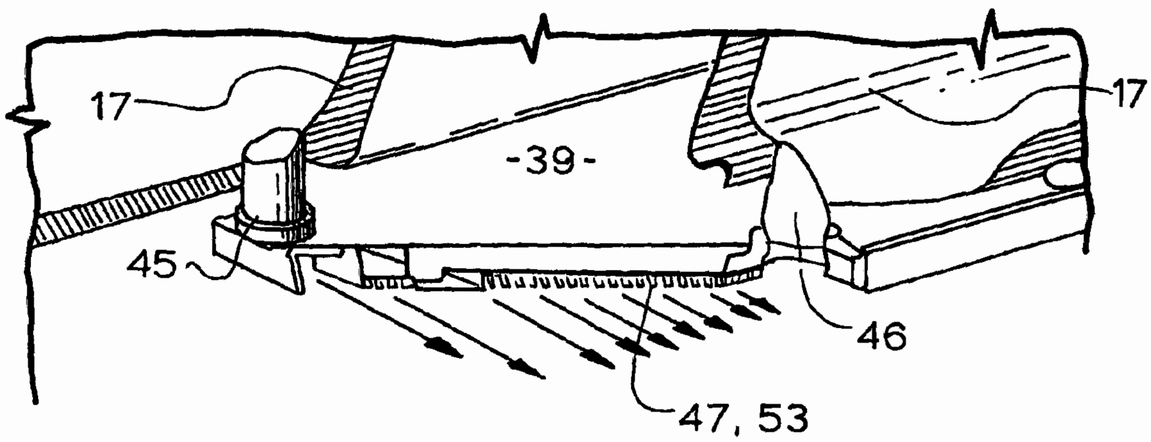

FIG. 4.

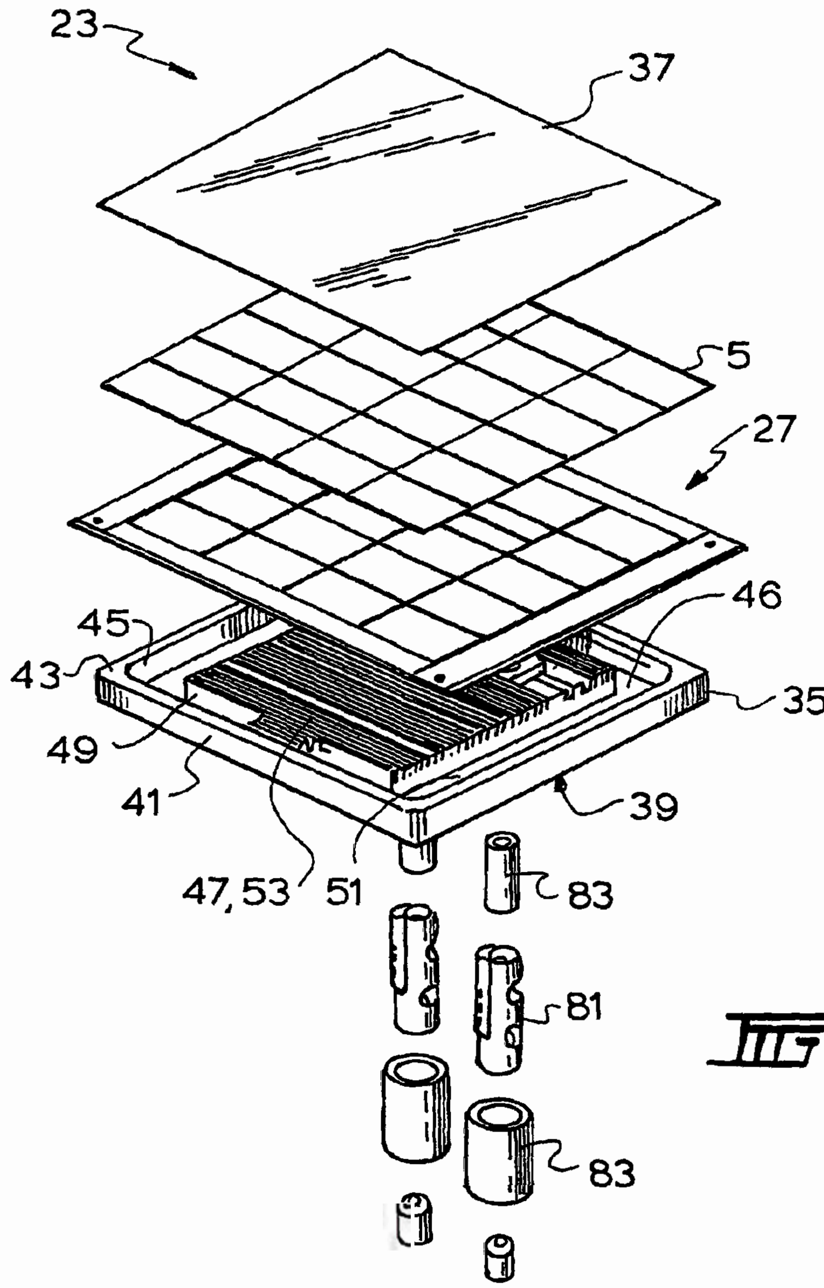

FIG. 5.

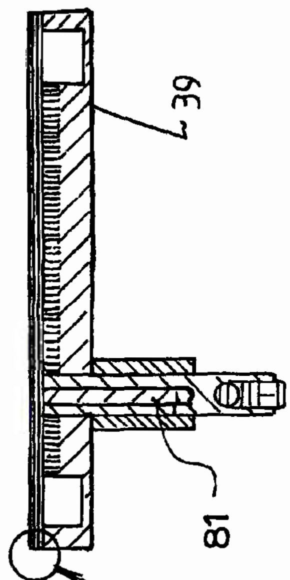

FIG. 7.

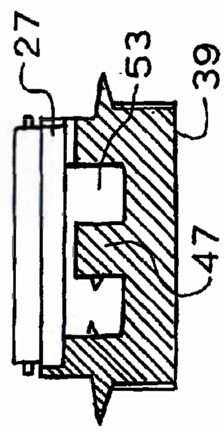

FIG. 9.

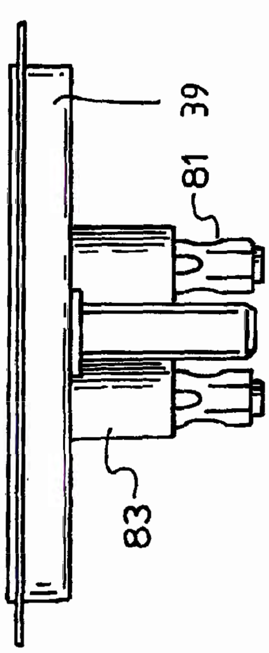

FIG. 6.

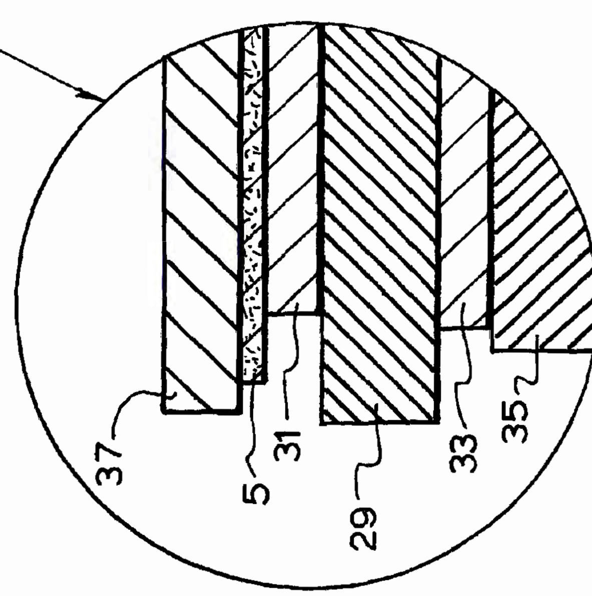

FIG. 8.

COOLING CIRCUIT FOR RECEIVER OF SOLAR RADIATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This is the National Stage of International Application No. PCT/AU02/00402, filed Mar. 28, 2002, and claims the benefit of Australian Patent Application No. PR4038, filed Mar. 28, 2001.

FIELD

The present invention relates to a receiver of a system for generating electrical power from solar radiation.

BACKGROUND AND SUMMARY

Solar radiation-based electrical power generating systems typically include:

(a) a receiver that includes a plurality of photovoltaic cells that convert solar energy into electrical energy and an electrical circuit for transferring the electrical energy output of the photovoltaic cells; and

(b) a means for concentrating solar radiation onto the photovoltaic cells of the receiver.

By way of example, the means for concentrating solar radiation may be a dish reflector that includes a parabolic array of mirrors that reflect solar radiation that is incident on a relatively large surface area of the mirrors towards a relatively small surface area of the photovoltaic cells.

In addition to the parabolic array of mirrors, the above-described dish reflector may also include a matched secondary solar radiation modification mirror system (such as a solar flux modifier).

Another, although not the only other, means for concentrating solar radiation is an array of spaced apart mirrors that are positioned to reflect solar radiation that is incident on a relatively large surface area of the mirrors towards a relatively small surface area of the photovoltaic cells.

The present invention relates more particularly, although by no means exclusively, to a large scale solar radiation-based electrical power generating system of the type described above that is capable of producing substantial amounts of electrical power ready for conditioning to at least 20 kW of standard 3 phase 415 volt AC power.

Applications for such large scale power generating systems include remote area power supply for isolated grids, grid-connected power, water pumping, telecommunications, crude oil pumping, water purification, and hydrogen generation.

One significant issue associated with development of commercially viable solar radiation-based electrical power generating systems of the type described above is long term performance of materials and structural integrity of components of the system made from materials as a consequence of:

(a) exposure to extremely high intensity solar radiation capable of producing high temperatures, i.e. temperatures considerably above 1000° C.;

(b) cycling between high and low intensities of solar radiation; and

(c) temperature variations between different parts of structural components.

The receiver is one area of particular importance in this regard.

Specifically, in large scale solar radiation-based electrical power generating systems of the type described above the photovoltaic cells are exposed to solar radiation intensities of at least 200 times the intensity of the Sun during optimum operating conditions. In addition, the photovoltaic cells are subjected to significant cycling between extremely high and low levels of solar radiation and to variations in solar radiation intensity across the surface of the receiver.

An object of the present invention is to provide a receiver that is capable of long term exposure to extremely high intensities of solar radiation, cycling between extremely high and low intensities of solar radiation, and temperature variations between different sections of components of the receiver.

According to the present invention there is provided a system for generating electrical power from solar radiation which includes:

(a) a receiver that includes a plurality of photovoltaic cells for converting solar energy into electrical energy and an electrical circuit for transferring the electrical energy output of the photovoltaic cells; and

(b) a means for concentrating solar radiation onto the receiver; and

the system being characterised in that the receiver includes a plurality of photovoltaic cell modules, each module includes a plurality of photovoltaic cells, each module includes an electrical connection that forms part of the receiver electrical circuit, the receiver includes a coolant circuit for cooling the photovoltaic cells with a coolant, and the coolant circuit includes a coolant flow path in each module that is in thermal contact with the photovoltaic cells so that in use coolant flowing through the flow path cools the cells.

The applicant has found that the above-described receiver is capable of extracting significant amounts of heat generated by incident solar radiation in an efficient and reliable manner. Specifically, the applicant has found that the preferred embodiment of the receiver described in more detail below is capable of extracting up to 50 W/cm^2 of exposed photovoltaic cell. Thus, the receiver addresses the significant issue that a large portion of incident radiation on receivers of large scale solar radiation-based electrical power generating systems is not converted to electricity and manifests itself as heat that reduces the efficiency of photovoltaic cells.

In addition, the modularity of the receiver addresses (at least in part) the issue that optimum locations for large scale solar radiation-based electrical power generating systems tend to be in regions that are remote from major population and manufacturing centres and, therefore, construction of the systems in such remote locations presents significant difficulties in terms of transportation of equipment to the sites, on-site construction, and on-going maintenance (including quick replacement of component parts) at the sites.

In addition, the modularity of the receiver makes it possible to enhance manufacture of the receiver because manufacture can be based on repeat manufacture of a relatively large number of relatively small modules rather than a small number of large components.

Preferably in use the coolant maintains the photovoltaic cells at a temperature of no more than 80° C.

More preferably in use the coolant maintains the photovoltaic cells at a temperature of no more than 70° C.

It is preferred particularly that in use the coolant maintains the photovoltaic cells at a temperature of no more than 60° C.

It is preferred more particularly that in use the coolant maintains the photovoltaic cells at a temperature of no more than 40° C.

Preferably each module includes a structure that supports the photovoltaic cells.

Preferably the support structure defines the coolant flow path for extracting heat from the photovoltaic cells.

Preferably the support structure includes:

(a) a coolant member that at least partially defines the flow path, the coolant member being formed from a material that has a high thermal conductivity; and

(b) a substrate interposed between the coolant member and the photovoltaic cells, the substrate including a layer formed from a material that has a high thermal conductivity and is an electrical insulator.

Preferably the coolant member acts as a heat sink.

The coolant member may be formed from any suitable high thermal conductivity material.

By way of example, the coolant member may be a high thermal conductivity metal or ceramic.

Preferably the coolant member is formed from copper.

Preferably the high thermal conductivity/electrical insulator layer of the substrate is formed from a ceramic material.

Preferably the substrate includes a metallised layer interposed between the photovoltaic cells and the high thermal conductivity/electrical insulator layer.

Preferably the substrate includes a metallised layer interposed between the high thermal conductivity/electrical insulator layer and the coolant member.

Preferably the coolant member includes a base, a wall that extends upwardly from the base and contacts the substrate whereby the base, the side wall and the substrate define an enclosed coolant chamber that forms part of the coolant flow path.

Preferably the coolant member includes a series of spaced-apart lands that extend from the base and contact the substrate in a central part of the chamber and define therebetween channels for coolant flow from near one end of the chamber to near an opposite end of the chamber.

Preferably the spaced apart lands are parallel so that the channels are parallel.

With the above-described arrangement there is direct thermal contact between the substrate and coolant flowing through the coolant chamber (including the channels) and between the substrate and the side wall and the lands. This construction provides an effective means for transferring heat from the photovoltaic cells via the substrate to the coolant. In particular, the side wall and the lands provide an effective means of increasing the available contact surface area with the coolant to improve heat transfer to the coolant. This is an important feature given the high levels of heat transfer that are required to maintain the photovoltaic cells at temperatures below 80° C., preferably below 60° C., more preferably below 40° C. A further advantage of the construction is that the side wall and the lands enable lateral movement of the substrate and the coolant member—as is required in many situations to accommodate different thermal expansion of the materials that are used in the construction of the modules. Accommodating different thermal expansion of such materials is an important issue in terms of maintaining long term structural integrity of the modules. In this context, it is important to bear in mind that the high levels of heat transfer that are required to maintain the photovoltaic cells at temperatures below 80° C. place considerable constraints on the materials selection for the components of the modules. As a consequence, preferred materials for different components of the modules and for bonding together different components of the modules are materials that have different thermal expansion. There are two aspects to the issue of materials selection and heat transfer. One aspect is the materials requirements of components of the modules, such as the substrate and the coolant member, to define heat flow paths from the photovoltaic cells to coolant flowing through the coolant chamber. The other aspect is the materials requirements for containing the high hydraulic pressures within the coolant chamber that are required to maintain coolant flow through the coolant chamber at required levels. In particular, the second aspect is concerned with materials selection to achieve sufficient bond strength between the substrate and the coolant member.

Preferably the base includes a coolant inlet and a coolant outlet for supplying coolant to and removing coolant from opposite ends of the chamber, the opposite ends of the chamber forming coolant manifolds.

The above-described coolant inlet, coolant manifolds, coolant outlet, and coolant channels define the coolant flow path of the support structure of the module.

Preferably the ratio of the total width of the channels and the total width of the lands is in the range of 0.5:1 to 1.5:1.

Preferably the ratio of the total width of the channels and the total width of the lands is of the order of 1:1.

Preferably the ratio of the height and the width of each channel is in the range of 1.5:1 to 5:1.

More preferably the ratio of the height and the width of each channel is in the range of 1.5:1 to 2.5:1.

It is preferred particularly the ratio of the height and the width of each channel be of the order of 3:1.

Preferably the receiver includes a frame that supports the modules in an array of the modules.

Preferably the support frame supports the modules so that the photovoltaic cells form an at least substantially continuous surface that is exposed to reflected concentrated solar radiation.

The surface may be flat, curved or stepped in a Fresnel manner.

Preferably the support frame includes a coolant flow path that supplies coolant to the coolant inlets of the modules and removes coolant from the coolant outlets of the modules.

Preferably the coolant is water.

Preferably the water inlet temperature is in the range of 20–30° C.

Preferably the water outlet temperature is in the range of 25–40° C.

Preferably the means for concentrating solar radiation onto the receiver is a dish reflector that includes an array of mirrors for reflecting solar radiation that is incident on the mirrors towards the photovoltaic cells.

Preferably the surface area of the mirrors of the dish reflector that is exposed to solar radiation is substantially greater than the surface area of the photovoltaic cells that is exposed to reflected solar radiation.

According to the present invention there is also provided a photovoltaic cell module for a receiver of a system for generating electrical power from solar radiation, which module includes: a plurality of photovoltaic cells, an electrical connection for transferring the electrical energy output of the photovoltaic cells, and a coolant flow path that is in thermal contact with the photovoltaic cells so that in use coolant flowing through the flow path cools the photovoltaic cells.

Preferred features of the module are as described above.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described further by way of example with reference to the accompanying drawings, of which:

FIG. **1** is a perspective view of a preferred embodiment of a system for generating electrical power from solar radiation;

FIG. **2** is a front view of the receiver of the system shown in FIG. **1** which illustrates the exposed surface area of the photovoltaic cells of the receiver;

FIG. **3** is a partially cut-away perspective view of the receiver with components removed to illustrate more clearly the coolant circuit that forms part of the receiver;

FIG. **4** is an enlarged view of the section of FIG. **3** that is described by a rectangle;

FIG. **5** is an exploded perspective view of a photovoltaic cell module that forms part of the receiver;

FIG. **6** is a side elevation of the assembled photovoltaic cell module of FIG. **5**;

FIG. **7** is a section along the line A—A of FIG. **6**;

FIG. **8** is an enlarged view of the circled region B in FIG. **7**; and

FIG. **9** is an enlarged view of the circled region C in FIG. **7**.

DETAILED DESCRIPTION

The solar radiation-based electric power generating system shown in FIG. **1** includes a parabolic array of mirrors **3** that reflects solar radiation that is incident on the mirrors towards a plurality of photovoltaic cells **5**.

The cells **5** form part of a solar radiation receiver that is generally identified by the numeral **7**.

As is described in more detail hereinafter, the receiver **7** includes an integrated coolant circuit. The surface area of the mirrors **3** that is exposed to solar radiation is substantially greater than the surface area of the photovoltaic cells **5** that is exposed to reflected solar radiation. The photovoltaic cells **5** convert reflected solar radiation into DC electrical energy. The receiver **7** includes an electrical circuit (not shown) for the electrical energy output of the photovoltaic cells.

The mirrors **3** are mounted to a framework **9**. The mirrors and the framework define a dish reflector.

A series of arms **11** extend from the framework **9** to the receiver **7** and locate the receiver as shown in FIG. **1**.

The system further includes:

(a) a support assembly **13** that supports the dish reflector and the receiver in relation to a ground surface and for movement to track the Sun; and

(b) a tracking system (not shown) that moves the dish reflector and the receiver as required to track the Sun.

As is noted above, the receiver **7** includes a coolant circuit. The coolant circuit cools the photovoltaic cells **5** of the receiver **7** with a coolant, preferably water, in order to minimise the operating temperature and to maximise the performance (including operating life) of the photovoltaic cells **5**.

The receiver **7** is purpose-built to include the coolant circuit.

FIGS. **3** and **4** illustrate components of the receiver that are relevant to the coolant circuit. It is noted that a number of other components of the receiver **7**, such as components that make up the electrical circuit of the receiver **7**, are not included in the Figures for clarity.

With reference to FIGS. **3** and **4**, the receiver **7** includes a generally box-like structure that is defined by an assembly of hollow posts **15**.

The receiver **7** also includes a solar flux modifier, generally identified by the numeral **19**, which extends from a lower wall **99** (as viewed in FIG. **3**) of the box-like structure. The solar flux modifier **19** includes four panels **21** that extend from the lower wall **99** and converge toward each other. The solar flux modifier **19** also includes mirrors **91** mounted to the inwardly facing sides of the panels **21**.

The receiver **7** also includes an array of 1536 closely packed rectangular photovoltaic cells **5** which are mounted to 64 square modules **23**. The array of cells **5** can best be seen in FIG. **2**. The term "closely packed" means that the exposed surface area of the photovoltaic cells **5** makes up at least 98% of the total exposed surface area of the array. Each module includes 24 photovoltaic cells **5**. The photovoltaic cells **5** are mounted on each module **23** so that the exposed surface of the cell array is a continuous surface.

The modules **23** are mounted to the lower wall **99** of the box-like structure of the receiver **7** so that the exposed surface of the combined array of photovoltaic cells **5** is a continuous plane.

The modules **23** are mounted to the lower wall **99** so that lateral movement between the modules **23** and the reminder of the receiver **7** is possible. The permitted lateral movement assists in accommodating different thermal expansion of components of the receiver **7**.

As is described in more detail hereinafter, each module **23** includes a coolant flow path. The coolant flow path is an integrated part of each module **23**. The coolant flow path allows coolant to be in thermal contact with the photovoltaic cells **5** and extract heat from the cells **5** so that the cells **5** are maintained at a temperature of no more than 80° C., preferably no more than 60° C., more preferably no more than 40° C.

The coolant flow path of the modules **23** forms part of the coolant circuit.

The coolant circuit also includes the above-described hollow posts **15**.

In addition, the coolant circuit includes a series of parallel coolant channels **17** that form part of the lower wall **99** of the box-like structure. The ends of the channels **17** are connected to the opposed pair of lower horizontal posts **15** respectively shown in FIG. **3**. The lower posts **15** define an upstream header that distributes coolant to the channels **17** and a downstream header that collects coolant from the channels **17**. The modules **23** are mounted to the lower surface of the channels **17** and are in fluid communication with the channels so that coolant flows via the channels **17** into and through the coolant flow paths of the modules **23** and back into the channels **17** and thereby cools the photovoltaic cells **5**.

The coolant circuit also includes a coolant inlet **61** and a coolant outlet **63**. The inlet **61** and the outlet **63** are located in an upper wall of the box-like structure. The inlet **61** is connected to the adjacent upper horizontal post **15** and the outlet **63** is connected to the adjacent upper horizontal post **15** as shown in FIG. **3**.

In use, coolant that is supplied from a source (not shown) flows via the inlet **61** into the upper horizontal post **15** connected to the inlet **61** and then down the vertical posts **15** connected to the upper horizontal post **15**. The coolant then flows into the upstream lower header **15** and, as is described above, along the channels **17** and the coolant flow paths of the modules **23** and into the downstream lower header **15**. The coolant then flows upwardly through the vertical posts

15 that are connected to the downstream lower header 15 and into the upper horizontal post 15. The coolant is then discharged from the receiver 7 via the outlet 63. The above-described coolant flow is illustrated by the arrows in FIGS. 3 and 4.

FIGS. 5 to 9 illustrate the basic construction of each module 23.

As is indicated above, each module 23 includes an array of 24 closely packed photovoltaic cells 5.

Each module 23 includes a substrate, generally identified by the numeral 27, on which the cells 5 are mounted. The substrate includes a central layer 29 of a ceramic material and outer metallised layers 31, 33 on opposite faces of the ceramic material layer 29.

Each module 23 also includes a glass cover 37 that is mounted on the exposed surface of the array of photovoltaic cells 5. The glass cover 37 may be formed to optimise transmission of useful wavelengths of solar radiation and minimise transmission of un-wanted wavelengths of solar radiation.

Each module 23 also includes a coolant member 35 that is mounted to the surface of the substrate 27 that is opposite to the array of photovoltaic cells 5.

The size of the coolant member 35 and the material from which it is made are selected so that the coolant member 35 acts as a heat sink. A preferred material is copper.

Furthermore, the coolant member 35 is formed to define a series of flowpaths for coolant for cooling the photovoltaic cells 5.

Each module 23 also includes electrical connections generally identified by the numeral 81 that form part of the electrical circuit of the receiver 7 and electrically connect the photovoltaic cells 5 into the electrical circuit. The electrical connections 81 are positioned to extend from the outer metallised layer 31 and through the substrate 27 and the coolant member 35. The electrical connections 81 are housed within sleeves 83 that electrically isolate the electrical connections.

The coolant member 35 includes a base 39 and a side wall 41 that extends from the base 39. The upper edge 43 of the side wall 41 is physically bonded to the substrate 27. It can be appreciated from FIG. 5 that the base 35 and the substrate 27 define an enclosed chamber. The base 39 includes a coolant inlet 45 (FIG. 4) and a coolant outlet 46 (FIG. 4). The coolant inlet 45 and the coolant outlet 46 are located in diagonally opposed corner regions of the base 39.

The coolant member 35 further includes a series of parallel lands 47 (FIG. 9) which extend upwardly from the base 39 and occupy a substantial part of the chamber. The upper surfaces of the lands 47 are physically bonded to the substrate 27. The lands 47 do not extend to the ends of the chamber and these opposed end regions of the chamber define a coolant inlet manifold 49 and a coolant outlet manifold 51. The lands 47 extend side by side substantially across the width of the chamber. The gaps between adjacent lands 47 define coolant flow channels 53.

It is evident from the above that the coolant inlet 45, the coolant manifold 49, the flow channels 53, the coolant outlet manifold 49, and the coolant outlet 46 define the coolant flow path of each module 23.

The applicant has found that selecting:

(i) the widths of the lands 47 and the channels 53 so that the ratio of the widths is of the order of 1:1; and

(ii) the height and width of the channels 53 so that the ratio of the height and the width is of the order of 2:1;

makes it possible to achieve sufficient heat transfer from the photovoltaic cells 5 to the coolant to maintain the photovoltaic cells 5 at a temperature of no more than 60° C. where, otherwise, an uncooled module would be at temperatures well in excess of 1000° C. in view of high intensities of solar radiation incident on the photovoltaic cells 5.

As is indicated above, the construction of the coolant member 35 makes it possible to achieve the high levels of heat transfer that are required to maintain the photovoltaic cells 5 at temperatures of no more than 60° C. and to accommodate substantially different thermal expansion of the coolant member 35 and the substrate 27 that otherwise would cause structural failure of the modules 23. Specifically, there is heat transfer from the substrate 27 to the coolant via direct contact of coolant with the substrate 27 and via the side wall 41 and the lands 47. The construction of the lands 47 as the means for defining the flow channels 53 substantially increases the heat transfer contact surface area with coolant. Specifically, the lands 47 provide an opportunity for heat transfer to the coolant via the sides and base of the channels 53. In addition, the lands 47 define a series of spaced "fingers" and this arrangement makes it possible to accommodate relative lateral movement of the substrate 27 and the coolant member 35 as a consequence of different thermal expansion of the materials from which these components are constructed and the materials that bond together these components.

FIG. 4 illustrates the position of one module 23 on the lower wall of the receiver 7. With reference to the Figure, the coolant inlet 45 opens into one coolant channel 17 of the coolant circuit and the diagonally-opposed coolant outlet 46 opens into an adjacent coolant channel 17 of the coolant circuit.

In use, as indicated by the arrows in FIGS. 4 and 5, coolant flows from one supply channel 17 into the inlet manifold 49 via the coolant inlet 45 and then flows from the coolant manifold 49 into and along the length of the channels 53 to the outlet manifold 51. Thereafter, coolant flows from the chamber via the coolant outlet 46 into the adjacent channel 17.

Many modifications may be made to the preferred embodiment described above without departing from the spirit and scope of the present invention.

By way of example, whilst the preferred embodiment includes 1536 photovoltaic cells 5 mounted to 64 modules 23 with 24 cells per module, the present invention is not so limited and extends to any suitable number and size of photovoltaic cells and modules.

By way of further example, whilst the photovoltaic cells are mounted so that the exposed surface of the cell array is a flat surface, the present invention is not so limited and extends to any suitable shaped surface, such as curved or stepped surfaces.

By way of further example, whilst the preferred embodiment includes the receiver coolant circuit that forms part of the support frame of the receiver, the present invention is not so limited and extends to arrangements in which the coolant circuit is not part of the structural frame of the receiver.

By way of further example, whilst the preferred embodiment includes a series of parallel elongate lands 47 which extend between the ends of the coolant chamber, the present invention is not so limited and it is not essential that the lands be parallel and it is not essential that the lands be elongate. Specifically, it is within the scope of the present invention that there be gaps in the lands 47. The gaps in the lands may be required in certain circumstances to improve lateral flexibility of the coolant member **35** relative to the substrate **27**.

By way of further example, whilst the preferred embodiment includes a dish reflector in the form of an array of parabolic array of mirrors **3**, the present invention is not so limited and extends to any suitable means of concentrating solar radiation onto a receiver.

By way of further example, whilst the preferred embodiment of the receiver is constructed from extruded components, the present invention is not so limited and the receiver may be made by any suitable means.

The invention claimed is:

1. A system for generating electrical power from solar radiation which includes:

(a) a receiver that includes (i) a plurality of modules, each module including a plurality of photovoltaic cells for converting solar energy into electrical energy, (ii) an electrical circuit for transferring the electrical energy output of the photovoltaic cells, and (iii) a frame that supports the modules in an array of modules so that the photovoltaic cells form an at least substantially continuous surface that is exposed to solar radiation; and

(b) a means for concentrating solar radiation onto the receiver; and

the system being characterised in that each module includes an electrical connection that forms part of the receiver electrical circuit, each module includes a support structure that supports the photovoltaic cells, the receiver includes a coolant circuit for cooling the photovoltaic cells with a coolant, the coolant circuit includes a coolant flow path in each module that is in thermal contact with the photovoltaic cells so that in use coolant flowing through the flow path extracts heat from the photovoltaic cells and thereby cools the cells, and the support structure in each module defines the coolant flow path for the module.

2. The system defined in claim **1** wherein the plurality of modules is arranged in a two-dimensional array of modules.

3. The system defined in claim **1** wherein the support structures are arranged such that there is parallel flow of coolant through the flow paths in the support structures.

4. The system defined in claim **1** wherein the support structure includes:

(a) a coolant member that at least partially defines the flow path, the coolant member being formed from a thermally conductive material; and

(b) a substrate interposed between the coolant member and the photovoltaic cells, the substrate including a thermally conductive layer formed from a thermally conductive material that is an electrical insulator.

5. The system defined in claim **4** wherein the coolant member acts as a heat sink.

6. The system defined in claim **4** wherein the coolant member of each support structure comprises a plurality of flow channels defining part of the flow path.

7. The system defined in claim **4** wherein the thermally conductive layer of the substrate is formed from a ceramic material.

8. The system defined in claim **4** wherein the substrate includes a metallised layer interposed between the photovoltaic cells and the thermally conductive layer.

9. The system defined in claim **4** wherein the substrate includes a metallised layer interposed between the thermally conductive layer and the coolant member.

10. The system defined in claim **4** wherein the coolant member includes a base, a wall that extends upwardly from the base and contacts the substrate whereby the base, the side wall and the substrate define an enclosed coolant chamber that forms part of the coolant flow path.

11. The system defined in claim **10** wherein the coolant member includes a series of spaced-apart lands that extend from the base and contact the substrate in a central part of the chamber and define therebetween channels for coolant flow from near one end of the chamber to near an opposite end of the chamber.

12. The system defined in claim **11** wherein the spaced apart lands are parallel so that the channels are parallel.

13. The system defined in claim **11** wherein the ratio of the total width of the channels and the total width of the lands is in the range of 0.5:1 to 1.5:1.

14. The system defined in claim **13** wherein the ratio of the total width of the channels and the total width of the lands is of the order of 1:1.

15. The system defined in claim **11** wherein the ratio of the height and the width of each channel is in the range of 1.5:1 to 5:1.

16. The system defined in claim **15** wherein the ratio of the height and the width of each channel is in the range of 1.5:1 to 2.5:1.

17. The system defined in claim **10** wherein the base includes a coolant inlet and a coolant outlet for supplying coolant to and removing coolant from opposite ends of the chamber, the opposite ends of the chamber forming coolant manifolds.

18. The system defined in claim **17** wherein the coolant inlet, coolant manifolds, coolant outlet, and coolant channels define the coolant flow path of the support structure of the module.

19. The system defined in claim **1** wherein the frame includes a coolant flow path that supplies coolant to the coolant inlets of the modules and removes coolant from the coolant outlets of the modules.

20. The system defined in claim **1** wherein the means for concentrating solar radiation onto the receiver is a dish reflector that includes an array of mirrors for reflecting solar radiation that is incident on the mirrors towards the photovoltaic cells.

21. The system defined in claim **20** wherein the surface area of the mirrors of the dish reflector that is exposed to solar radiation is substantially greater than the surface area of the photovoltaic cells that is exposed to reflected solar radiation.

22. A photovoltaic cell module for a receiver of a system for generating electrical power from solar radiation, which module includes: a plurality of photovoltaic cells, an electrical connection for transferring the electrical energy output of the photovoltaic cells, a coolant flow path that is in thermal contact with the photovoltaic cells so that in use coolant flowing through the flow path cools the photovoltaic cells, and a structure that supports the photovoltaic cells and defines the coolant flow path for extracting heat from the photovoltaic cells, the support structure including a coolant member formed from a thermally conductive material that at least partially defines the flow path, the support structure further including a substrate interposed between the coolant member and the photovoltaic cells, the substrate including a thermally conductive layer formed from a thermally conductive material that is an electrical insulator, and the coolant member including a base, a wall that extends upwardly from the base and contacts the substrate whereby the base, the side wall and the substrate define an enclosed coolant chamber that forms part of the coolant flow path.

23. The system defined in claim **22** wherein the coolant member acts as a heat sink.

24. The system defined in claim **22** wherein the coolant member comprises a plurality of flow channels.

25. The system defined in claim **22** wherein the thermally conductive layer of the substrate is formed from a ceramic material.

26. The system defined in claim **22** wherein the substrate includes a metallised layer interposed between the photovoltaic cells and the thermally conductive layer.

27. The system defined in claim **22** wherein the substrate includes a metallised layer interposed between the thermally conductive layer and the coolant member.

28. The system defined in claim **22** wherein the coolant member includes a series of spaced-apart lands that extend from the base and contact the substrate in a central part of the chamber and define therebetween channels for coolant flow from near one end of the chamber to near an opposite end of the chamber.

29. The system defined in claim **28** wherein the spaced apart lands are parallel so that the channels are parallel.

30. The system defined in claim **22** wherein the base includes a coolant inlet and a coolant outlet for supplying coolant to and removing coolant from opposite ends of the chamber, the opposite ends of the chamber forming coolant manifolds.

31. A system for generating electrical power from solar radiation which includes:

(a) a receiver that includes a plurality of photovoltaic cells for converting solar energy into electrical energy and an electrical circuit for transferring the electrical energy output of the photovoltaic cells; and

(b) a means for concentrating solar radiation onto the receiver; and the system being characterised in that the receiver includes a plurality of photovoltaic cell modules, each module includes a plurality of photovoltaic cells, each module includes an electrical connection that forms part of the receiver electrical circuit, each module includes a support structure that supports the photovoltaic cells, the receiver includes a coolant circuit for cooling the photovoltaic cells with a coolant, and the coolant circuit includes a coolant flow path in each module that is in thermal contact with the photovoltaic cells so that in use coolant flowing through the flow path extracts heat from the photovoltaic cells and thereby cools the cells, each support structure defines the coolant flow path in a corresponding module for extracting heat from the photovoltaic cells and includes a coolant member formed from a thermally conductive material that at least partially defines the flow path, and each support structure further includes a substrate interposed between the coolant member and the photovoltaic cells, the substrate including a layer formed from a thermally conductive material that is an electrical insulator, and each coolant member includes a base, a wall that extends upwardly from the base and contacts the substrate whereby the base, the side wall and the substrate define an enclosed coolant chamber that forms part of the coolant flow path.

32. The system defined in claim **31** wherein the coolant member includes a series of spaced-apart lands that extend from the base and contact the substrate in a central part of the chamber and define therebetween channels for coolant flow from near one end of the chamber to near an opposite end of the chamber.

33. The system defined in claim **32** wherein the spaced apart lands are parallel so that the channels are parallel.

34. The system defined in claim **32** wherein the ratio of the total width of the channels and the total width of the lands is in the range of 0.5:1 to 1.5:1.

35. The system defined in claim **34** wherein the ratio of the total width of the channels and the total width of the lands is of the order of 1:1.

36. The system defined in claim **32** wherein the ratio of the height and the width of each channel is in the range of 1.5:1 to 5:1.

37. The system defined in claim **36** wherein the ratio of the height and the width of each channel is in the range of 1.5:1 to 2.5:1.

38. The system defined in claim **31** wherein the base includes a coolant inlet and a coolant outlet for supplying coolant to and removing coolant from opposite ends of the chamber, the opposite ends of the chamber forming coolant manifolds.

39. The system defined in claim **38** wherein the coolant inlet, coolant manifolds, coolant outlet, and coolant channels define the coolant flow path of the support structure of the module.

* * * * *

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I, Fatima Beattie, the Commissioner of Patents, grant a Standard Patent with the following particulars:

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Solar Systems Pty Ltd
6 Luton Lane, Hawthorn, VIC, 3122, Australia

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(71) Applicant(s)
Solar Systems Pty Ltd

(72) Inventor(s)
Lasich, John Beavis

(74) Agent / Attorney
Griffith Hack, 509 St Kilda Road, Melbourne, VIC, 3004

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(71) Applicant *(for all designated States except US)*: **SOLAR SYSTEMS PTY LTD** [AU/AU]; 6 Luton Lane, Hawthorn, Victoria 3122 (AU).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **LASICH, John, Beavis** [AU/AU]; 11 Pretoria Street, Deepdene, Victoria 3103 (AU).

(74) Agent: **GRIFFITH HACK**; 509 St Kilda Road, Melbourne, Victoria 3004 (AU).

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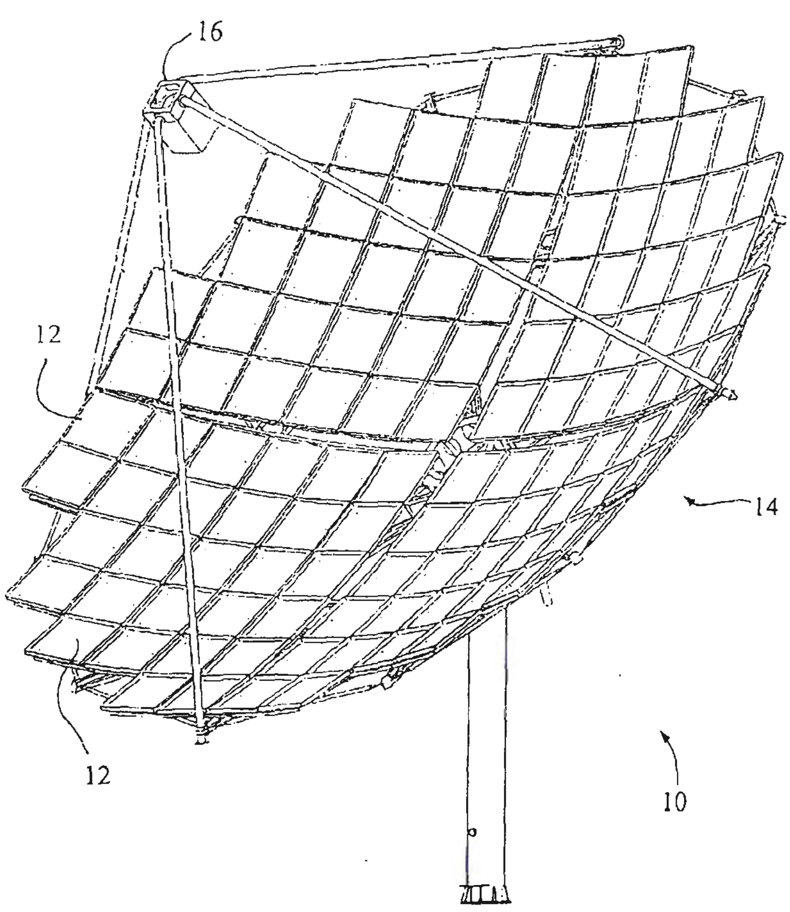
(54) Title: SOLAR TRACKING SYSTEM



(57) Abstract: The invention provides a solar tracking system for controlling the alignment of an instrument with respect to the sun, the instrument having a solar radiation receiver and a solar radiation collector for collecting solar radiation and directing the radiation towards the receiver, the system having: at least first and second detectors locatable so as to move with the receiver and receive radiation from the collector, for generating respective first and second output signals according to their respective exposure to solar radiation from the collector; a comparison means for comparing the first and second outputs and producing a comparison signal indicative thereof; and control means for controlling the alignment of the instrument according to the comparison signal.

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SOLAR TRACKING SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

This is the national phase of International Application No. PCT/AU02/00404, filed 28 March 2002, and is associated with Australian Patent Application No. PR4039, filed 28 March 2001, the content of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to a system and method for tracking the sun, of particular but by no means exclusive application in telescopes and solar power collectors.

BACKGROUND OF THE INVENTION

Existing techniques for tracking the sun rely typically on one or more of three methods. The diurnal motion of the sun is well understood, and consequently a telescope, for example, can be mounted on an accurately aligned alt-azimuth or equatorial mount. The axial drives of that mount are then computer controlled to maintain the telescope in an orientation that will point the objective lens or mirror of the telescope at the sun's calculated position.

This approach, however, requires the highly accurate initial alignment of the mount. This may be practical in a fixed instrument such as research telescope, where the accurate alignment of the mount is one facet of an overall extensive and precise installation procedure conducted by expert scientists and engineers, of lengthy duration and considerable expense. Such installation time and expense may not be acceptable in other applications, such as the installation of solar power collectors on a mass scale.

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A less accurate and cheaper alternative is to control the axial drives on the assumption that the sun follows the ecliptic (or even celestial equator) in an entirely regular manner, thus ignoring the effects of the equation of time and - where the sun is assumed to follow the celestial equator - the effects of the earth's axial tilt.

Another existing approach is so-called shadow bar sun sensing, in which a pair of sensors are mounted on a solar radiation collector (such as a dish or plane mirror) between a shadow bar. The shadow bar casts a shadow on one of the sensors if the collector is not pointing directly at the sun. The collector's attitude can then be adjusted on the basis of the outputs of these sensors until those outputs are equal.

These existing approaches, however, make no allowance for the subsequent effects of imperfect manufacturing tolerances on the orientation of the radiation receiver (to which the collector directs collected radiation) relative to the collector itself. The effect of such imperfections will also vary with the changing position of the sun and orientation of the collector, even if the receiver is fixed with respect to the collector. In fact the receiver may also shift slightly relative to the collector, owing to sagging in the receiver supports (which would commonly be used to hold the receiver at the focus of the collector), or to variations in the overall structure due to temperature fluctuations and the like.

For many applications these shortcomings may be acceptable, or at least tolerable, especially in systems where maximizing the collection of solar radiation is less sensitive to tracking precision. This may be the case in systems that do not concentrate the solar flux by means of, for example, a spherical or parabolic mirror. If a plane mirror is used, errors in tracking precision of even 5° may not excessively reduce collection efficiency. Indeed, many solar hot water heaters (typically with flat collection panels) perform no solar tracking whatsoever, so existing approaches - which provide at least some tracking - will clearly be of use in some applications. However, where the solar flux is concentrated (possibly by a factor of as much as three or more), a 5° tracking error may produce unacceptably high losses in collection efficiency.

SUMMARY OF THE INVENTION

The present invention provides, therefore, a solar tracking system for controlling the alignment of a solar power generator with respect to the sun, said generator having a solar radiation receiver comprising an array of power generating photovoltaic cells for converting solar radiation into electric current and a solar radiation collector for collecting solar radiation and directing said radiation towards said receiver, said system comprising:

at least first and second detectors for receiving radiation from said collector and generating respective first and second output signals according to their respective exposure to solar radiation from said collector;

a comparison means for comparing said first and second output signals and producing a comparison signal indicative thereof; and

control means for controlling said alignment according to said comparison signal;

wherein each of said detectors comprises one or more of said photovoltaic cells of said receiver.

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Thus, the detectors are exposed to solar radiation directed to them by the collector; it will be understood, however, that the collector could optionally include auxiliary mirrors provided to direct solar radiation towards the detectors (rather than the receiver).

In one embodiment, the system includes four of said detectors for generating respective first, second, third and fourth output signals according to their respective exposure to solar radiation from said collector.

In another embodiment, the collector includes auxiliary mirrors provided to direct solar radiation towards said detectors.

Preferably said receiver further includes at least first and second thermal detectors with thermal output signals indicative of the heating of said respective thermal detectors when exposed to said solar radiation, wherein said thermal detectors are at respective locations at the receiver periphery to be exposed to a portion of said solar radiation from said collector during normal operation of said generator and for providing a measure of the alignment of said solar radiation relative to said receiver, wherein said control means is arranged to receive said thermal output signals, to determine a temperature difference therefrom and to control said alignment to impose a maximum acceptable temperature difference, and to provide tracking on the basis of said thermal output signals then in the event of partial or total failure of the tracking control provided by said photovoltaic detectors.

Thus, a coarse level of tracking may be provided by sensing sun at the collector, with a finer level of tracking provided by means of the detectors associated with the receiver. Although separate, further comparison and control means may be employed for this coarser tracking, in one embodiment the further comparison means and the further control means are provided by the comparison means and the control means respectively. Also, the first and second sensors may be provided in the form of shadow bar sun sensors.

The system could employ the signals from photodetectors or temperature sensors (or from both), both of which will generally be sensitive to solar light flux. Consequently, the generator - or its mount - need not be aligned with the great precision required by other approaches, as the system aligns the generator according to the actual position of the sun, thereby correcting for misalignment in the mounting of the generator or receiver.

Preferably said comparison means is operable to control said alignment to maximize the sum of said first and second output signals.

Preferably said system includes at least one shadow means for casting a shadow onto said respective first and second detectors, wherein in use the area of said shadow on each detector depends on the alignment of said generator so that said first and second outputs are more highly sensitive to misalignment of said detectors with respect to said solar radiation.

Thus, if the detectors are located, say, either side of a shadow means, or each is provided with a plurality of side walls located to cast a shadow on that detector if misalignment occurs, at least one of the detector's outputs

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will drop with angle of misalignment θ much faster than by merely cos θ (in the example of a plane detector approximately perpendicular to the direction of the sun), thereby making the system more sensitive to misalignment.

Preferably said system includes a solar position predictor, for predicting the position of the sun on the basis of either a look-up table of solar positions or a solar position algorithm, and said control means is operable to employ said predicted position in controlling said alignment of said generator.

Thus, the coarse position of the generator with respect to the sun can be determined on the basis of, for example, a suitable almanac, equation(s) for the evolving altitude and azimuth (or right ascension and declination) of the sun, or the like.

Preferably said system includes four detectors, each of which comprises a grid of detector elements.

In one embodiment, said system is operable to control said alignment to maximize said electric current of said instrument.

For example, a first group of said photovoltaic cells may constitute said first detector, while a second group of said photovoltaic cells may constitute said second detector.

The present invention also provides a method of solar tracking for controlling the alignment of a solar power generator with respect to the sun, said generator having a solar radiation receiver comprising an array of power

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generating photovoltaic cells for converting solar radiation into electric current and a solar radiation collector for collecting solar radiation and directing said radiation towards said receiver, said method comprising:

locating at least first and second detectors for receiving radiation from said collector, the first and second detectors generating respective first and second output signals according to their respective exposure to solar radiation from said collector;

comparing said first and second output signals and producing a comparison signal indicative thereof; and

controlling said alignment according to said comparison;

wherein each of said detectors comprises one or more of said photovoltaic cells.

Preferably said method includes predicting the position of the sun on the basis of either a look-up table of solar positions or a solar position algorithm, and employing said predicted position in controlling said alignment of said generator.

Preferably said method includes employing four detectors, each of which comprises a grid of detector elements.

Preferably said method includes controlling said alignment to maximize an output of said generator.

The present invention still further provides a solar tracking system for controlling the alignment of a solar radiation receiver with respect to the sun, comprising:

at least first and second detectors forming a part of said receiver and receiving a portion of said solar radiation, for generating respective first and second output signals according to their respective exposure to solar radiation;

a comparison means for comparing said first and second outputs and producing a comparison signal indicative thereof; and

control means for controlling said alignment of said receiver according to said comparison signal;

whereby said detectors can function both to receive solar radiation as a part of said receiver and in controlling said alignment of said receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be more clearly ascertained, an embodiment will now be described, by way of example, with reference to the accompanying drawing, in which:

Figure 1 is a view of a solar electric power generator of the type to be controlled by a solar tracking control system according to one embodiment of the present invention;

Figure 2 is a view of the array of photovoltaic cells and flux modifier plates of the solar electric power generator of figure 1;

Figure 3 is a schematic representation of the array of photovoltaic cells of figure 2;

Figures 4A to 4D are views of respectively four subsets of photovoltaic cells of the array of figure 3; and

Figures 5A and 5B are schematic diagrams of the elevation axis controller and azimuth axis controller respectively of the tracking system of figure 1.

DETAILED DESCRIPTION OF THE INVENTION

A solar electric power generator of a type for controlling by means of a solar tracking control system according to an embodiment of the present invention is illustrated schematically at 10 in figure 1. The generator 10 includes an array of focussing mirrors 12 forming a dish 14, and a receiver 16 substantially at the focus of the dish 14. The receiver 16 includes an array of photovoltaic cells (see figure 2). The solar tracking control system is principally intended to maximize the power output of the generator 10. It should be noted, as will be understood by those in the art, that the optimal alignment in such an application may not be directly at the sun. Asymmetries in or misalignment of the dish 14 and receiver 16 of the solar electric power generator may mean that the greatest power output is achieved with an alignment that, by conventional measures, is not directly - or apparently directly - at the sun.

Referring to figure 2, the receiver 16 comprises a square array 18 of photovoltaic cells 20. In addition, the receiver 16 is equipped with four reflective flux modifier plates 22a,b,c,d surrounding the array 18, to reflect some of the solar flux (that would otherwise miss the array 18) onto the photovoltaic cells 20.

The four flux modifier plates 22a,b,c,d are cooled by means of coolant tubes 24.

The tracking system uses a combination of open loop and closed loop control to position the dish 14 and therefore receiver 16 in a manner that will achieve maximum electrical power output and safe operating conditions. The system's axial controllers account for mechanical and optical variations that arise out of such manufacturing non-conformity and/or operational effects.

The axial controllers of the system (discussed in greater detail below) continuously compute the position of the sun (both elevation and azimuth) in space. The resultant values of solar elevation and azimuth are translated into revolutions of the mechanical movement appropriate for the positioning system of the dish 14 and receiver 16, thereby aligning the dish 14 approximately to the sun (typically to within about ±1°), but without accounting for variations in the mechanical structure or optical performance of the dish.

To optimize the performance, in terms of power output, of receiver 16, any one of three input sources is integrated to achieve closed loop control. These sources are as follows:

1) Sun Sensor: The sun sensor comprises a pair of optical sensors (not shown) located on either side of a shadow plate. This unit is attached to the array 14 of mirrors 12 such that when the dish 14 is correctly aimed at the sun, each sensor is exposed to the same intensity of sun-light. The outputs of the light intensity sensors are compared and integrated. The feedback loop then attempts to equalize the intensity of the shadows and, as a result, align the dish 14 and therefore receiver 16 to the sun. This mode takes no account of the electrical power generated by the receiver 16, but may be used to account for gross mechanical errors prior to one of the more optimising tracking modes from becoming active.

2) Photovoltaic Array. If the photovoltaic array 18 is receiving useable radiation, the power generated in the top half of the array 18 is compared to the power generated in the bottom half of the array 18 (in the case of the elevation axis). Figure 3 is a schematic representation of the photovoltaic cell array 18, comprising sixteen modules 26 in a 4×4 grid, each of which itself comprises an array of cells. Referring to figures 4A and 4B, the power generated in an upper (in this view) set 28a of modules is thus compared to the power generated

in a bottom set 28b of modules. The feedback loop attempts to equalize the powers generated and therefore accommodate both physical variations in the dish structure and optical variations resulting in an uneven flux distribution. In practice this mode will maximise the electrical output from the dish.

Referring to figures 4C and 4D, essentially the same process is replicated in the azimuth axis, by comparing the power generated in a left (in this view) or - in the southern hemisphere installation - east set 28c of modules with the power generated in a right (or west) set 28d of modules; the feedback loop then attempts to equalize these generated powers.

3) Thermal Sensors. In the event that the temperature rise on any of the cooled flux modifier plates 22a,b,c,d surrounding the photovoltaic cell array 18 is excessive, the difference in temperature of the top and bottom flux modifier plates 22a and 22b is integrated (in the case of the elevation axis). The feedback loop attempts to equalize these temperatures thereby lowering the thermal stress placed on these flux modifiers. Similarly, the difference in temperature of the left and right flux modifier plates 22c and 22d is integrated in the case of the azimuth axis.

The control system automatically chooses the appropriate mode depending on the need for optimisation of power and safety, that is, the right temperature conditions, solar radiation level and photovoltaic (PV) module power output.

Figures 5A and 5B are schematic diagrams of the controllers 30 and 32 respectively of the tracking system, for controlling the dish 14. Figure 5A shows the elevation axis controller 30, figure 5B the azimuth axis controller 32. Except for the calculation of solar position, both axes use identical approaches.

In elevation axis controller 30, the sun's elevation 34 is calculated using a computer program running on a personal computer (PC) or programmable logic controller (PLC). The solar position information is converted to a required number of turns of the elevation drive of the dish 14 taking into account the geometry of the dish structure.

Disregarding the integrator for the present, this position command is applied to a feedback loop that comprises an elevation motor controller 36, an elevation drive motor 38, an elevation feedback encoder 40 and first elevation adder 42. The feedback loop acts to ensure that the difference in elevation between the predicted sun position (and therefore predicted dish position) and actual dish/receiver position 44 relative to the direction of the sun is zero. Thus, the elevation axis to the dish will follow the sun's position as predicted by the PC.

The elevation integrator 46 serves to make small adjustments to calculated solar positions to allow for the mechanical tolerance of the dish structure and any asymmetric behaviour of the optics of the dish 14 or of the receiver 16.

The elevation integrator source is selected by means of an elevation integrator source selector 48. When the source is selected to be "thermal" 50a, the difference between the top and the bottom flux modifier plate temperatures 52 and 54 respectively is integrated 56 over time and applied as an offset to the predicted sun position 34 by second elevation adder 58. This causes the dish to move until the integrated value approaches a 'null', that is, the flux modifier plate temperatures are equalized.

When the integrator source is selected to be "Photovoltaic" (PV) 50b, the sum 60 of the receiver's voltage due to the top half photovoltaic cell array (28a in figure 4A) is compared to the sum 62 of the receiver's voltage due to the bottom half of the array (28b in figure 4B). The resultant voltage is integrated 64, and the dish's moved in elevation until the receiver's array generates a symmetric voltage. This implies that the power generated in the top half of the receiver 16 is the same as the power generated in the bottom half of the receiver 16. This balance gives the maximum power output.

The sun sensor consists of two light intensity sensors placed on either side of a shadow means in the form of a shadow plate. The shadow plate is aligned to the elevation axis of the dish. When the integrator source is selected to be "sun sensor" 50c, the difference between the top and bottom light intensity outputs 66 and 68 respectively of these sensors is integrated 70. This causes the dish to align itself to the sun.

Elevation integrator source selector 48 also has an off position 50d.

In azimuth axis controller 32, the sun's azimuth 72 is calculated by the same computer program used to calculate elevation 34. The result is converted to the required number of turns of the azimuth drive of the dish 14 taking into account the geometry of the dish structure.

The position command is applied to a feedback loop that comprises an azimuth motor controller 74, an azimuth drive motor 76, an azimuth feedback encoder 78 and first azimuth adder 80. The feedback loop acts to ensure that the difference in azimuth between the predicted sun position (and therefore predicted dish position) and actual dish/receiver position 82 relative to the direction of the sun is zero. Thus, the azimuth axis to the dish will follow the sun's position as predicted by the PC.

The azimuth integrator 84 serves to make small adjustments to calculated solar positions to allow for the mechanical tolerance of the dish structure and any asymmetric behaviour of the optics of the dish 14 or of the receiver 16.

The azimuth integrator source is selected by means of an azimuth integrator source selector 86. (In practice, azimuth integrator source selector 86 and elevation integrator source selector 48 may be combined into a single source selector.) When the source is selected to be "thermal" 88a, the difference between the east and the west flux modifier plate temperatures 90 and 92 respectively is integrated 94 over time and applied as an offset to the predicted sun azimuth 72 by second azimuth adder 96. This causes the dish to move until the integrated value approaches a 'null', that is, the east and west flux modifier plate temperatures are equalized.

When the integrator source is selected to be "Photovoltaic" (PV) 88b, the sum 98 of the receiver's voltage due to the east half of the photovoltaic cell array (28c in figure 4C) is compared to the sum 100 of the receiver's voltage due to the west half of the array (28d in figure 4D). The resultant voltage is integrated 102, and the dish's moved in azimuth until the receiver's array generates a symmetric voltage. This implies that the power generated in the east half of the receiver 16 is the same as the power generated in the west half of the receiver 16. This balance gives the maximum power output.

The azimuth sun sensor consists of two light intensity sensors placed on either side of a shadow means in the form of a shadow plate. The shadow plate is aligned to the azimuth axis of the dish. When the integrator source is selected to be "sun sensor" 88c, the difference between the east and west light intensity outputs 104 and 106 respectively of these sensors is integrated 108. This causes the dish to align itself to the sun.

Azimuth integrator source selector 86 also has an "off" position 88d.

Referring to figures 5A and 5B, the selection of integrator source is based on the following criteria. If the temperature on any of the flux modifier plates 22a,b,c,d exceeds a prescribed limit (typically 60° C), or there is low electrical power being generated (below a preset threshold limit) whilst the flux modifier plates are, say, 5° C higher than the coolant temperature, thermal mode is selected and the control algorithm instructs the dish to move the dish based on the flux modifier plate temperatures. As mentioned above, the selection of the mode and the switching thereto is performed automatically by the control system, which chooses the appropriate mode depending on the circumstances.

If the temperature on any of the flux modifier plates 22a,b,c,d does not exceed the prescribed limit and the receiver 16 is generating electrical power above a preset limit, PV mode is selected and the control algorithm instructs the dish to move the dish 14 based on the receiver PV module electrical output.

If neither of the above conditions exists but a sufficient signal is available from the sun sensor, the sun sensor mode is selected. This will align the dish/receiver to the sun, but will not account for any asymmetry effecting the output of the receiver 16.

If there is low electrical power being generated (below a preset limit) the temperature on all of the flux modifier plates 22a,b,c,d is less than, say, 5° C above the coolant temperature, and there is insufficient light intensity for the sun sensor to work, the integrator source will be zero. Therefore, the integrator will maintain its previous value from the PC/PLC and the dish is moved according to the change in predicted values.

Modifications within the spirit and scope of the invention may readily be effected by persons skilled in the art. It is to be understood, therefore, that this invention is not limited to the particular embodiments described by way of example hereinabove.

For the purpose of this specification the words "comprising", "comprise" or "comprises" are understood to mean the inclusion of a feature but not necessarily exclusion of any other feature.

It is to be understood that, if any prior art is referred to herein, such reference does not constitute an admission that that prior art forms a part of the common general knowledge in the art, in Australia or in any other country.

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THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A solar tracking system for controlling the alignment of a solar power generator with respect to the sun, said generator having a solar radiation receiver comprising an array of power generating photovoltaic cells for converting solar radiation into electric current and a solar radiation collector for collecting solar radiation and directing said radiation towards said receiver, said system comprising:

at least first and second detectors for receiving radiation from said collector and generating respective first and second output signals according to their respective exposure to solar radiation from said collector;

a comparison means for comparing said first and second output signals and producing a comparison signal indicative thereof; and

control means for controlling said alignment according to said comparison signal;

wherein each of said detectors comprises one or more of said photovoltaic cells of said receiver.

2. A system as claimed in claim 1, including four of said detectors for generating respective first, second, third and fourth output signals according to their respective exposure to solar radiation from said collector.

3. A system as claimed in either claim 1 or 2, wherein said collector includes auxiliary mirrors provided to direct solar radiation towards said detectors.

4. A system as claimed in claim 1, wherein said receiver further includes at least first and second thermal detectors with thermal output signals indicative of the heating of said respective thermal detectors when exposed to said solar radiation, wherein said thermal detectors are

at respective locations at the receiver periphery to be exposed to a portion of said solar radiation from said collector during normal operation of said generator and for providing a measure of the alignment of said solar radiation relative to said receiver, wherein said control means is arranged to receive said thermal output signals, to determine a temperature difference therefrom and to control said alignment to impose a maximum acceptable temperature difference, and to provide tracking on the basis of said thermal output signals then in the event of partial or total failure of the tracking control provided by said photovoltaic detectors.

5. A system as claimed in any one of the preceding claims, wherein said comparison means is operable to control said alignment to maximize the sum of said output signals.

6. A system as claimed in any one of the preceding claims, including at least one shadow means for casting a shadow onto said respective detectors, wherein in use the area of said shadow on each detector depends on the alignment of said instrument so that said output signals are more highly sensitive to misalignment of said detectors with respect to said solar radiation.

7. A system as claimed in any one of the preceding claims, including a solar position predictor, for predicting the position of the sun on the basis of either a look-up table of solar positions or a solar position algorithm, and said control means is operable to employ said predicted position in controlling said alignment of said generator.

8. A system as claimed in any one of the preceding claims, including four detectors, each of which comprises a grid of photovoltaic cells of said array.

9. A system as claimed in any one of the preceding claims, wherein said system is operable to control said alignment to maximize said electric current.

10. A method of solar tracking for controlling the alignment of a solar power generator with respect to the sun, said generator having a solar radiation receiver comprising an array of power generating photovoltaic cells for converting solar radiation into electric current and a solar radiation collector for collecting solar radiation and directing said radiation towards said receiver, said method comprising:

locating at least first and second detectors for receiving radiation from said collector, the first and second detectors generating respective first and second output signals according to their respective exposure to solar radiation from said collector;

comparing said first and second output signals and producing a comparison signal indicative thereof; and

controlling said alignment according to said comparison;

wherein each of said detectors comprises one or more of said photovoltaic cells.

11. A method as claimed in claim 10, including predicting the position of the sun on the basis of either a look-up table of solar positions or a solar position algorithm, and employing said predicted position in controlling said alignment of said instrument.

12. A method as claimed in either claim 10 or 11, including employing four detectors, each of which comprises a grid of detector elements.

13. A solar tracking system substantially as hereinbefore described with reference to the accompanying drawings.

14. A method of solar tracking substantially as hereinbefore described with reference to the accompanying drawings.

Dated this 26th day of June 2006
<u>SOLAR SYSTEMS PTY LTD</u>
By their Patent Attorneys
GRIFFITH HACK
Fellows Institute of Patent and
Trade Mark Attorneys of Australia

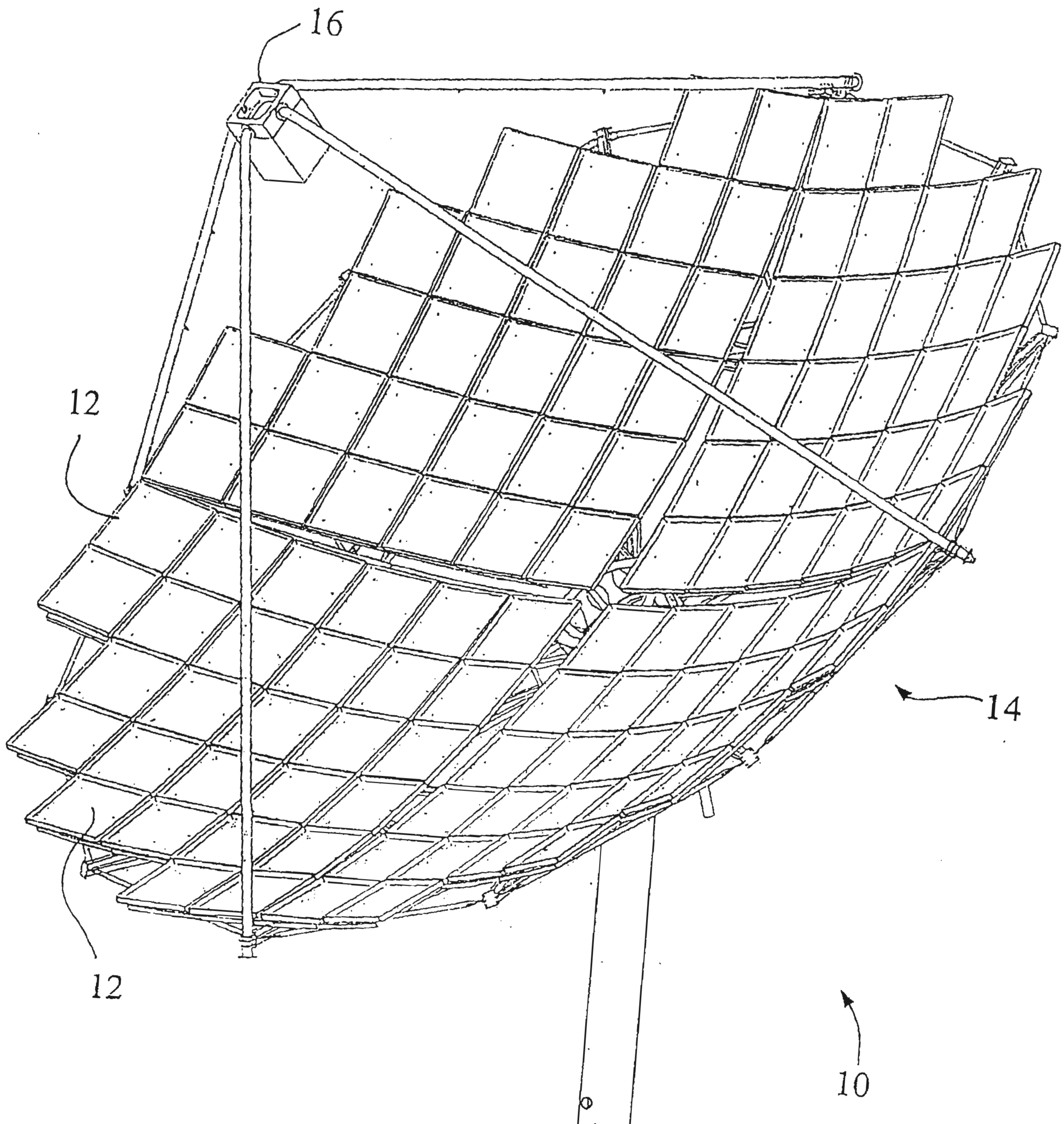

Figure 1

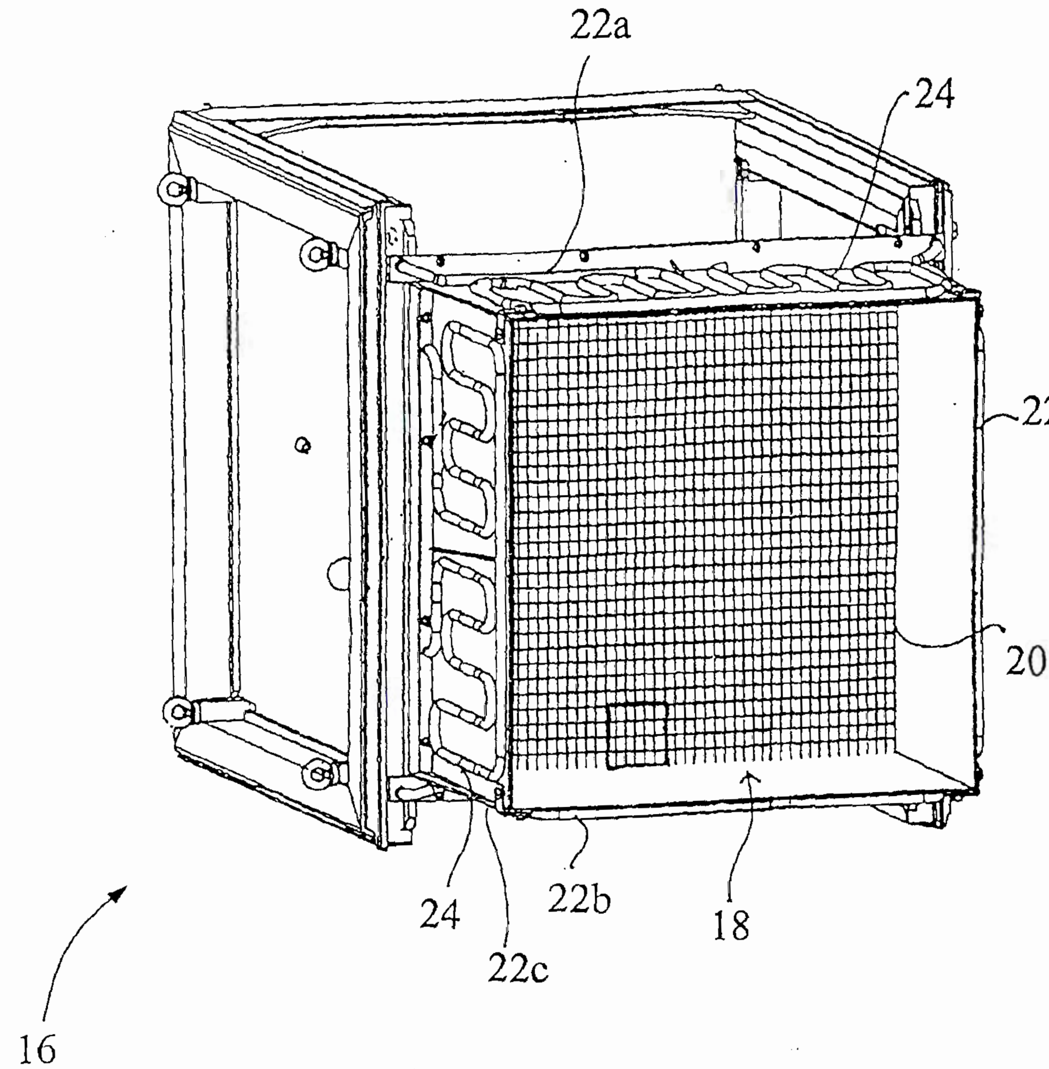

Figure 2

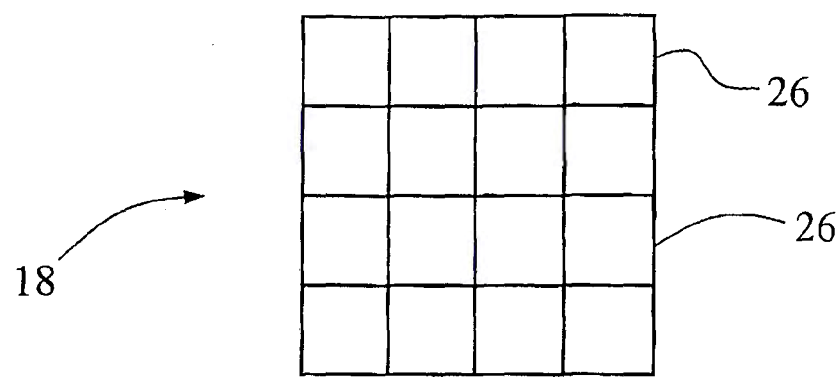

Figure 3

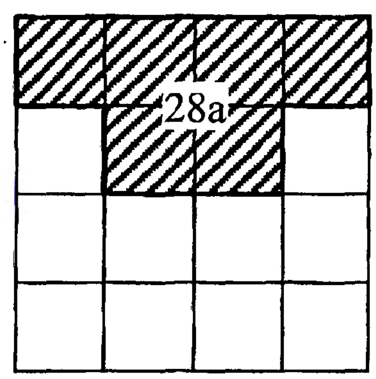

Figure 4A

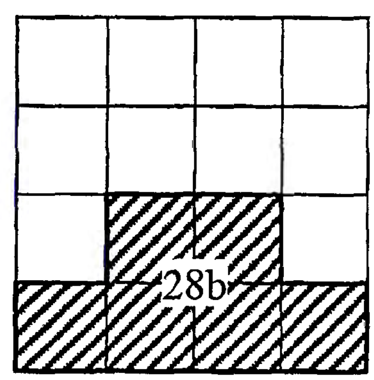

Figure 4B

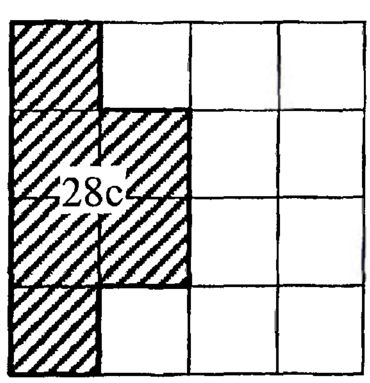

Figure 4C

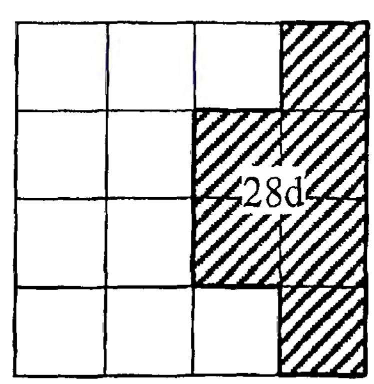

Figure 4D

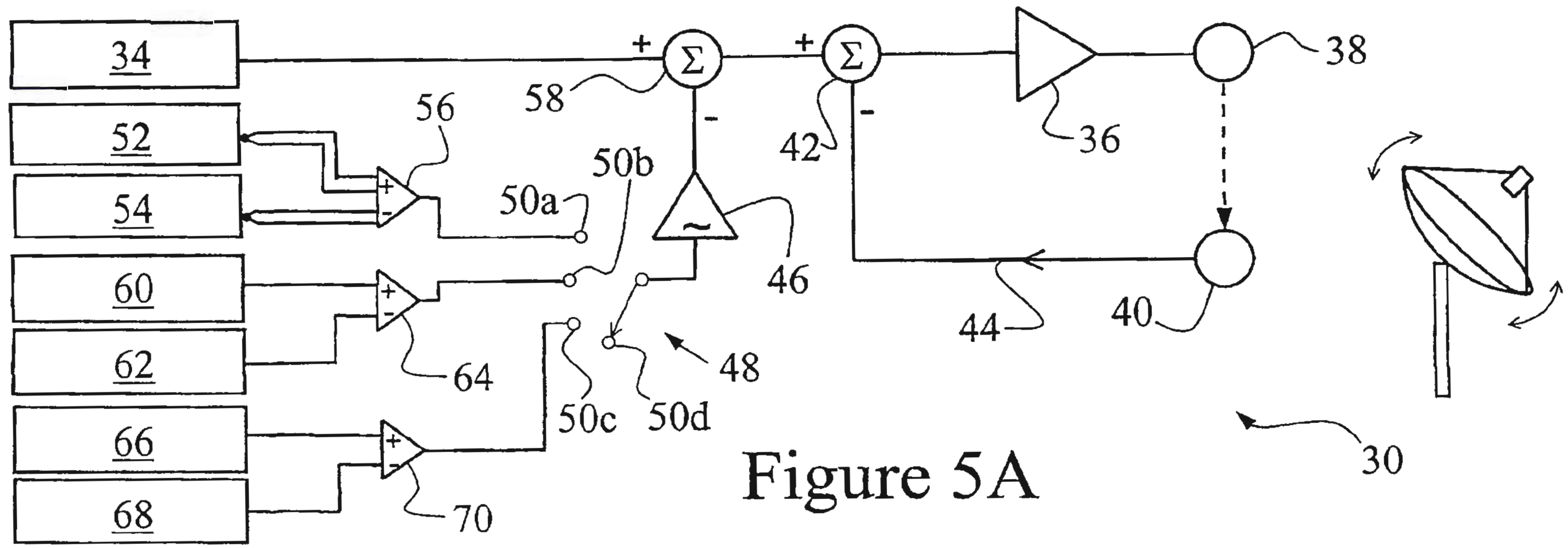

Figure 5A

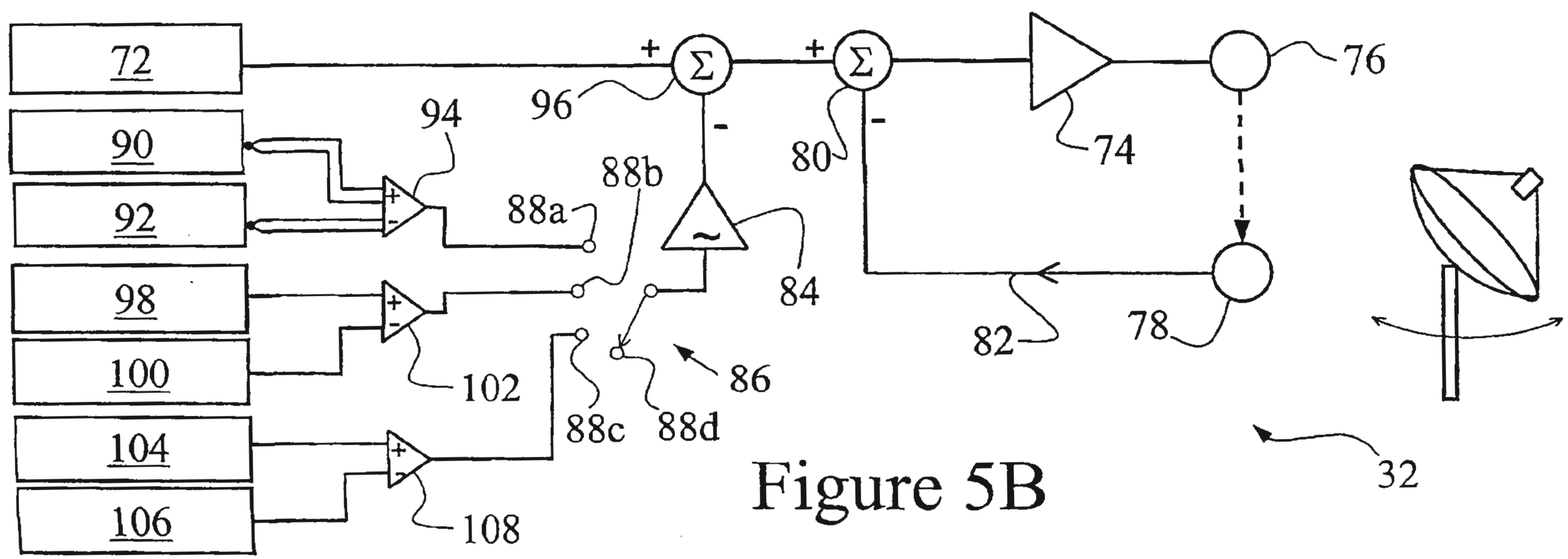

Figure 5B

2.5 Lasich J.B., 2001, “Solar Mirror Testing and Alignment”, Patent No. 2002244529B2, Australia

Australian Government

IP Australia

LETTERS PATENT

STANDARD PATENT

2007231815

I, David Johnson, the Acting Commissioner of Patents, grant a Standard Patent with the following particulars:

Name and Address of Patentee(s):

Solar Systems Pty Ltd
322 Burwood Road, Hawthorn, VIC, 3122, Australia

Name of Actual Inventor(s):

Lasich, John.

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Term of Letters Patent:

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(71) Applicant(s)
Solar Systems Pty Ltd

(72) Inventor(s)
Lasich, John

(74) Agent / Attorney
Griffith Hack, Level 3 509 St Kilda Road, Melbourne, VIC, 3004

(56) Related Art
US 5862799 A
CARLIN, FAQ about Collimating a Newtonian telescope (online, updated Oct 2000), (retrieved on 16/2/2006). Retrieved from the Internet: <URL: http://www.atmsite.org/contrib/Carlin/collimation/>

ABSTRACT

The invention provides a method of aligning each of a plurality of mirrors within an array, comprising: 1) determining a preferred pattern of light reflection from the array; 2) obtaining a characterization of the shape of each of the mirrors; 3) simulating the array and light reflection therefrom on the basis of the characterizations, and comparing the simulated light reflection with the preferred pattern of light reflection; and 4) varying the simulated array and repeating step 3) until the simulated light reflection is within acceptable tolerances of the preferred pattern of light reflection.

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AUSTRALIA

Patents Act 1990

COMPLETE SPECIFICATION

Standard Patent

Applicant:

Solar Systems Pty Ltd

Invention Title:

SOLAR MIRROR TESTING AND ALIGNMENT

The following statement is a full description of this invention, including the best method for performing it known to us:

SOLAR MIRROR TESTING AND ALIGNMENT

RELATED APPLICATION

This application is divided from patent application no. 2002244529 filed 3 April 2002, the content of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to a system and method for characterizing the shape of a mirror for use in, for example, a solar power generation system, and for employing such mirrors characterizations in, for example, aligning each of a plurality of such mirrors within an array for use as a solar concentrator or in a solar power generation system.

BACKGROUND OF THE INVENTION

Typically, existing methods for testing mirrors reflect light from the mirror and then adjust the mirror, such as by grinding or mechanical adjustment of a mirror support, until the pattern of light so reflected meets some predetermined standard. However, doing so can be time consuming and adds expense to the manufacture of the mirror.

SUMMARY OF THE INVENTION

In a first broad aspect, the present invention provides a method of aligning each of a plurality of mirrors within an array, comprising:

1) determining a preferred pattern of light reflection from the array;

2) obtaining a characterization of the shape of each of the mirrors;

3) simulating the array and light reflection therefrom on the basis of the characterizations, and comparing the simulated light reflection with the preferred pattern of light reflection; and

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4) varying the simulated array and repeating step 3) until the simulated light reflection is within acceptable tolerances of the preferred pattern of light reflection.

The preferred pattern of light reflection from the array preferably includes preferred patterns of light reflection for each mirror in the array.

Thus, there may be a need to produce a certain "shape" of beam at the focus of a set of mirrors. This shape is dictated by the needs of the optical receiver placed at the focus. Owing to production constraints, mirrors (such as those for solar concentrators in solar power generation systems) do not have perfect optical surfaces, so the theoretical alignment of a set of mirrors will not produce the anticipated result. Rather than attempting to improve production quality, the present invention determines the character of each mirror, and determines how each mirror should be oriented to produce a composite, reflected light beam that is substantially as prescribed.

Step 4) may comprise varying the simulated orientation of one or more mirrors, or varying the simulated location within the array of one or more mirrors, or both varying the simulated orientation of one or more mirrors and varying the simulated location within the array of one or more mirrors.

Preferably obtaining the characterization of each of the mirrors includes characterizing each of the mirrors.

Preferably the method includes obtaining the characterization of the shape each of the mirrors by characterizing each of a plurality of characterization locations on the respective mirror by observing reflection of a respective light beam from each of the locations (for example as described in Australian patent application no. 2002244529 filed 3 April 2002).

Preferably the method includes simulating the location of each respective mirror within the array such that mirrors more closely approximating a theoretical shape are located closer to a centre of the array than mirrors less closely approximating the theoretical shape. For example, if the mirrors are designed to be spherical mirrors, those closest to spherical would be located at the edge of the array (where deviations from spherical would have the greatest deleterious effect owing to higher angles of incidence) and those furthest from spherical would be located at the centre of the array.

In one embodiment, step 1) includes determining preferred patterns of light reflection for each mirror in the array, and the method includes subsequently:

5) reflecting light from each of the mirrors and observing reflected light therefrom;

6) comparing the reflected light with the preferred pattern of light reflection for each respective mirror; and

7) varying the location, orientation or both location and orientation of one or more of the mirrors and repeating steps 5) and 6) until for each mirror the light reflection is within acceptable tolerances of the preferred pattern of light reflection from the respective mirror.

Preferably the array of the mirrors is for use in an energy conversion system, such as a solar power generation system.

In a second broad aspect, the present invention provides an apparatus for determining an alignment each of a plurality of mirrors within an array, comprising computational means (such as a computer provided with a computer program) for performing the method of aligning each of a plurality of mirrors within an array as described above.

In a third broad aspect, the present invention provides a method of aligning a mirror, comprising:

1) determining a preferred pattern of light reflection from the mirror;

2) obtaining a characterization of the shape of the mirror;

3) simulating the mirror and light reflection therefrom on the basis of the characterization, and comparing the simulated light reflection with the preferred pattern of light reflection; and

4) adjusting a simulated orientation of the mirror and repeating step 3) until the simulated light reflection is within acceptable tolerances of the preferred pattern of light reflection.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be more clearly ascertained, an embodiment will now be described, by way of example, with reference to the accompanying drawing, in which:

Figure 1 is a schematic side view of an apparatus for determining the figure of a mirror according to one embodiment of the present invention;

Figure 2 is a schematic top view of the apparatus for determining the figure of a mirror of figure 1; and

Figure 3 is a view of a solar power generator with an array of the type to be simulated by the simulation program of the apparatus of figure 1.

DETAILED DESCRIPTION OF THE INVENTION

An apparatus for determining the figure of a mirror according to one embodiment of the present invention is shown generally at 10 in figures 1 and 2 with a mirror 12. Figure 1 is a side view of the apparatus 10, which includes a bank 14 of laser sources, a detecting surface in the form of target screen 16, a digital camera 18 and a data collection computer 20. Figure 2 is a top view, in which the individual laser sources 22a, 22b, etc. constituting the bank 14 of laser sources are shown. The mirror 12 is supported on a simple stand (not shown), while the target screen 16 and the laser sources 22a, 22b, etc. are mounted on a servo-motor driven, vertically translatable mount (also not shown), so that they can be translated vertically in concert. The laser sources 22a, 22b, etc. are mounted such that their respective laser beams 24a, 24b, 24c, etc. are horizontal.

In use, the bank 14 of laser sources is slowly translated downwards. The laser beams 24a, 24b, 24c, etc. are reflected by the test mirror 12 onto the target screen 16. Periodically a screen grab is collected from the output of the camera 18; at the same time, the instantaneous locations of the laser sources 22a, 22b, etc. are also collected. Those locations are obtained from the servo-motor controller (not shown) controlling the servo-motor, and from the known geometry of the apparatus 10 overall.

At each measurement, the location on the test mirror 12 at which each beam 24a, 24b, etc. impinges the mirror 12 can be deduced from the locations of the laser sources 22a, 22b, etc., in view of the horizontal nature of the beams 24a, 24b, etc. From this information and the locations at which each reflected beam intersects the target screen 16 may be deduced the gradient of the mirror at each location at which a beam was incident when a measurement was made. Consequently, the angle of reflection for any angle of incidence can subsequently be predicted for each of these locations.

It should be noted that as, in this embodiment, measurements are made progressively as the laser source/target screen assembly is translated vertically, the locations on the mirror 12 at which gradients are obtained are arranged in a grid of rows and columns (though, where the mirror 12 is curved - as shown in figures 1 and 2, this grid will also be curved in space).

When this procedure has been completed, the behaviour of the mirror 12 in reflecting light from, say, the sun can be predicted. The apparatus includes a simulation program (not shown) running on computer 20 or on another computer networked to computer 20.

For a mirror 12 (such as a spherical mirror that might be employed in a solar power generation system), it may be desirable to predict how light falling on the mirror 12 will be focussed or reflected. Consequently, the simulation program receives the gradient values for the mirror 12, and calculates the intensity distribution of solar radiation (comprising an essentially broad but parallel incident beam) after reflection from the mirror, typically at a predetermined distance from the mirror corresponding to the location of, for example, a solar collector. The simulation program can perform this simulation on the basis of light rays impinging on the mirror at the locations on the mirror's surface at which these gradient values have been determined.

Optionally the simulation program performs the simulation with additional simulated rays impinging the mirror at the locations other than where gradient values have been determined. It does this by treating each measured location as being at the centre of a flat, essentially rectangular region. The regions are rectangular owing to the regular spacing of the locations at which the gradient values have been obtained. Even though the mirror may be curved, this approximation should generally be acceptable provided that the size of the regions (determined by the spacing of the gradient measurements) are relatively small. The spacing of the gradient measurements can be selected to ensure that this approximation is acceptable.

Subsequently, if the intensity distribution is less than adequate, the simulated orientation of the mirror can be adjusted and the intensity distribution recalculated by the simulation program. This can be repeated until an optimal or acceptable intensity distribution is obtained.

The simulation program can also be used to simulate an array of two or more such mirrors, such as an array of mirrors for a solar power generator. Such a solar power generator is illustrated generally at 30 in figure 3. The generator includes an array 32 of mirrors 34 and a collector 36 (comprising a square array of photovoltaic cells) approximately at the focus of the array 32. Once a grid of gradient values has been determined for each mirror and provided to the simulation program, the simulation program simulates the desired array by treating each mirror as being at a simulated location and orientation within the array. The intensity distribution of the array can then be simulated as described above for a single mirror.

One possible preferred simulation produces a substantially even intensity distribution over the collector so that, in an actual solar power generator, the energy is distributed and the collector does not develop hot-spots.

The simulated orientations of any of the mirrors can then be adjusted and/or the simulated locations of one or more mirrors can be modified, until the desired or an acceptable intensity distribution is obtained.

In running the simulation program, the mirrors simulated as located towards the periphery of the array of mirrors are preferably those which, when their gradient values were determined, to most closely conform to the design specifications for the mirrors. For example, if the mirrors were intended to approximate spherical mirrors, those most closely spherical would be simulated as at the edge of the array of mirrors, where higher angles of incidence of sunlight will occur. Greater deviations from the intended spherical shape can be tolerated in individual mirrors where low angles of incidence (near the centre of the array) are expected.

If the array is to be installed in an actual installation (such as a solar concentrator of a solar power generator), each mirror in the array of mirrors can, according to the present invention, be aligned using a laser source or group of laser sources with respect to a target placed at or near the focal region of the array.

The array is assembled according to the results of the simulation. Then, at the installation site, the array is located with its optical axis pointing upwards, and with the laser source or group of laser sources suspended above the array such that their beams point vertically downwards. The laser source or sources are shone onto each mirror in turn and the pattern of reflected light on the target observed. The orientation of each mirror is then adjusted until the pattern on the target agrees to an acceptable degree with that predicted in the simulation for that mirror. As the simulation sought to define locations and

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orientations for the mirrors to provide the optimal reflected intensity distribution or "focal shape" for energy conversion (in the case of a solar concentrator), this field alignment technique should ensure that that optimal arrangement is achieved.

Modifications within the spirit and scope of the invention may readily be effected by persons skilled in the art. It is to be understood, therefore, that the invention is not limited to the particular embodiments described by way of example hereinabove.

For the purpose of this specification the words "comprising", "comprise" or "comprises" are understood to mean the inclusion of a feature but not necessarily exclusion of any other feature.

It is to be understood that, if any prior art is referred to herein, such reference does not constitute an admission that that prior art forms a part of the common general knowledge in the art, in Australia or in any other country.

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CLAIMS:

1. A method of aligning each of a plurality of mirrors within an array, comprising:

1) determining a preferred pattern of light reflection from said array;

2) obtaining a characterization of the shape of each of said mirrors;

3) simulating said array and light reflection therefrom on the basis of said characterizations, and comparing said simulated light reflection with said preferred pattern of light reflection; and

4) varying said simulated array and repeating step 3) until said simulated light reflection is within acceptable tolerances of said preferred pattern of light reflection.

2. A method as claimed in claim 1, wherein said preferred pattern of light reflection from said array includes preferred patterns of light reflection for each mirror in said array.

3. A method as claimed in either claim 1 or 2, wherein step 4) comprises varying the simulated orientation of one or more mirrors, or varying the simulated location within said array of one or more mirrors, or both varying the simulated orientation of one or more mirrors and varying the simulated location within said array of one or more mirrors.

4. A method as claimed in any one of the preceding claims, wherein said obtaining a characterization of each of said mirrors includes characterizing each of said mirrors.

5. A method as claimed in any one of the preceding claims, including obtaining said characterization of the shape each of said mirrors by characterizing each of a plurality of

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characterization locations on said respective mirror by observing reflection of a respective light beam from each of said locations.

6. A method as claimed in claim 1, including simulating the location of each respective mirror within said array such that mirrors more closely approximating a theoretical shape are located closer to a centre of said array than mirrors less closely approximating said theoretical shape.

7. A method as claimed in claim 1, wherein step 1) includes determining preferred patterns of light reflection for each mirror in said array, and the method includes subsequently:

5) reflecting light from each of said mirrors and observing reflected light therefrom;

6) comparing said reflected light with said preferred pattern of light reflection for each respective mirror; and

7) varying the location, orientation or both location and orientation of one or more of said mirrors and repeating steps 5) and 6) until for each mirror said light reflection is within acceptable tolerances of said preferred pattern of light reflection from said respective mirror.

8. A method as claimed in any one of the preceding claims, wherein said array of said mirrors is for use in an energy conversion system.

9. A method as claimed in any one of the preceding claims, wherein said array is for use in a solar power generation system.

10. An apparatus for determining an alignment each of a plurality of mirrors within an array, comprising computational means for performing the method of aligning

each of a plurality of mirrors within an array as claimed in any one of claims one of the preceding claims.

11. An apparatus as claimed in claim 10, wherein said apparatus comprises a computer provided with a computer program.

12. A method of aligning a mirror, comprising:

1) determining a preferred pattern of light reflection from said mirror;

2) obtaining a characterization of the shape of said mirror;

3) simulating said mirror and light reflection therefrom on the basis of said characterization, and comparing said simulated light reflection with said preferred pattern of light reflection; and

4) adjusting a simulated orientation of said mirror and repeating step 3) until said simulated light reflection is within acceptable tolerances of said preferred pattern of light reflection.

13. A method of aligning each of a plurality of mirrors within an array substantially as hereinbefore described by reference to the accompanying drawing.

14. An apparatus for determining an alignment each of a plurality of mirrors within an array substantially as hereinbefore described by reference to the accompanying drawing.

15. A method of aligning a mirror substantially as hereinbefore described by reference to the accompanying drawing.

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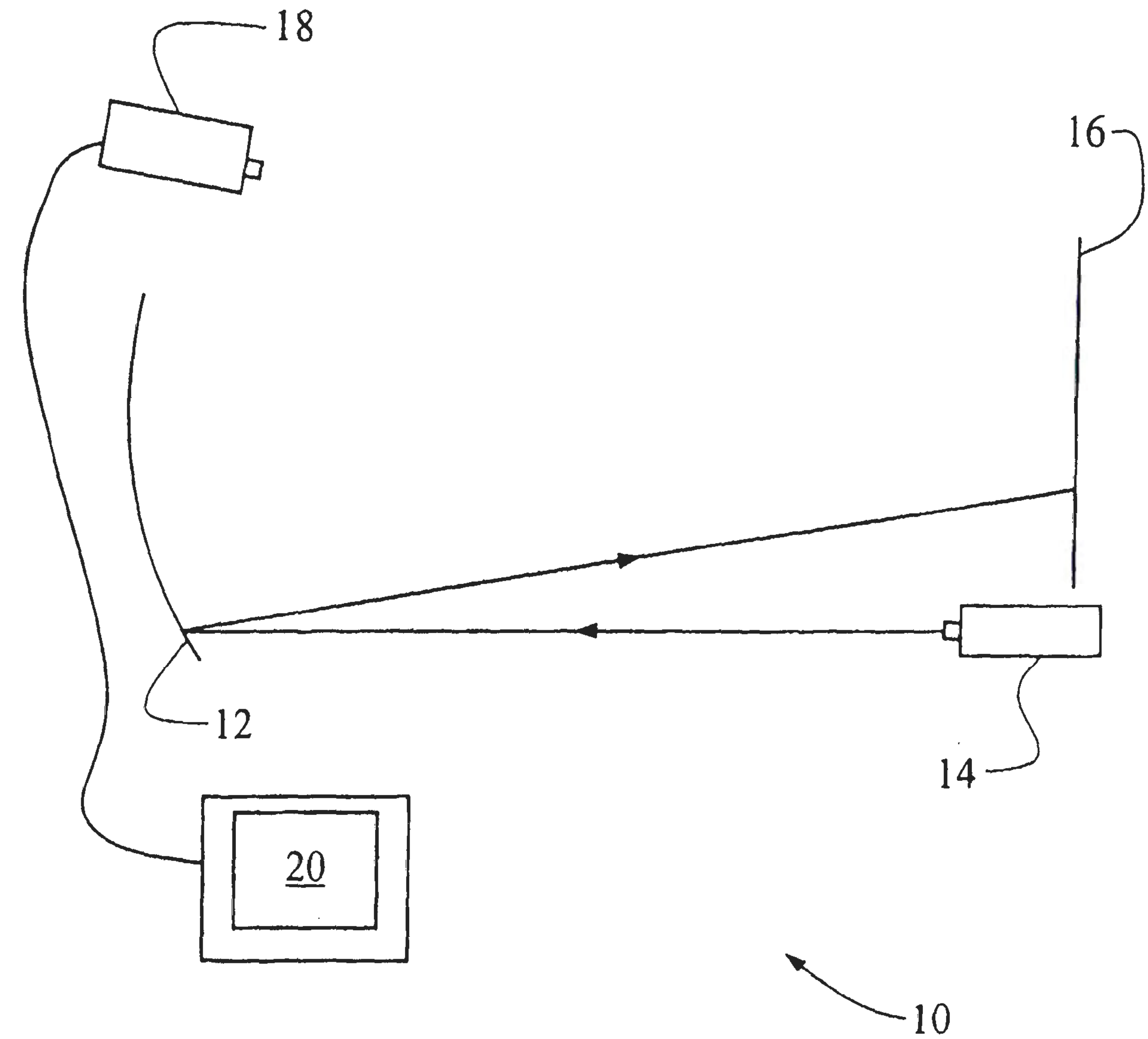

Figure 1

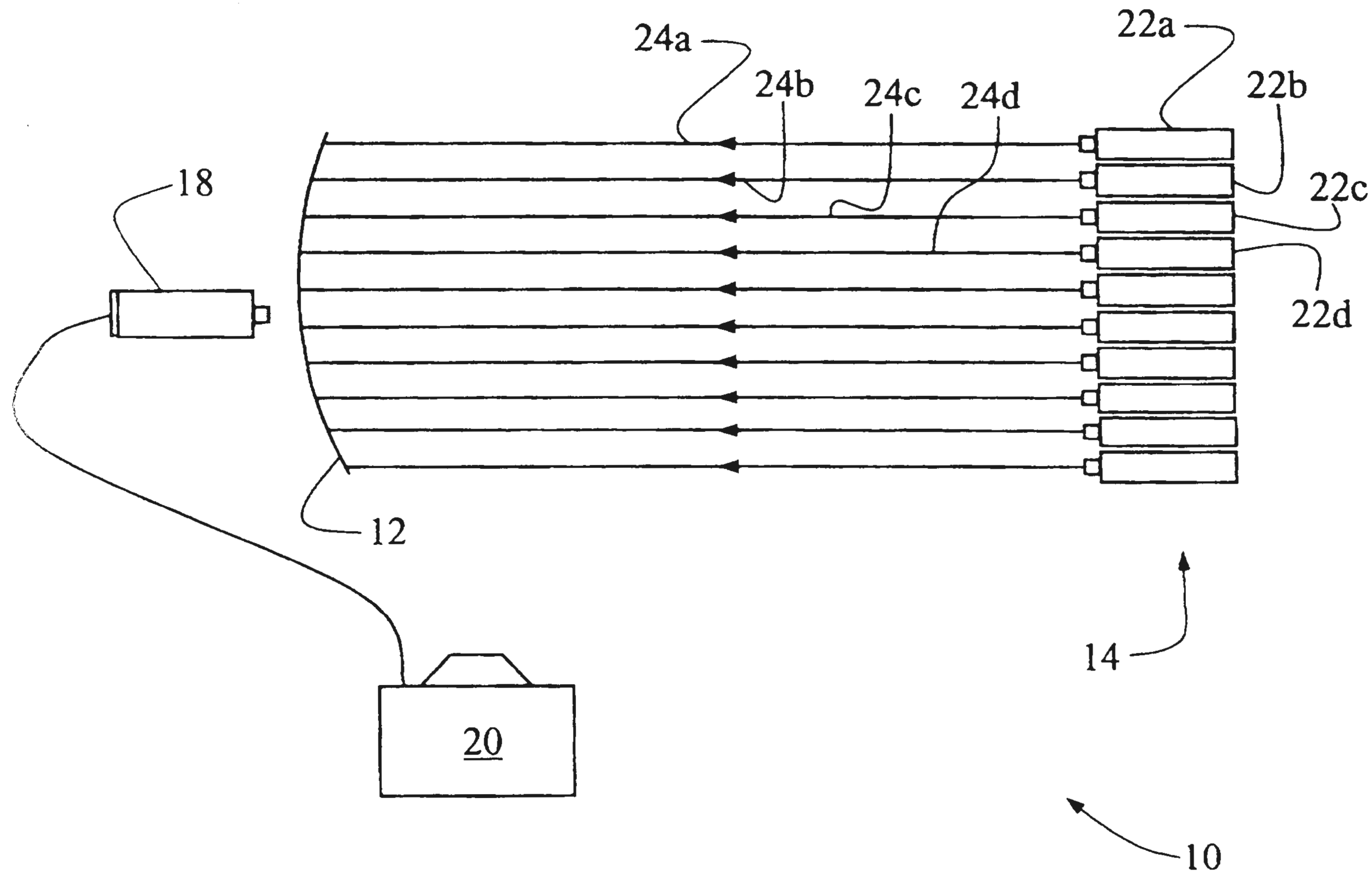

Figure 2

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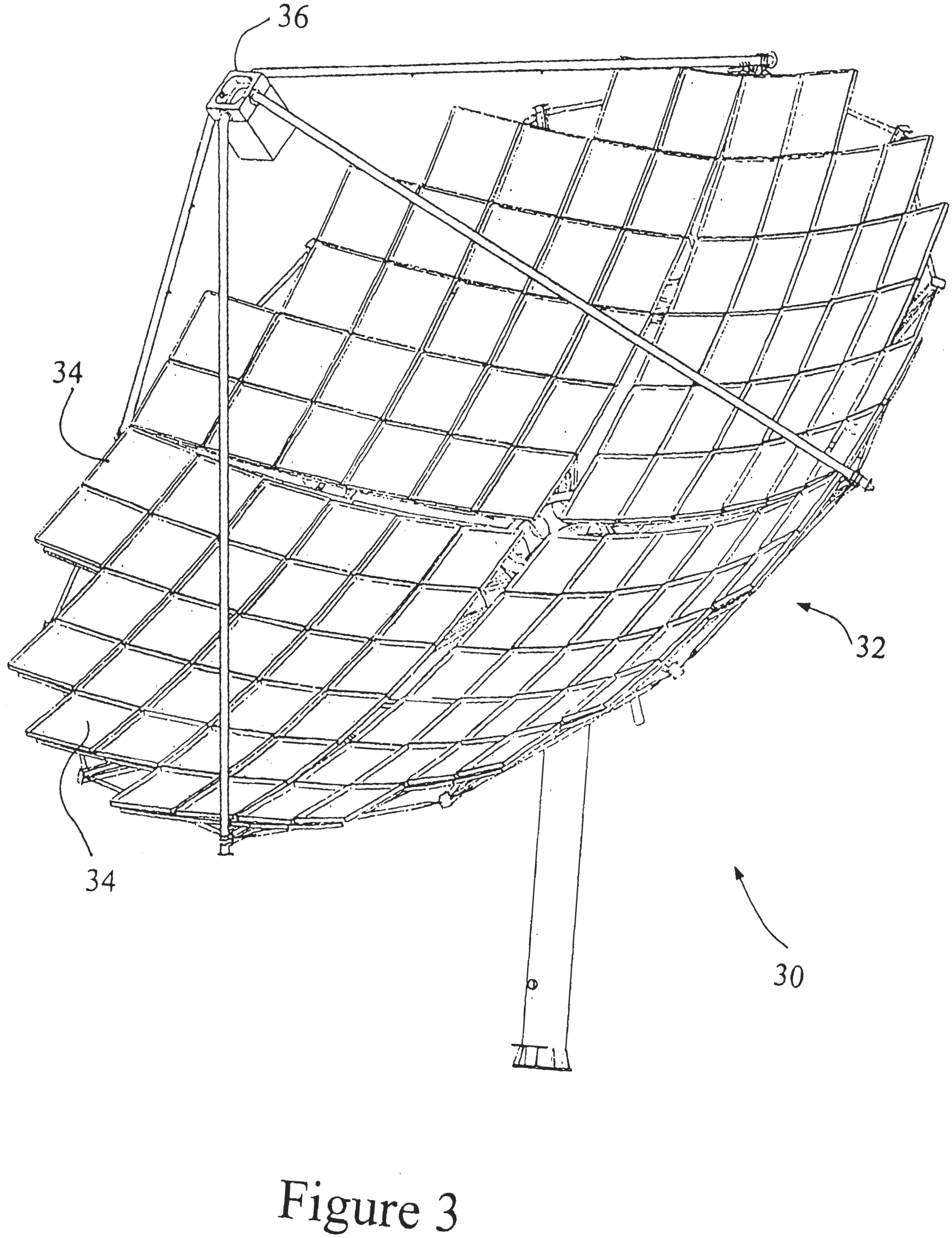

Figure 3

2.6 Lasich J.B., 2001, “A Method of Manufacturing Mirrors for a Dish Reflector”, Patent No: US7550054B2, USA

The United States of America

The Director of the United States Patent and Trademark Office

Has received an application for a patent for a new and useful invention. The title and description of the invention are enclosed. The requirements of law have been complied with, and it has been determined that a patent on the invention shall be granted under the law.

Therefore, this

United States Patent

Grants to the person(s) having title to this patent the right to exclude others from making, using, offering for sale, or selling the invention throughout the United States of America or importing the invention into the United States of America for the term set forth below, subject to the payment of maintenance fees as provided by law.

If this application was filed prior to June 8, 1995, the term of this patent is the longer of seventeen years from the date of grant of this patent or twenty years from the earliest effective U.S. filing date of the application, subject to any statutory extension.

If this application was filed on or after June 8, 1995, the term of this patent is twenty years from the U.S. filing date, subject to any statutory extension. If the application contains a specific reference to an earlier filed application or applications under 35 U.S.C. 120, 121 or 365(c), the term of the patent is twenty years from the date on which the earliest application was filed, subject to any statutory extensions.

Acting Director of the United States Patent and Trademark Office

US007550054B2

(12) United States Patent
Lasich

(10) Patent No.: US 7,550,054 B2
(45) Date of Patent: Jun. 23, 2009

(54) METHOD OF MANUFACTURING MIRRORS FOR A DISH REFLECTOR

(75) Inventor: John Beavis Lasich, Balwyn (AU)

(73) Assignee: Solar Systems Pty Ltd., Hawthorn, Victoria (AU)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 740 days.

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(86) PCT No.: PCT/AU02/00401

§ 371 (c)(1),
(2), (4) Date: Sep. 26, 2003

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PCT Pub. Date: Oct. 10, 2002

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(30) Foreign Application Priority Data

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(51) Int. Cl.
B32B 15/00 (2006.01)

(52) U.S. Cl. 156/254; 156/196; 156/516; 126/689; 126/690; 126/691; 126/573; 126/600; 126/680; 60/641.15; 60/659

(58) Field of Classification Search 126/689, 126/690, 691, 573, 600, 680; 60/641.15, 60/659; 156/196, 254, 516
See application file for complete search history.

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Primary Examiner—Philip C Tucker
Assistant Examiner—Kimberly K McClelland
(74) *Attorney, Agent, or Firm*—Klarquist Sparkman, LLP

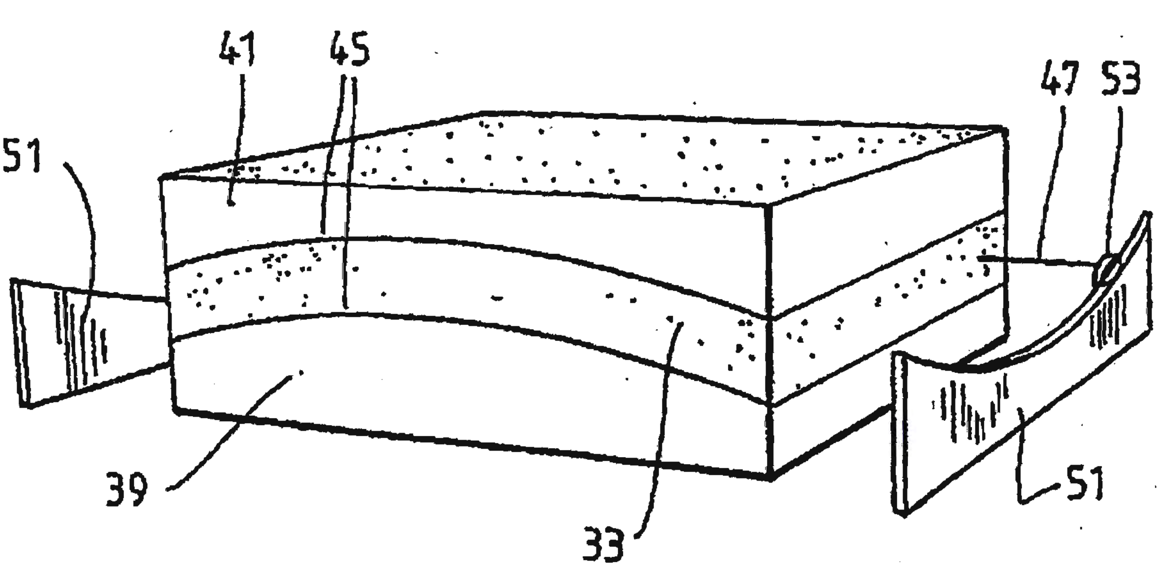
(57) ABSTRACT

A method of manufacturing a mirror for a dish reflector of a system for generating electrical power from solar radiation is disclosed. The method includes the steps of:

(a) shaping a blank of a deformable material to have a concave surface that is a required surface profile for a mirror; and

(b) glueing, laminating or otherwise adhering together a back surface of a sheet of reflective glass and the concave surface of the shaped blank to form the mirror.

12 Claims, 2 Drawing Sheets



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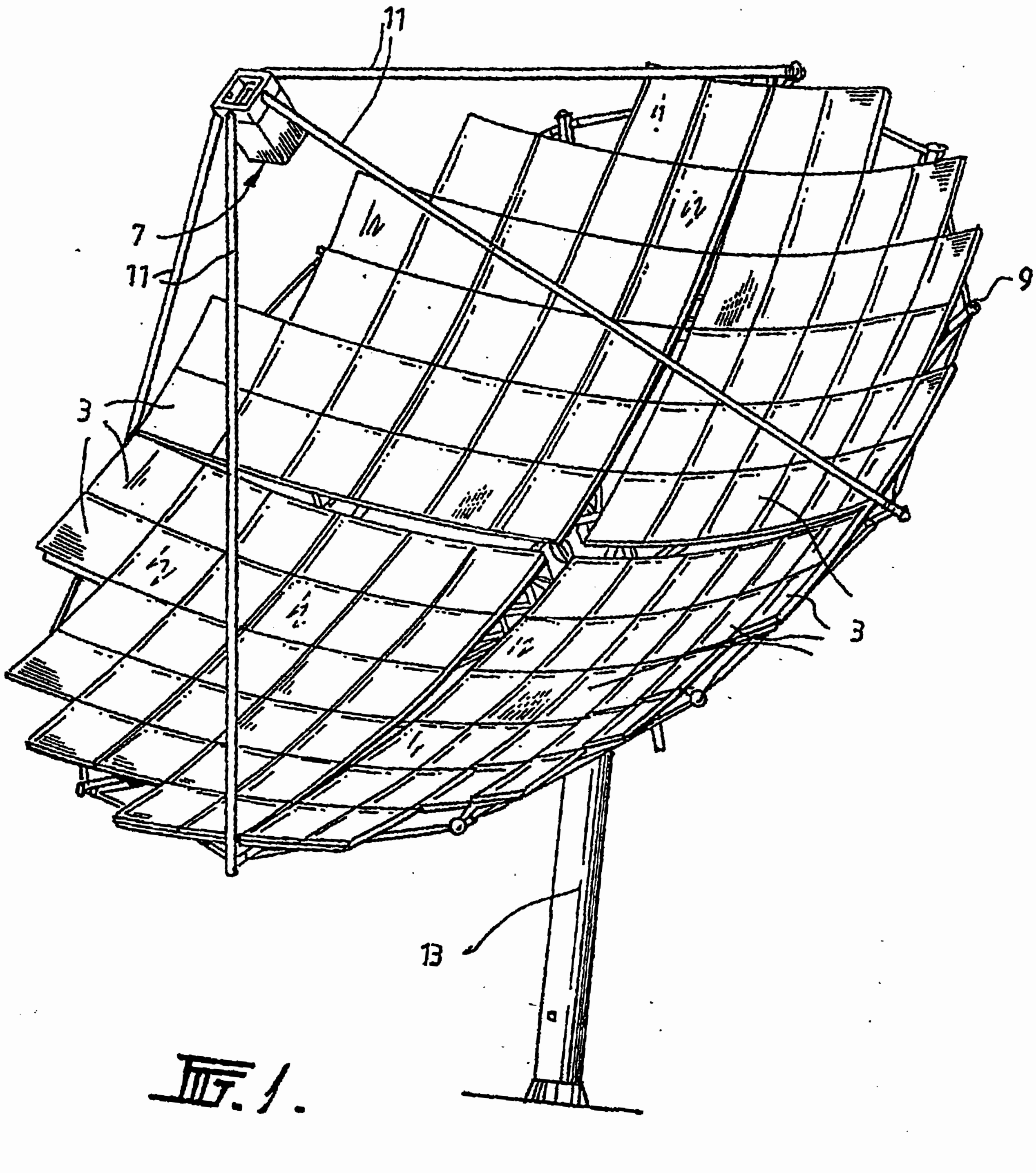

FIG. 1.

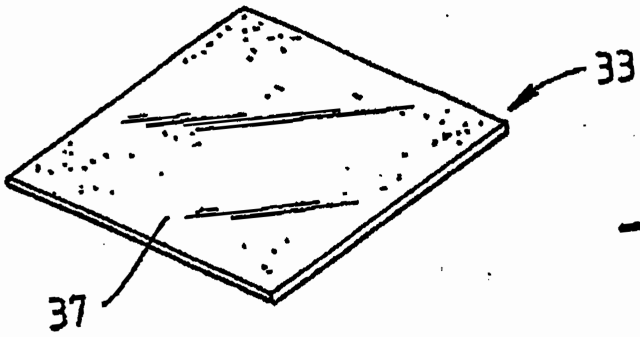

FIG. 2.

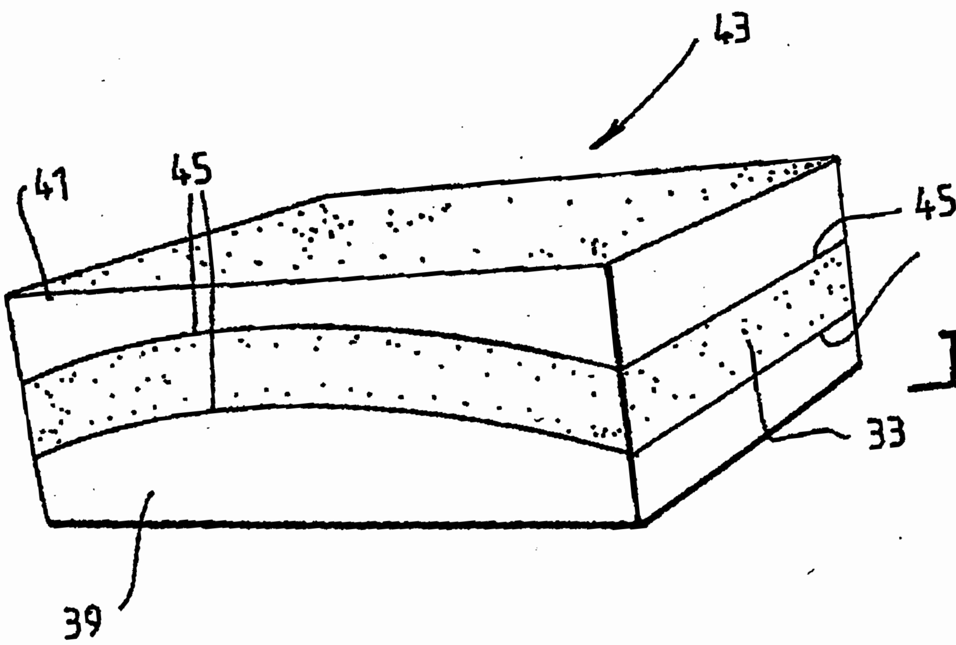

FIG. 3.

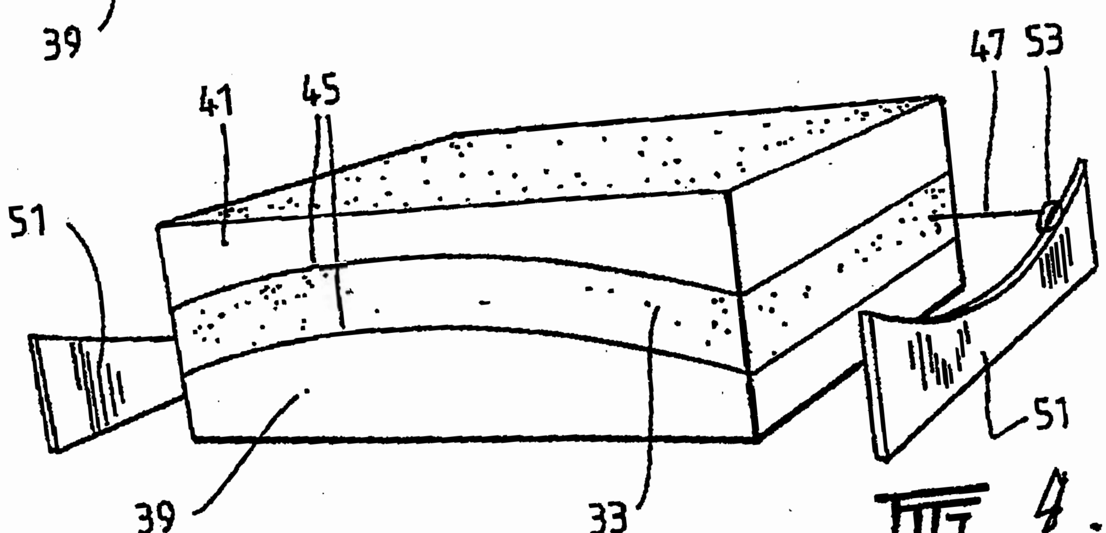

FIG. 4.

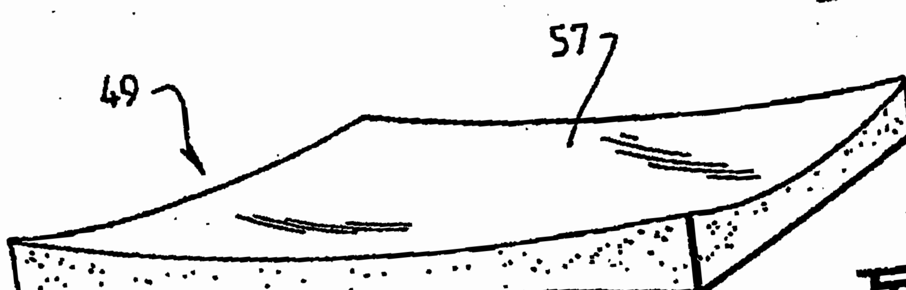

FIG. 5.

METHOD OF MANUFACTURING MIRRORS FOR A DISH REFLECTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This is the National Stage of International Application No. PCT/AU02/00401, filed Mar. 28, 2002, and claims the benefit of Australian Patent Application No. PR4037, filed Mar. 28, 2001.

The present invention relates to a method of manufacturing mirrors.

The present invention relates more particularly to a method of manufacturing mirrors for a dish reflector that forms part of a system for generating electrical power from solar radiation.

The present invention relates more particularly to a method of manufacturing mirrors for a dish reflector of an electrical power generating system that includes:

(a) a receiver that includes a plurality of photovoltaic cells that convert solar energy into electrical energy and an electrical circuit for the electrical energy output of the photovoltaic cells; and

(b) a dish reflector that includes an array of mirrors, for example a parabolic array of mirrors, that reflect solar radiation that is incident on the mirrors towards the photovoltaic cells.

Typically, the surface area of the mirrors that is exposed to solar radiation is relatively large compared to the exposed surface area of the photovoltaic cells.

The present invention relates more particularly to a large scale solar radiation-based electrical power generating system of the type described above that is capable of producing substantial amounts of electrical power ready for conditioning to at least 20 kW of standard 3 phase 415 volt AC power.

Applications for such large scale power generating systems include remote area power supply for isolated grids, grid-connected power, water pumping, telecommunications, crude oil pumping, water purification, and hydrogen generation.

One significant issue associated with development of a commercially viable solar radiation-based electrical power generating system of the type described above is to be able to manufacture components of the system cost effectively in a straightforward and uncomplicated manner and on a mass production basis to a consistently high quality.

The mirrors of the dish reflector are one area that is particularly important in this regard.

A conventional method of manufacturing mirrors involves locating relatively thick (of the order of 2 cm) flat sheets of glass into appropriately curved moulds and allowing the glass to slump into the moulds and thereby adopt the curved shape. There are quality issues associated with mirrors made by this method, particularly as the size of the mirrors increases and surface ripples and other irregularities resulting from slumping a flat sheet into a curved sheet become more pronounced. In addition, such mirrors tend to be susceptible to damage on a large scale when exposed to hail and other extreme weather conditions.

An object of the present invention is to provide a method of manufacturing mirrors of a dish reflector that is straightforward, not complicated, and cost effective and can manufacture mirrors on a mass production basis to a consistently high quality.

According to the present invention there is provided a method of manufacturing a mirror for a dish reflector of a system for generating electrical power from solar radiation which includes the steps of:

(a) shaping a blank of a deformable material to have a concave surface that is a required surface profile for a mirror; and

(b) glueing, laminating or otherwise adhering together a back surface of a sheet of reflective glass and the concave surface of the shaped blank to form the mirror.

The applicant has found that the above-described method makes it possible to manufacture lightweight mirrors of a high quality and durability in a straightforward manner and inexpensively when compared with the above-described conventional slump glass method. The high quality and durability is due to a number of factors. One factor is that the mirror can be made from relatively thin glass, typically no more than 3mm, and it is possible to use high quality glass that has high surface smoothness that is not affected by the method. Another, although not the only, other factor is that thinner glass is less susceptible to large scale damage due to hail strike and damage tends to be confined to the regions of direct contact.

Preferably step (b) includes pressing together the glass sheet and the shaped blank and allowing a bond to form between the glass sheet and the required concave surface.

The required concave surface may be any suitable surface. By way of example, the required concave surface may be part spherical, parabolic or hyperbolic.

Preferably step (a) of shaping the blank includes the steps of:

(i) positioning the blank between two opposed curved former surfaces, whereby positioning the blank between the former surfaces so that the former surfaces contact the blank deforms the blank so that the blank conforms to the former surfaces;

(ii) while the blank is positioned in the former between the former surfaces, cutting the blank along a pre-determined path of movement and separating the blank into parts, each part having a cut surface; and

(iii) releasing the parts of the blank from the former and returning the parts to a state that the blank was in prior to deforming the blank in step (i), with the result that the cut surface of at least one of the parts defines the required concave surface.

In a situation where the required concave surface is part spherical, in one although not the only embodiment of the present invention step (a) of shaping the blank includes the steps of:

(i) positioning a blank of a deformable material between two halves of a former, each half of the former having a curved former surface that defines part of a cylinder, whereby positioning the blank between the halves so that the former surfaces contact the blank deforms the blank so that the blank conforms to the curved former surfaces and defines part of a cylinder, the longitudinal axis of the cylinder defining a first axis;

(ii) while the blank is positioned between the former halves, cutting the blank along a cylindrical path of movement in the direction of the first axis and separating the blank into two parts, namely a first part and a second part, each part having a cut surface, the longitudinal axis of the cylindrical path of movement defining a second axis, the second axis being perpendicular to the first axis, and

(iii) releasing the parts from the former and returning the parts to a state that the blank was in prior to deforming the blank in step (i), with the result that the cut surfaces of the parts define part spherical surfaces, with the first part having a concave surface and the second part having a convex surface.

With this embodiment, one option for step (b) includes positioning the convex surface of the second part against the front surface of the glass sheet, thereby sandwiching the glass sheet between the first and second parts, and thereafter pressing the two parts together to form the bond between the glass sheet and the first part.

With this embodiment, another although not the only other option for step (b) includes positioning the first part and the glass sheet in a press assembly that has a press member that has a convex surface that is complimentary to the concave surface of the first part, thereby sandwiching the glass sheet between the press member and the first part, and thereafter pressing the two parts together to form the bond between the glass sheet and the first part.

In a situation where the required concave surface is part spherical, in another although not the only other embodiment of the present invention step (a) of shaping the blank includes the steps of:

(i) positioning a blank of a deformable material between two halves of a former, each half of the former having a curved former surface that defines part of a sphere, whereby positioning the blank between the halves so that the former surfaces contact the blank deforms the blank so that the blank conforms to the curved former surfaces and defines part of a sphere;

(ii) while the blank is positioned between the former halves, cutting the blank along a straight path of movement and separating the blank into parts, and

(iii) releasing the parts from the former and returning the parts to a state that the blank was in prior to deforming the blank in step (i), with the result that the cut surface of at least one of the parts defines a part spherical surface.

The blank may be formed from any suitable material.

One such suitable material is polystyrene foam.

The blank may be any suitable shape.

One suitable shape is a quadrilateral prism.

Preferably the blank is a rectangular prism.

The dimensions of the blank depend in large part on the mirror size required.

By way of example, in a situation where the required mirror is a mirror with a square perimeter with 1.1m sides, it is preferred that the blank be 1 m square and have a thickness of 70 mm.

The mirror may be any suitable shape.

By way of example, the mirror may be square, hexagon, rectangular, or circular.

Preferably the major dimension of the sides of the mirror is at least 0.5 m.

Preferably the mirror has a square perimeter with sides that are at least 0.8 m long.

Preferably the thickness of the glass sheet is no more than 4 mm.

More preferably the thickness of the glass sheet is no more than 2 mm.

It is preferred particularly that the thickness of the glass sheet be no more than 1 mm.

According to the present invention there is also provided a system for generating electrical power from solar radiation which includes:

(a) a receiver that includes a plurality of photovoltaic cells that convert solar energy into electrical energy and an electrical circuit for transferring the electrical energy output of the photovoltaic cells, and

(b) a dish reflector that includes an array of mirrors that reflect solar radiation that is incident on the mirrors towards the photovoltaic cells, the mirrors being manufactured by the above-described method.

The present invention is described further by way of example with reference to the accompanying drawings, of which:

FIG. 1 is a perspective view of a preferred embodiment of a system for generating electrical power from solar radiation;

FIG. 2 is a perspective view of a blank for use in a preferred embodiment of a method of manufacturing mirrors for the dish reflector of the system shown in FIG. 1;

FIG. 3 is a perspective view that illustrates a first step of the method which includes positioning the blank between the two halves of a former;

FIG. 4 is a perspective view that illustrates a second step of the method which includes operating a wire cutter and cutting the blank located in the former; and

FIG. 5 is a perspective view of one of the two parts of the cut blank formed in FIG. 4.

The solar radiation-based electric power generating system shown in FIG. 1 includes an array of mirrors 3 that reflects solar radiation that is incident on the mirrors 3 towards a plurality of photovoltaic cells (not shown) that form part of a solar radiation receiver, generally identified by the numeral 7.

In the arrangement shown in FIG. 1 the array of mirrors is parabolic. The array may be any other suitable shape.

The surface area of the mirrors 3 that is exposed to solar radiation is substantially greater than the surface area of the photovoltaic cells that is exposed to reflected solar radiation.

In use, the photovoltaic cells convert reflected solar radiation into DC electrical energy.

The receiver 7 includes an electrical circuit (not shown) for the electrical energy output of the photovoltaic cells.

The mirrors 3 are mounted to a framework 9. The mirrors 3 and the framework define a dish reflector.

A series of arms 11 extend from the framework 9 to the receiver 7 and locat the receiver as shown in the Figures.

The system further includes:

(a) a support assembly 13 that supports the dish reflector and the receiver in relation to a ground surface and for movement to track the Sun; and

(b) a tracking system (not shown) that moves the dish reflector and the receiver as required to track the Sun.

The photovoltaic cells of the receiver 7 are cooled by coolant, preferably water, in order to minimise the operating temperature and to maximise the performance (including operating life) of the photovoltaic cells. The receiver 7 is purpose-built to include a coolant circuit that supplies coolant that cools the photovoltaic cells.

In the arrangement shown, the dish reflector includes 112 mirrors 3. Each mirror has a square perimeter with 1 m sides. Each mirror 3 has a part spherical surface.

In accordance with the preferred embodiment of the method of the present invention, each mirror 3 is formed by a sequence of steps which includes:

(a) shaping a blank of a suitable material, such as polystyrene foam, to have a part spherical concave surface; and

(b) adhering a reflective glass sheet to the concave surface of the shaped blank.

The sequence of steps described in sub-paragraph (a) of the preceding paragraph is partially illustrated in FIGS. 2-5.

FIG. 2 illustrates one suitable form of blank 33. The blank 33 is a rectangular prism having 1 m sides and a thickness of 60 mm. The blank 33 has parallel flat upper and lower surfaces 37.

With reference to FIG. 3, a first step of the method of forming a mirror 3 includes locating the blank 33 between two halves 39, 41 of a former assembly, generally identified by the numeral 43.

Each half 39, 41 of the former assembly 43 includes a cylindrical surface 45 having a radius of the order of 16 m.

Positioning the blank 33 so that it is sandwiched between the halves 39, 41 deforms the blank 33 from the shape shown in FIG. 2 so that the blank 33 assumes a part cylindrical shape, as shown in FIG. 3.

With reference to FIG. 4, a second step of the method of forming a mirror 3 includes moving a wire cutter 47 along a cylindrical path of movement through the deformed blank 33 and thereby cutting the blank into two parts, namely an upper part and a lower part.

The cylindrical path is defined by cylindrical tracks 51 located on opposite sides of the former assembly 43. Opposite ends of the wire cutter 47 are connected to guides 53 that are mounted on the tracks 51. With this arrangement, movement of the guides 53 along the tracks 51 constrains the wire cutter to move in the cylindrical path defined by the tracks 51.

The cylindrical tracks 51 are positioned so that the axis of the cylinder is perpendicular to the axis of the deformed blank 33.

After cutting the blank 33, the next step of the method includes removing the two parts of the blank 33 from the former assembly 43 and returning the parts to the undeformed state, ie the original pre-former assembly state. Consequently, the cut surfaces of the blank 33 form a concave surface in one of the parts and a convex surface in the other of the parts.

FIG. 5 illustrates the part, generally identified by the numeral 49, that has the concave surface. In the Figure, the concave surface is identified by the numeral 57.

The next step of the method of forming a mirror 3 includes adhering a sheet of reflective glass (not shown) onto the concave surface 57 of the part 49.

The mirror 3 may be adhered by any suitable means. By way of example, the mirror 3 may be adhered by the use of a suitable glue. By way of further example, the mirror 3 may be adhered by the use of a suitable laminating compound.

The next step of the method of forming a mirror 3 includes pressing together the glass cover sheet and the part 49 for a period of time that is sufficient to allow a bond to form between the two contacting surfaces, thereby forming the mirror 3.

The above-described method has a number of important features. By way of example, the method is straightforward and uncomplicated and makes it possible to mass produce mirrors of consistent quality using low capital cost equipment.

Many modifications may be made to the preferred embodiment of the method of the present invention that is described above without departing from the spirit and scope of the present invention.

The invention claimed is:

1. A method of manufacturing a mirror for a dish reflector of a system for generating electrical power from solar radiation which includes the steps of:

(a) shaping a blank of a deformable material to have a concave surface that is a required surface profile for a mirror; and

(b) adhering a back surface of a sheet of reflective glass to the concave surface of the shaped blank to form the mirror;

wherein the concave surface is part spherical and step (a) of shaping the blank further includes the steps of:

(i) positioning the blank between two halves of a former, each half of the former having a curved former surface that defines part of a cylinder, wherein the act of positioning comprises positioning the blank between the halves so that the former surfaces contact the blank and deforms the blank so that the blank conforms to the curved former surfaces and defines part of a cylinder, the longitudinal axis of the cylinder defining a first axis;

(ii) while the blank is positioned between the former halves, cutting the blank along a cylindrical path of movement in the direction of the first axis and separating the blank into a first part and a second part, each part having a cut surface, the longitudinal axis of the cylindrical path of movement defining a second axis, the second axis being perpendicular to the first axis, and

(iii) releasing the parts from the former and returning the parts to a state that the blank was in prior to deforming the blank in step (i), with the result that the cut surfaces of the parts define part spherical surfaces, with the first part having a concave surface and the second part having a convex surface.

2. The method defined in claim 1 wherein step (b) includes pressing together the glass sheet and the first part of the shaped blank and allowing a bond to form between the glass sheet and the concave surface.

3. The method defined in claim 1 wherein step (b) includes positioning the convex surface of the second part against the front surface of the glass sheet, thereby sandwiching the glass sheet between the first and second parts, and thereafter pressing the two parts together to form the bond between the glass sheet and the first part.

4. The method defined in claim 1 wherein step (b) includes positioning the first part and the glass sheet in a press assembly that has a press member that has a convex surface that is complimentary to the concave surface of the first part, thereby sandwiching the glass sheet between the press member and the first part, and thereafter pressing the two parts together to form the bond between the glass sheet and the first part.

5. The method defined in claim 1 wherein the blank is formed from polystyrene foam.

6. The method defined in claim 1 wherein the blank is a quadrilateral prism.

7. The method defined in claim 1 wherein the blank is a rectangular prism.

8. The method defined in claim 1 wherein the major dimension of the sides of the mirror is at least 0.5 m.

9. The method defined in claim 1 wherein the mirror has a square perimeter with sides that are at least 0.8 m long.

10. The method defined in claim 1 wherein the thickness of the glass sheet is no more than 4 mm.

11. The method defined in claim 1 wherein the thickness of the glass sheet is no more than 2 mm.

12. The method defined in claim 1 wherein the thickness of the glass sheet is no more than 1 mm.

* * * * *

2.7 Lasich J.B., 2003, “Bypass Diode for Photovoltaic Cells”, Patent No. 2004239803, Australia

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(71) Applicant(s)
Solar Systems Pty Ltd

(72) Inventor(s)
Lasich, John Beavis

(74) Agent / Attorney
Griffith Hack, Level 3 509 St Kilda Road, Melbourne, VIC, 3004

(56) Related Art
US 4577051
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(71) Applicant (*for all designated States except US*): SOLAR SYSTEMS PTY LTD [AU/AU]; 6 Luton Lane, HAWTHORN, Victoria 3122 (AU).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): LASICH, John, Beavis [AU/AU]; 11 Pretoria Street, DEEPDENE, Victoria 3103 (AU).

(74) Agent: GRIFFITH HACK; 509 St Kilda Road, MELBOURNE, Victoria 3004 (AU).

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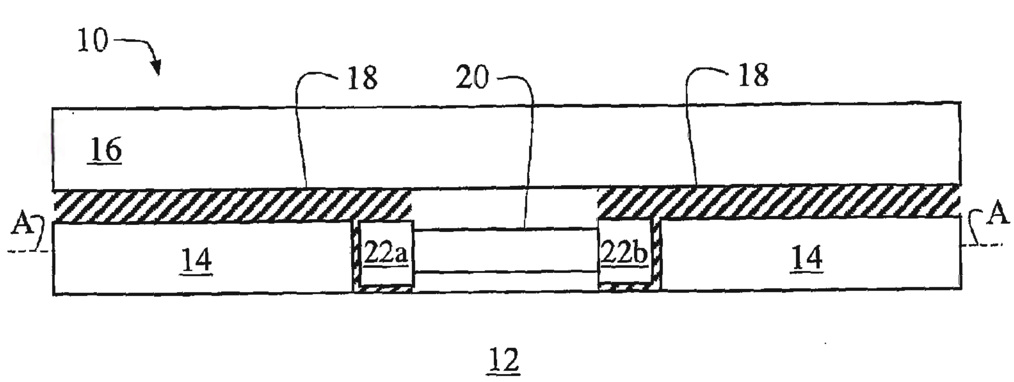
(54) Title: BYPASS DIODE FOR PHOTOVOLTAIC CELLS



(57) **Abstract:** A photovoltaic power module (10), comprising a substrate (12) provided with a circuit, one or more photovoltaic cells (16) mounted to the substrate and electrically connected to the circuit, and one or more bypass diodes (20), each corresponding to a respective one or more of the cells, wherein each of the diodes is located between the substrate and the cells and between conducting portions (14) of the circuit. Solder (18) connects the bypass diode, the conducting portions, and the photovoltaic cell.

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BYPASS DIODE FOR PHOTOVOLTAIC CELLS

RELATED APPLICATION

This application is based on and claims the benefit of the filing date of US provisional application serial no. 60/471342 filed 19 May 2003, the contents of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

The present invention relates to a bypass diode for a photovoltaic cell, of particular but by no means exclusive application in photovoltaic cell modules for use in solar concentrators of solar photovoltaic power systems.

Multijunction solar cells are used in solar concentrator photovoltaic power systems for generating power owing to their high efficiency. Although such solar cells are expensive, these efficiencies are sufficiently high to render such arrangements economically feasible. However, to maintain the reliability of such arrangements in which multiple cells are arranged in series, it is desirable to have a bypass diode for each cell in a series. The bypass diode prevents overloading of its corresponding cell when that cell has a reduced power output owing to poor illumination or performance, or some other malfunction. This allows the series of cells constituting a module to continue operating.

The number of cells in series, which determines the bus voltage, is usually greater than a hundred, so the bypassing of a single, failed cell will result in a power loss of 1% or less. The bypass diodes thus allow the system to keep operating with minimal loss of output.

One existing system is illustrated in US Patent No. 6,020,555, in which each cell is connected in parallel with its corresponding bypass diode resulting in a series of diodes in parallel with a series of cells.

However, in existing arrangements, where the bypass diodes are essentially adjacent to the cells, are unsuitable for systems with closely packed cells, such as dish concentrator or central receiver systems.

SUMMARY OF THE INVENTION

The present invention provides in a first aspect a photovoltaic power module, comprising:

a substrate;

one or more photovoltaic cells mounted to the substrate;

metallised zones constituting a circuit and provided between the substrate and the photovoltaic cells, the metallised zones being electrically and thermally coupled to the photovoltaic cells; and

one or more bypass diodes each corresponding to a respective one or more of the photovoltaic cells;

wherein each of the bypass diodes is located between the substrate and the photovoltaic cells and at least in part between respective conducting portions of the metallised zones such that the respective bypass diode defines an electrical path substantially parallel to the substrate and wherein the metallised zones underlie a substantial portion of each of the photovoltaic cells.

Preferably the circuit comprises a printed or laminated circuit and each of the bypass diodes is located between and in a common plane with neighbouring metallised zones of the printed or laminated circuit.

Alternatively, however, if it is not possible to obtain or employ diodes that are sufficiently thin to be accommodated by one of the metallised zones (which may have a thickness of only 0.3 mm) the substrate may include one or more recesses that at least partially (though conceivably wholly) accommodate the diodes (preferably one diode per recess). Thus, in this embodiment the diodes are also between the substrate and the cells (there still being substrate material on the side of the diodes opposite the cells), but the diodes are also at least to some extent surrounded by substrate material.

Preferably the conducting portions of the circuit (in one embodiment the metallised zones) fit or accommodate the diodes. Preferably the terminals of each of the diodes are metallised to complement the shape of the conducting portions.

The present invention provides in a further aspect a method of bypassing one or more photovoltaic cells in a photovoltaic power module, comprising:

locating one or more bypass diodes, each corresponding to a respective one or more of the photovoltaic cells, between the photovoltaic cells and a substrate of the module, and at least in part between conducting portions of metallised zones constituting a circuit provided on the substrate between the substrate and the photovoltaic cells, such that the bypass diodes define respective electrical paths substantially parallel to the substrate;

electrically and thermally coupling the metallised zones to the photovoltaic cells such that the metallised zones underlie a substantial portion of each of the photovoltaic cells; and

electrically coupling the bypass diodes to the metallised zones with the bypass diodes arranged to bypass a corresponding one or more photovoltaic cells if a voltage across the corresponding one or more photovoltaic cells drops below a predetermined level or is reversed.

Preferably the circuit is a printed or laminated circuit. Preferably each of the diodes is located between and in a common plane with neighbouring metallised zones of the circuit.

Preferably the method includes contouring portions of the circuit (in one embodiment the metallised zones) to fit the diodes. Preferably the terminals of each of the diodes are metallised to complement the shape of the conducting portions.

In one embodiment, the method includes providing one or more recesses in the substrate for at least partially (and in some cases wholly) accommodating the diodes (preferably one diode per recess). Thus, in this embodiment the diodes are located between the cells and the substrate (there still being substrate material on the side of the diodes opposite the cells), but the diodes are also at least to some extent surrounded by substrate material.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be more clearly ascertained, embodiments will now be described by way of example, with reference to the accompanying drawing, in which:

Figure 1 is a cross-sectional view of a portion of a photovoltaic module according to an embodiment of the present invention;

Figure 2 is a schematic plan view of a bypass diode and adjacent metallised circuit of the module of figure 1;

Figure 3 is a plan view comparable to figure 2 but more closely to scale of the bypass diode and adjacent metallised circuit of the module of figure 1; and

Figure 4 is a cross-sectional view of a portion of a photovoltaic module according to another embodiment of the present invention.

DETAILED DESCRIPTION

A representative detail of a photovoltaic module according to an embodiment of the present invention is shown in cross-section at 10 in figure 1. The module includes an insulating substrate 12 with a thickness of 0.6 mm. The substrate 12 forms part of a printed circuit comprising the substrate 12 and metallised zones 14. The metallised zones 14 have a thickness of approximately 0.3 mm.

Each of a plurality of photovoltaic cells 16 is soldered to the metallised zones 14 by means of solder 18 (shown hashed in the figure). For each solar cell 16, a bypass diode 20 with terminals 22a and 22b is provided between that cell 16 and the substrate 12. Each cell 16 is connected in parallel across its respective bypass diode 20.

The diode 20 is electrically coupled to the appropriate portions of the metallised zones 14 of the circuit board by solder 18, so that it is in parallel with the corresponding cell 16.

In an alternative embodiment, the photovoltaic module includes a plurality of groups of cells. Each group of cells is then provided with a bypass diode 20, and the group of cells is connected in parallel with its corresponding bypass diode 20.

Each bypass diode 20 has a thickness approximately equal to or somewhat less than that of the metallised zones 14, hence also approximately equal to or somewhat less than 0.3 mm. The bypass diodes 20 thus do not increase the thickness of the module 10 and, being beneath the cells 16, do not restrict how closely the cells 16 can be packed in the module 10.

It is envisaged that, during manufacture, the diodes 20 would be positioned on the solder paste printed substrate 12, after which the solar photovoltaic cells 16 would be placed over the diodes 20 onto the metallised zones 14. In this manner the diode is integrated into the closely packed module 10 without requiring additional diode space around the photovoltaic cells 16.

Figure 2 is a plan view of cross-section AA from figure 1, through the plane of the metallised zones 14 and the diode

20, with the alignment of solar cell 16 (or, in an alternative embodiment, cell 16 and adjacent cells 16′ and 16″) shown by means of a dotted lines. In this (plan) view, it will be apparent how the metallised zones 14 are shaped to accommodate the diode 20 and, in particular, terminals 22a and 22b of diode 20. Solder 18 establishes the necessary electrical contact between the diode 20 and the metallised zones 14 of the circuit board.

The device is shown schematically for the sake of clarity. In reality, the diode 20 is smaller than it appears compared with the metallised zones 14. Thus, the gap between the metallised zones 14 would typically be about 0.7 mm, widening to about 1.5 mm to accommodate the diode 20. Thus, the area without metal for the cells to be soldered to is small.

The width (from left to right in this view) of the metallised zones 14 would typically be about 15 mm, while the width (from top to bottom in this view) of cell 16 would typically be about 10 mm. Neighbouring solar cells (16, 16′, 16″) are thus very close.

Figure 3 is comparable to figure 2, but more closely to scale so that a better idea of the relative sizes of the diode, cells and metallised zones can be ascertained.

Figure 4 is a cross-sectional view (comparable to that of figure 1) of a representative detail 30 of a photovoltaic module according to an alternative embodiment. In this figure, like reference numerals have been used to identify like features when compared with the embodiment of figure 1.

As in the embodiment of figure 1, the diode module of this embodiment includes an insulating substrate 32 with a thickness generally of 0.6 mm. The substrate 32 forms part of a printed circuit comprising the substrate 32 and metallised zones 14. The metallised zones 14 have a thickness of approximately 0.3 mm. However, bypass diode 34 (with terminals 36a and 36b) has a thickness greater than that of diode 20 of figure 1 and hence greater than that of metallised zones 14. Thus, a shallow recess 38 is provided in substrate 32 in order to accommodate bypass diode 34 to a depth sufficient to ensure that bypass diode 34 does not extend upwardly beyond the metallised zones 14. The solder 18 extends downwardly into the recess 38 to a sufficient extent to ensure good electrical contact is made with terminals 36a and 36b.

This embodiment allows the use of diodes with a somewhat greater thickness than in the embodiment shown in figure 1, which in some applications may be desirable or necessary owing to diode availability or cost.

Thus, the bypass diode arrangement of this invention allows one to minimize the impedance of thermal transfer between the cell and the substrate. Such impedance - particularly in high intensity or high power applications - could otherwise seriously compromise performance or even render the device impractical.

Modifications within the scope of the invention may be readily effected by those skilled in the art. It is to be understood, therefore, that this invention is not limited to the particular embodiments described by way of example here and above.

In the claims that follow and in the preceding description of the invention, except where the context requires otherwise owing to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

Further, any reference herein to prior art is not intended to imply that such prior art forms or formed a part of the common general knowledge.

CLAIMS:

1. A photovoltaic power module, comprising:

a substrate;

one or more photovoltaic cells mounted to said substrate;

metallised zones constituting a circuit and provided between said substrate and said photovoltaic cells, said metallised zones being electrically and thermally coupled to said photovoltaic cells; and

one or more bypass diodes each corresponding to a respective one or more of said photovoltaic cells;

wherein each of said bypass diodes is located between said substrate and said photovoltaic cells and at least in part between respective conducting portions of said metallised zones such that said respective bypass diode defines an electrical path substantially parallel to said substrate and wherein said metallised zones underlie a substantial portion of each of said photovoltaic cells.

2. A photovoltaic power module as claimed in claim 1, wherein said circuit comprises a printed or laminated circuit and each of said bypass diodes is located between and in a common plane with neighbouring metallised zones of said printed or laminated circuit.

3. A photovoltaic power module as claimed in either claim 1 or 2, wherein each of said bypass diodes has a thickness that is substantially equal to or less than the thickness of said metallised zones.

4. A photovoltaic power module as claimed in any one of the preceding claims, wherein the substrate includes one or more recesses that at least partially accommodate the bypass diodes.

5. A photovoltaic power module as claimed in any one of

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the preceding claims, wherein the conducting portions have contours that fit or accommodate said bypass diodes.

6. A photovoltaic power module as claimed in any one of the preceding claims, wherein each of said bypass diodes has metallised terminals that complement the shape of said conducting portions.

7. A photovoltaic power module as claimed in any one of the preceding claims, wherein said bypass diodes do not protrude towards said photovoltaic cells beyond said metallised zones.

8. A photovoltaic power module as claimed in any one of the preceding claims, wherein each of said bypass diodes are thermally coupled to said metallised zones via at least two cooling paths.

9. A photovoltaic power module as claimed in any one of the preceding claims, wherein an electrically conductive bonding material is provided between said photovoltaic cells and said metallised zones that electrically couples said photovoltaic cells to said metallised zones, and said bypass diodes are below a plane defined by an upper surface of said electrically conductive bonding material.

10. A photovoltaic power module as claimed in claim 9, wherein said electrically conductive bonding material bonds said substrate to said bypass diodes.

11. A photovoltaic power module as claimed in any one of the preceding claims, wherein said bypass diodes have lower faces below a plane defined by an upper surface of said metallised zones.

12. A photovoltaic power module as claimed in any one of the preceding claims, wherein said bypass diodes have

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lower faces proximate an upper surface of said substrate.

13. A photovoltaic power module as claimed in any one of the preceding claims, wherein each of said bypass diodes has a thickness that is substantially equal to the thickness of said metallised zones.

14. A solar concentrator including a photovoltaic power module as claimed in any one of claims 1 to 13.

15. A method of bypassing one or more photovoltaic cells in a photovoltaic power module, comprising:

locating one or more bypass diodes, each corresponding to a respective one or more of said photovoltaic cells, between said photovoltaic cells and a substrate of said module, and at least in part between conducting portions of metallised zones constituting a circuit provided on said substrate between said substrate and said photovoltaic cells, such that said bypass diodes define respective electrical paths substantially parallel to said substrate;

electrically and thermally coupling said metallised zones to said photovoltaic cells such that said metallised zones underlie a substantial portion of each of said photovoltaic cells; and

electrically coupling said bypass diodes to said metallised zones with said bypass diodes arranged to bypass a corresponding one or more photovoltaic cells if a voltage across said corresponding one or more photovoltaic cells drops below a predetermined level or is reversed.

16. A method as claimed in claim 15, wherein the circuit is a printed or laminated circuit.

17. A method as claimed in either claim 15 or 16, including locating each of said bypass diodes between and in a common plane with neighbouring metallised zones of

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said circuit.

18. A method as claimed in any one of claims 15 to 17, including providing each of said bypass diodes with a thickness that is substantially equal to or less than the thickness of said metallised zones.

19. A method as claimed in any one of claims 15 to 18, including providing said substrate with one or more recesses for at least partially accommodating said bypass diodes.

20. A method as claimed in any one of claims 15 to 19, including contouring portions of the circuit to fit or accommodate said bypass diodes.

21. A method as claimed in any one of claims 15 to 20, wherein each of said bypass diodes has metallised terminals that complement the shape of said conducting portions.

22. A method as claimed in any one of claims 15 to 20, comprising electrically coupling said photovoltaic cells to said metallised zones with an electrically conductive bonding material provided between said photovoltaic cells and said metallised zones, and locating said bypass diodes below a plane defined by a upper surface of said electrically conductive bonding material.

23. A method as claimed in claim 22, comprising bonding said substrate to said bypass diodes with said electrically conductive bonding material.

24. A method as claimed in any one of claims 15 to 23, comprising locating said bypass diodes with lower faces of said bypass diodes below a plane defined by an upper surface of said metallised zones.

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25. A method as claimed in any one of claims 15 to 24, comprising locating said bypass diodes with lower faces of said bypass diodes proximate an upper surface of said substrate.

26. A method as claimed in any one of claims 15 to 25, including providing each of said bypass diodes with a thickness that is substantially equal to the thickness of said metallised zones.

27. A photovoltaic cell as hereinbefore described with reference to figures 1 to 3 or to figure 4 of the accompanying drawings.

28. A method as hereinbefore described with reference to figures 1 to 3 or to figure 4 of the accompanying drawings.

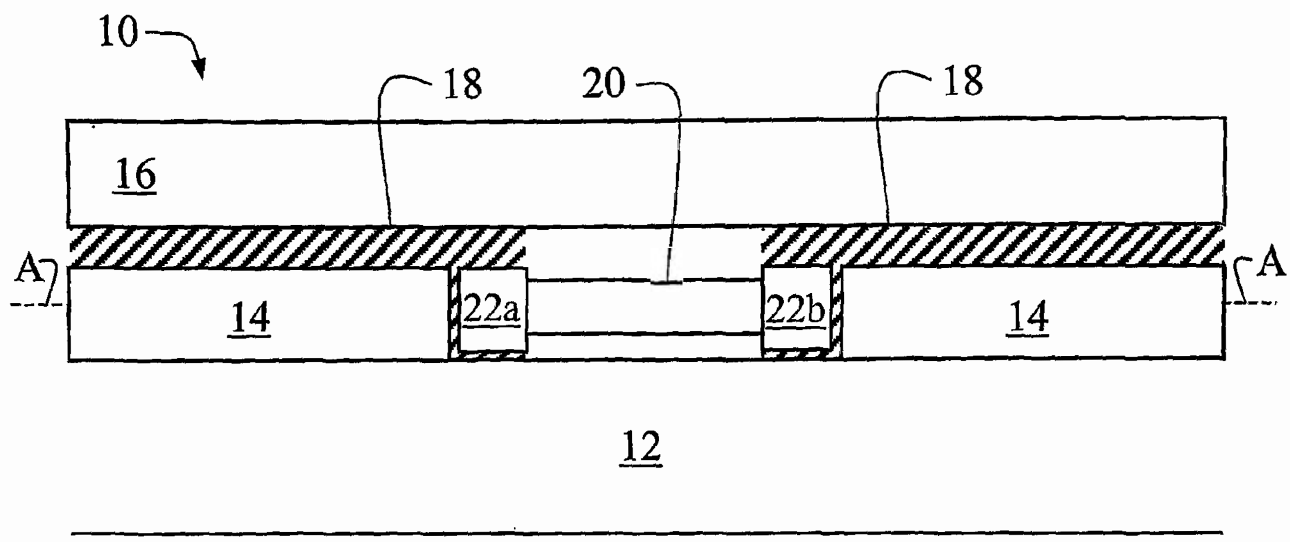

Figure 1

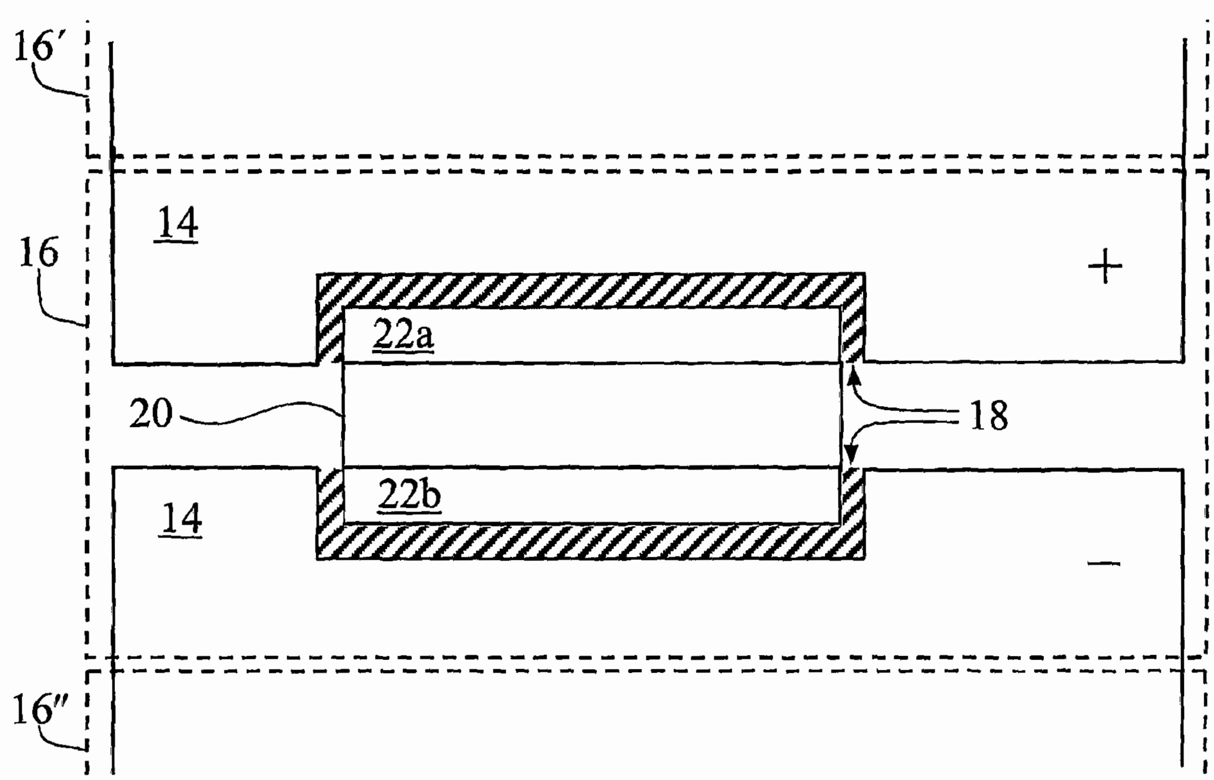

Figure 2

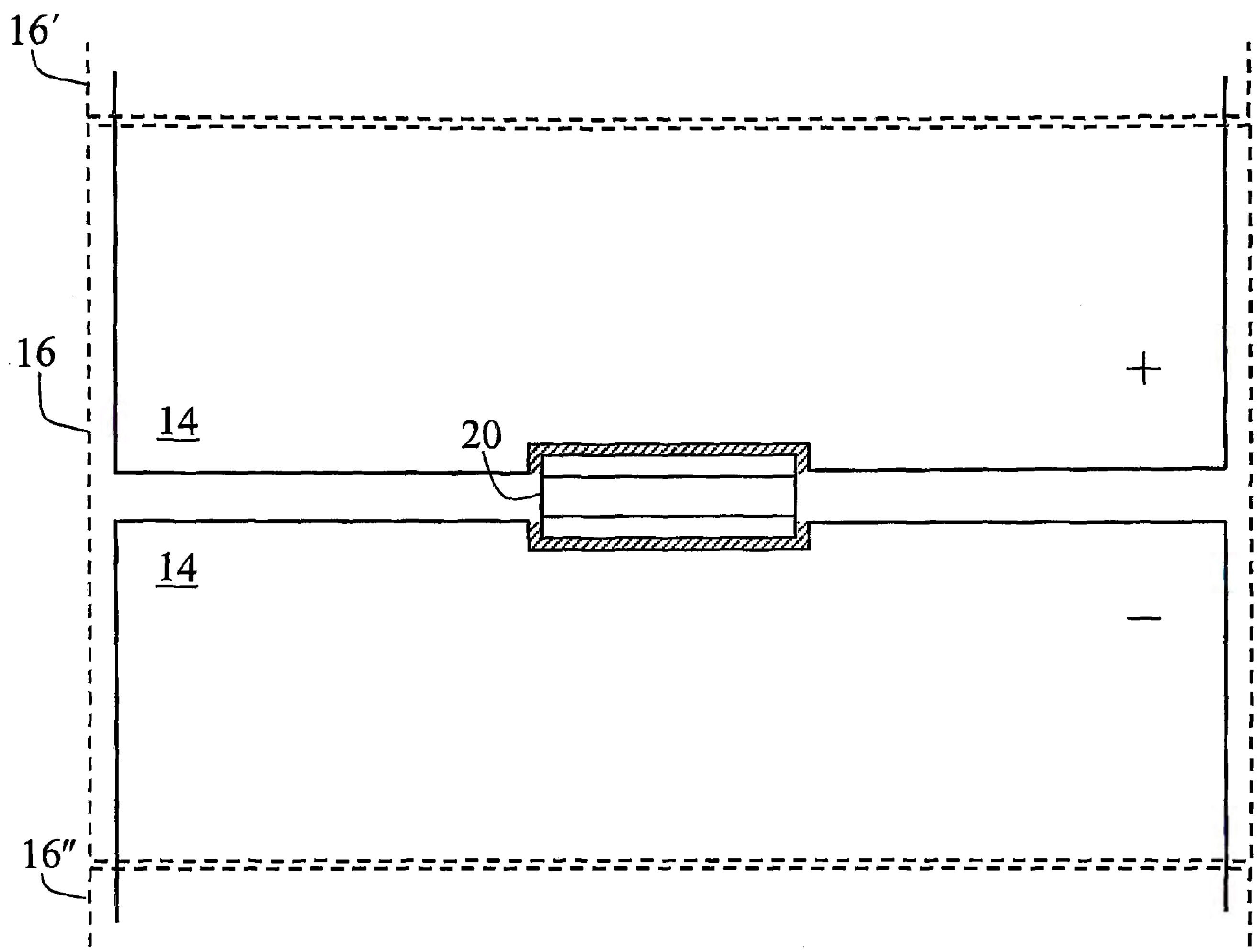

Figure 3

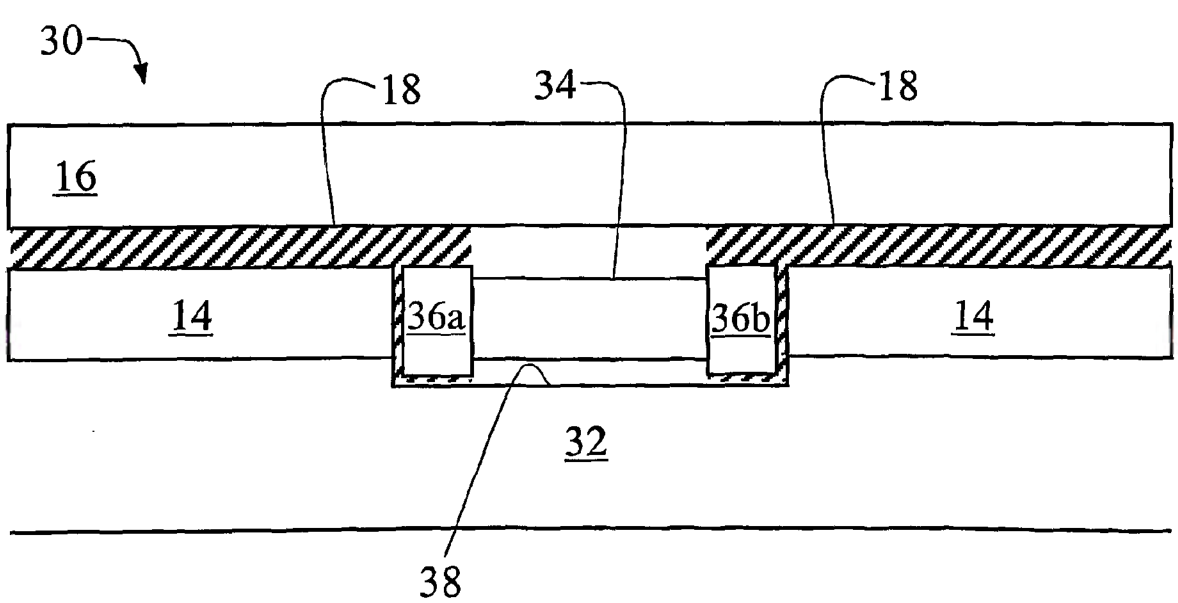

Figure 4

2.8 Lasich J.B., 2003, “Extracting Heat from An Object”, Patent Application No. 1661187, World International Property Organisation

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(71) Applicant (*for all designated States except US*): **SOLAR SYSTEMS PTY LTD** [AU/AU]; 6 Luton Lane, Hawthorn, Victoria 3122 (AU).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): **LASICH, John, Beavis** [AU/AU]; 11 Pretoria Street, Balwyn, Victoria 3103 (AU).

(74) Agent: **GRIFFITH HACK**; 509 St Kilda Road, Melbourne, Victoria 3004 (AU).

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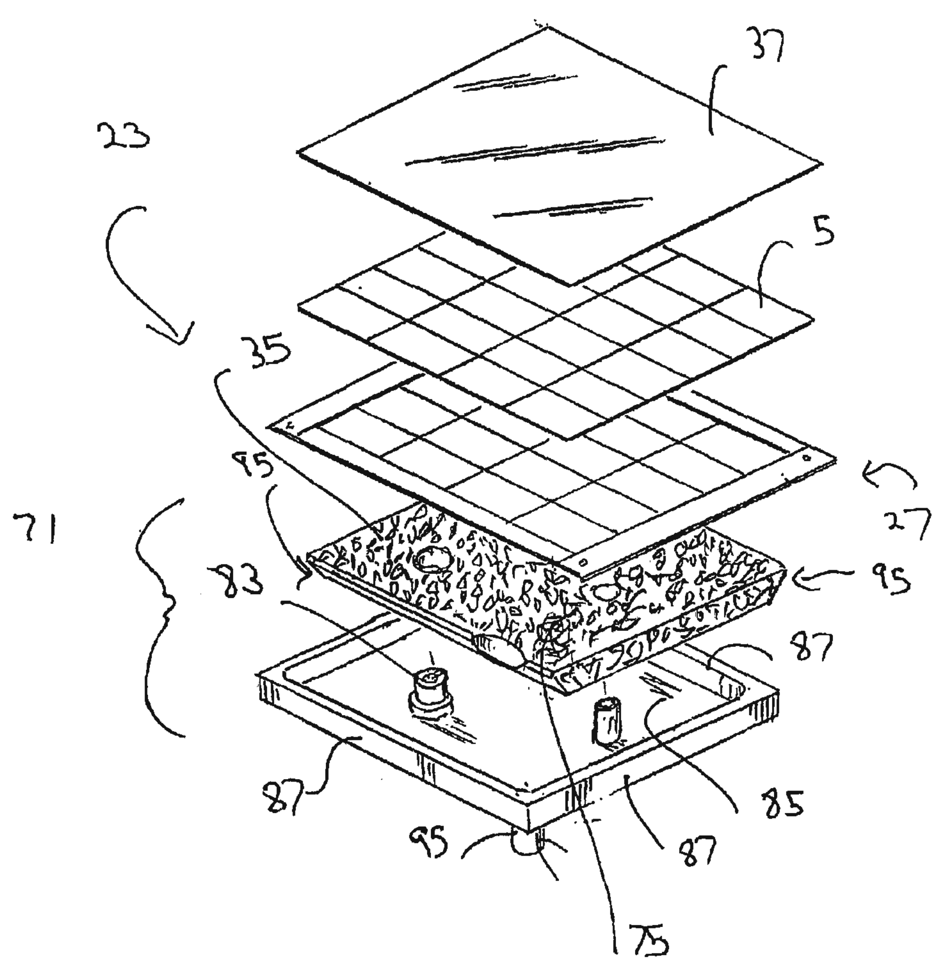

(57) Abstract: A photovoltaic cell module (23) for a receiver of solar electrical power generating system including an assembly for extracting heat from photovoltaic cells (5) is disclosed. The assembly includes a coolant chamber (85) positioned behind and in therinal contact with the exposed surface of the photovoltaic cells. The coolant chamber has an inlet an outlet for the cooling fluid. The coolant chamber is filled with a plurality of beads, rods, bars or balls (95) of high thermal conductivity that are in thermal contact with the photovoltaic cells and each other. They are placed in the chamber to form their shape and sintered to weld them into that shape permanently. Together they form a large surface area for heat transfer and define a three dimensional labyrinth that can conduct heat therethrough away from the photovoltaic cell or cells.

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EXTRACTING HEAT FROM AN OBJECT

The present invention relates to an assembly for extracting heat from an object.

The present invention relates generally to extracting heat from objects in situations where high rates of heat transfer are required in relatively confined spaces with low energy input to extract the heat.

One such situation is the extraction of heat from an array of photovoltaic cells in a concentrated solar radiation-based electrical power generating system and the present invention is described hereinafter, by way of example, in the context of this application but is not limited to this application.

Solar radiation-based electrical power generating systems typically include:

(a) a receiver that includes (i) an array of photovoltaic cells that convert solar energy into electrical energy and (ii) an electrical circuit for transferring the electrical energy output of the photovoltaic cells; and

(b) a means for concentrating solar radiation onto the photovoltaic cells of the receiver.

The present invention is applicable particularly, although by no means exclusively, to large scale solar radiation-based electrical power generating systems of the type described above that are capable of producing substantial amounts of electrical power ready for conditioning to at least 20kW of standard 3 phase 415 volt AC power.

Applications for such large scale power generating systems include remote area power supply for isolated grids, mains grid-connected power, water pumping, telecommunications, crude oil pumping, water purification, and hydrogen generation.

One significant issue associated with the development of commercially viable solar radiation-based electrical power generating systems of the type described above is being able to extract sufficient heat from the photovoltaic cell array to facilitate long term performance of materials of the cell array in situations in which there is:

(a) exposure to extremely high intensity solar radiation capable of producing high temperatures, i.e. temperatures considerably above 1000°C;

(b) cycling between high and low intensities of solar radiation;

(c) temperature variations between different parts of the cell array; and

(d) different rates of thermal expansion of different materials that make up the cell array and associated components.

In large scale solar radiation-based electrical power generating systems of the type described above the photovoltaic cells are exposed to solar radiation intensities of at least 200 times the intensity of the Sun during optimum operating conditions. In addition, the photovoltaic cells are subjected to significant cycling between extremely high and low levels of solar radiation and to variations in solar radiation intensity across the surface of the receiver.

International application PCT/AU02/00402 in the name of the applicant discloses a receiver of a solar radiation-based electrical power generating system that includes a plurality of cell modules that are connected together electrically. The International application discloses that each module includes a plurality of photovoltaic cells and a particular form of an assembly for extracting heat from the array of photovoltaic cells.

An object of the present invention is to provide an alternative heat extraction assembly for a cell array that makes it possible for the cell array to be sufficiently cooled to withstand long term exposure to extremely high intensities of solar radiation, cycling between extremely high and low intensities of solar radiation, temperature variations between different sections of components of the modules and the receiver, and different rates of thermal expansion of different materials that make up the cell array.

In general terms, the present invention provides a photovoltaic cell module for a receiver of solar radiation-based electrical power generating system. The module includes an assembly for extracting heat from the photovoltaic cells. The heat extraction assembly includes a coolant chamber positioned behind and in thermal contact with the exposed surface of the photovoltaic cells. The coolant chamber includes an inlet for a coolant and an outlet for heated coolant. The heat extraction assembly also includes a plurality of beads, rods, bars or balls of high thermal conductivity material in the coolant chamber that are in thermal contact with the photovoltaic cells and each other and together have a large surface area for heat transfer and define a three dimensional labyrinth within the coolant chamber that can conduct heat therethrough away from the photovoltaic cell or cells to coolant flowing through the labyrinth from the inlet to the outlet of the coolant chamber.

In more specific terms, according to the present invention there is provided a photovoltaic cell module for a receiver of solar radiation-based electrical power generating system, the module including:

(a) one or more than one photovoltaic cell having an exposed surface for solar radiation;

(b) an electrical connection for transferring the electrical energy output of the photovoltaic cell or cells to an output circuit, and

(c) an assembly for extracting heat from the photovoltaic cell or cells, the assembly including (i) a housing positioned behind and in thermal contact with the exposed surface of the photovoltaic cell or cells, the housong including a base and side walls extending from the base, with the base, the side walls and the photovoltaic cell or cells defining a coolant chamber, and the housing including an inlet for supplying a coolant into the chamber and an outlet for discharging the coolant from the chamber, and (ii) a coolant member located in the coolant chamber in heat transfer relationship with the photovoltaic cell or cells, the coolant member including a plurality of beads, rods, bars or balls of high thermal conductivity material that are in thermal contact and have a large surface area for heat transfer and define a three dimensional labyrinth that can conduct heat therethrough away from the photovoltaic cell or cells via the substantial number of heat transfer pathways formed by the thermally connected beads, rods, bars or balls and has a substantial number of coolant flow passages for a coolant that, in use of the module, is supplied to the coolant chamber via the inlet and flows through the coolant member and is discharged from the coolant chamber via the outlet.

The invention is a simple, economic, compact, efficient heat sink based on a labyrinth of thermally conductive material and voids with optimised ratios for heat conductance located within a coolant chamber and capable of extracting substantial amounts of heat from the photovoltaic cell/cells. The labyrinth has a large surface area for high heat transfer to the coolant, an optimised void space to facilitate sufficient coolant flow to remove concentrated heat energy from the photovoltaic cell/cells with low pressure drop of coolant and consequential low coolant pumping power required to circulate the coolant. In particular, the heat sink of the invention achieves necessary heat extraction from the photovoltaic cell/cells within a significant constraint of locating the heat sink wholly behind the projected cell area and thereby allowing the exposed receiver area to be entirely comprised of photovoltaic cell/cells. This space constraint is not encountered with heat sinks used in other non-solar energy applications and is a significant constraint in the context of solar radiation-based electrical power generating systems.

The applicant has found that the above-described cell module, which is characterised by a substantial number of heat transfer pathways formed by the thermally contacting beads, rods, bars or balls and the substantial number of coolant flow passages, is capable of extracting significant amounts of heat generated by incident concentrated solar radiation in an economical, efficient and reliable manner. In particular, the applicant has found that the labyrinth structure of the coolant member makes it possible to direct heat energy progressively away from the photovoltaic cell or cells and the beads, rods, bars or balls of high thermal conductivity material and thereafter to the coolant.

Thus, the cell module addresses the significant issue that a large portion of incident concentrated radiation on photovoltaic cells of receivers of large scale solar radiation-based electrical power generating systems is not converted to electricity and manifests itself as heat that would normally reduce the efficiency of photovoltaic cells substantially by increasing their operating temperature.

In particular, the applicant has found that the above-described cell module makes it possible to extract sufficient heat generated by incident concentrated solar radiation so that the temperature difference between the inlet coolant temperature and the front faces of the photovoltaic cells is less than 40°C, typically less than 30°C, more typically less than 25°C, and in recent test work less that 20°C and that this result can be achieved with a low pressure drop of coolant, typically less than 100 kPa, typically less than 60 kPa, and more typically less than 40 kPa across the coolant inlet and coolant outlet of the cell module. The low pressure drop is an important consideration because it means that it is possible to minimise the energy requirements for circulating coolant through the module.

In one set of specific test work the applicant has found that the above-described cell module could be operated to maintain a temperature difference of 20.5°C between the inlet coolant temperature and the front faces of the photovoltaic cells and that under these operating conditions 30 W heat per cm^2 of exposed surface area of cell was being removed from the above-described cell module, 8.1 W electricity per cm^2 of exposed cell surface area was generated by the module, and 6 W heat per cm^2 of exposed surface area of cell was reflected by the module as infrared radiation. The coolant flow path of the module 23 forms part of the coolant circuit. In total, the cell had incident on it and processed a total of 44.1 W power (in the forms of heat, electricity, and infrared radiation) per cm^2 of exposed surface area of cell. Normally, an energy density of this level would produce temperatures of at least 600°C and at these temperatures the cell would be destroyed.

In addition, the applicant has found that the above-described cell module can be manufactured relatively inexpensively and with consistent performance.

Preferably the heat extraction assembly is located wholly behind and does not extend laterally beyond the exposed surface area of the photovoltaic cell or cells.

Preferably the coolant member includes beads, rods, bars or balls of high thermal conductivity material that are thermally connected together by sintering the beads, rods, bars or balls together. One advantage of sintering over some other options for connecting the beads, rods, bars or balls together is that there is direct contact between the beads, rods, bars or balls and the direct contact optimises heat transfer between the beads, rods, bars or balls.

Preferably the surface area for heat transfer provided by the beads, rods, bars or balls of high thermal conductivity material is at least 5, and more preferably at least 10, times the surface area of the front surface of the mass of beads, rods, bars or balls of high thermal conductivity material that are in direct contact with the substrate. Consequently, the coolant member is a particularly effective heat transfer member.

Preferably the coolant member at least

substantially occupies the volume of the coolant chamber.

Preferably the coolant inlet is located in one side wall of the housing or in the base of the housing in the region of that side wall and the coolant outlet is located in an opposed side wall or in the base in the region of that side wall.

With this arrangement, preferably the coolant member is shaped so that the coolant chamber includes a manifold in fluid communication with the coolant inlet extending along the inlet side wall and a manifold in fluid communication with the coolant outlet extending along the outlet side wall. The applicant has found in test work that this arrangement of inlet and outlet manifolds ensures that the pressure drop encountered through any flow path parallel to the plane of the photovoltaic cell or cells is substantially equal thereby facilitating even cooling throughout the entire area of the heat sink. This is an important issue in situations where the heat extraction assembly is located wholly behind and does not extend laterally beyond the surface area of the photovoltaic cell or cells. Where the heat sink extends laterally beyond the extent of the device being cooled, even cooling is not an issue.

Preferably the housing includes a weir extending upwardly from the base inwardly of the inlet side wall and defining a barrier to coolant flow across the coolant chamber from the coolant inlet.

Preferably the housing includes a weir extending upwardly from the base inwardly of the outlet side wall and defining a barrier to coolant flow from the coolant chamber to the coolant outlet.

The applicant has found in test work that the weirs improve the distribution of coolant through the coolant chamber and thereby minimise temperature variations within the chamber and increase the overall thermal conductance of the heat extraction assembly. In particular, the weir on the inlet side causes preferential flow of coolant from the inlet side away from the base and towards the plane of the photovoltaic cell or cells and thereafter parallel to the cell/cells towards the weir on the outlet side. The weir on the outlet side preferentially directs heated coolant flow away from the cell/cells towards the base and from the housing. The end result is that the weirs concentrate coolant flow in the upper sections of the coolant chamber where maximum higher levels of heat extraction are required.

Preferably the beads, rods, bars or balls of the high thermal conductivity material have a major dimension of 0.8 - 2.0 mm.

More preferably the beads, rods, bars or balls of the high thermal conductivity material have a major dimension of 0.8 - 1.4 mm.

Test work carried out by the applicant was based on the use of cylindrical rods of 1.2 mm diameter and 1.3 mm length. The rods were formed by cutting 1.2 mm diameter electrical wire.

Preferably the packing density of the beads, rods, bars or balls of the high thermal conductivity material decreases with distance away from the substrate. This feature facilitates heat transfer away from the from the photovoltaic cell or cells.

Preferably the coolant flow passages occupy between 20 and 30 % of the volume of the coolant member.

It is noted that in any given situation there is a need to strike a balance between the volume occupied by the beads, rods, bars or balls of high thermal conductivity material (ie the heat sink capacity of the coolant member), the amount of surface area for heat transfer provided by the beads, rods, bars or balls (ie the capacity of the coolant member to transfer heat to the coolant), and the void space available for flow of the coolant through the coolant member (ie the capacity of the coolant member to allow coolant flow therethrough). The volume and surface area of the beads, rods, bars or balls and he void space are interrelated and may have a competing impact on each other that needs to be considered on a case by case basis when designing a coolant member for a given situation.

Preferably the coolant member acts as a heat sink.

The coolant member may be formed from any suitable high thermal conductivity material.

Preferably the high thermal conductivity material is copper or a copper alloy.

Preferably the copper or a copper alloy is resistant to corrosion and/or erosion by the coolant.

Preferably the cell module includes a substrate on which the photovotaic cell or cells are mounted and to which the housing is mounted.

Preferably the substrate is formed from or includes one or more than one layer of a material that is an electrical insulator.

Preferably the substrate is formed from a material that has a high thermal conductivity.

One suitable material for the substrate is aluminium nitride. This ceramic material is an electrical insulator and has a high thermal conductivity.

Preferably the substrate includes a metallised layer interposed between the photovoltaic cell or cells and the electrical insulator layer or layers.

Preferably the substrate includes a metallised layer interposed between the electrical insulator layer or layers and the coolant member.

According to the present invention there is provided a method of manufacturing the above-described photovoltaic cell module that includes:

(a) forming the coolant member by supplying a predetermined mass of plurality of beads, rods, bars or balls of high thermal conductivity material into a mould of a predetermined shape and thereafter heating the beads, rods, bars or balls of high thermal conductivity material and sintering the beads, rods, bars or balls of together to form the coolant member;

(b) locating the coolant member in the housing; and

(c) mounting the photovotaic cell or cells to the housing.

According to the present invention there is provided a method of manufacturing the above-described photovoltaic cell module that includes:

(a) forming the coolant member by supplying a predetermined mass of plurality of beads, rods, bars or balls of high thermal conductivity material into the housing and thereafter heating the beads, rods, bars or balls of high thermal conductivity material and sintering the beads, rods, bars or balls of together to form the coolant member within the housing; and

(b) mounting the photovotaic cell or cells to the housing, for example by soldering or sintering the substrate to the housing.

Preferably the above-described methods include grinding the surface of the coolant member that forms a contact surface with the substrate to increase the surface area of contact between the beads, rods, bars or balls of high thermal conductivity material and the substrate.

According to the present invention there is provided a method of manufacturing the above-described photovoltaic cell module that includes forming the coolant member by supplying a predetermined mass of plurality of beads, rods, bars or balls of high thermal conductivity material into the housing and locating the substrate on the housing and thereafter heating the beads, rods, bars or balls of high thermal conductivity material and sintering the beads, rods, bars or balls of together to form the coolant member within the housing and bonding the coolant member to the housing and the substrate. One advantage of this method is that there is a better thermally conductive connection between the substrate and the coolant member than is achieved with a soldered connection.

According to the present invention there is also provided a system for generating electrical power from solar radiation which includes:

(a) a receiver that includes a plurality of photovoltaic cells for converting solar energy into electrical energy and an electrical circuit for transferring the electrical energy output of the photovoltaic cells; and

(b) a means for concentrating solar radiation onto the receiver; and

the system being characterised in that the receiver includes a plurality of the above-described photovoltaic cell modules, an electrical circuit that includes the photovoltaic cells of each module, and a coolant circuit that includes the heat extraction assembly of each module.

Preferably in use the coolant maintains the photovoltaic cells at a temperature of no more than 80°C.

More preferably in use the coolant maintains the photovoltaic cells at a temperature of no more than 70°C.

It is preferred particularly that in use the coolant maintains the photovoltaic cells at a temperature of no more than 60°C.

It is preferred more particularly that in use the coolant maintains the photovoltaic cells at a temperature of no more than 40°C.

Preferably the receiver includes a frame that supports the modules in an array of the modules.

Preferably the support frame supports the modules so that the photovoltaic cells form an at least substantially continuous surface that is exposed to reflected concentrated solar radiation.

The surface may be flat, curved or stepped in a Fresnel manner.

Preferably the support frame includes a coolant flow path that supplies coolant to the coolant inlets of the modules and removes coolant from the coolant outlets of the modules.

Preferably the coolant is water.

Preferably the water inlet temperature is as cold as can be obtained reasonably.

Typically, the water inlet temperature is in the range of 10-30°C.

Typically the water outlet temperature is in the range of 20-40°C.

Preferably the means for concentrating solar radiation onto the receiver is a dish reflector that includes an array of mirrors for reflecting solar radiation that is incident on the mirrors towards the photovoltaic cells.

Preferably the surface area of the mirrors of the dish reflector that is exposed to solar radiation is substantially greater than the surface area of the photovoltaic cells that is exposed to reflected solar radiation.

The present invention is described further by way of example with reference to the accompanying drawings, of which:

Figure 1 is a perspective view of a preferred embodiment of a system for generating electrical power from solar radiation in accordance with the present invention;

Figure 2 is a front view of the receiver of the system shown in Figure 1 which illustrates the exposed surface area of the photovoltaic cells of the receiver;

Figure 3 is a partially cut-away perspective view of the receiver with components removed to illustrate more clearly the coolant circuit that forms part of the receiver;

Figure 4 is an exploded perspective view of an embodiment of a photovoltaic cell module in accordance with the present invention that forms part of the receiver;

Figure 5 is a top plan view of the housing of the cell module shown in Figure 4;

Figure 6 is a section along the line 5-5 of Figure 5;

Figure 7 is a perspective view of another embodiment of a housing of a photovoltaic cell module in accordance with the present invention;

Figure 8 is a top plan view of the housing shown in Figure 7; and

Figure 9 is a top plan view of another embodiment of a housing of a photovoltaic cell module in accordance with the present invention.

The solar radiation-based electric power generating system shown in Figure 1 includes a parabolic array of mirrors 3 that reflects solar radiation that is incident on the mirrors towards a plurality of photovoltaic cells 5.

The cells 5 form part of a solar radiation receiver that is generally identified by the numeral 7.

The general arrangement of the receiver 7 is shown in Figures 2 and 3.

Figures 1 to 3 are identical to Figures 1 to 3 of International application PCT/AU02/00402 and the disclosure in the International application is incorporated herein by cross-reference.

The surface area of the mirrors 3 that is exposed to solar radiation is substantially greater than the surface area of the photovoltaic cells 5 that is exposed to reflected solar radiation.

The photovoltaic cells 5 convert reflected solar radiation into DC electrical energy.

The receiver 7 includes an electrical circuit (not shown) for the electrical energy output of the photovoltaic cells.

The mirrors 3 are mounted to a framework 9. The mirrors and the framework define a dish reflector.

A series of arms 11 extend from the framework 9 to the receiver 7 and locate the receiver as shown in Figure 1.

The system further includes:

(a) a support assembly 13 that supports the dish reflector and the receiver in relation to a ground surface and for movement to track the Sun; and

(b) a tracking system (not shown) that moves the dish reflector and the receiver as required to track the Sun.

The receiver 7 also includes a coolant circuit. The coolant circuit cools the photovoltaic cells 5 of the receiver 7 with a coolant, preferably water, in order to minimise the operating temperature and to maximise the performance (including operating life) of the photovoltaic cells 5.

The receiver 7 is purpose-built to include the coolant circuit.

Figures 2 and 3 illustrate components of the receiver that are relevant to the coolant circuit. It is noted that a number of other components of the receiver 7, such as components that make up the electrical circuit of the receiver 7, are not included in the Figures for clarity.

With reference to Figures 2 and 3, the receiver 7 includes a generally box-like structure that is defined by an assembly of hollow posts 15.

The receiver 7 also includes a solar flux modifier, generally identified by the numeral 19, which extends from a lower wall 99 (as viewed in Figure 3) of the box-like structure. The solar flux modifier 19 includes four panels 21 that extend from the lower wall 99 and converge toward each other. The solar flux modifier 19 also includes mirrors 91 mounted to the inwardly facing sides of the panels 21.

The receiver 7 also includes an array of 1536 closely packed rectangular photovoltaic cells 5 which are mounted to 64 square modules 23. The array of cells 5 can best be seen in Figure 2. The term "closely packed" means that the exposed surface area of the photovoltaic cells 5 makes up at least 98% of the total exposed surface area of the array. Each module includes 24 photovoltaic cells 5. The photovoltaic cells 5 are mounted on each module 23 so that the exposed surface of the cell array is a continuous surface. It is noted that the heat extraction assembly 71 described hereinafter makes it possible to provide a receiver with such close packing of photovoltaic cells 5 up to 100%.

The modules 23 are mounted to the lower wall 99 of the box-like structure of the receiver 7 so that the exposed surface of the combined array of photovoltaic cells 5 is a continuous plane.

As is described in more detail hereinafter, each module 23 includes a coolant flow path. The coolant flow path is an integrated part of each module 23. The coolant flow path allows coolant to be in thermal contact with the photovoltaic cells 5 and extract heat from the cells 5 so that the front faces of the cells 5 are maintained at a temperature of no more than 80°C, preferably no more than 60°C, more preferably no more than 40°C.

As is indicated above, in specific test work the applicant found that the above-described cell module could be operated to maintain a temperature difference of 20.5°C between the inlet coolant temperature and the front faces of the photovoltaic cells and that under these operating conditions 30 W heat per cm^2 of exposed surface area of cell was removed from the above-described cell module, 8.1 W electricity per cm^2 of exposed cell surface area was generated by the module, and 6 W heat per cm^2 of exposed surface area of cell was reflected by the module as infrared radiation. The coolant flow path of the module 23 forms part of the coolant circuit. In total, the cell had incident on it and processed a total of 44.1 W power (in the forms of heat, electricity, and infrared radiation) per cm^2 of exposed surface area of cell. Normally, an energy density of this level would produce temperatures of at least 600°C and at these temperatures the cell would be destroyed.

The coolant circuit also includes the above-described hollow posts 15.

In addition, the coolant circuit includes a series of parallel coolant channels 17 that form part of the lower wall 99 of the box-like structure. The ends of the channels 17 are connected to the opposed pair of lower horizontal posts 15 respectively shown in Figure 3. The lower posts 15 define an upstream header that distributes coolant to the channels 17 and a downstream header that collects coolant from the channels 17. The modules 23 are mounted to the lower surface of the channels 17 and are in fluid communication with the channels so that coolant flows via the channels 17 into and through the coolant flow passages of the modules 23 and back into the channels 17 and thereby cools the photovoltaic cells 5.

The coolant circuit also includes a coolant inlet 61 and a coolant outlet 63. The inlet 61 and the outlet 63 are located in an upper wall of the box-like structure. The inlet 61 is connected to the adjacent upper horizontal post 15 and the outlet 63 is connected to the adjacent upper horizontal post 15 as shown in Figure 3.

In use, coolant that is supplied from a source (not shown) flows via the inlet 61 into the upper horizontal post 15 connected to the inlet 61 and then down the vertical posts 15 connected to the upper horizontal post 15. The coolant then flows into the upstream lower header 15 and, as is described above, along the channels 17 and the coolant flow passages of the modules 23 and into the downstream lower header 15. The coolant then flows upwardly through the vertical posts 15 that are connected to the downstream lower header 15 and into the upper horizontal post 15. The coolant is then discharged from the receiver 7 via the outlet 63.

Figures 4 to 6 illustrate the basic construction of one embodiment of each module 23.

As is indicated above, each module 23 includes an array of 24 closely packed photovoltaic cells 5.

Each module 23 includes a substrate, generally identified by the numeral 27, on which the cells 5 are mounted. The substrate includes a central layer (not shown) of a ceramic material and outer metallised layers (not shown) on opposite faces of the ceramic material layer.

Each module 23 also includes a glass cover 37 that is mounted on the exposed surface of the array of photovoltaic cells 5. The glass cover 37 may be formed to optimise transmission of useful wavelengths of solar radiation and minimise transmission of un-wanted wavelengths of solar radiation.

Each module 23 also includes an assembly 71 to facilitate extraction of heat from the photovoltaic cells 5. The assembly 71 is formed from a high thermal conductivity material. A preferred material is copper.

The assembly 71 is located wholly behind and therefore has less cross sectional area than the exposed surfaces of the photovoltaic cells 5.

The assembly 71 includes a housing 79 and a coolant member 35 located in the housing.

The housing 79 includes a base 85 and side walls 87 extending from the base. The substrate 27 is mounted on the housing 79, whereby the base 85, the side walls 87, and the substrate 27 define a coolant chamber.

The housing 79 further includes an inlet 91 for supplying a coolant such as water into the coolant chamber and an outlet 93 for discharging the coolant from the chamber. The inlet 91 is in the form of a circular hole located in the base 85 in one corner of the housing 79. The outlet 93 is in the form of a circular hole located in the base 85 in a diametrically-opposed corner of the housing 79.

The coolant member 35 is shaped to substantially occupy the volume of the coolant chamber. The upper surface 75 of the coolant member is formed as a flat surface and contacts the substrate 27.

The coolant member 35 includes a plurality of beads, rods, bars or balls of high thermal conductivity material that are sintered and thereby thermally connected together and form a porous mass that has a large volume and a large surface area for heat transfer. The beads, rods, bars or balls form a substantial number of continuous heat transfer pathways that extend through the coolant member 35. The mass of beads, rods, bars or balls is a porous rather than a solid mass and there are spaces between the sintered beads, rods, bars or balls. The spaces define a substantial number, typically at least 1000, of continuous coolant flow passages that extend through the coolant member 35. In overall terms the coolant member 35 is in the form of a labyrinth defined by the sintered beads, rods, bars or balls and the coolant flow passages in the spaces between the sintered beads, rods, bars or balls.

The above arrangement is such that, in use, coolant supplied under pressure to the coolant chamber via the coolant inlet 91 flows through the substantial number of coolant flow passageways in the coolant member 35 and discharges from the coolant chamber via the coolant outlet 93. The arrangement is such that the substantial number of heat transfer pathways conduct heat away from the front faces of the cells 5 and the heat conducted through the pathways is transferred to coolant flowing through the substantial number of coolant flow passageways.

In any given situation, factors such as the shape and size of the beads, rods, bars or balls, the packing density of the beads, rods, bars or balls, the volume occupied by the beads, rods, bars or balls, the heat transfer characteristics of the heat transfer pathways formed by the sintered beads, rods, bars or balls, and the volumetric flow rate of coolant through the coolant flow passageways are selected having regard to achieving a target rate of extraction of heat from the module 23.

The opposed end walls 95 of the coolant member 35 that are in the regions of the coolant inlet 91 and the coolant outlet 93 are downwardly tapered so that the end walls 95, the base 85 and the side walls 87 define inlet and outlet manifolds 45 that are in fluid communication with the coolant inlet and outlet and extend along the side walls 87 and therefore can supply coolant to and receive coolant from the whole of the side walls 95 of the coolant member 35.

Each module 23 also includes electrical

connections (not shown) that form part of the electrical circuit of the receiver 7 and electrically connect the photovoltaic cells 5 into the electrical circuit. The electrical connections are positioned to extend from the outer metallised layer of the substrate 27 and through one of two hollow sleeves 83 extending from the base 85 of the housing 79.

It is evident from the above that the coolant inlet 91, the coolant manifolds 45, the coolant flow passageways in the coolant member 35, and the coolant outlet 93 define a coolant flow path of each module 23.

As is indicated above, the construction of the coolant member 35 makes it possible to achieve the high levels of heat transfer that are required to maintain the photovoltaic cells 5 at temperatures of no more than 60°C and to accommodate substantially different thermal expansion of the coolant member 35 and the substrate 27 that otherwise would cause structural failure of the modules 23.

The embodiment of the module 23 shown in Figures 7 and 8 is the basic construction shown in Figures 4 to 6 and the same reference numerals are used to describe the same parts.

In addition, the module 23 includes 2 ridges 101 that extend from the base 85 inboard of and parallel to the inlet and outlet manifolds 45. The ridges 101 form a barrier or weir to coolant flow from and to the inlet and outlet manifolds 45. In general terms, the ridges 101 improve the distribution of coolant through the coolant chamber and thereby minimise temperature variations within the chamber and increase the overall thermal conductance of the heat extraction assembly 71. More specifically, coolant is forced to flow over the inlet ridge 101 in order to flow through the lower coolant flow passageways in the coolant flow member 25 and then over the outlet ridge 101 in order to flow from the lower coolant flow passageways into the outlet manifold 45. Consequently, the ridges 101 increase the path length of coolant through the lower coolant flow passageways compared to the coolant path length through upper coolant flow passageways. The ridges 101 promote greater coolant flow through the upper flow passageways, and this is an advantage in terms of optimising heat transfer from the coolant member 25.

The embodiment of the module 23 shown in Figure 9 is the basic construction shown in Figures 7 and 8 and the same reference numerals are used to describe the same parts. The main difference between the embodiments is that the inlet 91 and the outlet 93 are in the form of slots rather than circular openings. The use of slots has been found to be beneficial in certain circumstances in terms of improving the distribution of coolant through the coolant chamber.

There are a number of options for manufacturing the modules 23 shown in the Figures.

One option includes separately forming the coolant member 35, thereafter positioning the coolant member in the housing 79, and thereafter positioning the substrate 27 on the housing/coolant member. In this option, the coolant member may be formed by formed in a suitable mould and include sintering the mass of beads, rods, bars, balls of high thermal conductivity together. Furthermore, in this option the substrate 27 may be soldered onto exposed edges of the side walls 87 of the housing 79 and the exposed front face of the coolant member 35.

Another option includes placing a mass of beads, rods, bars, balls of high thermal conductivity material directly in the housing 79 and sintering the material in situ in the housing, and thereafter sintering the substrate 27 on to the assembly of the housing 79 and the coolant member 35.

Many modifications may be made to the preferred embodiment described above without departing from the spirit and scope of the present invention.

By way of example, whilst the preferred embodiment includes 1536 photovoltaic cells 5 mounted to 64 modules 23 with 24 cells per module, the present invention is not so limited and extends to any suitable number and size of photovoltaic cells and modules.

By way of further example, whilst the photovoltaic cells are mounted so that the exposed surface of the cell array is a flat surface, the present invention is not so limited and extends to any suitable shaped surface, such as curved or stepped surfaces.

By way of further example, whilst the preferred embodiment includes the receiver coolant circuit that forms part of the support frame of the receiver, the present invention is not so limited and extends to arrangements in which the coolant circuit is not part of the structural frame of the receiver.

By way of further example, whilst the preferred embodiment includes a dish reflector in the form of an array of parabolic array of mirrors 3, the present invention is not so limited and extends to any suitable means of concentrating solar radiation onto a receiver. One such suitable means is a series of heliostats arranged to focus solar radiation on to a receiver.

By way of further example, whilst the preferred embodiment of the receiver is constructed from extruded components, the present invention is not so limited and the receiver may be made by any suitable means.

By way of further example, whilst the preferred embodiment of the coolant member 35 includes a plurality of beads, rods, bars or balls of high thermal conductivity material that are sintered and thereby in thermal contact, the present invention is not so limited and the beads, rods, bars or balls may be connected together thermally in any suitable way. Other options include ultrasonic welding, resistance welding, and plasma processing.

By way of further example, whilst the preferred embodiment is described in the context of the extraction of heat from an array of photovoltaic cells that are contacted by concentrated solar radiation, the present invention is not so limited and extends to the extraction of heat derived from any source of intense radiation.

CLAIMS:

1. A photovoltaic cell module for a receiver of solar radiation-based electrical power generating system, the module including:

(a) one or more than one photovoltaic cell having an exposed surface for solar radiation;

(b) an electrical connection for transferring the electrical energy output of the photovoltaic cell or cells to an output circuit, and

(c) an assembly for extracting heat from the photovoltaic cell or cells, the assembly including (i) a housing positioned behind and in thermal contact with the exposed surface of the photovoltaic cell or cells, the housong including a base and side walls extending from the base, with the base, the side walls and the photovoltaic cell or cells defining a coolant chamber, and the housing including an inlet for supplying a coolant into the chamber and an outlet for discharging the coolant from the chamber, and (ii) a coolant member located in the coolant chamber in heat transfer relationship with the photovoltaic cell or cells, the coolant member including a plurality of beads, rods, bars or balls of high thermal conductivity material that are in thermal contact and have a large surface area for heat transfer and define a three dimensional labyrinth that can conduct heat therethrough away from the photovoltaic cell or cells via the substantial number of heat transfer pathways formed by the thermally connected beads, rods, bars or balls and has a substantial number of coolant flow passages for a coolant that, in use of the module, is supplied to the coolant chamber via the inlet and flows through the coolant member and is discharged from the coolant chamber via the outlet.

2. The cell module defined in claim 1 wherein the heat extraction assembly is located wholly behind and does not extend laterally beyond the exposed surface area of the photovoltaic cell or cells.

3. The cell module defined in claim 1 or claim 2 wherein the surface area for heat transfer provided by the beads, rods, bars or balls of high thermal conductivity material is at least 5 times the surface area of the front surface of the mass of beads, rods, bars or balls of high thermal conductivity material that are in direct contact with the substrate.

4. The cell module defined in any one of the preceding claims wherein the coolant member at least substantially occupies the volume of the coolant chamber.

5. The cell module defined in any one of the preceding claims wherein the coolant inlet is located in one side wall of the housing or in the base of the housing in the region of that side wall and the coolant outlet is located in an opposed side wall or in the base in the region of that side wall.

6. The cell module defined in claim 5 wherein the coolant member is shaped so that the coolant chamber includes a manifold in fluid communication with the coolant inlet extending along the inlet side wall and a manifold in fluid communication with the coolant outlet extending along the outlet side wall.

7. The cell module defined in claim 5 or claim 6 wherein the housing includes a weir extending upwardly from the base inwardly of the inlet side wall and defining a barrier to coolant flow across the coolant chamber from the coolant inlet.

8. The cell module defined in any one of claims 5 to 7 wherein the housing includes a weir extending upwardly from the base inwardly of the outlet side wall and defining a barrier to coolant flow from the coolant chamber to the coolant outlet.

9. The cell module defined in any one of the preceding claims wherein the beads, rods, bars or balls of the high thermal conductivity material have a major dimension of 0.8 - 2.0 mm.

10. The cell module defined in any one of the preceding claims wherein the beads, rods, bars or balls of the high thermal conductivity material have a major dimension of 0.8 - 1.4 mm.

11. The cell module defined in any one of the preceding claims wherein the packing density of the beads, rods, bars or balls of the high thermal conductivity material decreases with distance away from the substrate.

12. The cell module defined in any one of the preceding claims wherein the coolant flow passages occupy between 20 and 30 % of the volume of the coolant member.

13. The cell module defined in any one of the preceding claims includes a substrate on which the photovoltaic cell or cells are mounted and to which the housing is mounted.

14. The cell module defined in claim 13 wherein the substrate is formed from or includes one or more than one layer of a material that is an electrical insulator.

15. The cell module defined in claim 13 or claim 14 wherein the substrate is formed from a material that has a high thermal conductivity.

16. The cell module defined in claim 14 wherein the substrate includes a metallised layer interposed between the photovoltaic cell or cells and the electrical insulator layer or layers.

17. The cell module defined in claim 14 or claim 16 wherein the substrate includes a metallised layer interposed between the electrical insulator layer or layers and the coolant member.

18. A method of manufacturing the photovoltaic cell module defined in any one of the preceding claims that includes:

(a) forming the coolant member by supplying a predetermined mass of plurality of beads, rods, bars or balls of high thermal conductivity material into a mould of a predetermined shape and thereafter heating the beads, rods, bars or balls of high thermal conductivity material and sintering the beads, rods, bars or balls of together to form the coolant member;

(b) locating the coolant member in the housing; and

(c) mounting the photovotaic cell or cells to the housing.

19. A method of manufacturing the photovoltaic cell module defined in any one of claims 1 to 17 that includes:

(a) forming the coolant member by supplying a predetermined mass of plurality of beads, rods, bars or balls of high thermal conductivity material into the housing and thereafter heating the beads, rods, bars or balls of high thermal conductivity material and sintering the beads, rods, bars or balls of together to form the coolant member within the housing; and

(b) mounting the photovotaic cell or cells to the housing, for example by soldering or sintering the substrate to the housing.

20. The method defined in claim 18 or claim 19 includes grinding the surface of the coolant member that forms a contact surface with the substrate to increase the surface area of contact between the beads, rods, bars or balls of high thermal conductivity material and the substrate.

21. A method of manufacturing the photovoltaic cell module defined in any one of claims 1 to 17 includes forming the coolant member by supplying a predetermined mass of plurality of beads, rods, bars or balls of high thermal conductivity material into the housing and locating the substrate on the housing and thereafter heating the beads, rods, bars or balls of high thermal conductivity material and sintering the beads, rods, bars or balls of together to form the coolant member within the housing and bonding the coolant member to the housing and the substrate.

22. A system for generating electrical power from solar radiation which includes:

(a) a receiver that includes a plurality of photovoltaic cells for converting solar energy into electrical energy and an electrical circuit for transferring the electrical energy output of the photovoltaic cells; and

(b) a means for concentrating solar radiation onto the receiver; and the system being characterised in that the receiver includes a plurality of the photovoltaic cell modules defined in any one of claims 1 to 16, an electrical circuit that includes the photovoltaic cells of each module, and a coolant circuit that includes the heat extraction assembly of each module.

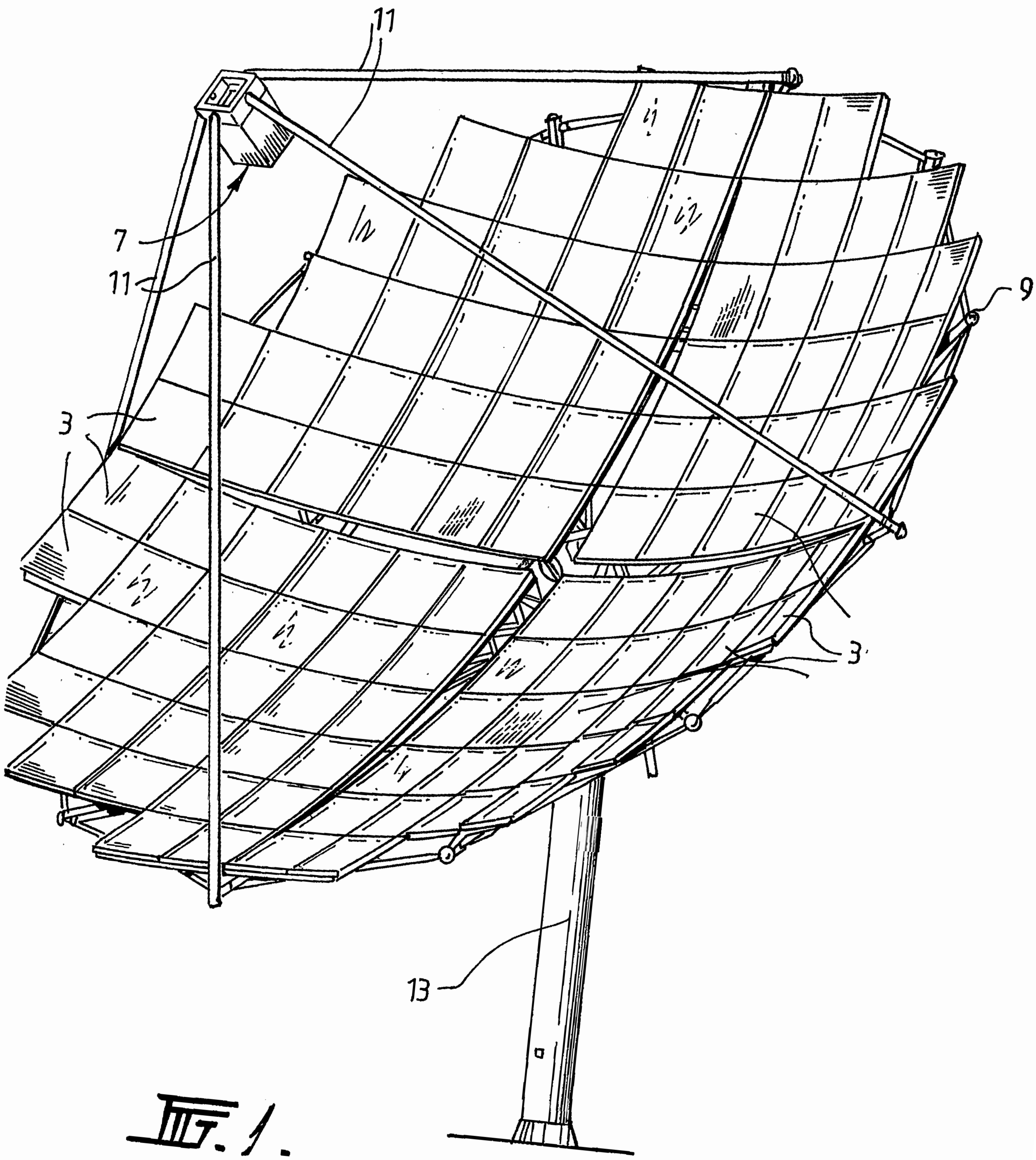


Fig. 1.

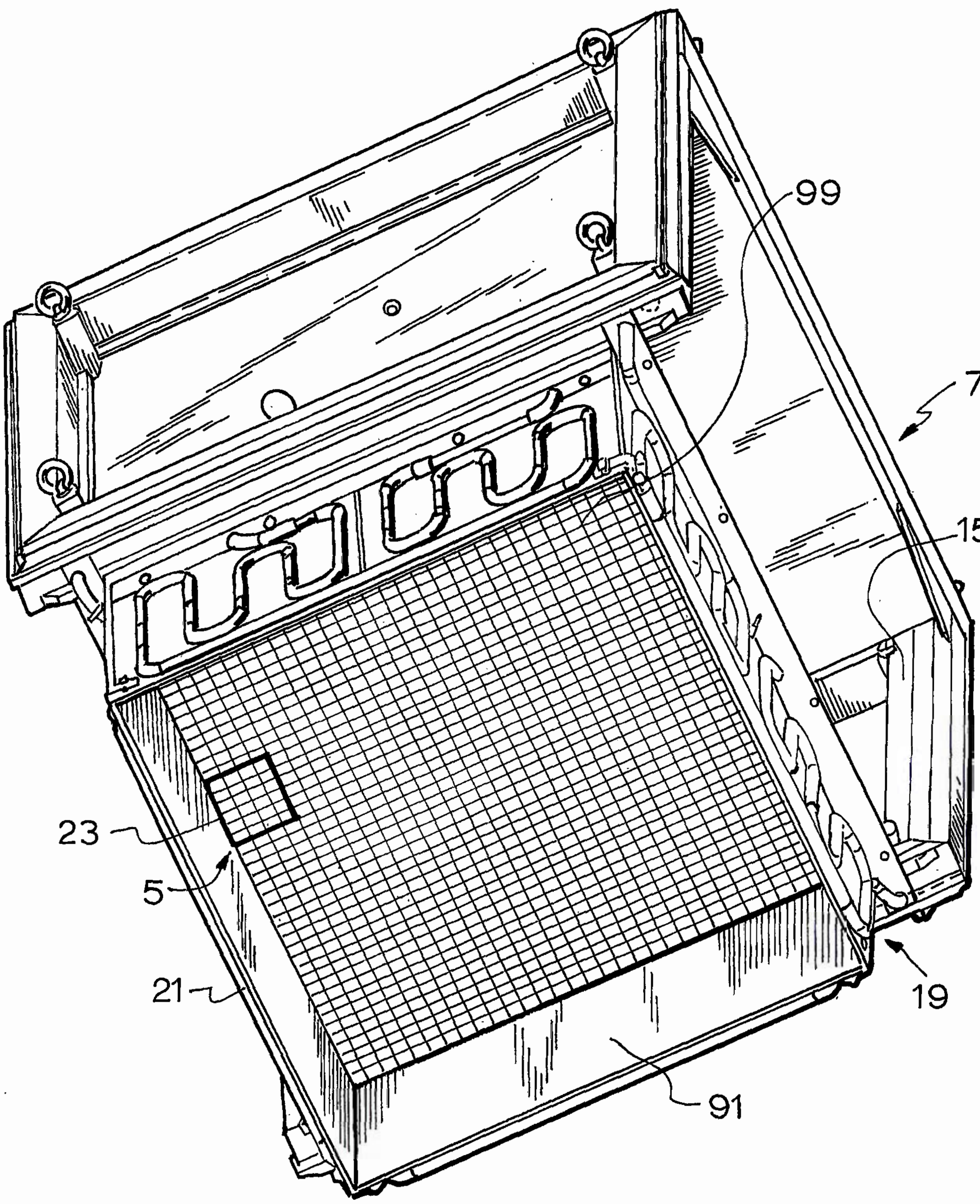


FIG. 2.

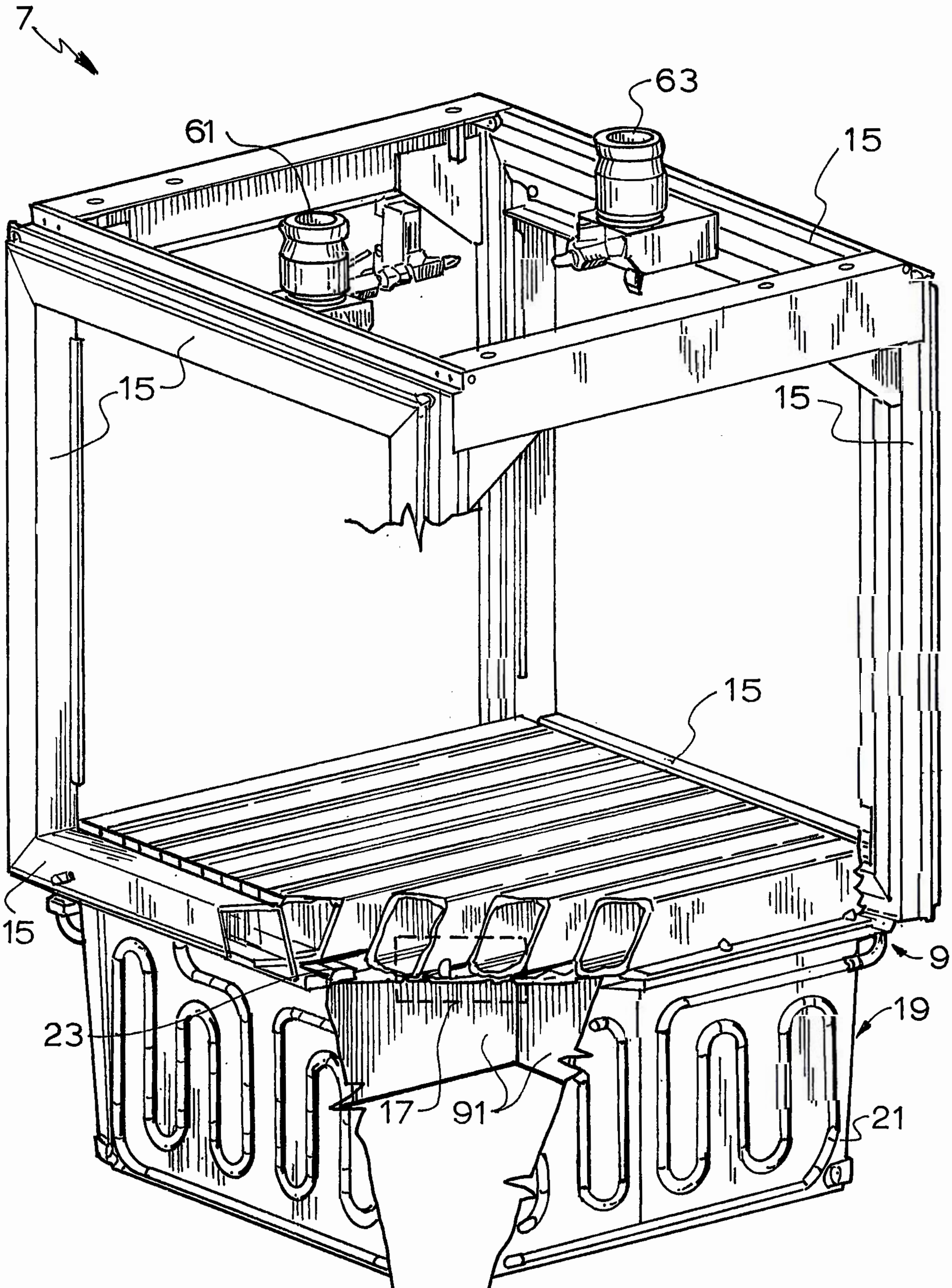


FIG. 3.

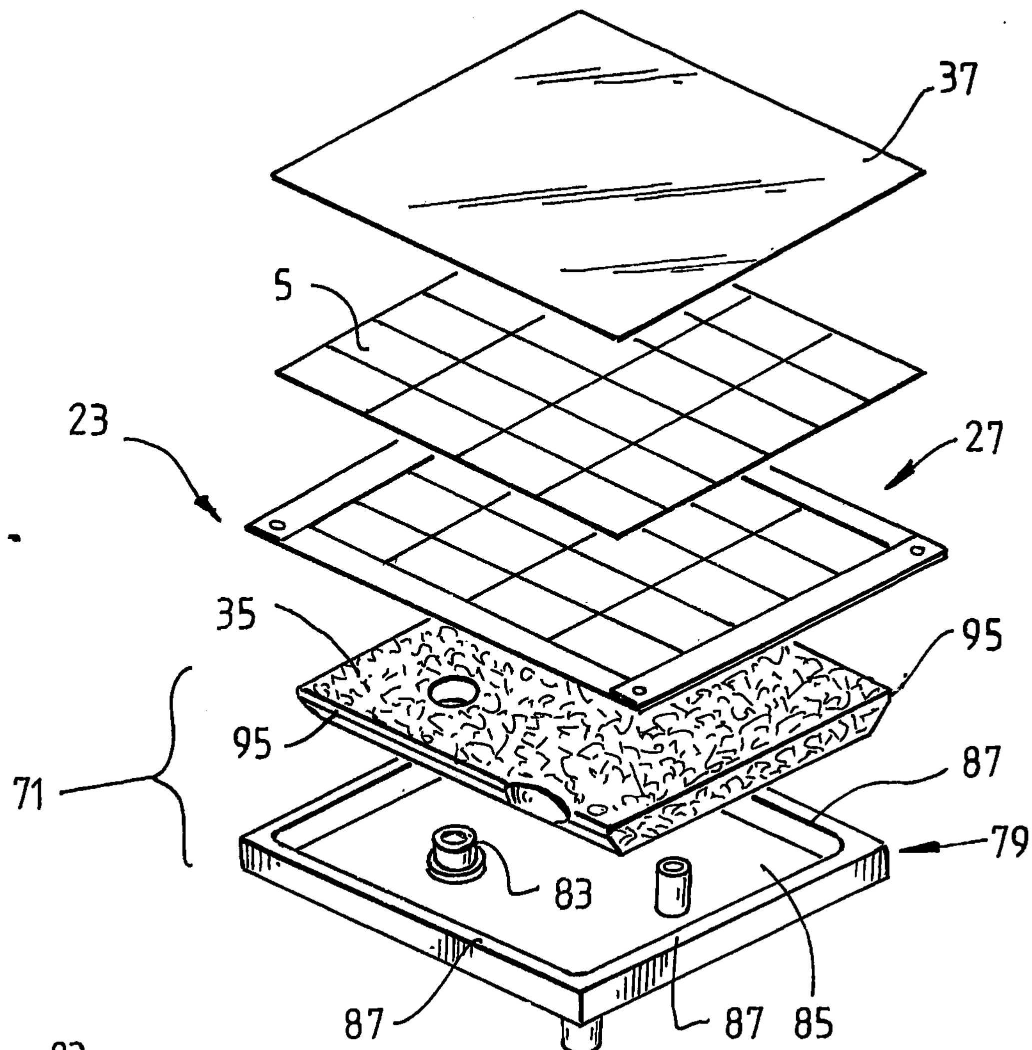


FIG. 4.

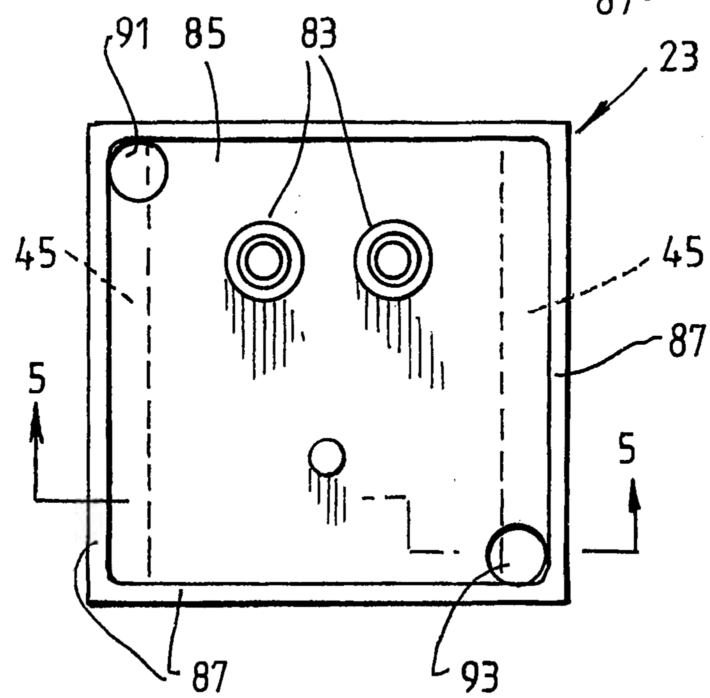


FIG. 5.

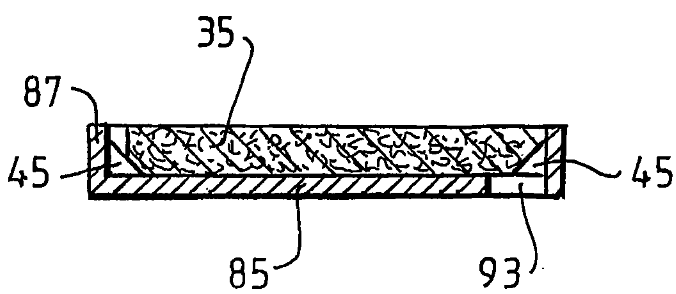


FIG. 6.

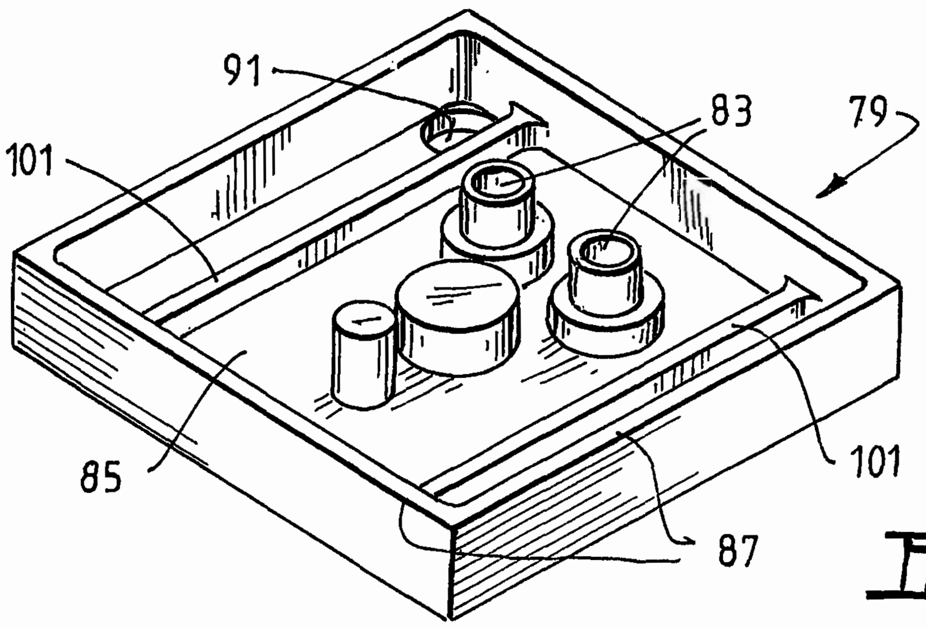


FIG. 7.

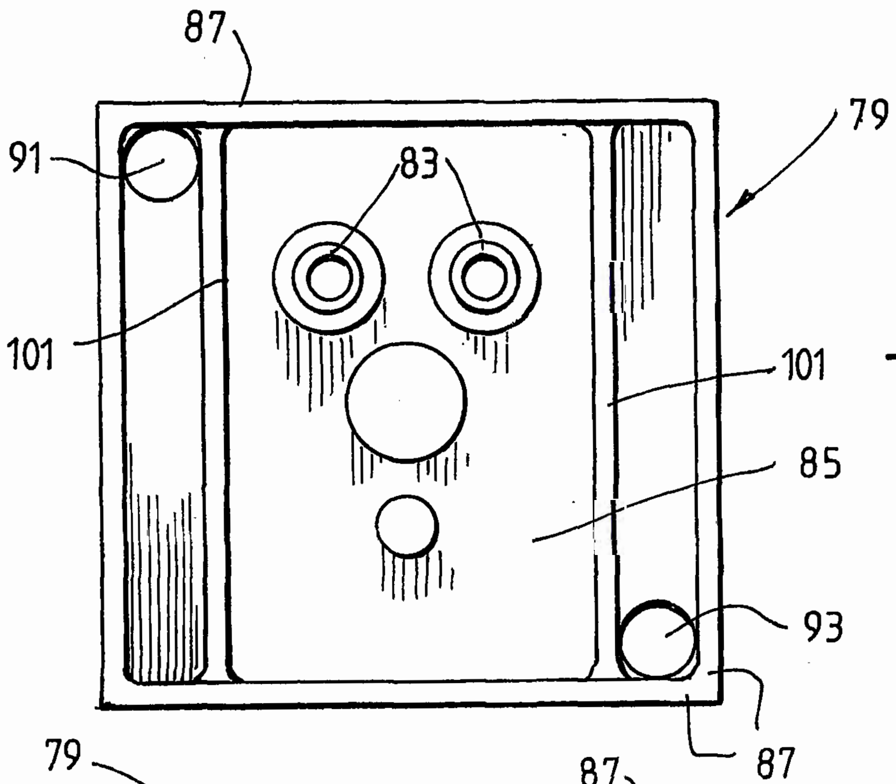


FIG. 8.

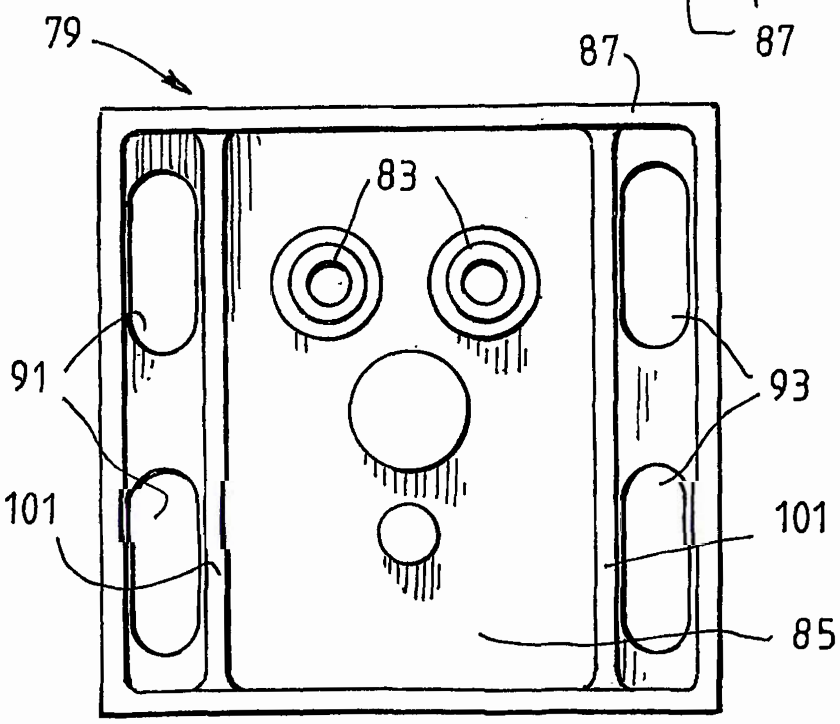


FIG. 9.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2004/001170

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. 7: H01L 31/052, H02N 6/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI: (H01L or H02N or F24J) and (PHOTOVOLT or SOLAR or SUN or PHOTOCELL) and {[(COOL+ or (TEMP or HEAT)(4D)(REDUC+ or CONDUCT+ or CARR+ or EXTRACT+ or TRANSFER+ or LOWER+ or DISSIPAT+ or REMOV+ or EXCHANG+))] or [((SURFACE AREA) or POROUS or LABYRINTH? or HOLES or GAPS or RANDOM or CONVOLUT+ or PASSAGE+ or PATHWAYS or CHANNELS]) or [(BEADS or RODS or BARS or BALL+ or SHAPE+ or MASS+ or PILE+)] }and (WELD+ or SINTER+ or MOULD+ or HEAT+ or MELT+) and (COOLANT or (COOL+(4D)(FLUID or LIQUID))

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 1996/007857 A (REKSTAD)14 March 1996	
A	US 5 092 767 A (DEHLSEN) 3 March 1992	
A	GB 1 541 221 A (DRAKE) 28 February 1979	
A	WO 2001/094006 A (ABB LUMMUS GLOBAL, INC) 13 December 2001	
A	WO 1999/009356 A (MAYRHOFER) 25 February 1999	
A	WO 2002/080286 A (SOLAR SYSTEMS PTY LTD) 10 October 2002	

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 October 2004	15 OCT 2004

Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	S. T. PRING Telephone No : (02) 6283 2210

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report	Patent Family Member		
WO 1996/007857	AU 34864/95, (698042)	CA 2 198 897	DE 695 02 957
	EP 776 448	JP 10/502728	
US 5 092 767	NONE		
GB 1 541 221	NONE		
WO 2001/094006	AU 65326/01		
WO 1999/009356	EP 897 090	AU 87182/98,	JP 2001/515198
WO 2002/080286	US 2004103680	EP 1 374 317	

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX

2.9 Lasich J.B., 2004, "A Tracking System", Patent Application No. US7589302, USA

US 20070062516A1

(19) United States
(12) Patent Application Publication (10) Pub. No.: US 2007/0062516 A1
Lasich (43) Pub. Date: Mar. 22, 2007

(54) TRACKING SYSTEM

(75) Inventor: **John Beavis Lasich**, Deepdene (AU)

Correspondence Address:
MERCHANT & GOULD PC
P.O. BOX 2903
MINNEAPOLIS, MN 55402-0903 (US)

(73) Assignee: SOLAR SYSTEMS PTY LTD, Hawthorn, Victoria (AU)

(21) Appl. No.: **10/557,453**

(22) PCT Filed: **May 19, 2004**

(86) PCT No.: **PCT/AU04/00666**

§ 371(c)(1),
(2), (4) Date: **Aug. 10, 2006**

Related U.S. Application Data

(60) Provisional application No. 60/471,344, filed on May 19, 2003.

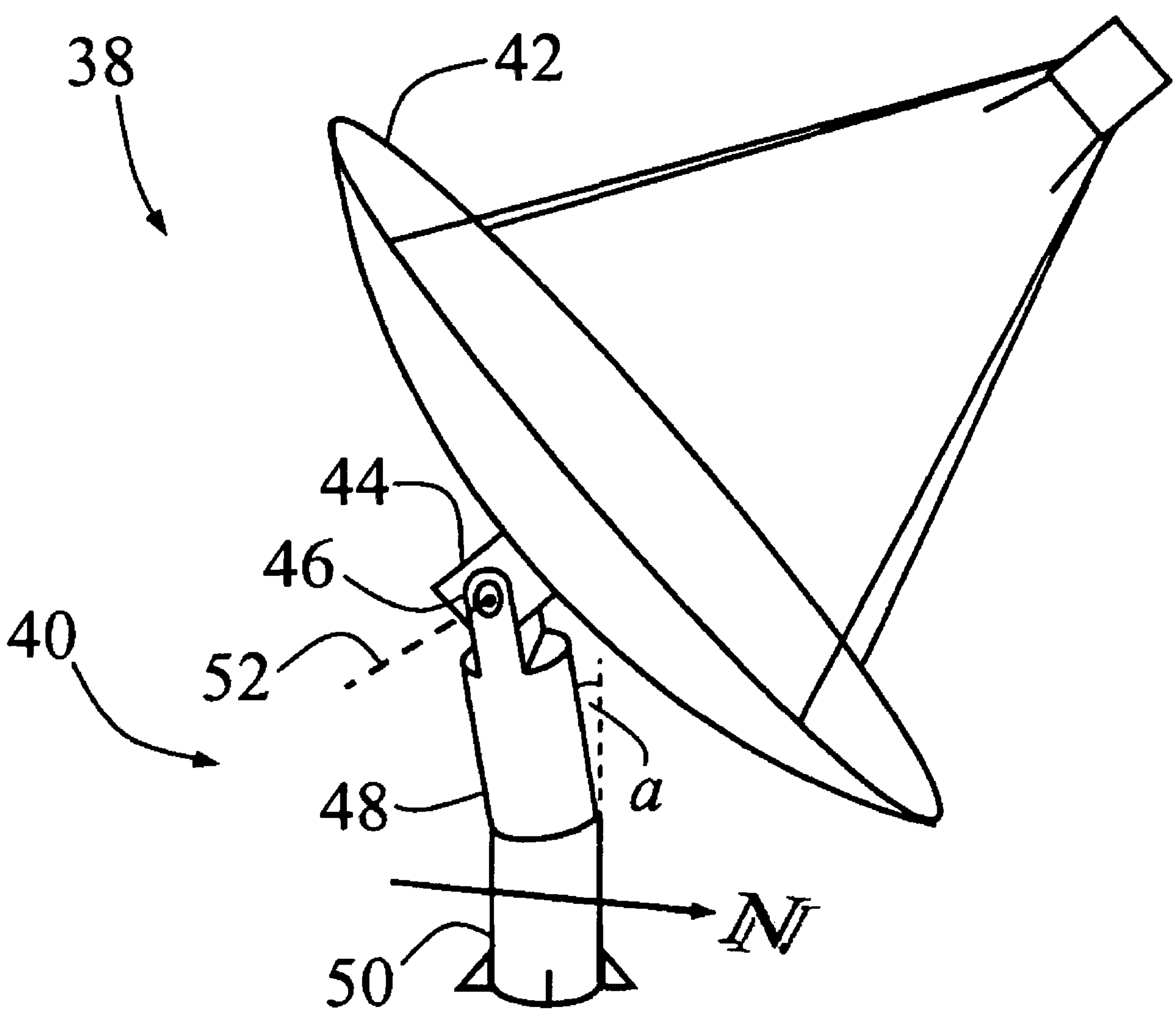
Publication Classification

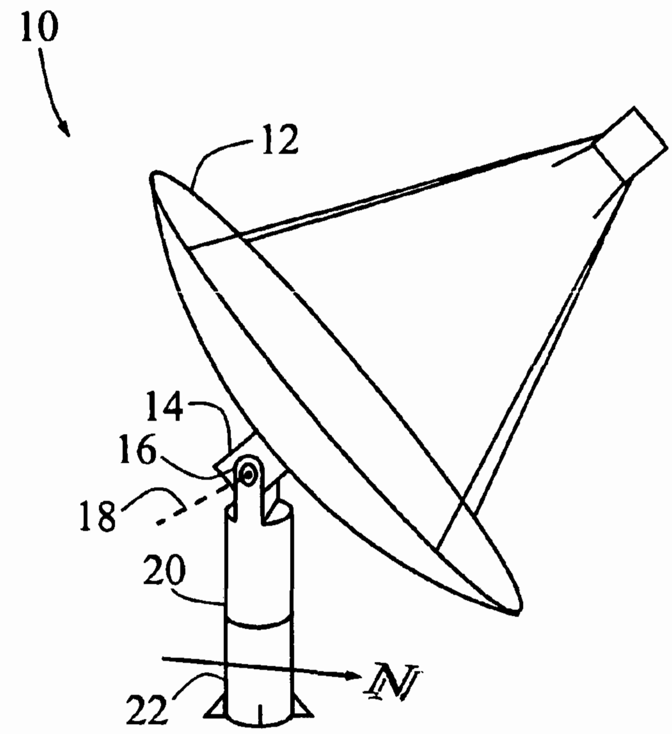
(51) **Int. Cl.**
F24J 2/38 (2006.01)

(52) **U.S. Cl.** **126/574**

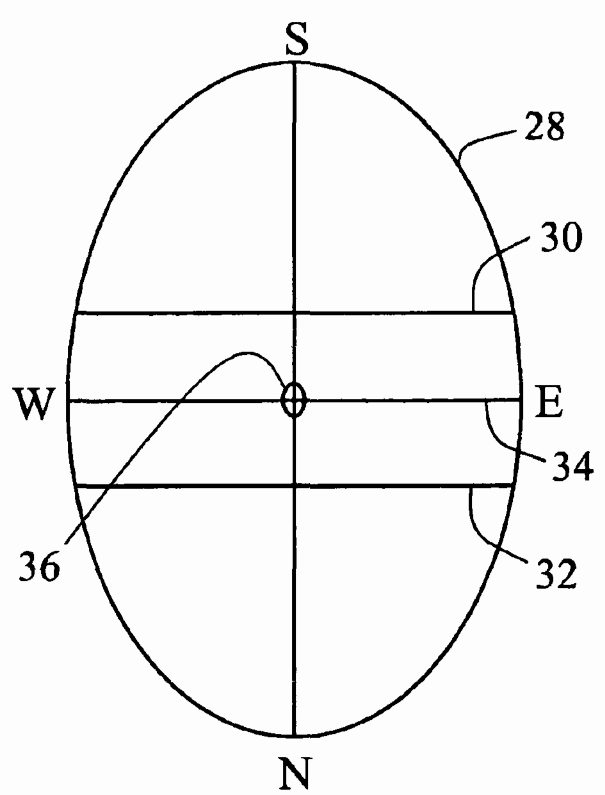
(57) **ABSTRACT**

A tracking system for tracking an object, the system having a first axis and a second axis perpendicular to the first axis. The first axis is at an angle to the vertical such that the object (or equivalently its path) does not intersect the first axis.

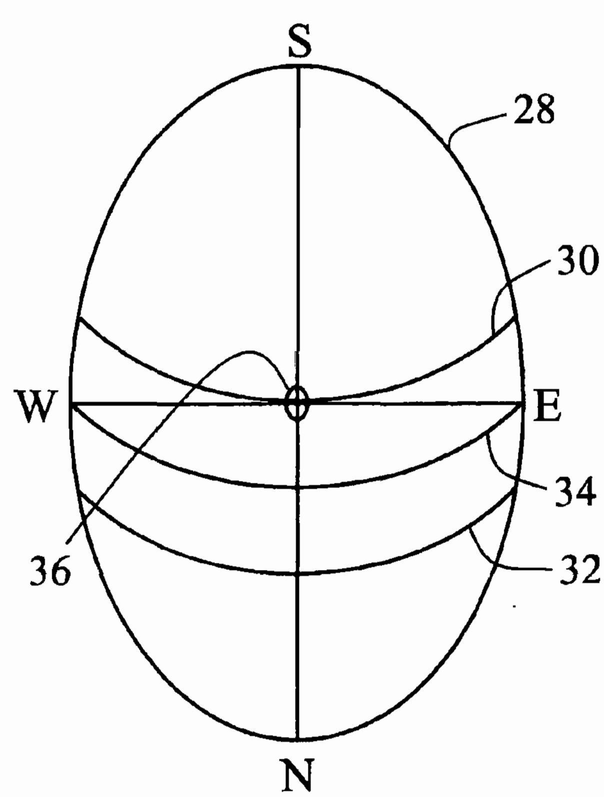




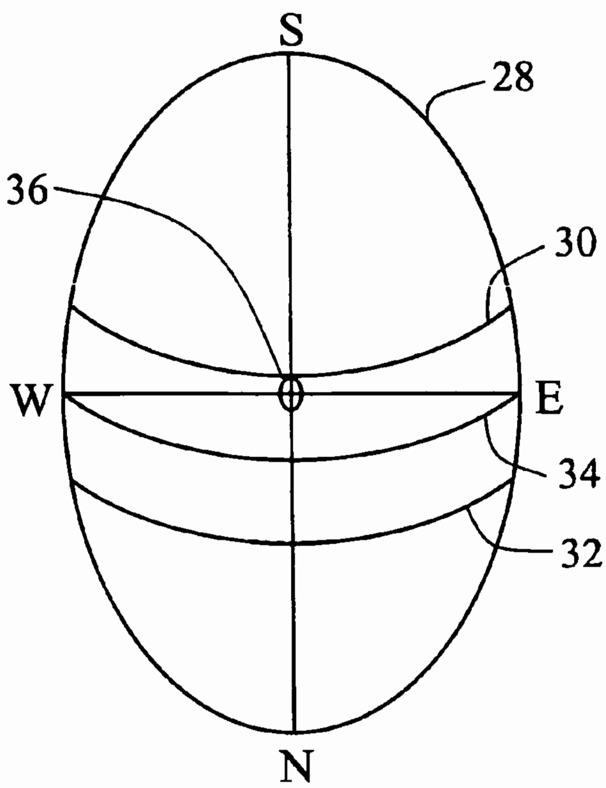
Background Art
Figure 1



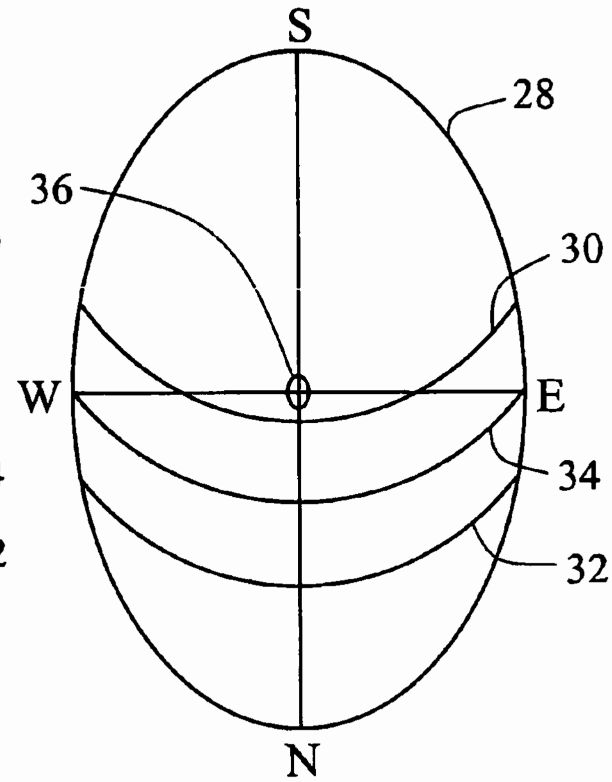
Background Art
Figure 2



Background Art
Figure 3



Background Art
Figure 4



Background Art
Figure 5

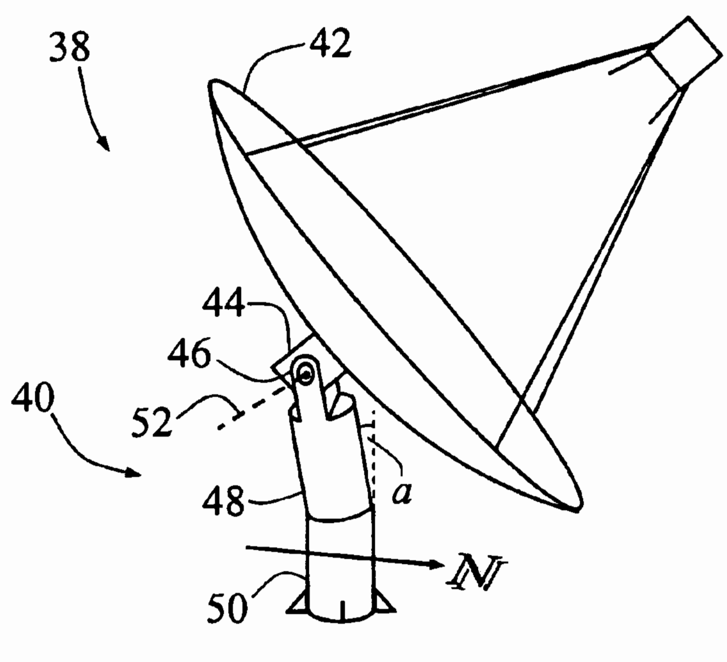


Figure 6

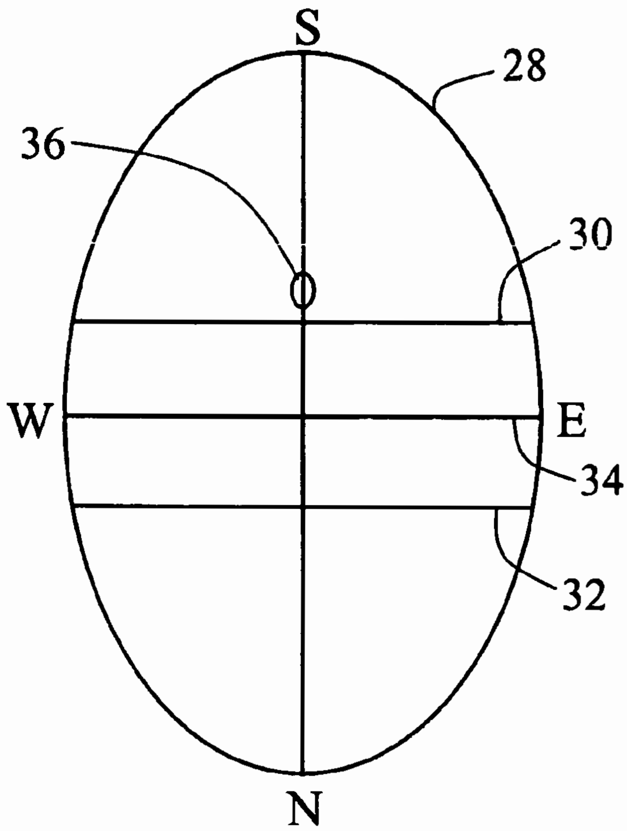


Figure 7

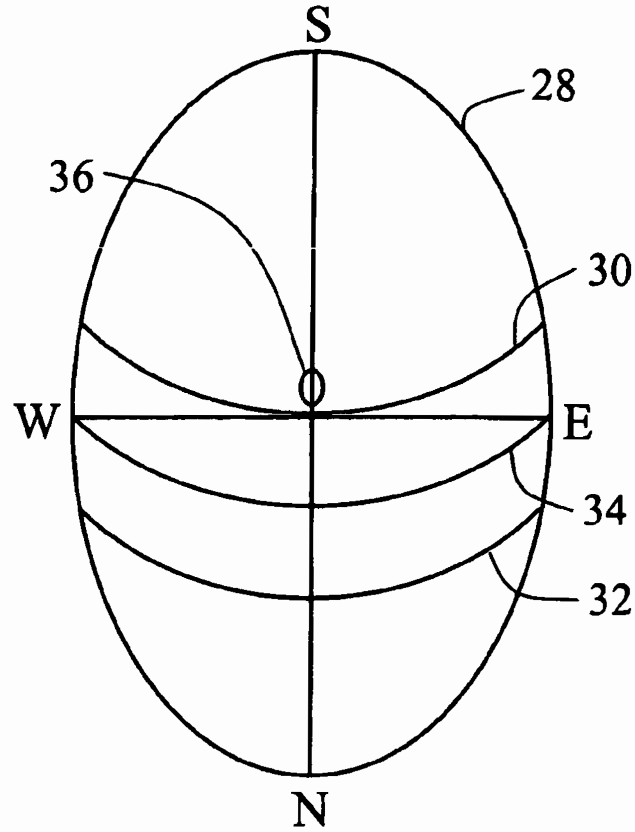


Figure 8

TRACKING SYSTEM

RELATED APPLICATION

[0001] This application is based on and claims the benefit of the filing date of U.S. provisional application Ser. No. 60/471,344 filed 19 May 2003, the contents of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to a tracking system of particular but by no means exclusive application in tracking celestial objects such as the sun, and of particular use with a solar tracking system such as for use in solar power generation.

BACKGROUND OF THE INVENTION

[0003] An altitude-azimuth or "alt-azimuth" tracking system has two axes, a first axis that is vertical, about which the system rotates to a desired azimuth (or bearing) measured eastwards from north, and a second, horizontal axis (which itself rotates on the first axis), about which the system rotates to the desired altitude, i.e. angle above the horizon. With these two (vertical and horizontal) axes, the tracking system can point an instrument such as a telescope or solar power collector at any point above the horizon. By driving both axes in a suitable manner, that instrument can be held in alignment with the tracked object. This might comprise, for example, tracking the sun from sunrise to sunset.

[0004] An example of a background art solar energy collector with dish concentrator, mounted on an alt-azimuth tracking system and located in the southern hemisphere, is shown generally at **10** in FIG. **1**. The dish concentrator **12** is located on a mount **14**. The mount is supported in a yoke **16** which allows the mount **14** to rotate about horizontal axis **18**. The yoke **16** is supported on a drum **20**, rotatable about a vertical axis. The drum **20** is supported by a pylon **22**. As illustrated, this arrangement **10** would be suitable for tracking the sun from the southern hemisphere and hence will more often than not be pointing (as shown) northwards.

[0005] However, if a tracked object passes directly overhead (viz. through the zenith) a problem can arise. For example, if the object is the sun, such an event will occur in the tropics (i.e. between latitude 23.5° north and 23.5° south) around two times of the year. On the equator, for example, this occurs at the vernal and autumnal equinoxes, that is, approximately 21 March and 21 September. As seen from the equator on the equinoxes, the sun rises due east (i.e. azimuth 90°, altitude 0°), and then sets due west (i.e. azimuth 270°, altitude 0°) essentially twelve hours later. For the first six hours, the altitude increases from 0 to 90° at 15° per hour, while for the second six hours the altitude decreases from 90° to 0° at the same rate. The azimuth remains at 90° for the first six hours and at 270° for the second six hours. To track the sun under these conditions, therefore, a conventional altitude-azimuth tracking system is required to rotate from azimuth 90° to azimuth 270° when the sun reaches zenith, essentially instantaneously. This, as will be appreciated by those in the art, is mechanically impossible.

[0006] Consequently, while the first (or vertical) axis of the tracking system is rotating from azimuth 90° to azimuth 270°, a period without effective tracking can occur. In the example of a solar power generator, this can lead to a loss in power output.

[0007] It must also be borne in mind that altitude-azimuth tracking systems have motors adapted for their application, and hence generally have limited power and therefore speed. For a solar tracking system, these motors are designed to drive the two axes relatively slowly, and it would typically be necessary to employ more powerful motors if it were desired to compensate for the above described problem by driving the tracking system at a faster rate than usual and thereby minimising any tracking delay.

[0008] As will also be appreciated, this problem does not arise if an equatorial or polar mount is employed, but altitude-azimuth mounts have advantages (in terms of cost, and ease of construction and erection) that make them highly desirable and widely used.

[0009] If this problem is experienced, accurate tracking can recommence after the delay caused by this effect, and the delay (in which data for energy collection is interrupted or reduced) depends on the maximum speed with which the tracking system can switch azimuth from 90° to 270°.

[0010] For example, if the maximum azimuth tracking speed is 38° per minute, then to drive the azimuth from 90° to 270° (i.e. by 180°) would take 180° divided by 38° per minute, or 4.74 minutes. If the sun is being tracked, over the course of 4.74 minutes the sun will have moved 1.18°. A zone of 1.18° diameter, centred on the vertical tracking axis projected on the sky, will thus have been either lost or have afforded reduced energy collection.

[0011] Owing to the sun's seasonal motion, which is approximately sinusoidal, it dwells longer at the tropics than at the equator. Consequently, for a solar tracking system located on or near the tropics of Capricorn and Cancer, this problem can occur over a series of days around the solstices. On the equator, the problem should occur over fewer days, around the equinoxes.

[0012] FIG. **2** illustrates the problem for a solar tracking system with the above characteristics located on the equator. This figure (and FIGS. **3**, **4**, **5**, **7** and **8**) are polar diagrams of the sky with the zenith at the centre and the horizon at the circumference **28**, with north (N) at the bottom. South (S), east (E) and west (W) are also indicated, as are the sun's track **30** on 21 December (the northern hemisphere winter solstice) at declination −23.5°, the sun's track **32** on 21 June (the northern hemisphere summer solstice) at declination ±23.5°, and the sun's track **34** on 21 March and 21 September (the equinoxes) at declination 0°.

[0013] The above mentioned zone of 1.18° diameter, above the vertical tracking axis, is indicated (though not to scale) at **36**. As can be seen from this figure, this zone **36** is located (for a solar tracking system at latitude 0°) on the celestial equator, and hence is entered by the sun around noon on and around the time of the equinoxes.

[0014] For the same solar tracking system located at latitude 23.5° south (such as Alice Springs, in the Northern Territory, Australia), the situation is as depicted in FIG. **3**. Zone **36** is located at declination −23.5°, so the sun passes through zone **36** when on solar track **30**, that is, on and around the northern hemisphere winter solstice (or southern hemisphere summer solstice) around 21 December.

[0015] Thus, this zone **36** is centred on or between the declination −23.5° and +23.5°, with the worst case (in this scenario) occurring when the outer edge of the zone **36** falls on or near these extremes. This occurs, again for this example, when the centre of zone **36** is located at declination (23.5−1.18/2)=±22.91°. Because the sun dwells around the tropics, it will pass into the declination of this zone **36** as it approaches the tropics, and back into that declination, so that there may be weeks around the solstice when the sun passes through zone **36** and this tracking problem arises. This situation is depicted for a tracking system located at latitude 22.91° south in FIG. **4**.

[0016] Finally, for the same solar tracking system located outside the tropics, the problem does not occur. Thus, for the same solar tracking system located at Melbourne, Victoria, Australia (i.e. latitude 37.5° south), the sun never approaches zone **36** (which lies at declination—37.5°), as my be seen from FIG. **5**.

SUMMARY OF THE INVENTION

[0017] The present invention provides, therefore, a tracking system for tracking an object, comprising:

[0018] a first axis; and

[0019] a second axis perpendicular to said first axis;

[0020] wherein said first axis is at an angle to the vertical such that said object (or equivalently its path) does not intersect said first axis.

[0021] Thus, the object—which being celestial has an apparent motion and therefore path—should not pass through the first axis. When the object is the sun, for example, the ecliptic plane (being the path of the sun) should not be parallel to the first axis.

[0022] Preferably said angle has a component of at least A in a direction away from the equator, where:

$$A = 23.5^\circ - |\lambda| + \frac{45^\circ}{2\sigma}$$

and where λ is the latitude of said tracking system and σ is the maximum angular velocity with which said tracking system can evolve said first axis in degrees per minute.

[0023] More preferably, said angle has a component at least 2° (and still more preferably at least 5°) greater than A in a direction away from the equator.

[0024] Most preferably said angle has a component greater than A in a direction away from the equator determined so as to minimize the additional cost associated with high tolerance or mechanical demands.

[0025] Thus, if the tracking system is used in a location where this problem arises (i.e. where the sun passes overhead or nearly so), tilting the first (i.e. in a conventional alt-azimuth tracking system, vertical) axis by at least A will prevent this occurring.

[0026] The tracking system may include at least one photosensor (possibly in the form of a thermal sensor) for sensing light (including infrared radiation) received—either directly or indirectly—from a tracked object to refine the tracking of the object.

[0027] Thus, arranging the first axis at an angle to the vertical will generally introduce an error in the tracking, but this can be compensated for if necessary by providing a photosensor locked to the tracked object and operable to adjust the tracking of the tracking system.

[0028] In one embodiment, the system tracks said object by means of suitably calculated tables or progressive calculation.

[0029] Alternatively, the system tracks said object by means of altitude-azimuth tables or calculations, translated on the basis of said angle to values appropriate for said first and second axes.

[0030] The present invention also provides a tracking system for tracking an object, comprising:

[0031] a first axis;

[0032] a second axis perpendicular to said first axis; and

[0033] adjustment means for adjusting the angle of said first axis to the vertical;

[0034] whereby said angle can be adjusted to be such that said object does not intersect said first axis.

[0035] Preferably said angle has a component of at least A in a direction away from the equator, where:

$$A = 23.5^\circ - |\lambda| + \frac{45^\circ}{2\sigma}$$

and where λ is the latitude of said tracking system and a is the maximum angular velocity with which said tracking system can evolve said first axis in degrees per minute.

[0036] The present invention still further provides a method of tracking an object, comprising:

[0037] arranging a first tracking axis at an angle to the vertical; and

[0038] arranging a second tracking axis perpendicular to said first tracking axis;

[0039] wherein said angle is such that said object does not intersect said first tracking axis.

[0040] Preferably said angle has a component of at least A in a direction away from the equator, where:

$$A = 23.5^\circ - |\lambda| + \frac{45^\circ}{2\sigma}$$

and where λ is the latitude of said tracking system and a is the maximum angular velocity with which said tracking system can evolve said first axis in degrees per minute.

[0041] More preferably, the angle has a component at least 2° (and still more preferably at least 5°) greater than A in a direction away from the equator.

[0042] Most preferably the angle has a component greater than A in a direction away from the equator determined so as to minimize the additional cost associated with high tolerance or mechanical demands.

BRIEF DESCRIPTION OF THE DRAWINGS

[0043] In order that the present invention may be more clearly ascertained, an embodiment will now be described, by way of example, with reference to the accompanying drawing, in which:

[0044] FIG. **1** is a view of an exemplary background art solar energy collector with dish concentrator, mounted on an alt-azimuth tracking system;

[0045] FIG. **2** is a polar diagram of the sky with horizon at the circumference, depicting the region where the sun cannot be adequately tracked by means of an exemplary background art solar energy collector located at the equator;

[0046] FIG. **3** is a polar diagram of the sky with horizon at the circumference, depicting the region where the sun cannot be adequately tracked by means of an exemplary background art solar energy collector located at Alice Springs (latitude 23.5° south);

[0047] FIG. **4** is a polar diagram of the sky with horizon at the circumference, depicting the region where the sun cannot be adequately tracked by means of an exemplary background art solar energy collector located at the 22.91° south;

[0048] FIG. **5** is a polar diagram of the sky with horizon at the circumference, depicting that there is no region where the sun cannot be adequately tracked for-an exemplary background art solar energy collector located at in Melbourne (latitude 37.5° south);

[0049] FIG. **6** is a view of a solar energy collector with dish concentrator with a tracking system according to an embodiment of the present invention;

[0050] FIG. **7** is a polar diagram of the sky with horizon at the circumference, depicting that there is no region where the sun cannot be adequately tracked for the solar energy collector of FIG. **6** located at the equator; and

[0051] FIG. **8** is a polar diagram of the sky with horizon at the circumference, depicting that there is no region where the sun cannot be adequately tracked for the solar energy collector of FIG. **6** located at Alice Springs (latitude 23.5° south).

DETAILED DESCRIPTION

[0052] According to this embodiment, a solar tracking system is provided with a maximum tracking speed in what—in an alt-azimuth tracking system—would be the vertical axis of 38° per minute. As discussed above, this maximum speed creates a zone of 1.18° diameter located about what would be—in the prior art—the projection of the vertical axis, in which inadequate solar tracking is possible. Consequently, the solar tracking system of this embodiment endeavours to avoid the sun ever passing within a zone of 1.18° diameter of that axis.

[0053] FIG. **6** is a view of a solar energy collector **38** located in the southern hemisphere within the tropics, with dish concentrator with the solar tracking system of this embodiment, the tracking system generally at **40**. The solar energy collector is generally identical with that of FIG. **1**, including a dish concentrator **42** and mount **44**.

[0054] Tracking system **40** comprises essentially the same components as that of FIG. **1**, including yoke **46**, drum **48** and pylon **50**. However, drum **48** is not rotatable about a vertical axis but is tilted in a southwards direction so that it is rotatable about an axis tilted by an angle a to the vertical.

[0055] The minimum value of a is determined as follows.

[0056] Because the collector is located in the tropics, a vertical axis for drum **48** would position the problematic zone of the sky described above (in which no adequate tracking is possible with a prior art alt-azimuth tracking system) about the zenith, through which the sun will eventually pass. The axis of drum **48** (which defines where this zone lies) should thus avoid that part of the sky 23.5° either side of the celestial equator, as well as a further half-diameter of the zone. This ensures that, despite its finite size, the zone does not extend to the sun when the sun is at located at 23.5° south.

[0057] The sun will pass further south than the zenith by at most $23.5°-|\lambda|$, to which should be added half the diameter of this zone. The zone has a diameter equal to the distance the sun moves while the tracking of a prior art alt-azimuth system—at its maximum speed—changes azimuth from 90° to 270°. This takes $180°/\sigma$, where c is the maximum angular velocity with which the tracking system can evolve the first in degrees per minute (the first axis being—in prior art alt-azimuth systems—the vertical axis). In this example this is 38° per minute. The sun moves at 15° per hour or 0.25° per minute, so it moves $(0.25\times180/\sigma)=45°/\sigma$ in this time, which is accordingly the diameter of this zone.

[0058] Thus, what in the prior art is the vertical axis should avoid a region of the sky from $[23.5°+|\lambda|+45°/2\sigma]$ south of the zenith to $[23.5°+|\lambda|+45°/2\sigma]$ north of the zenith in order not to intersect this zone.

[0059] Thus, drum **48** is tilted to the vertical by angle a so that this zone is never intersected by the axis of drum **48**. This is done by arranging drum **48** with a tilt in a southern direction of:

$$a=23.5°-|\lambda|+45°/2\sigma$$

[0060] Hence, the tracking system **40** has a first axis tilted away from the direction of the equator of a, while its second axis **52** (through yoke **46**) is perpendicular to this first axis. In prior art alt-azimuth arrangements, this second axis is horizontal; in system **40** it will precess such that, when the system **40** points northwards (as shown in FIG. **6**), it is horizontal. This will also be so when the system **40** points southwards. Otherwise the second axis will be inclined to the horizontal.

[0061] Inclination a of the first axis means that alt-azimuth solar position tables or calculations must be modified if they are to be used for system **40**, but this is a straightforward spherical geometry transformation. Alternatively, entirely new tables can be generated, or calculations performed as necessary, by means of a suitably programmed computer-control drive system.

[0062] The collector **38** is also preferably provided with one or more photosensors for trimming the tracking of the system **40**, and these can also be used to correct the effect of using alt-azimuth solar position calculations. Alternatively, these photosensors can be used to fine tune more accurate tables or calculations created or performed correctly for the system **40** and taking into account the effect of the inclination of the first axis.

[0063] FIG. **7** is a polar diagram of the sky (with horizon at the circumference) for this embodiment, with the collector **38** located at the equator and with a first axis tilted southwards from the vertical by 27°. The above calculation of a for system **40** gives a value of a=24.1°. This value of a is treated as a minimum value for the inclination of the first axis. It should be remembered that setting the inclination of the first axis precisely according to this calculation would require the tracking system **40** to be driven at its maximum speed until the Sun has moved out of the avoided zone, and assumes that pylon **50** has been constructed precisely vertically. It also makes no allowance for wear or sagging in the various components of the collector **38** with aging, or other imperfections. Consequently, while this calculation provides for the angle at which the first axis should—in a ideal system—be inclined to the vertical; in practice the first axis is inclined by a few degrees more and hence at 27° in FIG. **7**, to ensure that the zone **36** remains well clear of the sun's path at all times of the year.

[0064] FIG. **8** is another polar diagram of the sky (with horizon at the circumference) for this embodiment, with the collector **38** located at Alice Springs, latitude 23.5° south. The above calculation of a for system **40** at this latitude gives a value of a=0.59°. As discussed above, this figure provides the inclination of the first axis in an ideal arrangement but, in practice, the first axis should be inclined by a few degrees more to allow for the factors described above. Hence, FIG. **8** depicts an inclination of drum **48** and hence of the first axis of 5°. Again, this inclination ensures that the zone **36** remains well clear of the sun's path at all times of the year.

[0065] Modifications within the scope of the invention may be readily effected by those skilled in the art. It is to be understood, therefore, that this invention is not limited to the particular embodiments described by way of example hereinabove.

[0066] In the claims that follow and in the preceding description of the invention, except where the context requires otherwise owing to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

[0067] Any reference herein to prior art is not intended to imply that that prior art forms or formed a part of the common general knowledge.

1. A tracking system for tracking a celestial object for use in a location where the object passes through or near the zenith, comprising:

a first axis for tracking the object generally in azimuth; and

a second axis for tracking the object generally in altitude and perpendicular to said first axis;

wherein said first axis is oriented at an angle to the vertical so that an upward projection of said first axis is removed from the apparent path of the object by an amount that renders the speed of said tracking system sufficient to maintain tracking of the object as the object passes through or near the zenith.

2. A system as claimed in claim 1, wherein said angle has a component of at least A in a direction away from the equator, where:

$$A = 23.5^\circ - |\lambda| + \frac{45^\circ}{2\sigma}$$

and where λ is the latitude of said tracking system and σ is the maximum angular velocity with which said tracking system can evolve said first axis in degrees per minute.

3. A system as claimed in claim 2, wherein said angle has a component at least 2° greater than A in a direction away from the equator.

4. A system as claimed in claim 2, wherein said angle has a component at 5° greater than A in a direction away from the equator.

5. A system as claimed in claim 2, wherein said angle has a component greater than A in a direction away from the equator determined so as to minimize the additional cost associated with high tolerance or mechanical demands.

6. A system as claimed in claim 1, further comprising at least one photosensor for sensing light received either directly or indirectly from a tracked object to refine the tracking of said object.

7. A system as claimed in claim 1, operable to track said object by means of suitably calculated tables or progressive calculation.

8. A system as claimed in claim 1, operable to track said object by means of altitude-azimuth tables or calculations, translated on the basis of said angle to values appropriate for said first and second axes.

9. A tracking system for tracking a celestial object for use in a location where the object passes through or near the zenith, comprising:

a first axis for tracking the object generally in azimuth;

a second axis for tracking the object generally in altitude and perpendicular to said first axis; and

adjustment means for adjusting the angle of said first axis to the vertical;

whereby said angle can be adjusted so that an upward projection of said first axis is removed from the apparent path of the object by an amount that renders the speed of said tracking system sufficient to maintain tracking of the object as the object passes through or near the zenith.

10. A system as claimed in claim 9, wherein said angle has a component of at least A in a direction away from the equator, where:

$$A = 23.5^\circ - |\lambda| + \frac{45^\circ}{2\sigma}$$

and where λ is the latitude of said tracking system and σ is the maximum angular velocity with which said tracking system can evolve said first axis in degrees per minute.

11. A method for tracking a celestial object for use in a location where the object passes through or near the zenith, comprising:

arranging a first axis for tracking the object generally in azimuth;

arranging a second axis for tracking the object generally in altitude perpendicular to said first axis; and

orienting said first axis at an angle to the vertical so that an upward projection of said first axis is removed from the apparent path of the object by an amount that renders the speed of said tracking system sufficient to maintain tracking of the object as the object passes through or near the zenith.

12. A method as claimed in claim 11, wherein said angle has a component of at least A in a direction away from the equator, where:

$$A = 23.5^\circ - |\lambda| + \frac{45^\circ}{2\sigma}$$

and where λ is the latitude of said tracking system and σ is the maximum angular velocity with which said tracking system can evolve said first axis in degrees per minute.

13. A method as claimed in claim 12, wherein said angle has a component at least 2° greater than A in a direction away from the equator.

14. A method as claimed in claim 12, wherein said angle has a component at 5° greater than A in a direction away from the equator.

15. A method as claimed in claim 12, wherein said angle has a component greater than A in a direction away from the equator determined so as to minimize the additional cost associated with high tolerance or mechanical demands.

16. A method for providing a tracking system for tracking a celestial object at a location where the object passes through or near the zenith, comprising:

providing at said location an alt-azimuth tracking system having an azimuth axis and an altitude axis; and

arranging said alt-azimuth tracking system so that said azimuth axis is oriented at an angle to the vertical so that an upward projection of said azimuth axis is removed from the apparent path of the object by an amount that renders the speed of said tracking system sufficient to maintain tracking of the object as the object passes through or near the zenith.

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