Chapter 3

Prototype Design and Construction of an Asymmetric Compound Parabolic Photovoltaic Concentrator System

3.1 Introduction

At solar noon the maximum and minimum solar altitude angle of 61.45° and 14.55° respectively, correspond to the latitude of 52°N (London, UK) and daylight hours/day vary from about 18 to 8 hours. There is thus a large variation in daily available solar energy between June and December. Because of winter longer nights and cold weather, the average energy requirement in the winter is much higher compared to the summer. Non-imaging Asymmetric Compound Parabolic Photovoltaic Concentrators (ACPPVC) designed for the UK climate and latitude were analysed using the 'comprehensive unified' model (Eames et al., 2001). The ACPPVC's were truncated (Rabl, 1985) to reduce reflector material and thus initial cost.

3.2 An Asymmetric Compound Parabolic Concentrator for PV Application

Asymmetric non-imaging concentrators as an alternative to symmetric compound parabolic concentrators have the following advantages (Mills and Giutronich, 1978):

- Increased design flexibility. Asymmetric concentrators can be tailored to compensate for cyclical climatic or demand variations.
- Increased operational flexibility. If a sudden demand were to require an increase in output, more frequent tracking could be used to achieve substantially greater concentrations. This cannot be done with symmetrical non-imaging concentrators.
- Collection of diffuse radiation. An asymmetric concentrator can accept a wide range of the diffuse component of incident solar radiation compared to a symmetric CPC.

Because of these advantages and its angular acceptance functions (as detailed in Chapter 2) the asymmetric compound parabolic concentrator is the best suitable candidate for building integrated photovoltaic applications as proposed in Chapter 2. Two proposed systems were:

1. ACPPVC-50: 50° truncated acceptance half-angle asymmetric compound parabolic photovoltaic concentrator having concentration ratio of 2.0.
2. ACPPVC-60: 60° truncated acceptance half-angle asymmetric compound parabolic photovoltaic concentrator having concentration ratio of 1.71.

The ACPPVC-50 was design and fabricated for indoor and outdoor experimental characterisation due to its concentration ratio is 14.5% higher compared to ACPPVC-60.

3.3 System Truncation

An asymmetric compound parabolic concentrator has two different parabolic reflectors determined by their focal points and parabolic axis as shown in figure 3.3.1. Parabola SP refers to the upper reflector and parabola RQ refers to the lower reflector and their axis are at $RR^{/}$ and $SS^{/}$ respectively, PQ is the aperture of the system. All solar rays incident within the acceptance range on the aperture PQ are reflected by either reflector and reach the absorber RS. The system has two asymmetric acceptance-half angles denoted by θ_s and θ_a. For the system studied, θ_s=50° and θ_a=0° i.e. the lines MN and SQ are parallel.

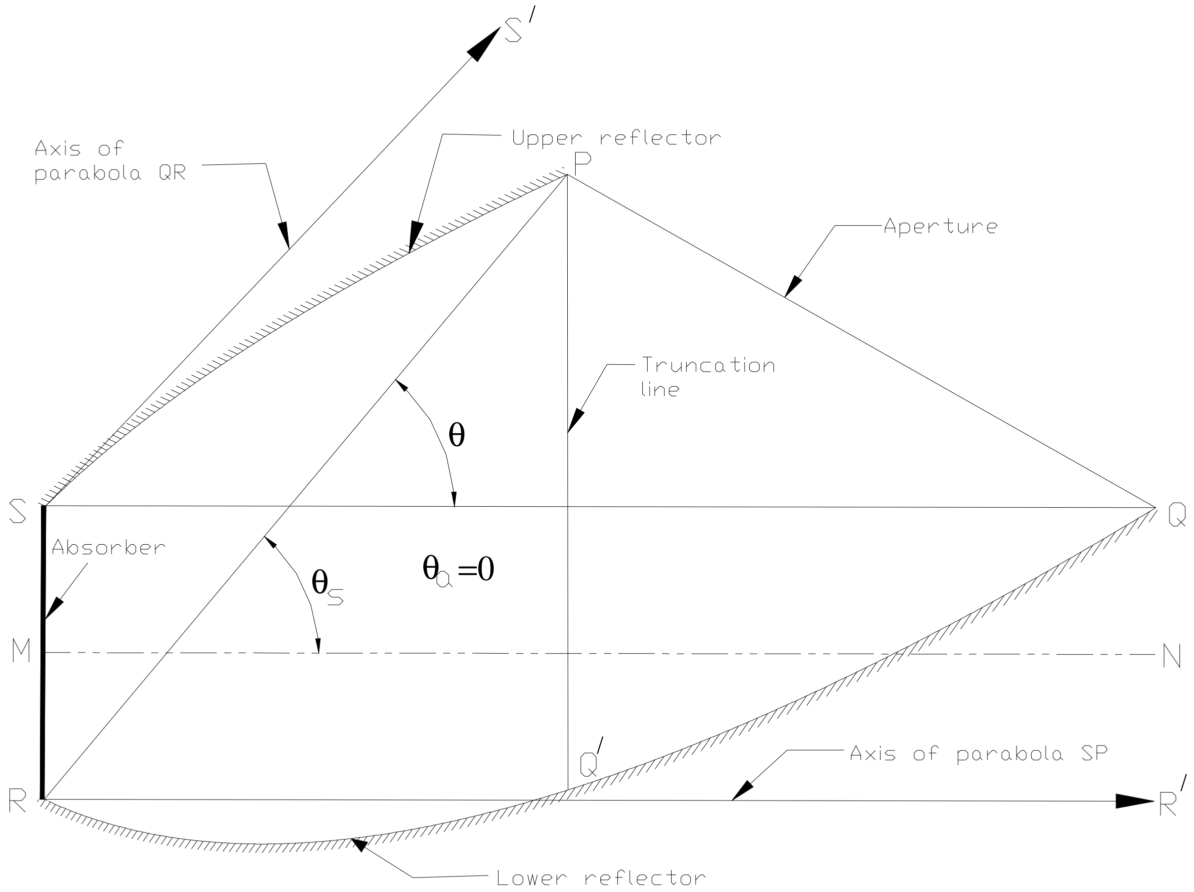


Figure 3.3.1 Asymmetric compound parabolic concentrator for building integration in the UK with acceptance-half angles of 0° and 50°.

Asymmetric compound parabolic concentrators can be truncated to reduce the material used and thus the manufacturing cost (Rabl, 1985). The vertical truncation line PQ/ is shown in figure 3.3.1. A 54% truncation of the reflector RQ has been made for this ACPPVC-50 system. For this truncation of 54%, the concentration ratio decreased by 15% to give a concentration ratio of 2.01. The adopted truncation has the following advantages over the untruncated system

- significant reduction in reflector material and thus overall system cost
- overall increase in the diffuse solar radiation collection
- flat façade is produced that reduces accrual of dust and salt deposits.

3.4 Design and Construction of the Prototype ACPPVC-50 System

The basic design consideration for any system depends on the materials selected for different components and the individual component design and construction. The components of the ACPPVC-50 are the aperture, reflectors, the PV absorber, a back-plate and a support frame. The individual component design and construction details are described in this chapter.

3.4.1 Aperture Design and Construction

Aperture material transmittance is a function of both the wavelength and solar incidence angle of solar radiation. Low iron glass contains less Fe_2O_3 and therefore absorbs less incident solar energy compared with high iron content glass (Duffie and Beckman, 1991). A 4 mm thick low iron glass sheet with an extinction coefficient of 4.1 m^{-1} has been considered for the aperture glass cover with an effective transmittance of approximately 0.92. The dimensions of the aperture cover are illustrated in figure 3.4.1.1.

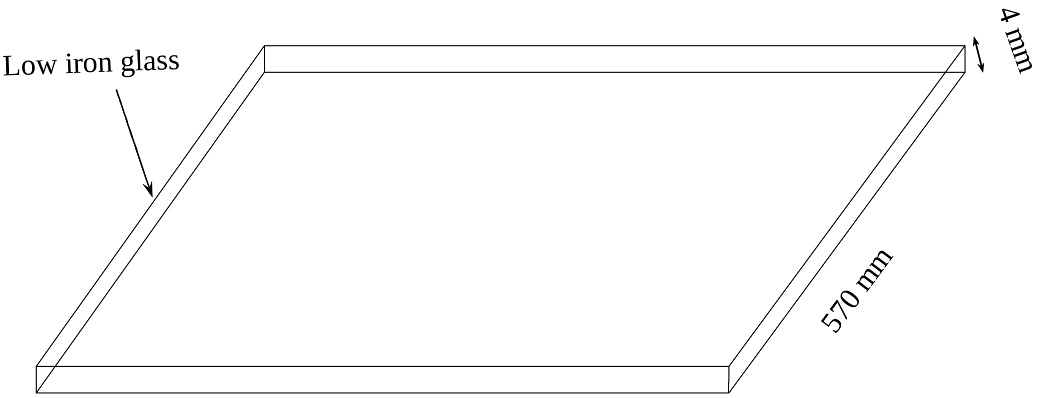


Figure 3.4.1.1 Aperture cover specification for the ACPPVC-50 system.

3.4.2 Reflector Design

A computer program “acpct.pas” was written in PASCAL to calculate the data points for the two reflectors. The parametric equations used were:

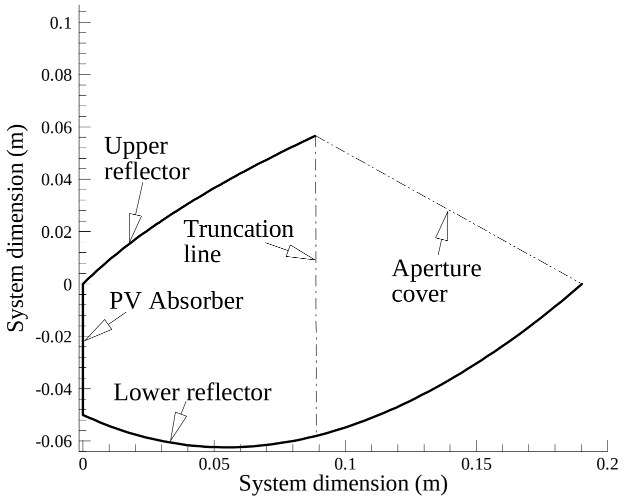
$$\left.\begin{aligned} x &= \left(at^2 - a\right)\cos\theta + 2at\sin\theta \\ y &= \left(at^2 - a\right)\sin\theta - 2at\cos\theta \end{aligned}\right\} \tag{3.4.2.1}$$

where “a” is the photovoltaic absorber length and the value of “t” varies as

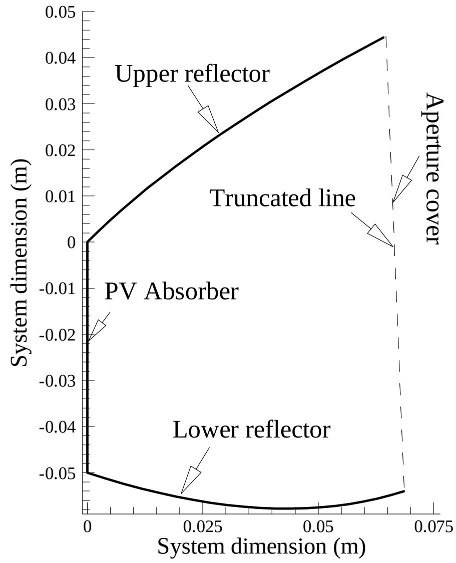
$$\frac{(1-\sin\theta)}{\cos\theta} \le t \le \frac{(1+\sin\theta)}{\cos\theta} \tag{3.4.2.2}$$

for the angular values θ=0° and θ=50°.

Data points calculated by “acpct.pas” were transferred into “Tecplot” (Anon, 2001a) to generate reflector profiles as shown in figure 3.4.2.1. Once the untruncated reflector profile was completed, the (x,y) co-ordinates were determined for the truncation line depending on the level of concentration required. For the untruncated reflector the concentration ratio was 2.32 shown in figure 3.4.2.1 (a). The concentration ratio was 2.01 when the reflector was truncated as shown in figure 3.4.2.1(b).



(a)



(b)

Figure 3.4.2.1 Computer generated asymmetric compound parabolic reflector profile (a) untruncated system (pointing out the truncation line) (b) truncated system.

3.4.2.1 **Reflector Substrate**

A 0.15 mm thick stainless steel reflector substrate provided a heat conducting fin to dissipate heat and thus reduce solar cell temperature. To one side of the reflector substrate was attached 61-68 micron thick self-adhesive mirror reflector, to the other side 2 or 6 mm thick aluminium reflector supports were attached for indoor and outdoor experimental characterisation respectively as shown in figure 3.4.2.1.1 The computer generated data points were transferred to “AUTOCAD” (Anon, 2001b) to draw the profile in a “dxf” format to enable construction of the reflector support using a CNC machine. A thermally conductive adhesive bonded the aluminium reflector support to the stainless steel reflector substrate (Anon, 2001c). In figure 3.4.2.1.1 two M4 holes were used to clamp the aluminium reflector support during CNC machining. A lower hole just below the aluminium back plate kept the system in its original position along with the adjacent reflector support through an M4 aluminium bar. The reflector support modified for outdoor experimental characterisation (as shown in figure 3.4.2.1.2) was attached by M3 screws to the rear aluminium substrate.

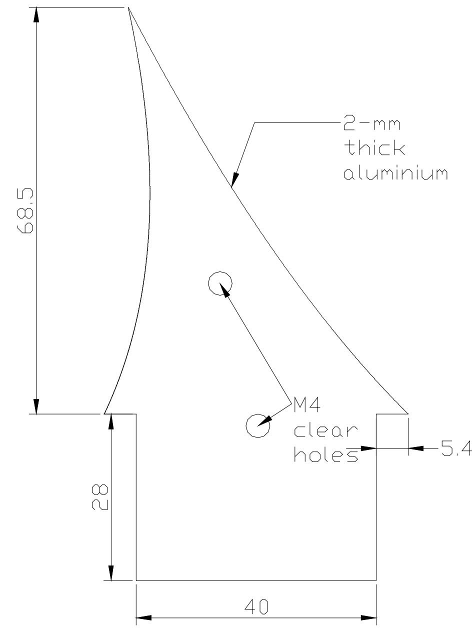


Figure 3.4.2.1.1 Aluminium reflector support for the asymmetric compound parabolic photovoltaic concentrator.

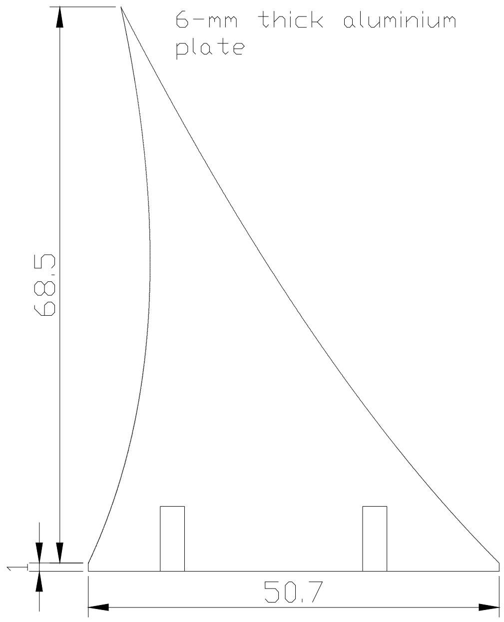


Figure 3.4.2.1.2 Modified reflector support design for outdoor experimental characterisation of the ACPPVC-50.

3.4.2.2 **Reflecting Material**

Self adhesive "Radiant Mirror VM2000" (Anon, 2001d) was chosen for the reflecting material due to its quoted reflectivity being greater than 0.98. The reflecting material is a multi-layer polymer film, the outside layer being polyethylenenaphthalate with 98% visible light specular reflection. Being metal free it is non-corroding and non-conductive. VM2000 is thermally stable with a maximum continuous use temperature of up to 150°C with low levels of shrinkage. The physical and chemical properties of the reflector material used are shown in table 3.4.2.2.1 (Anon, 2001d).

		Test Method[1]	Units	Typical Value
Properties	Optical: Luminous Reflectivity	ASTM E1164-94 ASTM E387-95	%	>98
	Colour	3M TM	a^* / b^*	-2< a^* / b^* <2
	Bandwidth (>90% Luminous Reflectivity)	3M TM	nm	(400-415)-(775-1020) nm (0°-80° aoi)
	Transmits Wavelengths	3M TM	nm	>775 and <1020
	Absorbs Wavelengths	3M TM	nm	<400
	Usage Angle	3M TM	degrees	0-90
	Physical Thickness	3M TM	microns	61.0-68.6
	Tensile Strength	ASTM D-882	Kg m^{-1}	>625
	Elongation @break	ASTM D-882	%	>60
	Modulus	ASTM D-882	Pa	>0.08
	Heat Shrinkage,150°C, 15min. MD CW	3MTM	%	<1
	Yield		m^2/kg	11.2

Table 3.4.2.2.1 Physical and chemical properties of Radiant Mirror VM2000 reflector film (Anon, 2001d).

3.4.3 PV Absorber Design

A material with high thermal conductivity is required to transfer heat efficiently away from the solar cells to the ambient surroundings, cooling the solar cell and thus leading to improved PV performance. The PV absorber design is divided into two components, a back plate and the PV.

3.4.3.1 PV Solar Cell Absorber

The solar cells used in this work were monocrystalline "BP SATURN" half-size solar cells (Anon, 2001e). The metallisation process used for the manufacture of laser grooved, buried grid "SATURN" solar cells (Eager et al., 2002) is based on electroless chemical plating. The electrical characteristics of ten sample solar cells are presented in table 3.4.3.1.1. The average solar cell efficiencies are all over 16% with fill factors of 75% and higher. These measurements were reported at nominal operating cell temperature (NOCT) conditions (Eager et al., 2002).

[1] Manufacture specified test method

		Current (A)	V_{oc} (V)	I_{sc} (A)	Fill factor (%)	Efficiency (%)
Cell Specimen	1	3	0.607	5.225	76.2	16.4
	2	3	0.604	5.161	77.5	16.4
	3	3	0.606	5.218	75.7	16.2
	4	1	0.605	5.090	77.9	16.3
	5	0.7	0.605	5.202	77.9	16.3
	6	2.1	0.607	5.203	77.9	16.7
	7	2.1	0.608	5.237	76.6	16.6
	8	2.1	0.606	5.041	77.6	16.1
	9	0.7	0.607	5.173	78.1	16.7
	10	0.7	0.608	5.241	78.1	16.9

Table 3.4.3.1.1 Electrical test results for ten full size Saturn solar cells (Eager et al., 2002).

3.4.4 **Back Plate Design and Construction**

A 3-mm thick aluminium plate was used to provide a base for the photovoltaic solar cells. The back plate designed for indoor experimental characterisations is shown in figure 3.4.4.1. 1.5-mm deep slots between two consecutive reflector supports provided space for back electrical connection of the solar cells which allowed the cells to rest flat against the back plate. The 2-mm thick reflector supports were fitted into 40-mm rectangular slots to hold the reflector supports in place as shown in the cross-sectional view of a three trough reflector support in figure 3.4.4.2.

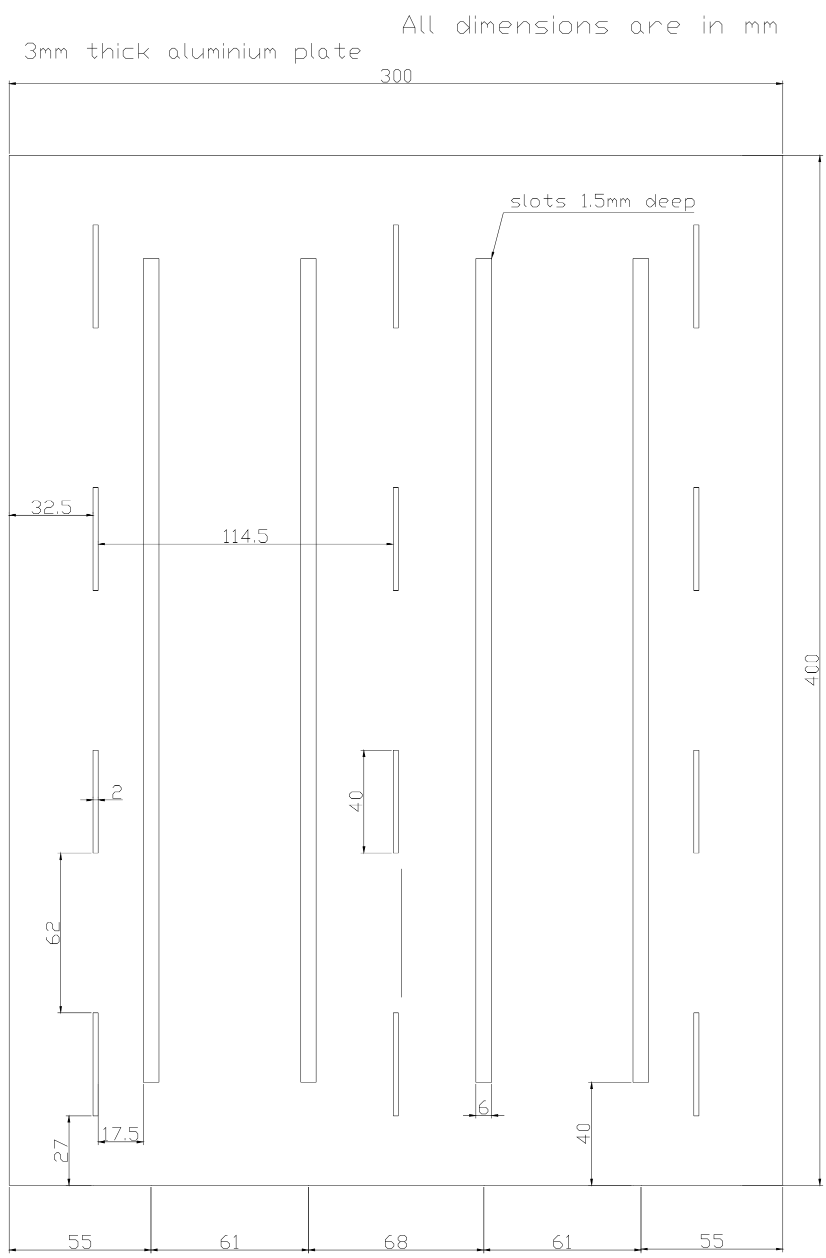


Figure 3.4.4.1 Back plate design for indoor experimental characterisation of an ACPPVC-50 system.

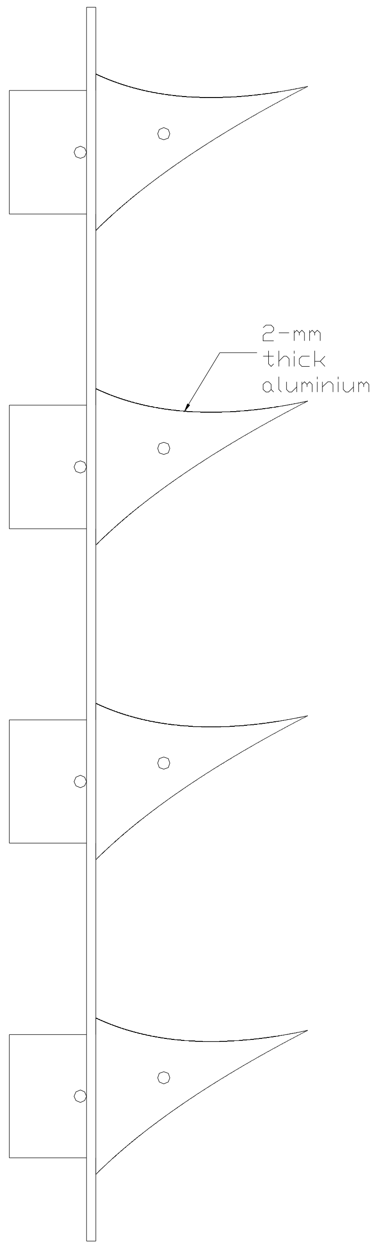


Figure 3.4.4.2 Cross-sectional view of back plate and three trough reflector support.

A plan view of the modified design of the aluminium back plate used for outdoor experimental characterisation is shown in figure 3.4.4.3. Two 3-mm thick aluminium sheets were required for the rear aluminium back plate (the vacuum chamber used to encapsulate the EVA could not accommodate the size if constructed in a single plate). A cross sectional view of the two plates along with a five trough reflector support is shown in figure 3.4.4.4. The two plates were screwed together at the space provided between two consecutive reflector supports. The nodes of the reflector support base were 10 and 15-mm apart from the central line. A short circuit between more than two points at the solar cell back will cause ohmic losses and may create hot spots and reduce the maximum power point (Partain, 1995). Two 1.5-mm deep slots between two consecutive reflector supports ensured that the back connectors position prevented any electrical contact with back aluminium plate.

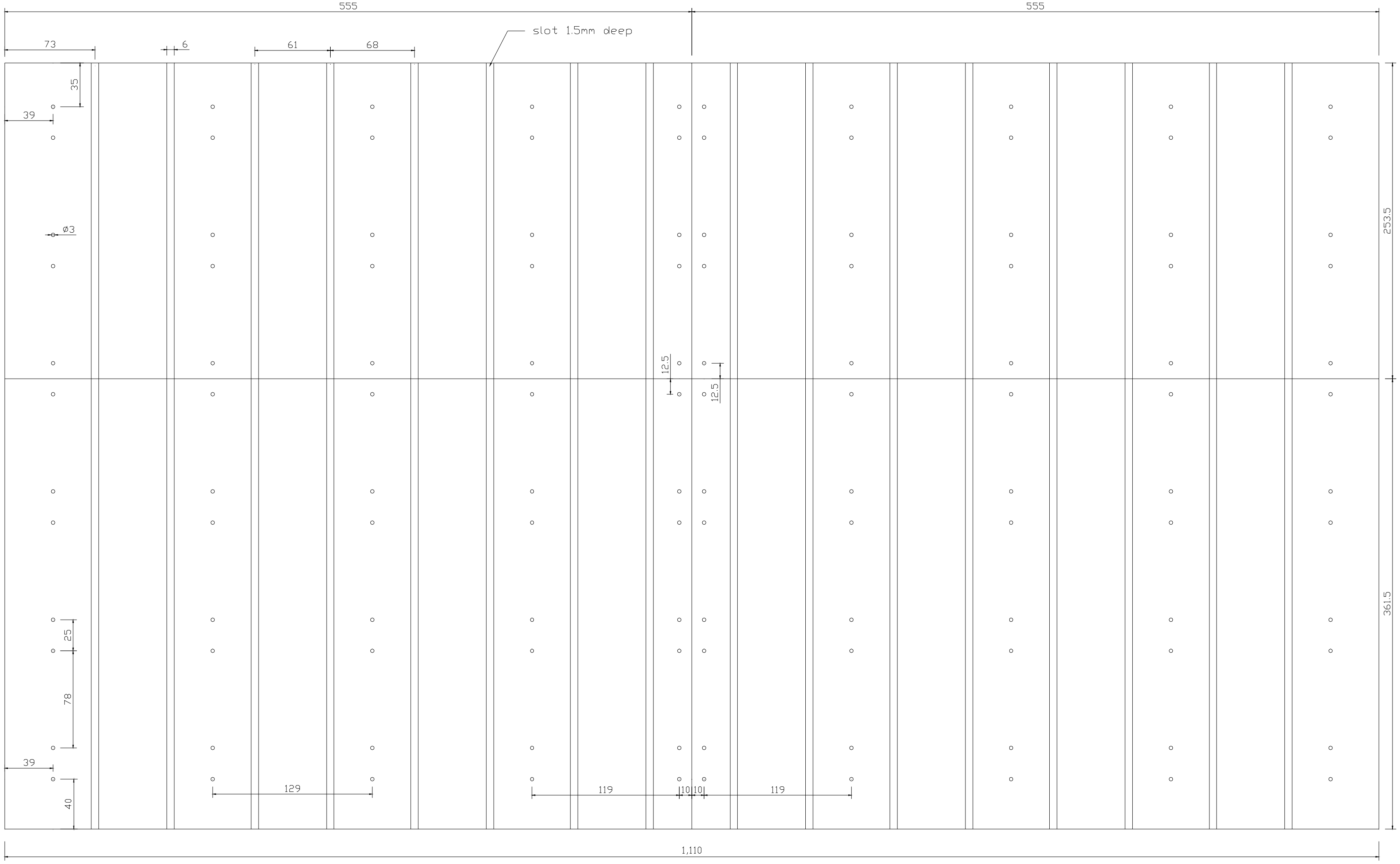


Figure 3.4.4.3 Top view of rear aluminium plate of the ACPPVC-50 used for outdoor experimental characterisation.

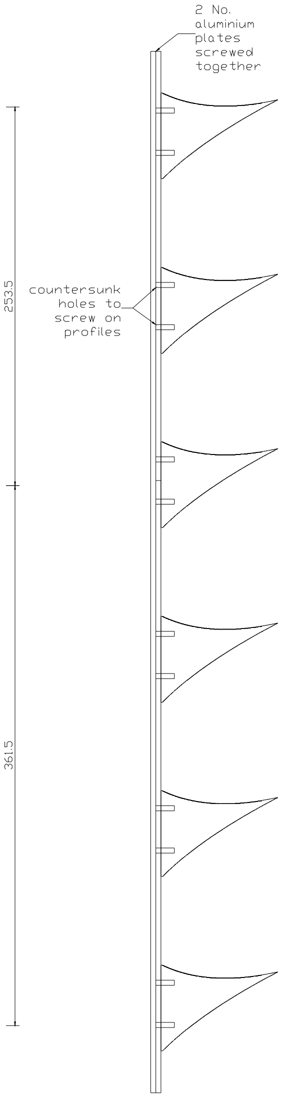


Figure 3.4.4.4 Cross-sectional view of five trough reflector support.

3.4.5 Supporting PV Reflector System Enclosure and Frame

Direct exposure of the EVA encapsulated solar cells and the reflector material to solar radiation may effect the system in the following ways;

- The UV component of direct sunlight may degrade and damage the reflecting material.
- Direct exposure of the EVA to sunlight can cause yellowing (Komp, 1995). This does not change the spectral response of the photovoltaic solar cells but it reduces the incident solar radiation that can reach the solar cells. This lowers the power output of the system and thus the efficiency of the PV module.
- The PV material, EVA and reflecting material may be effected by moisture and salt accrual that scatters incident direct solar radiation (Rauchenbach, 1980).

To avoid such problems the glass aperture cover described previously was used, placed within an adjustable wooden supporting frame shown in figure 3.4.5.1. The base frame was screwed to the rear aluminium back plate as shown in figure 3.4.5.1(a). The gaps between the reflector end and glass cover could be set to 10, 20, 30 or 40-mm. Two rubber gaskets were used at either end of the frame and the top frame was screwed to the base frame. Any gaps were filled with silicon sealant to prevent moisture or water penetration.

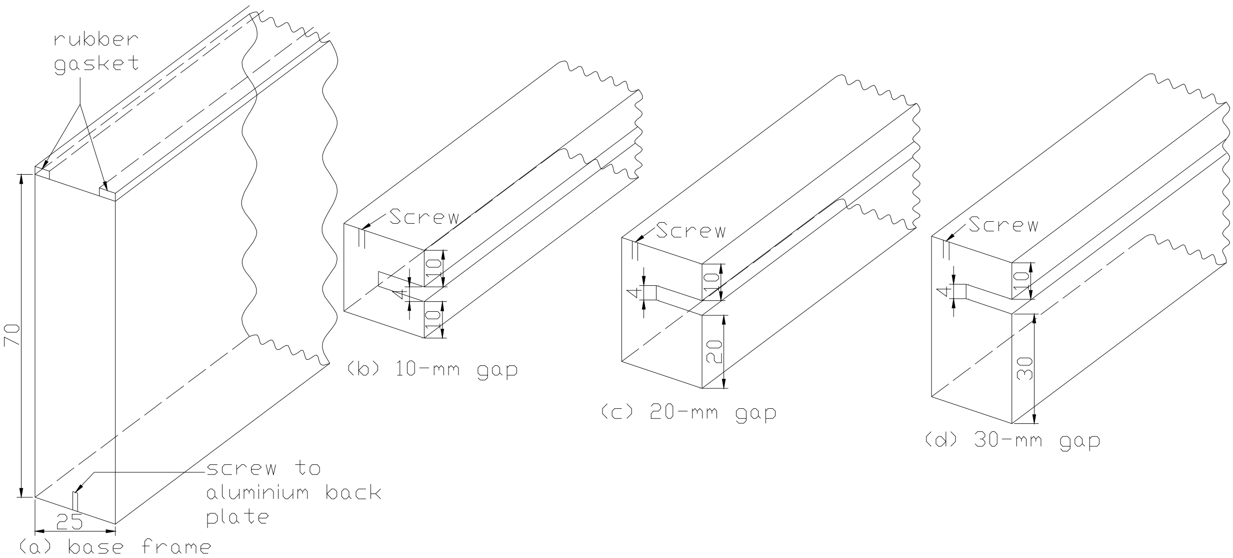


Figure 3.4.5.1 Adjustable wooden supporting frame for the ACPPVC-50 system: (a) base frame (b) top frame with 10-mm gap between reflector end and glass cover (c) top frame with 20-mm gap between reflector end and glass (d) top frame with 30-mm gap between reflector end and glass cover.

3.5 Assembly of Different Components and Fabrication of System

One system was fabricated for indoor experimental characterisation and two systems were constructed for the outdoor experimental characterisation. For both indoor and outdoor systems the fabricating procedures were similar with only the system design differing.

3.5.1 Fabrication of the Reflector Mould

The reflector mould was fabricated using the same computer generated profile as the reflector. The reflector mould shown in figure 3.5.1.1. was used to maintain the reflector profile during the attachment of reflector support to the reflectors. This is further discussed in section 3.5.5.

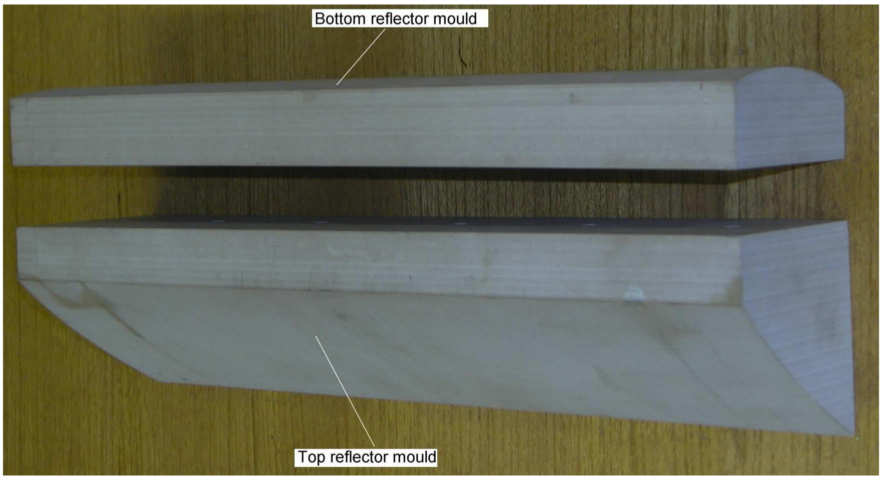


Figure 3.5.1.1 Top and bottom reflector mould.

3.5.2 Fabrication of Reflector Supports

The reflector support was fabricated based on the design shown in figure 3.4.2.1.1 and figure 3.4.2.1.2. The computer generated data points were transferred to "AUTOCAD" which was then used to cut 2-mm and 6-mm thick aluminium plate to the profile required. Aluminium 2-mm thick was used for the reflector support for the indoor experimental characterisation and 6-mm thick aluminium was used for the reflector support for the outdoor experimental system characterisation as described previously. A fabricated reflector support is shown in figure 3.5.2.1. Two holes were required to clamp the aluminium plate during machining to achieve the desired accurate asymmetric parabolic reflector geometry. Two tapped holes in the bottom of the reflector support allow attachment to the rear aluminium back plate.

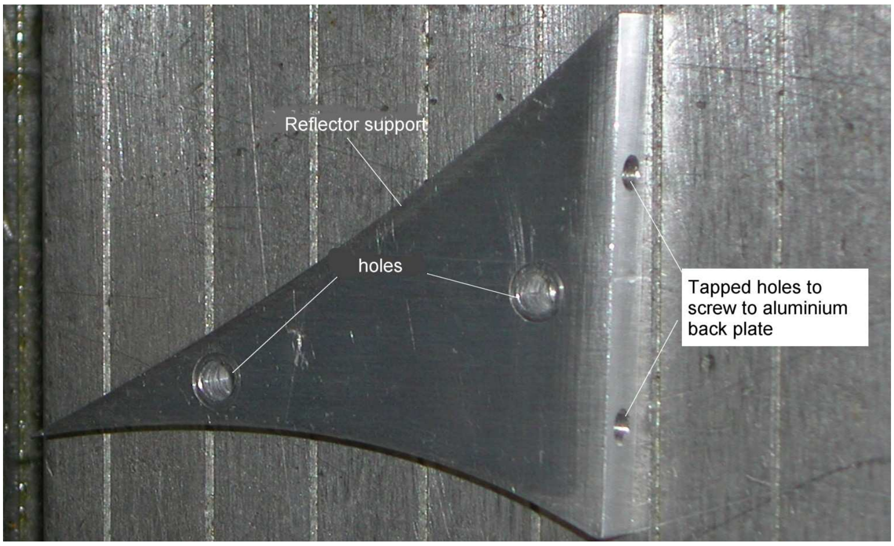


Figure 3.5.2.1 A 6-mm thick aluminium reflector support.

3.5.3 Construction of the Rear Aluminum Back Plate and Placement of the Reflector Supports

Two 3-mm thick aluminium plates were used for the rear of the ACPPVC-50. The upper plate was divided into four and joined together with the bottom plate. The constructed rear aluminium back plate is shown in figure 3.5.3.1. There were two 6-mm wide and 1.5-mm deep slots between consecutive reflector supports. Each slot provided space to pass the back connector from one solar cell to the next avoiding electrical short circuits between any solar cell and the metal plate and allow the solar cells to rest against the aluminium back plate. M3 holes enabled the reflector support to be screwed to the rear aluminium back plate. Figure 3.5.3.2 shows the placement of each individual reflector support on the aluminium back plate. The reflector support is placed on the rear aluminium back plate as shown in figure 3.5.3.3.

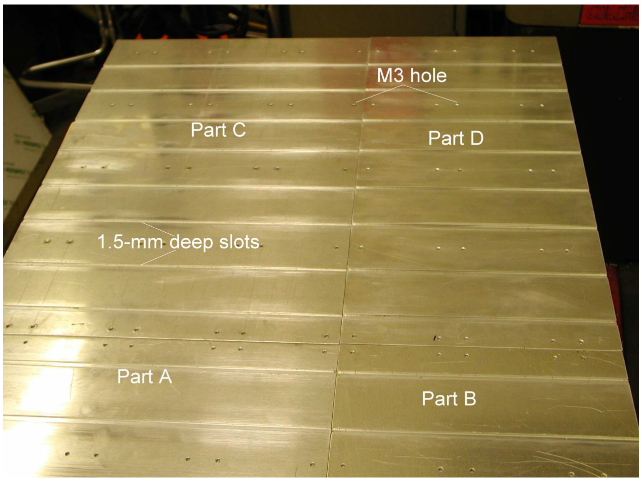


Figure 3.5.3.1 Construction of the rear aluminium back plate. Four aluminium plates of 3mm thick were screwed to a single aluminium plate.

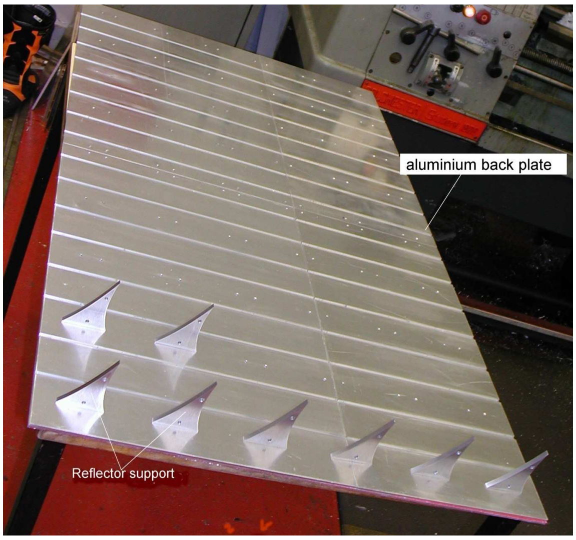


Figure 3.5.3.2 Locating reflector supports on to the rear aluminium back plate.

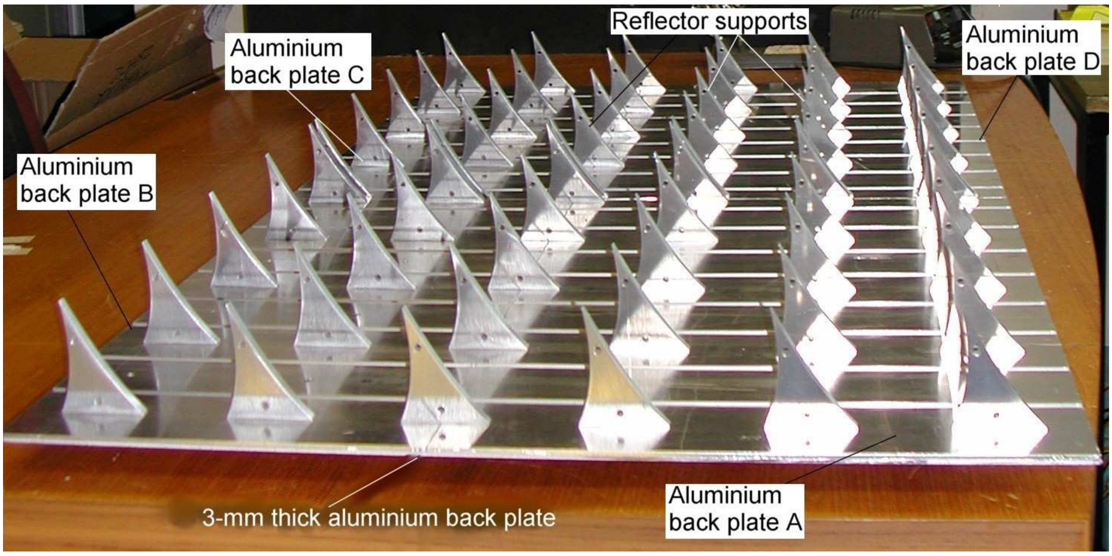


Figure 3.5.3.3 Reflector supports placed on the rear aluminium back plate.

3.5.4 Solar Cell Soldering and Interconnection

Solar cells can be connected in a number of ways depending on the output requirement as follows:

- Series connection to increase the output voltage keeping same output current. This minimised the ohmic power losses through connecting cables provided between the PV panel and load as shown in figure 3.5.4.1(a).
- Parallel connection to increase the output current keeping the same output voltage as shown in figure 3.5.4.1(b).
- A combination of series and parallel connections to increase both current and voltage depending on the number of solar cells connected in series or parallel as shown in figure 3.5.4.1(c).

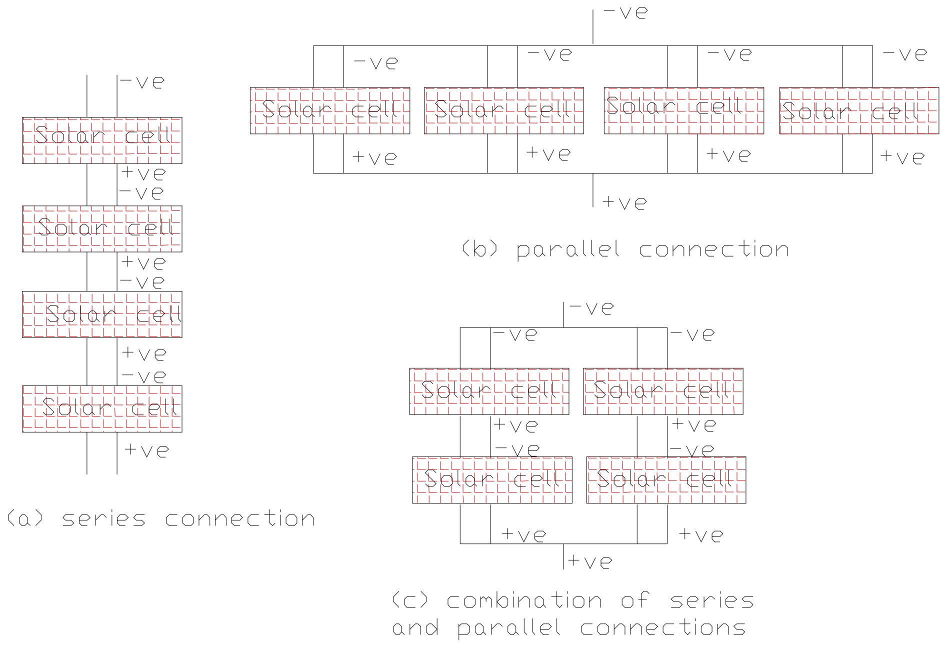


Figure 3.5.4.1 Solar cell connections (a) series connection to increase voltage (b) parallel connection to increase current (c) combination of series and parallel connections to increase current and voltage.

BP solar cells (Anon, 2001e) are designed to have contacts soldered to them. The back contacts and front fingers are applied to the cells in a number of ways, including electroless, nickel plating, vacuum metallizing and silk-screen printing. Low temperature solder was used for tabbing the solar cells. The chemical composition, and physical characteristics of the solder are given in table 3.5.4.1. The use of low temperature solder with a 0.65 mm diameter resin core (Anon, 2001f) provided a good electrical connection between the tabbing strips and the solar cells. A fiber brush was used to clean the cell surface and provide a key for soldering. The main purpose of soldering solar cells were as follows:

- To increase the effective current produced at the solar cells. In solar cells, with interaction of incoming photon flux (incident solar radiation), the generated electrons may recombine before reaching the cell fingers. Soldered connections allow a better flow of electrons and increases the power output.

- To increase the current or voltage as required in a single solar strip. The electron transport inside a semiconductor is poorer than in the metal conductor. Although soldering the front surface may increase the series resistance and may create a shadow on the solar cell surface, it effectively increases the electron transport and thus power output (Partain, 1995).

Chemical composition: (wt %)										
Composition	Sn	Pb	Bi	Sb	Cu	Zn	Fe	Al	As	Cd
Standards	42~44	Bal	13~15	≤0.3	≤0.05	≤0.003	≤0.03	≤0.005	≤0.03	≤0.005
Physical properties										
Solidus (°C)	135									
Liquidus (°C)	165									
Specific gravity	9.1									
Flux content (%)	3.0 ± 0.5									
Chloride & Bromide	0									
Insulation resistance (Ω)	$>1\times10^{11}$									
Spreadability (%)	>80									
Dryness	Chalk powder should be easily removed from each test piece.									
Solution resistance (Ω cm)	>50,000									

Table 3.5.4.1 The physical and chemical properties of the low temperature solder used (Anon, 2001f).

The following procedure was used for soldering the solar cells:

- The solar cells were cleaned with a fiber brush, front and back to remove the copper oxide allowing better contact between the busbar-line and the front connection.
- The tin/lead coated copper tab was cleaned and cut in to 152-mm lengths, ensuring that each of the connectors between the solar cells were straight.
- Masking tape was used either side of the cell front connection to ensure no spreading of flux residue onto the active surface area of the solar cell.
- The soldering iron was heated to 230ºC for soldering the front connections of the solar cell.
- Only a small amount of solder was used on one side of the prepared tin/lead coated copper tab. Precautions were needed to avoid excess use of solder on the tab that might increase the series resistance of the solar cell.

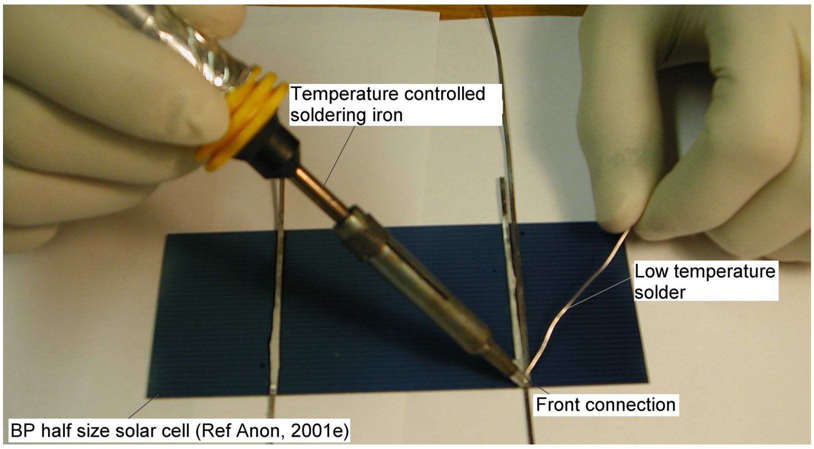


Figure 3.5.4.2 Soldering of front connection of solar cells.

- Placing the soldering tab on top of the front contact and dragging the solder iron along it as shown in figure 3.5.4.2. This procedure completed the soldering and the tabing of the negative terminal of solar cell.
- Solar cells were located on to the rear aluminium plate between each reflector support with their back connections upwards to allow each individual cell to be located accurately between the two reflectors.
- The solder iron was heated to 230ºC and a tin/lead coated copper tab placed on top of the back contact.
- The soldering iron was slowly dragged over the solder tab to connect the negative terminal of the first solar cell to the positive terminal of the second solar cell.
- The same procedure was repeated for five solar cells connected in each string as shown in figure 3.5.4.3, eight such strings were made for each system to provide the option to make either series or parallel connections.
- The interconnected solar cells were encapsulated with Ethylene Venyl Acetate (EVA) to avoid any short circuits.

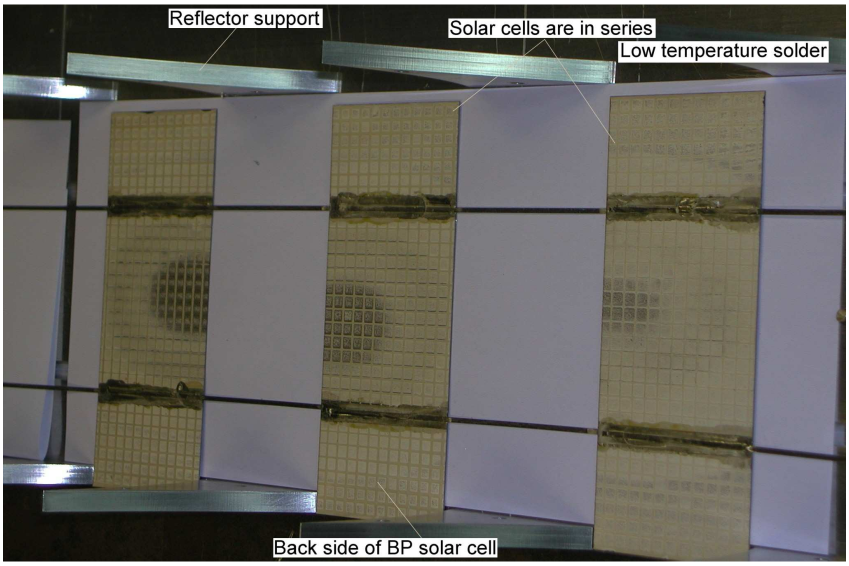


Figure 3.5.4.3 Alignment and interconnection of individual solar sells in series. The solar cells were located between two reflector supports during soldering to ensure their accurate positioning.

3.5.5 Attachment of Reflector onto the Reflector Supports

Self adhesive "Radiant VM2000" (Anon, 2001d) reflector film was attached to a 0.15 mm thick stainless steel substrate to produce the system reflectors. The individual reflectors were then bonded to the aluminium reflector supports using "Output-315" (Anon, 2001g) adhesive, the physical properties of "Output-315" are presented in table 3.5.5.1.

Property	Value
Tensile shear strength	7 $N.mm^{-2}$
Coefficient of thermal expansion	1.1×10^{-4} /ºC
Thermal conductivity at 30ºC	0.815 Wm^{-1}ºC^{-1}
Outgassing	4.5% TLM[2]
Operating temperature	-55ºC to 150ºC

Table 3.5.5.1 Chemical properties of "Output-315" thermally conductive adhesive (Anon, 2001g).

The major features of this adhesive are:

- high thermal conductivity
- rapid room temperature cure
- self-shimming properties ensured a consistent 0.15 mm gap (This provides uniform electrical insulation between bonded components).

The adhesive was applied to the aluminium reflector supports and the activator placed on to the corresponding region of the stainless steel reflector substrate. When the reflectors were placed on the reflector support, the reflector mould shown in figure 3.5.1.1 was positioned to allow an even pressure across the reflector surfaces to ensure accurate system profile. The attachment procedure for the mirror reflector on the reflector support is shown in figure 3.5.5.1. Three to four hours were required to cure the adhesive. The same procedure was repeated for all other reflectors. Figure 3.5.5.2 shows the ACPPVC-50 with the reflector attached to the aluminium back plate.

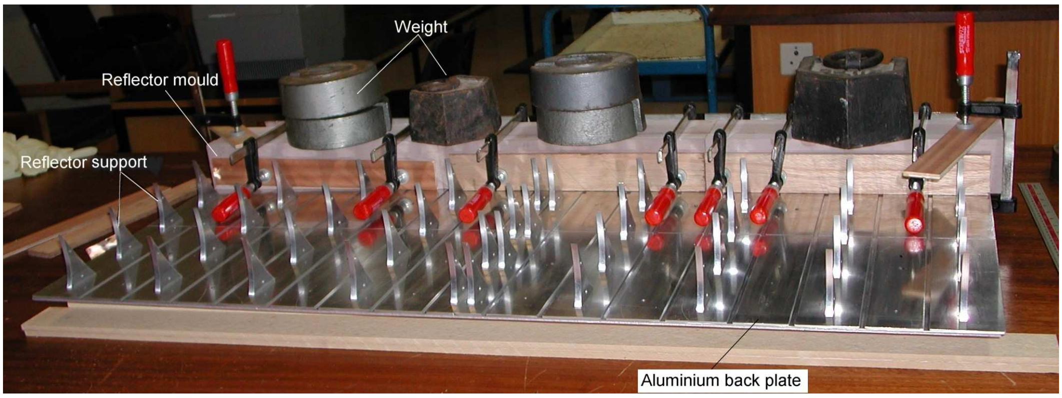


Figure 3.5.5.1 Attachment of mirror reflector to the reflector support. The mirror was attached to a 0.0003 m thick stainless steel back plate.

[2] Manufacturer specified test method

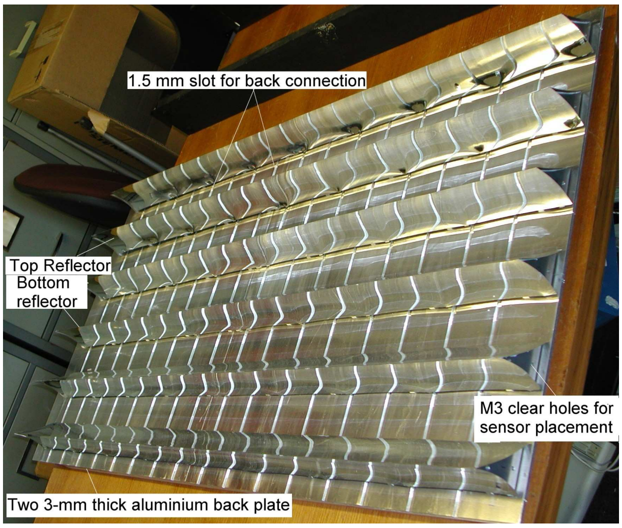


Figure 3.5.5.2 Asymmetric compound parabolic photovoltaic concentrator with mirror reflectors attached to the rear aluminium back plate.

3.5.6 **Encapsulation of Solar Cells**

The solar cells were encapsulated in Ethylene Vinyl Acetate (EVA) (Anon, 2001h) to avoid;

- short circuiting between the solar cells and the metal back plate.
- direct exposure of the cells to the environment leading to solar cell damage (Komp, 1995).
- cracking of the very fragile solar cells.

The physical and chemical properties of EVA used in this work are shown in table 3.5.6.1.

Property		
Specific Density (kg m^{-3})		0.93
Water Absorption Rate (%)		0.07
Elongation (%)		800
Tensile Strength (Pa)		0.292
Compression strength (Pa)		0.2103
Flexural Strength (Pa)		0.203
Flexural Modulus (Pa)		1.2615
Hardness:		R40[3]
Deflection Temperature (°C) at	9.57×10^{-3} Pa:	63
	0.038 Pa	35
Utilisation Temperature (°C)	Min:	25
	Max:	55
Melting Point (°C)		80
Coefficient of Expansion (m $°C^{-1}$)		0.00009

Table 3.5.6.1 Physical and chemical properties of EVA (Anon, 2001h).

[3] Manufacturer specified test method

The following procedures were used for encapsulation of the solar cells:

- The aluminium back plate surface was cleaned using acetone wipes.
- A single layer of EVA was placed on the aluminium back plate and placed in a vacuum chamber.
- The pressure inside the vacuum oven was reduced to 0.5 mbar to remove air trapped between the EVA and the back plate.
- The back plate and EVA were heated at 120°C for 75 minutes to bond the EVA to the back plate.
- The aluminium back plate was taken outside the vacuum oven and solar cells placed on top of the EVA coated aluminium back plate. A second layer of EVA was applied as shown in figure 3.5.6.1. Care was required to ensure that no solar cells moved from their original position.
- The whole back plate coated in EVA was put back inside the vacuum chamber as shown in figure 3.5.6.2.
- The vacuum oven pressure was reduced to 0.5 mb and the temperature was set to 120°C where it remained constant for 75 minutes.
- The air inlet valve was opened and the vacuum oven allowed to cool for 6 hours to ambient.
- A similar procedure was repeated for all other parts of the aluminium back plate until encapsulation was complete.

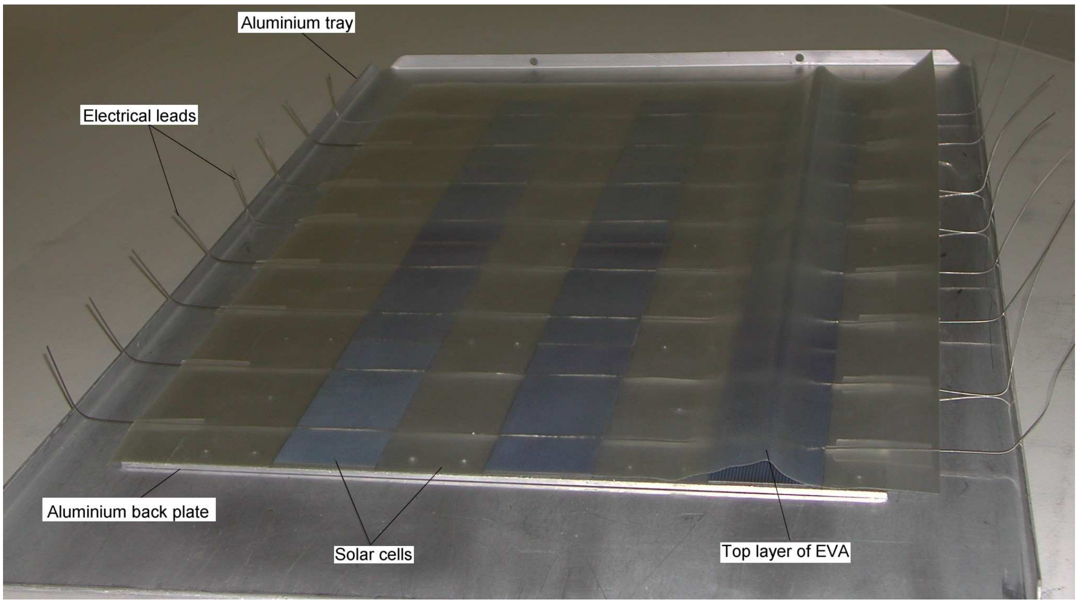


Figure 3.5.6.1 Line up of solar cells on the aluminium back plate. Individual solar cells are connected in series.

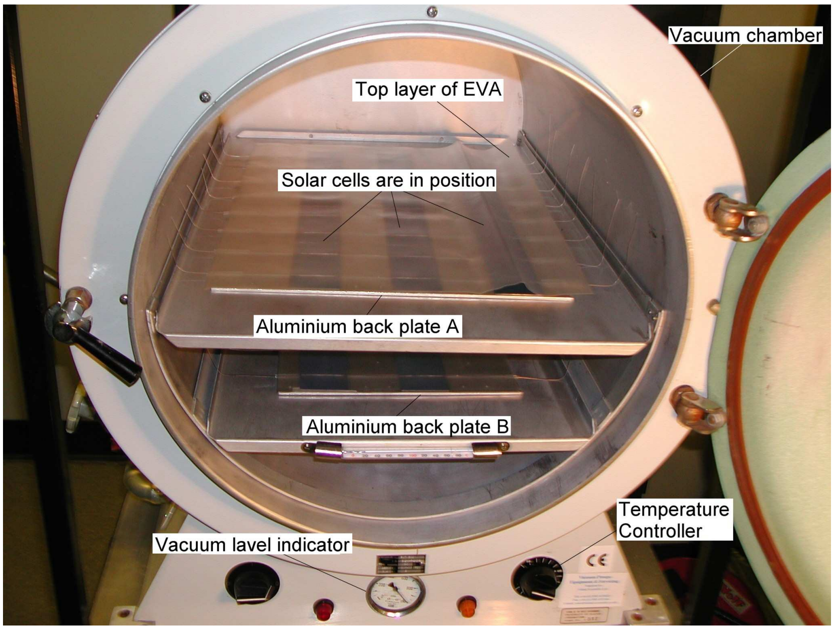


Figure 3.5.6.2 Encapsulation of solar cells with EVA in a vacuum oven.

After encapsulation the solar cells were tested for short circuits. One solar cell was found to have shorted with the aluminium back plate in the first system. The solar cell was replaced as shown in figure 3.5.6.3. To prevent reoccurrence of this problem a thin layer of plastic was positioned between the solar cells used and the back plate during fabrication in the second system, otherwise the same fabrication procedure was used.

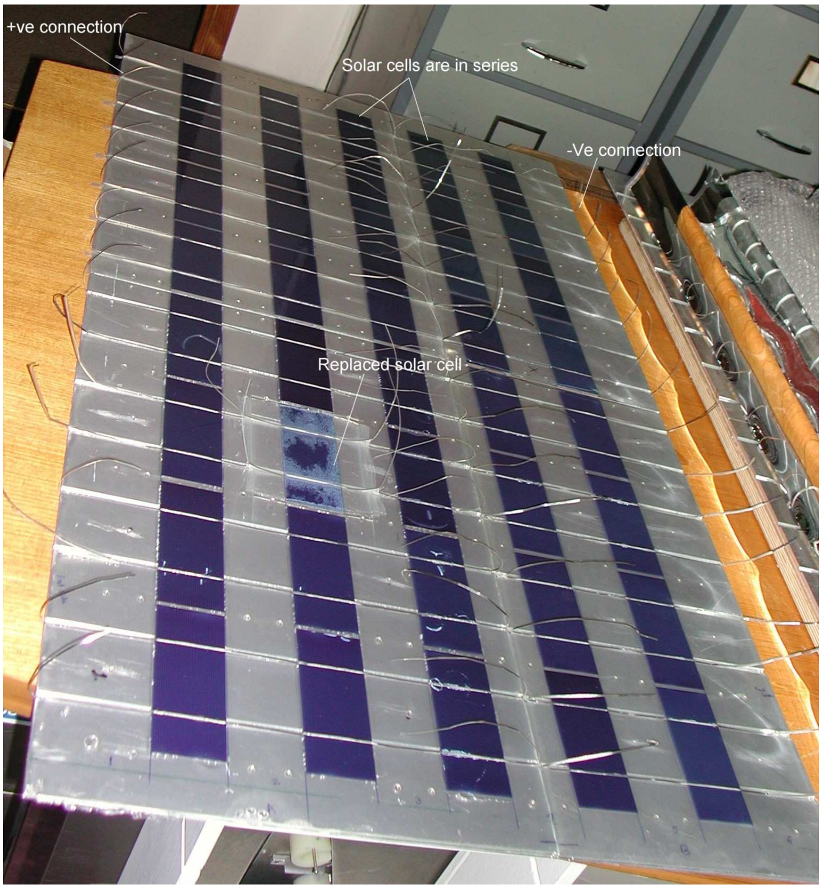


Figure 3.5.6.3 Solar cells encapsulated on to the aluminium back plate clearly showing the replaced solar cell.

3.5.7 Reflector Placement on to the Encapsulated Solar Cells

The reflector troughs were placed on the aluminium back plate with the encapsulated solar cells as shown in figure 3.5.7.1. Insulating tape was used at the sharp edges of the reflector to prevent contact with the front connection of the solar cells. Transparent and yellow heat shrink was used to coat the external electrical leads to avoid short circuits. The constructed ACPPVC-50 system without the wooden frame or cover glass is shown in figure 3.5.7.2.

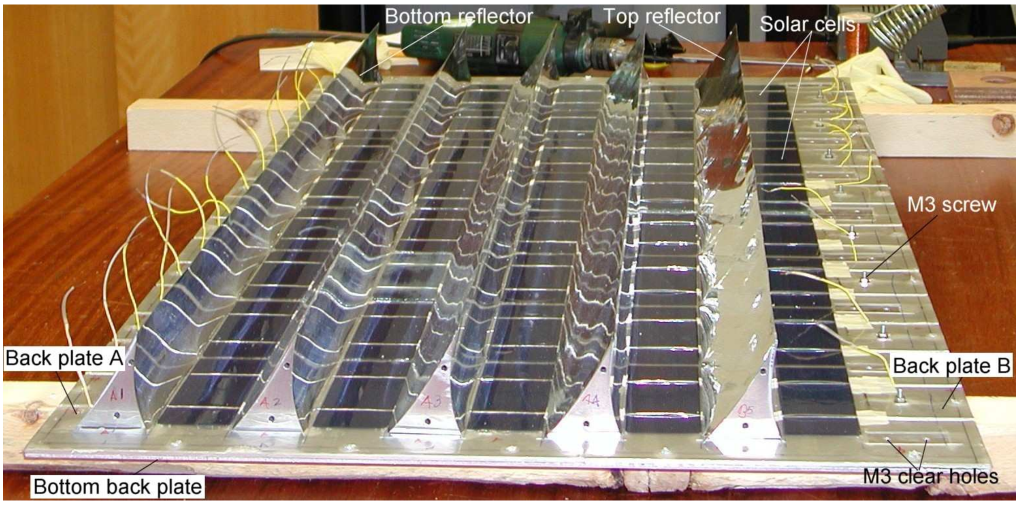


Figure 3.5.7.1 Placement of detachable reflector troughs on the aluminium back plate with the encapsulated PV cells.

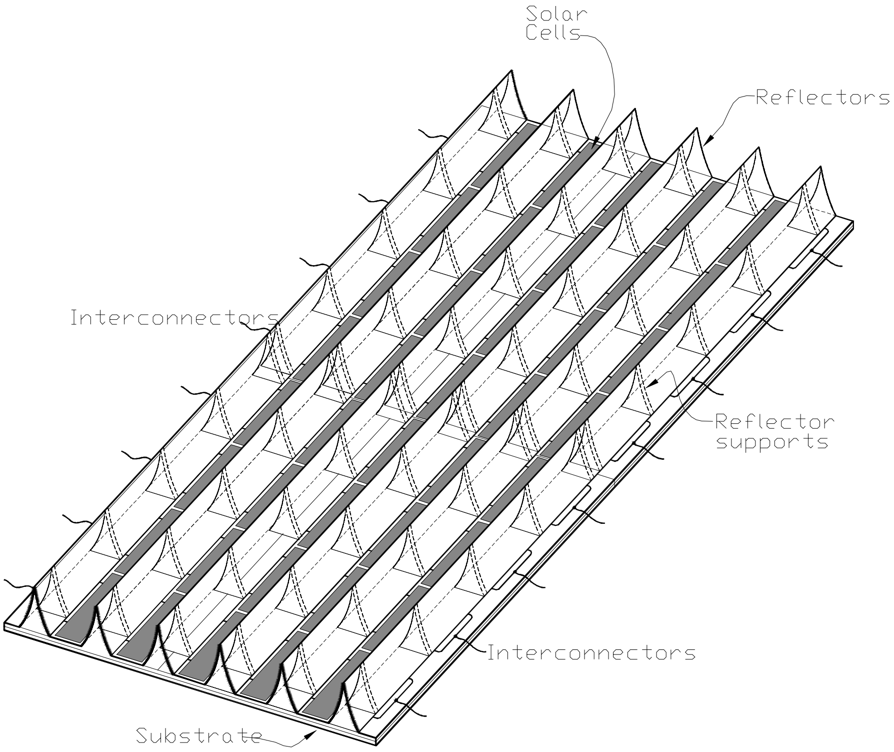


Figure 3.5.7.2 The ACPPVC-50 system used for outdoor experimental characterisation without the wooden frame or cover glass.

3.5.8 PV Reflector System Frame

A supporting frame shown in figure 3.4.5.1 was made to hold the 4-mm thick glass cover for the ACPPVC-50 as shown in figure 3.5.8.1. A rubber gasket prevented water or moisture ingress into the system, and thus damage to the EVA or solar cells. A silicon sealant was applied to all joints and gaps in the ACPPVC-50. The internal electrical connections are shown in figure 3.5.8.2.

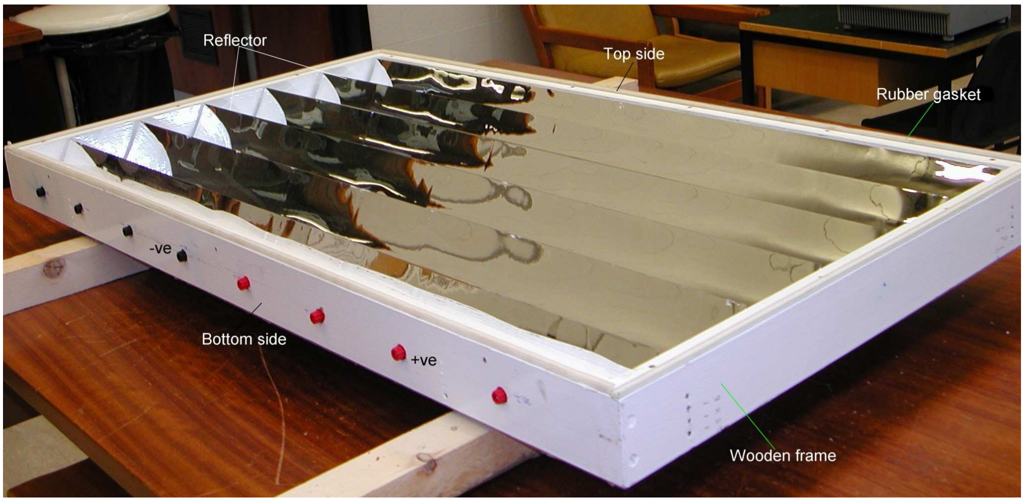


Figure 3.5.8.1 Asymmetric compound parabolic photovoltaic concentrator with wooden frame.

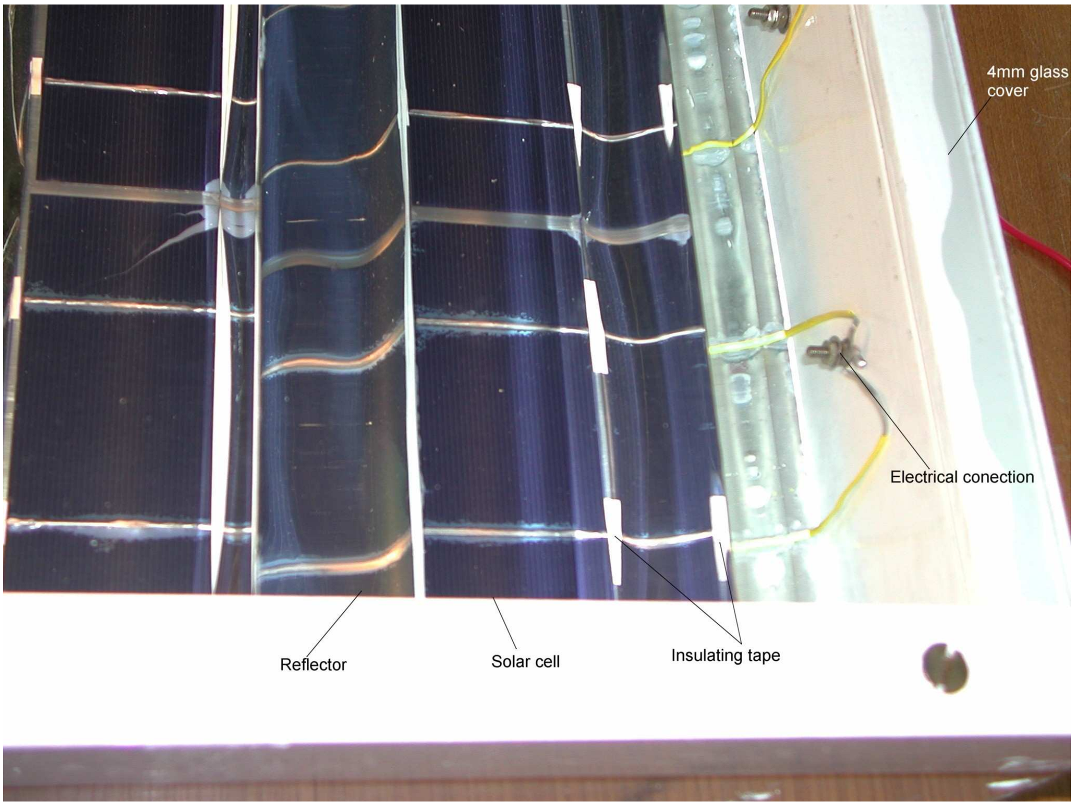


Figure 3.5.8.2 Internal electrical connections of solar cells through the wooden frame. Each series of solar cells are connected individually to each electrical connector.

3.6 The Final Specification of the ACPPVC-50 Systems Fabricated

3.6.1 The Prototype ACPPVC-50 Used for Indoor Experiments

The number of solar cells required and the physical characteristics of the prototype ACPPVC-50 system used for indoor experimental characterisation are shown in table 3.6.1.1. The constructed system is illustrated in figure 3.6.1.1. Three solar cells in each of two rows were connected in series with both rows connected in series externally to increase the voltage developed.

System dimension (Module)	0.25m × 0.30m
Single solar cell dimension	50mm × 125mm
Type of solar cell	Rectangular
No of solar cells	6

Table 3.6.1.1 Physical characteristics of prototype ACPPVC-50 system used for indoor experimental characterisation.

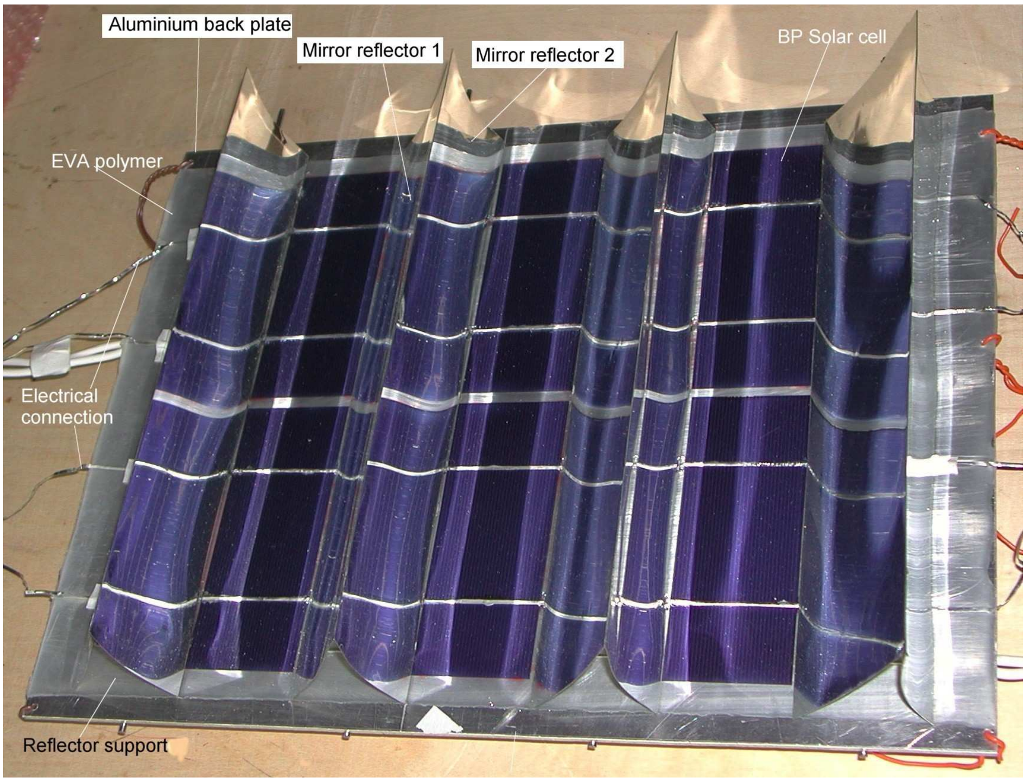


Figure 3.6.1.1 Fabricated asymmetric compound parabolic photovoltaic concentrator used for indoor experimental characterisation.

3.6.2 The Prototype ACPPVC-50 Used for Outdoor Experiments

The physical dimensions of both the outdoor systems are presented in table 3.6.2.1. Five solar cells were connected in series in each of the strings, each system having eight strings that can be connected either in series or parallel combinations externally. Different views of the ACPPVC-50 used for the experimental characterisation are shown in figures 3.6.2.1 and 3.6.2.2. The side view of the first system is shown in figure 3.6.2.3 and a plan view of the constructed ACPPVC-50 used for outdoor experimental characterisation shown in figure 3.6.2.4. To permit the experimental investigation of the effect of the width of the air gap between the reflector tip and the glass cover on the convective flow inside the concentrator, the gap between the adjustable wooden frame could be changed to 20, 30 mm. In the second system alternative electrical connections were used as shown in figure 3.6.2.5

	System 1	System 2
System dimension (Module)	1.110m × 0.615m	1.110m × 0.615m
Single solar cell dimension	50mm × 125mm	50mm × 125mm
Type of solar cell	Rectangular	Rectangular
Number of solar cells	40	40

Table 3.6.2.1 System dimension for outdoor experimental characterisation

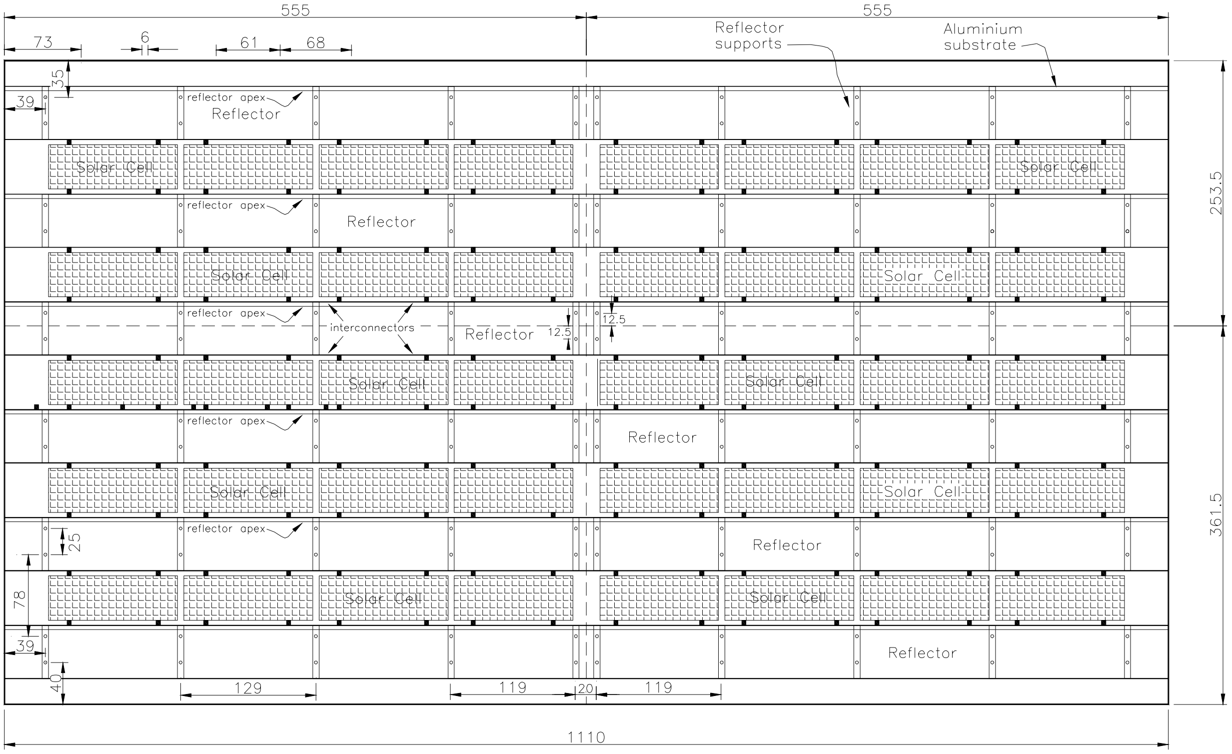


Figure 3.6.2.1 Top view of the ACPPVC-50 system used for outdoor experimental characterisation.

3.7 Conclusions

A suitable design and fabrication process has been developed to produce concentrating PV panel. The fabrication of this system indicates the potential for mass manufacture of multi-trough asymmetric concentrators to be mounted vertical façade in the UK. The designed system with a concentration ratio of

2.01 requires 50% less photovoltaic material compared to a similar flat PV panel. The Aluminium back plate provided a heat sink for the hot solar cells, increasing the heat loss coefficient to ambient thus effectively reducing the solar cell operating temperatures. Although a glass aperture cover mounted in a wooden frame is shown to decrease the heat loss from the system, it is necessary to prevent dust accumulation and/or any deformation of the reflectors, in order to maintain system optical performance.

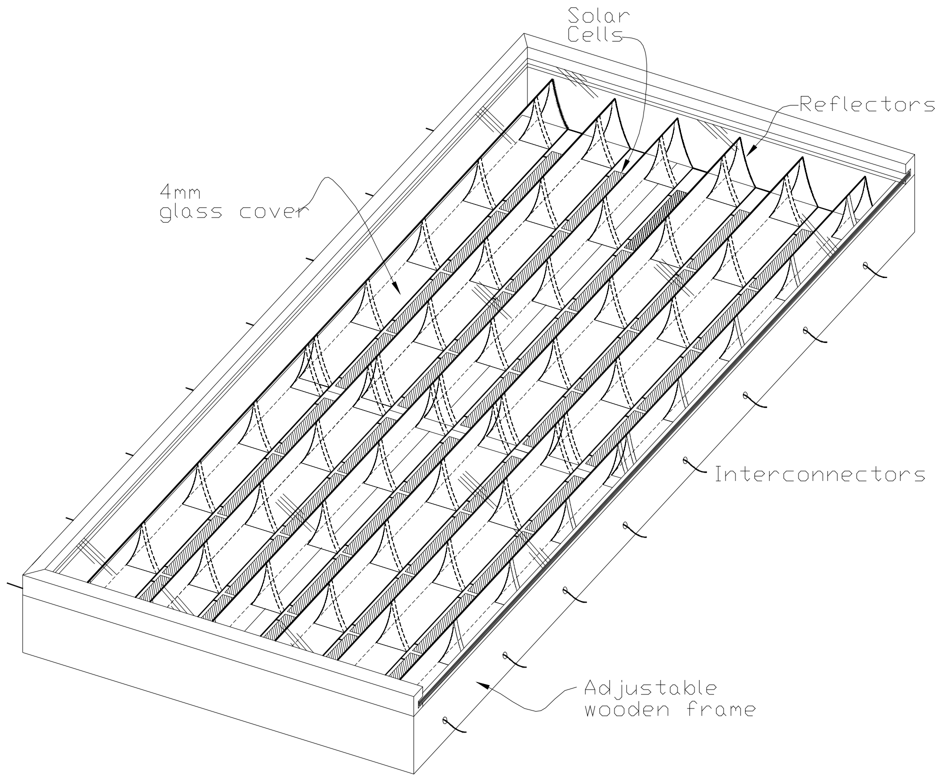


Figure 3.6.2.2 The full Asymmetric compound parabolic photovoltaic concentrator system.

Figure 3.6.2.3 Side view of the asymmetric compound parabolic photovoltaic concentrator used for outdoor experimental characterisation.

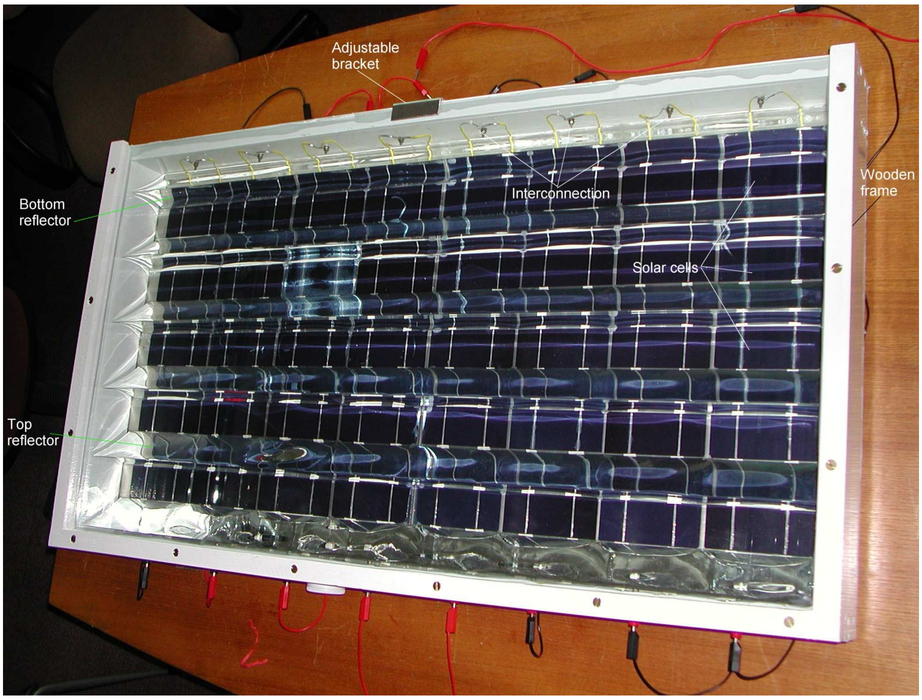


Figure 3.6.2.4 The plan view of the asymmetric compound parabolic photovoltaic concentrator used for outdoor experimental characterisation.

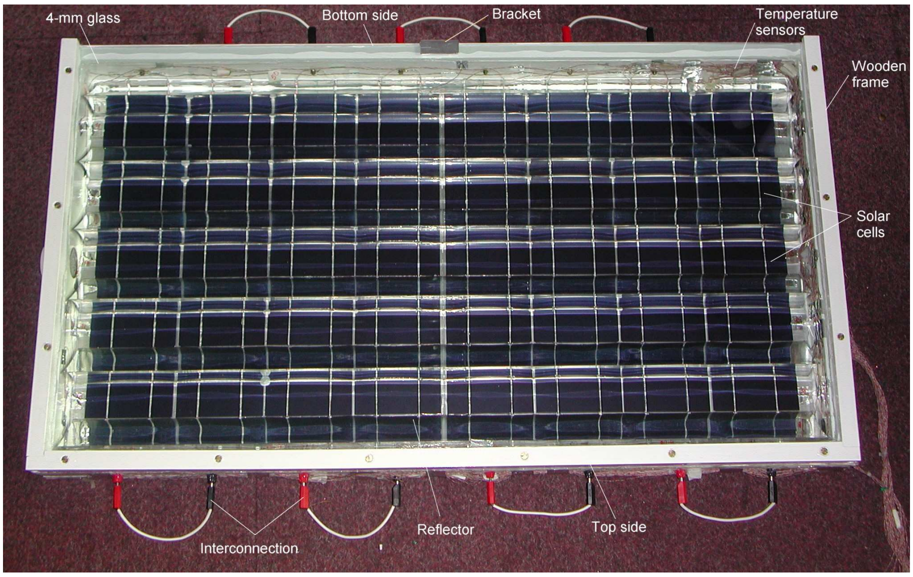


Figure 3.6.2.5 The plan view of the 2nd ACPPVC-50 with temperature sensors inside the system.