

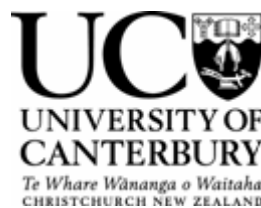
# The Solar Energy Tracker

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B.E. (Elect)

A thesis presented for the degree of  
Masters of Engineering  
in  
Electrical and Electronic Engineering  
at the  
University of Canterbury,  
Christchurch, New Zealand

July 2008



## **Abstract**

Reference is increasingly being made towards the need for the world to find new and renewable forms of energy, especially for electric power generation, but also for space heating and the heating of water. Solar energy is one of the cheapest forms of renewable energy available and is so far one of the most underutilised resources. One contribution makes reference to the way forward as being 'using concentrating solar power which uses parabolic mirrors to focus the solar heat (energy) and generate steam to drive electric generators' as is currently happening in the utility power marketplace in the USA.

This thesis deals with the issues surrounding the original development of a two axis solar energy tracking system (SET) in 1997. The subsequent redesign, development and upgrade, undertaken from 2002 to 2006, with its performance and efficiency being measured in 2006 and 2007 using a specially configured measurement and recording system. A Solar Energy Tracker (SET) is designed to track the sun moving in two axes, reflecting the solar radiation received on its mirrors to a target mounted at the end of a boom, at the focal point of the mirrors.

In late 2005 and early 2006, a solar thermal hot water manufacturer and installer heard about the developments and requested some form of involvement, especially if Christchurch Polytechnic Institute of Technology (CPIT) provided research input and assisted in the further development and testing of solar thermal hot water systems. This sponsor offered two projects in 2006 and again in 2007. Other solar thermal hot water suppliers also requested involvement in the research and development being performed at CPIT, which led in August 2006, December 2006, June 2007 and December 2007, to a number of other solar thermal hot water and air wall systems being installed.

Progressively, the roof of C block at CPIT has become full of solar thermal hot water systems and solar air wall systems, both of the conventional type and those with newer technologies at the core of their development.

This thesis outlines the stages in the redesign and development of the SET, and the various stages in its testing, development and refinement up to its present form. The thesis chapters are written based around the mechanical and electrical design, the auto-tracking and daylight controls, the PLC (programmable logic controller) controller, the mirror and substrate testing, the SCADA (Supervisory Control And Data Acquisition) system, the testing and comparison with other domestic solar thermal hot water systems and finally the testing of the SET itself. It also details the future developments and outlines possible uses for the SET in its redefined form.

With clean and polished mirrors the SET has proven itself capable of achieving a temperature rise across the target of 15 °C at a flow rate of 4 l/m. On some occasions this temperature rise can be in excess of 20 °C, but testing thus far, has shown this cannot be sustained for any worthwhile period of time (15-30 minutes). This translates to an efficiency of 5-10 % when related to an energy produced per twenty four hour time period. However, if the efficiency is calculated for the actual period of generation, 'generation efficiency,' then this figure rises to 24 %.

An overview is given of associated solar thermal hot water and solar air wall system research and development (that is ongoing at CPIT) as well as the performance and efficiency graphs for the solar thermal hot water systems on test. No manufacturer's, industry or brand trade names are mentioned, as this research is still confidential and commercially sensitive. However, the technology involved and characterised by each solar thermal system is recorded in a generic sense.

The SET was originally developed with the purpose of heating hot water and today this is still the intent. The possible applications for this hot water are many and varied from electricity generation, space heating and further into developing or new industrial processes. The performances of the other domestic solar thermal hot water systems currently under test, are compared with the figures from the SET, with the maximum efficiency, presently available, being from an evacuated tube heat pipe system at up to 65 %, whereas traditional finned flat plate technologies have efficiencies after twelve months of up to 48 %.

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## 1.0 Introduction

In order to maximise the capture of solar energy, a collector or absorber must be able to track or follow the sun throughout the day as the sun moves relative to the earth. In order to do this effectively it must be able to track in both the X (horizontal or azimuth) and Y (vertical or elevation) axes. A Solar Energy Tracker (SET) is designed to track the sun moving in two axes, reflecting the solar radiation received on its mirrors to a target mounted at the end of a boom, at the focal point of the mirrors thereby maximising the amount of solar energy which can be reflected onto a target.

The SET was originally conceived by two engineers in Queenstown, Jim Finnie and Dave McLaren, in 1996. They believed that a 'two axis tracking system is superior in that almost all of the area of the sun's energy striking the mirrors is redirected to the target,' (reference manual). Elsewhere in the same manual the inventors state that for the SET 'carbon tax is not applicable' and 'the (original) electronic system is independent from the global positioning system control (GPS)'. In the operations manual other advantages are listed such as:

- No air pollution
- Is not dependent on any fuel from the earth's planet
- Has no spent fuel to dispose of
- No dangerous fuel to be transported
- No fuel storage required.

The SET in its original form was progressively built in 1997, with operational testing commencing in late 1997 and 1998. At its original location in Queenstown, the SET was installed in one of the inventor's backyards, complete with tripod extension legs and mounting pods, which allowed the SET to operate from a flat platform, as shown in Figure 1.1. The SET was originally designed to be completely self contained using a Photo-Voltaic (PV) panel to charge a 12 V DC battery which supplied the energy required to operate the SET. The PV panel is evident in the centre top of the

Figure 1.1. A 12 V DC battery was located in the boom counterweight box. This was the only power supply used at that time for the SET.



Figure 1.1. The SET in its original installation in Queenstown, 1997.

At this time the market place and the government of the day expressed interest in the project with widespread news media coverage occurring in both the local and national papers, and on television both locally and internationally. However, despite all this, no money for the development of the second stage of the SET was forthcoming. The original inventors became frustrated with the project and sold off the PV panel and the battery to recover some of the costs of the development. The SET was dismantled into several parts and stored in one of the inventor's sheds. In 2002, the author contacted one of the inventors about the project and the whole concept of tracking the sun in two axes. This led to the SET being shipped to Christchurch for the testing and further proving of the two axis tracking concept, proving of the performance claims of the inventors, and updating and redesigning parts of the SET leading to its improvement as documented in this thesis. The SET was subsequently donated from the inventor's trust account to the author and Christchurch Polytechnic Institute of Technology (CPIT) for research and development, with the condition of royalty payments being made to the two inventors if ever the SET was commercialised. The details of the agreement

are confidential to the original inventors, CPIT, the author, and all staff and students working on the SET.

The SET was delivered to CPIT in August 2002. At the CPIT main campus there is no clear field site available, so use of a flat roof space was necessary. It was decided to mount the SET on the roof of C block where it had a largely uninterrupted view of solar activity and was not susceptible to major shadows. The consulting engineers, Powell Fenwick, could find no issues with the mounting of the SET in this position. In 2003, a crane was used to lift the heavy sections on to the roof where they were subsequently manhandled into position and then mounted on existing satellite dish rails which are connected through the roof to the actual structure of the building.

In the CPIT installation the extension legs and the pods of the original unit were not required, with a mounting adaptor plate being manufactured and placed across the ends of two of the base mounting tripod frame 'Y' legs, and then secured to satellite mounting rails. The rear leg of the 'Y' was secured to a central satellite mounting rail via another adaptor and a specially manufactured support leg, as shown in Figure 1.2.

Rear Y leg support with mounting adaptor.



Figure 1.2. Rear 'Y' leg support with mounting adaptor bracket securing to satellite rail, mid 2003.

The SET was mounted facing almost due north (2 degrees off true north), and is shown from three different angles in Figure 1.3. The only limitation in this location was the position of a tracking satellite dish immediately to the west of the SET, which would reduce the late afternoon solar activity for the SET. Figure 1.3 a b & c show the position of the SET on C block roof as viewed from the third floor mezzanine (a) and looking north, from an adjoining C block building on the north side of the quadrangle (b) and in perspective from the third floor mezzanine (c), as shown with the arrows below.

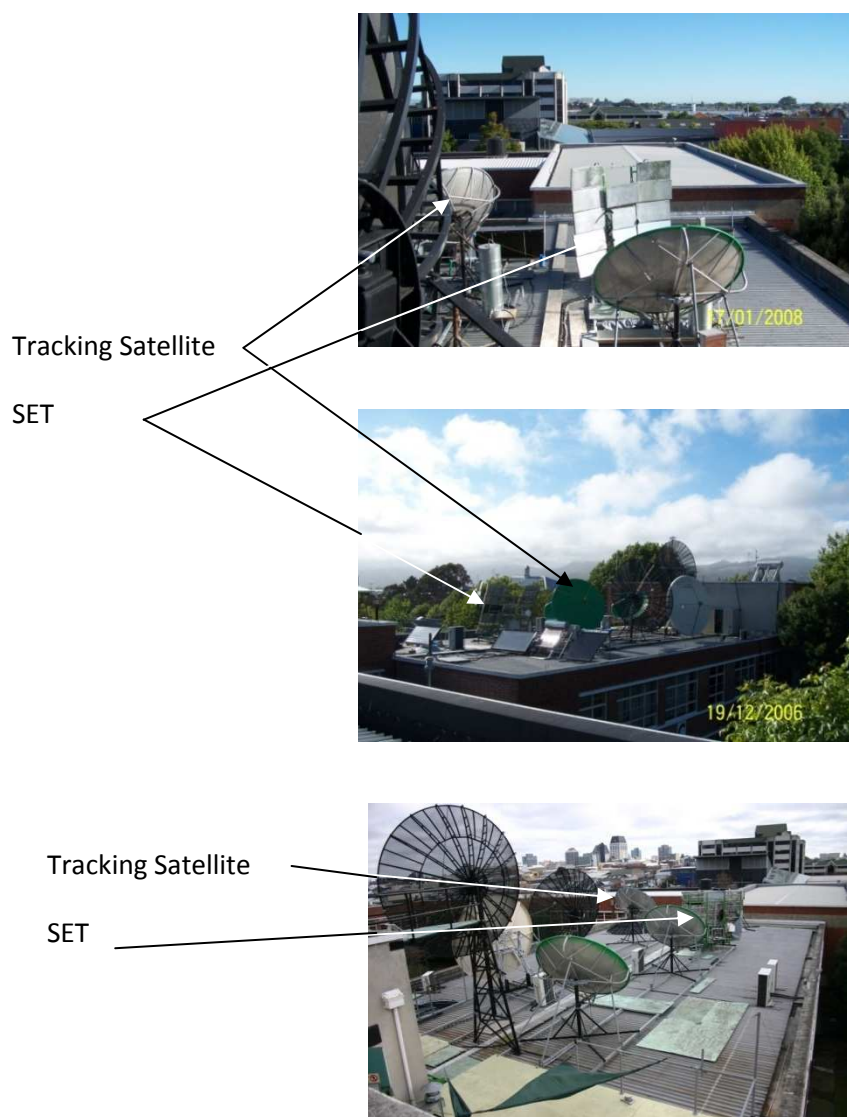


Figure 1.3 a, b & c. The position of the SET amongst satellite dishes on the second floor roof of C Block.

At the time of the installation, the view from C block to the East was also unobstructed, however in 2005 a third floor was added to the building on the east side which now precludes the SET from receiving early morning solar activity, especially in winter, as can be seen from Figure 1.4, with this photograph taken in February 2006 at 0752.



Figure 1.4. The third floor extension to E block, to the east side of the SET, sunrise (0752) on 17<sup>th</sup> February 2006, with the SET boom to the lower right of picture.

A panoramic view from an adjoining building to C block is shown in Figure 1.5. The sun's winter arc is recorded and is shown in Figure 1.6 east building and the tracking satellite visible.



Figure 1.5. C block panorama view, as viewed from an adjoining building: a) from south-east, b) east, c) north-east, d) north, e) north-west, f) west.





Figure 1.6. The sun's position at a) sunrise, b) midday and c) sunset on the shortest day, 20<sup>th</sup> June 2006.

Figure 1.7, shows the overall plan view of the solar thermal equipment on C block roof with dates of critical additions and changes. The arrows indicate key features of the layout.

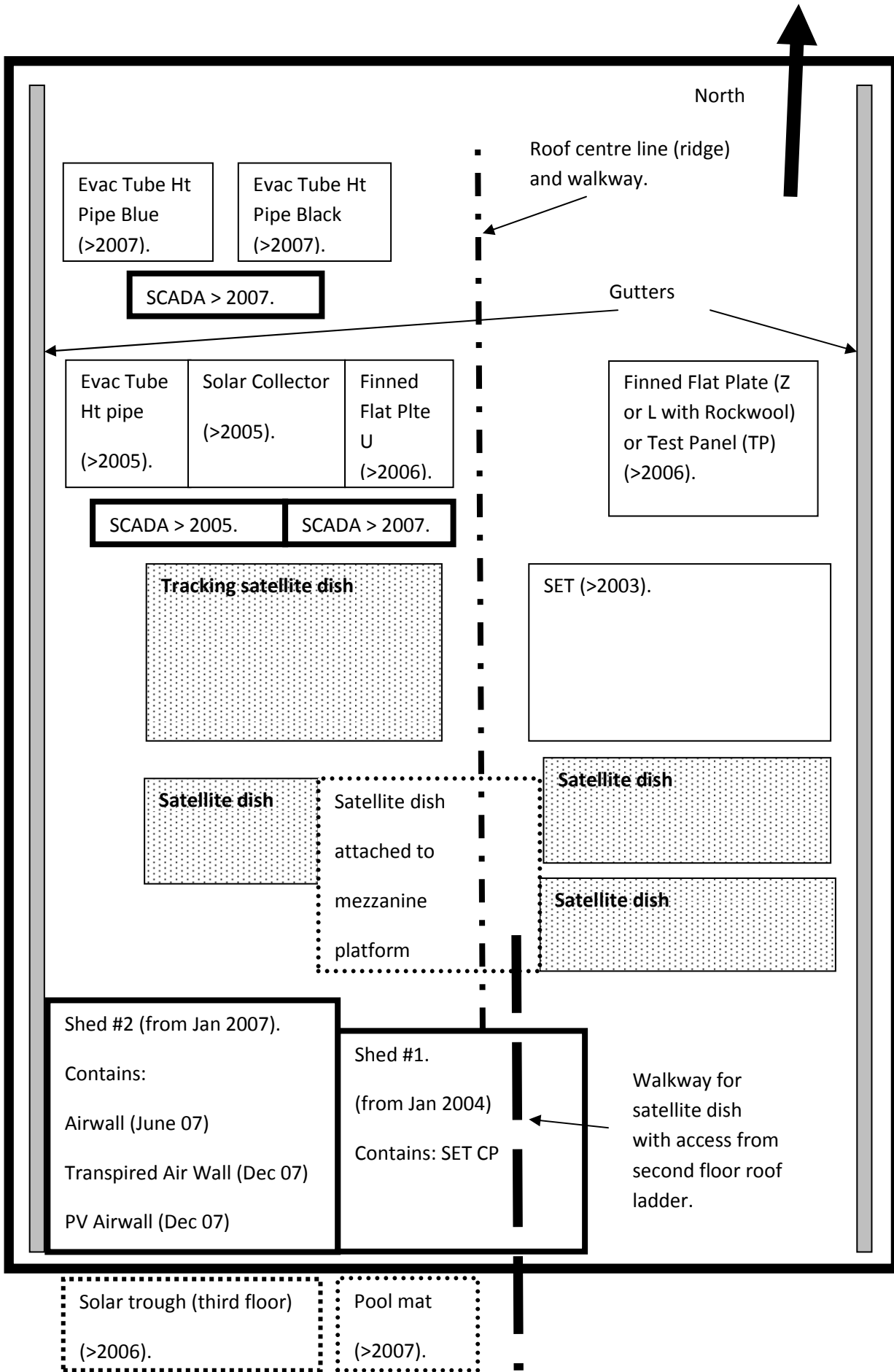


Figure 1.7. C Block roof, solar thermal systems layout.

With reference to Figure 1.7 the SET tracking positions can be defined as X- being west (track to the left), X+ being east (track to the right), Y- being boom down and Y+ being boom up, as viewed from the control panel (rear) of the SET. A Supervisory Control And Data Acquisition (SCADA) system was installed to monitor many aspects of the SET's testing. This is located in shed 1 as shown in Figure 1.7. The SET as mounted in its new location, subsequently re-commissioned, then developed and improved, is shown in Figure 1.8.



Figure 1.8. The SET in operation February 2007.

The CPIT sponsored coiled flat plate pool mat failed in 2005, due to perished pipework, and consequently the total failure of all solar thermal systems, led in part to research into local (NZ) solar thermal hot water manufacturers and suppliers. This led to the author and CPIT being approached by a local Christchurch hot water solar thermal systems manufacturer and supplier in late 2005 to find out what solar thermal research and development activity opportunities were available at CPIT. In 2006 this sponsor offered two research and development projects as part of the final year project course of the 3 year, B Eng Tech programme at CPIT. The sponsor was pleased with the outcome and the results as presented. This subsequently changed aspects of the specifications on this supplier's collectors.

The Solar Industry Association (SIA) visited in 2006 and in 2007, having become aware of the research activities being performed. The SIA expressed interest in obtaining and using, without any form of payment or recognition for the current solar thermal hot water sponsor(s), the research and

results obtained to that point. This was respectfully declined by the author and the solar hot water system sponsor(s).

In 2007, the same sponsor put up two more projects and again was pleased with the results. At various times during 2006 and 2007, other solar industry equipment manufacturers and suppliers approached CPIT and in 2007 two more sponsors proposed research and development projects.

This has seen the solar thermal research facility at CPIT expand progressively every year since 2003.

This additional research and development activity has been undertaken on the basis that each solar manufacturer's research is conducted independently by students, but reviewed and overseen by the author and sponsor, with the author being allowed to publish generic results only, and only after a sponsor's approval.

This has proved to be a winning solution for the various sponsors and for the author, as it has provided the author with the ability to compare various solar thermal hot water systems and technologies, as well as assisting in the maturing of the solar thermal industry in NZ with research and development.

The thesis is written into chapters which follow the development of the SET at CPIT. Chapter 2 presents a literature search of technologies associated with solar thermal hot water heating systems, concentrators and tracking systems. Chapters 3, 4 and 5 cover the mechanical design, motor drives and the electrical circuitry required to operate the tracking functions of the SET. Chapters 6 and 7 detail two of the more critical areas of the SET's operation with the daylight and auto-tracking controls being covered in Chapter 6, and the PLC operation of the SET being covered in Chapter 7, with mention being made of the different subroutines in the PLC programme. Chapter 8 covers the testing of the mirror substrates. Chapters 9 & 10 address the topics of the Supervisory Control And Data Acquisition (SCADA) recording system which was set-up to measure and record all data, with Chapter 10 also covering the set-up and comparison of other standard domestic solar thermal hot

water systems. Chapter 11 sets out the results which were achieved from the SET in operation. The thesis concludes in Chapter 12 with an overview of the SET and suggestions for future developments.

In some instances, whilst developing a particular aspect of the SET, a problem would occur which required the solution of a number of different parts. The discussion of that particular area and the associated issue(s) has been left tied together in the text for continuity and to allow decisions taken to be rationalised.

The SET has become a complex piece of machinery and due to this complexity no circuit diagrams or 'as built' wiring drawings of the completed control panel are detailed in the thesis. The SET PLC code which controls the safe operation of the SET is likewise complex and is not included, however block diagrams and descriptions of PLC operation and subroutines are reviewed.

## 2.0 Literature search

### 2.1 Preliminary review

In 2002, when the possibility of the author acquiring a two axis tracking solar energy collector was first mooted, the author spent some time performing detailed research into solar thermal energy systems and dual axis tracking systems. Up to this point, 2002, tracking systems were thought to be the preserve of the home hobbyist, as little could be found in the journals of that era from either the Institute of Electrical and Electronic Engineering (IEEE) or Institute of Electrical Engineers (IEE) now Institute of Engineering and Technology (IET), especially any complete solar thermal dual axis tracking systems that were of direct commercial application.

At that time, the investigation undertaken by the author indicated that some researcher's had tried a two axis tracking system<sup>[1]</sup> but that the complication of having a second axis to control and the interlocking of this, along with the additional mechanical engineering required for the second axis, had proved to be too difficult for many. A larger number of people had attempted single axis tracking and some had linked this with PV panels, with one claiming a 30 % increase in daily energy output from a rotating frame<sup>[2]</sup>. This circuit used two Light Dependent Resistors (LDRs) feeding into a comparator. This then drove an H bridge comprising MTP3055's MOSFETS, with the drive motion being achieved by a 3 V DC barbecue spit motor. A third LDR was used for sensing night time and causing the system to reset to the East or home position. In a similar vane Wright<sup>[3]</sup> describes how to achieve the most out of PV panels using a precision tracking circuit. In this circuit, three photo-resistors are utilised which drive a TIP120 Darlington transistor.

Fletcher<sup>[1]</sup>, an administrator for the National Aeronautics and Space Administration (NASA), in Altadena, California, describes a dual axis sun tracker. A parabolic reflector was supported so that it could track the sun. The reflector frame containing two wheels and a central pivot are positioned essentially in a triangular configuration. The two wheels rotate on tracks, with an elevation frame provided on the top of the azimuth frame. The elevation frame includes curved rails which define a

portion of an arc, extending vertically. The reflector then rides with wheels captured within these curved rails, the wheels of the azimuth frame being driven by an azimuth actuator. The reflector structure is counterbalanced about its elevation axis by a pendulum cable system which is driven by a motor for changes in elevation. The focal point of the parabolic reflector is a heat engine or a receiver mounted independently of the reflector. A suitable means is then provided for moving the reflector about its two axes in order to track the sun. The article is not clear on the mechanism for performing this task, other than to state it is a 'motor driven actuator'. In the background to the invention, the author's claim, in a comparison of solar energy collected by non-tracking systems, single axis tracking systems and dual axis tracking systems, that a dual axis tracking system is capable of 'harvesting' 78-80 % of all the available direct normal radiation, whereas the single axis tracker collects 30-35 % and non-tracking systems collect 17-20 %. The article then translates this into temperatures achievable by the collector, with non-tracking systems reaching 300-400 °F single axis trackers 500-600 °F and dual axis tracking systems ranging between 1000-2000 °F. The article concludes with the comment that when deciding on the choice of a collector for an application, the type of collector and tracking system (non-tracking, single or dual axis tracking systems), the initial capital costs and annual operating costs all need to be taken into consideration, with the primary determinants usually being the latter.

Kreider<sup>[4]</sup>, describes several solar processes for the concentration of sunlight, stating the clear requirement for tracking systems. A relationship between temperature and the concentration ratio of a concentrator is also given. Performance of a tracking parabolic trough system and the enhancement of this performance using a Fresnel lens system are given along with details and the performance of flat plate and evacuated tube systems (referred to as tubular collectors).

Daniels<sup>[5]</sup>, describes a system for extracting solar power from a parabolic reflector collector using clear Mylar mirrors, and further describes a small scale pilot plant using a 60" wide collector focusing solar energy onto a 2" pipe, with a 30:1 solar multiplication or sun factor, an inlet water

temperature of 25 °C and a water outlet temperature of 95 °C at 3 gal/hr, and quotes a theoretical 'efficiency of radiation of 40 %'. Water is used as the transfer medium rather than oil, but again no mention is made of a tracking system.

## 2.2 Definitions

Wikipedia<sup>[6]</sup>, states some definitions on direct and indirect solar power, with direct being classified as when the sun hits a surface and indirect being when a second step in the process is required. For example, hydroelectric dams and wind turbines are indirectly powered by solar energy through its interaction with the earth's atmosphere and the resulting weather phenomena. Further, a distinction is made between passive solar systems, which rely on the thermosyphon principle, and active solar systems, which rely on additional mechanisms such as circulation pumps or air blowers for circulating or cooling the collector. All of the systems under development and research at CPIT, including the SET in its present form, are classified as being direct active systems. A further definition is called a pumped system. This is where a storage tank is placed inside the building and a circulation or storage pump or air blower system is used for circulating between the storage tank or room and the collector.

Wikipedia<sup>[6]</sup> defines the different types of Concentrating Solar Plants (CSP) with the heliostat being defined as a plant where there is an array of flat, movable mirrors to focus the sun's rays onto a central tower or target. The energy collected is used to boil water for use in steam turbines, however in latter designs this medium has been replaced by oil. In the latest designs, liquid sodium is used. Sodium is a metal with a high heat capacity, thus allowing the collected energy to be stored and drawn off throughout the evening. One of the issues with this system is the large land area required for the mirrors. This system lends itself to countries where there are vast tracts of un-useable or waste land, for example a desert.

Another CSP plant to receive a mention by Wikipedia<sup>[6]</sup> is the parabolic trough, consisting of a series of troughs rather like rainwater guttering with a hollow pipe running its length. Sunlight is reflected



by the mirror and concentrated onto the pipe. The heat transfer fluid, oil in some systems, absorbs this heat from the concentrated sunlight which is then used to power a steam turbine, as per the Kramer Junction Power plant<sup>[7]</sup>.

A dish or parabolic reflector power plant is defined by Wikipedia<sup>[6]</sup>, as being like a large satellite dish but with the inside surface made of mirror material. The sun's energy is focussed to a single point and can therefore achieve very high temperatures. Typically the dish is coupled (either close coupled or remotely) to a Stirling Cycle Engine, but sometimes this can also be a steam engine. This creates a rotational kinetic energy that can be converted to electricity using an electric generator. Sometimes to increase the temperature, a Fresnel lens or reflector is used to increase the intensity of light onto a smaller linear absorber.

Lastly, Wikipedia<sup>[6]</sup> defines a solar chimney as a solar thermal power plant where air passes under a very large agricultural glass house (between 2 and 30 kilometres in diameter). This is heated by the sun and the air is channelled upward toward a convection tower. As the air rises naturally, it is used to drive turbines and generate electricity. A solar chimney essentially resembles a large greenhouse with a hollow pipe rising from its centre. As air is heated under the glass collector it rises in the chimney, where it powers the turbines. Sklar<sup>[8]</sup> mentions that a solar chimney plant has been trialled as a demonstration plant in Madrid, Spain, from 1986 to 1989, but is yet to be trialled commercially. In the Madrid example, the collector has a diameter of 240 m, a surface area of 46,000 m<sup>2</sup>, with the chimney, which houses the power turbines, being 10 m in diameter and 195 m tall. This type of plant suits either a 'U' shaped valley configuration where there is a large flat floor or large areas of waste land.

The Energy Efficiency and Conservation Authority (EECA)<sup>[9]</sup>, defines an open loop system as one where the water from the storage cylinder is circulated through the collector panel and heated directly. By contrast, a closed loop system is one where water from the storage cylinder is circulated

through a heat exchanger and heated by a primary heat transfer fluid which has itself been heated in the collector panel.

Latif<sup>[10]</sup> of 3E-Energy Ltd, states that a “closed loop glycol system is 15 % more efficient than an open loop system.” EECA<sup>[9]</sup> also believe that a solar thermal system can supply up to 75 % of a household’s summer hot water requirements and between 25 and 45 % in winter. Payback is estimated at between 7 and 15 years for a solar thermal hot water system (when the installation includes a new hot water cylinder), depending on the region and electricity rates and charges.

The EECA<sup>[9]</sup> article defines flat plate collectors (which according to them is the most common type), as a flat sheet absorber or envelope of specially blackened metal, which absorbs the sunlight and transfers the heat produced into the water or transfer fluid flowing through the collector. This is usually enclosed with a transparent cover {e.g. glass} to reduce heat loss and allow the collector to act as a ‘greenhouse’. An evacuated tube system (not really explained in the article) works on a ‘thermos flask’ principle with a selective absorber coating applied to the inner vacuum tube.

Sometimes these operate on the thermosyphon principle, but more often the sealed copper pipe is connected into a continuous flow manifold. The transfer medium contained in the copper pipes has a low boiling temperature. The mounting angle of the collector is also considered important and is taken as being the latitude of the installation  $\pm 20^\circ$ . Lastly, the collector area is given as about 1 m<sup>2</sup> per 40 - 70 litres of cylinder volume.

The Sola60 ‘Solar Water Heating’ pamphlet<sup>[11]</sup>, states savings for a finned flat plate collector of ‘up to 75 %’ with findings that ‘an independent study (Feb 2001) shows the Sola60 system tested from 10 to 25 % higher kilowatt output than all other companies tested’. It goes on to state and quotes a ‘67 % saving if auto electric boost (is) set to 50 °C. This claim is this further supported with graphs and other technical information showing an average efficiency in excess of 66 % for their design of collector. This claim assumes that the temperature of the hot water cylinder thermostat is set to 50 °C which contravenes the Building Code Act (now part of the Department of Building, Ministry for

the Environment) which states that 'once in 24 hours the hot water cylinder must reach or exceed 70 °C' to kill off any Legionella bacteria. It also contravenes the Ministry of Health (MOH)<sup>[12]</sup> & EECA guidelines which state the same but set the temperature at 60 °C. Also, no mention is made of the testing method, whether the panel faced due north or whether it was located in a more north-west aspect, the mounting angle of the test panel and the age of the test panel. The MOH & EECA guidelines were published in 'Consumer'<sup>[13]</sup>.

### **2.3 Ongoing reviews**

One of the earliest parabolic trough collectors is the CSP in the Mojave Desert operated by the Kramer Junction Company (KJC). The KJC website<sup>[7]</sup> and Leutz<sup>[14]</sup> both state that the plant comprises five, 30 MW solar thermal generating facilities located in the Mojave desert at Kramer Junction, California. The designed total combined output of the plants was to be approximately 165 MW. Originally designed and developed in the mid 1980's by LUZ Industries, Solel Solar Systems<sup>[15]</sup>, who now own and operate the site, has improved the overall efficiency and technology significantly in the last few years. This plant was the first solar field commercially developed, and now is one of nine solar fields and plants in the Solar Electric Generating System (SEGS), with a combined peak output of 354 MW. These plants regulate their power supply through the use of supplemental natural gas-fuelled electric generating plants. In this system the parabolic shaped mirror focuses the solar energy onto a pipe passing through the centre and focal point of each parabolic dish. The media used in the pipes is oil, and the parabolic dishes are linked in a series and parallel configuration to achieve a maximum temperature rise across the complete solar field. The oil in turn is then used to heat a water loop which in turn operates a steam plant for the generation of electricity.

Guiney<sup>[16]</sup> discusses a unique system in which the parabolic mirrors are fixed in position but the heat pipe tube rotates in an arc, following the sun's position. Guiney concludes with the comment that 'solar thermal systems are the most cost effective method of generating large-scale solar electric power'.

Quaschnig<sup>[17]</sup> discusses solar thermal technologies in general, and also features the prototype Spanish dish/engine parabolic dish collector and concludes that the electricity generation costs of the dish/engine systems is much higher than for the parabolic trough or tower power (heliostats) plants and 'only series production can achieve further significant cost reductions for Dish-Stirling systems'. This justifies the choices so far made with the SET and reinforces the decision to retain the SET as a solar thermal hot water plant.

Teske<sup>[18]</sup> follows this up with the generation costs of the parabolic trough (with central pipe and classified as the most mature solar thermal technology) are given as 'US 10-13 cents/kWh' with an expectation that with new advances in technology this may fall to '5 Eurocents/kWh'. Similarly generation costs anticipated for the heliostat (or central tower or tower power) which is expected to drop to '5 Eurocents/kWh'. Finally, the parabolic dish/engine systems with 'an attainable, medium-term goal is a figure of less than 15 Eurocents/kWh'.

Feuermann<sup>[19]</sup>, in this paper describes a solar mini dish concentrator (diameter 200mm) coupled to a fibre optic wand 'with boost flux concentrators in built achieving a measured flux level of 11-12 kilo-sun at a remote target up to 20 m away'. The paper is primarily focussed on using the assembled mini-parabolic dish with a fibre-optic probe taking the concentrated solar energy away from the focal point, with medical surgery appearing to be the primary area of interest. This paper also mentions a dual axis tracking system, which it claims were readily available in 2002. The paper lists two companies who manufacture automatic tracking systems. However, no mention is made of the technology either company uses in their tracking systems. There was only one company that supplied a tracker with 'essentially a continuous tracking motion' and the other tracking system 'moved in sharp distinct steps of 0.1 degrees'. This latter tracking system proved not to be suitable for a medical application where power densities of the order of  $10 \text{ W/mm}^2$  were required.

Feuermann<sup>[19]</sup>, also mentions the method of testing the mirror coating finish, with lasers being used to show light refraction and the size of the light spot. The mirrors are silver coated diamond with a 96 % reflectivity.

Small Power Systems<sup>[20]</sup>, the company with the continuous tracking system has been taken over or merged with another company called Tracstar. This company has a range of tracking systems with most of them used with a tracking PV panel. They also manufacture dual axis tracking systems for larger commercial clients as would be used in parabolic mirror systems or dish type tracking systems. However, no mention is made of the method and technology used for the electronic tracking control.

Quaschnig<sup>[21]</sup> lists and discusses the different types of solar hot water heating as is typically used in a domestic environment, for example flat plates, and evacuated tubes. An estimated theoretical collector efficiency graph is given. The article then concludes by discussing the possible application for centralised solar district heating and the forthcoming revolution in the solar collector marketplace. The possible application for solar thermal hot water, whilst it is not a new idea, is a possible future application for the SET.

PowerLight Corporation<sup>[22]</sup> of California is working with K & S Consulting Group and Deutsche Structured Finance (both German companies), in using PowerLight's solar tracking technology to generate electricity and directly feed this into the German power grid. Called the Bavarian Solarpark, the system will use 57,600 PV panels and generate 10 MW of electric power.

Vasylyev<sup>[23]</sup> describes a systems in which a Fresnel lens is used to achieve a 20:1 sun factor onto a PV cell to generate electricity. There is no tracking with this design, but the slat design of the Fresnel lens is of possible interest for a future development of the SET to increase the level of solar energy delivered to the target.

Moates<sup>[24]</sup> states that a tracking (PV) array in winter produces 15 % more power than a stationary array. In summer this figure jumps to being 40 to 60 % more power. However, the tracker was a

manually cable driven device as 'he simply couldn't afford a self tracking mount', which he estimated to cost at that time US\$1000 for the size of the PV panels in use.

An article from Monash University School of Engineering and Science<sup>[25]</sup>, details how students have created an energy saving solar tracker using stepper motors, National Instruments Lab VIEW FlexMotion software, a PV panel, and photo-diodes mounted in a special pyramid shape on a flat perspex sheet. The photodiodes were positioned such that the opposite pairs tracked both the horizontal and vertical light source. The rationale for tracking was to optimise and increase the output of the PV panel when compared to a stationary or fixed position PV panel.

An IET<sup>[26]</sup> feature article reports that Stirling Energy Systems (SES) energy developer, Bruce Osborne, has signed a 20 year power purchase agreement with an electricity supplier in Southern California for the supply of 500 MW of power, from 20,000 dishes in the Mojave Desert. This project is based on a pilot plant containing 6 dishes on trial at the Sandia National Laboratories in Albuquerque, New Mexico. These dishes automatically start-up, track the sun in two axis, respond to clouds and wind as needed and shut down at sunset.

Winston<sup>[27]</sup> undertakes a comprehensive review of all types of solar thermal and solar electric systems including two axis tracking concentrators using parabolic dishes and Fresnel lenses. These systems are then coupled to various turbines or to a Stirling cycle engine for electricity generation. Secondary reflectors or concentrators have been proposed 'to improve performance' by either 'increasing the concentration ratio, or reducing the tracking and tolerance requirements'. The shape of the primary parabolic dish is discussed, and the further advances which can be achieved by the fitting of a trumpet (secondary receiver) with a thermal receiver. Other systems such as parabolic trough collectors and heliostats are mentioned as well as any refinements of both technologies, such as a beam down central receiver plant where flat mirrors reflect the sun's energy to a tower, as with a conventional heliostat. However, at the top of the tower, the energy is further concentrated and then reflected to the ground [called the Weizmann Solar Tower], which at lower power levels can be

used for heating and cooling applications as well as electric power generation. In high sun concentrations this could be used for laser pumping, medical solar surgery and 'the benefit of mankind'.

'Redrok'<sup>[28]</sup> an American home hobbyist website, lists a number of hobbyist single and dual axis trackers for small scale PV generation, or electricity generation. These systems use a combination of H bridge operational amplifiers and 555 timing circuits, and LED's as the light sensor. It is hoped to be able to investigate the possibilities of some of these light tracking and sensing circuits with a future development of the SET.

Sklar<sup>[29]</sup>, in a review issue, gives details of; a solar chimney in Spain; the Solar One power tower in the Californian desert, a planned heliostat in Spain, as well as the building of a parabolic trough with central pipe by Sola4genix Energy for the Arizona Public Service. Further details are given of the prototype dish/engine reflector developed by Sandia National Laboratories. This was later joined by a further five dish/engine systems. These dishes are comprised of eighty-two small mirrors formed into the shape of a parabolic dish with a Stirling cycle engine mounted at the focal point of the mirrors.

Grossman<sup>[30]</sup> mentions a case study of a parabolic trough generator built in the early 1990s. The article outlines three major economic incentives for the use of solar technologies and features, and gives detailed cost analysis and models for analysing net present value, economic benefits in employment, and from the exporting of local electrical energy to the grid. The article is based around the LUZ and later, Solel, parabolic trough system developed by LUZ which was originally an Israeli-US Company. Whilst interesting from a financial viewpoint, the article offers nothing of real benefit to the SET development. Cameron<sup>[31]</sup> outlines the different solar thermal electric technologies currently available, with an overview of the previous year, the current developments and planned developments with parabolic dish/engine systems being only available from Stirling

Engine Systems, in the US, with six being trialled at the Sandia research centre, in Arizona, USA.

These six systems use an external combustion engine.

Stirzaker<sup>[32]</sup> details the testing towers and development facilities developed by the Spanish based on Dr Volker Quaschnig's solar thermal plant designs. The article outlines the research and development performed on heliostats with flat mirrors and on parabolic trough reflectors with a central pipe.

Gunther Portfolio<sup>[33]</sup> reviews two different types of concentrator's. The first concentrator, developed by Prof. Jeffrey Gordon and Daniel Feuermann of Ben-Gurion University of the Negev, in Israel, is called the SolFocus mini-dish concentrator. The second concentrator, developed by the Fraunhofer Institute for Solar Energy Systems (Freiburg, Germany) and Loffe Physico-Technical Institute (St Petersburg, Russia) is called a FLATCON<sup>®</sup> (Fresnel Lens All-glass Tandem cell CONcentrator) and available through Concentrix Solar. The SolFocus system uses mini dishes and Fresnel lens with sun-tracking, whilst the FLATCON<sup>®</sup> systems uses an array of Fresnel lens mounted inside the top glass plate module. Both systems concentrate the sun's energy directly onto a PV cell. No details on the tracking method are divulged from either company. The use of a Fresnel lens and its mounting may be of future use for the SET. Leutz<sup>[34]</sup> also mentions the SolFocus system and the use of Fresnel lens concentrators.

The Environmental Protection Agency, which is part of the Queensland Government, funded a 'Stanwell solar concentrator'.<sup>[35]</sup> The Stanwell Corporation Ltd, received a grant in 2000, from the Queensland Sustainable Energy Innovation Fund to develop a solar thermal power generator at the Stanwell Power Station in Central Queensland. The system uses an array of mirrors fixed to a steel frame in the form of a parabolic trough, pivoting around an 'A' frame made from steel. The troughs then track the sun. This system has a central pipe from which high pressure steam is produced, at a pressure of up to 5000 kPa. No details are given on how the system has matured or developed since 2000, nor on how the system tracks the sun.



Marken<sup>[36]</sup> answers a readers letter querying 'why there are no parabolic trough collectors for the home market', replying that 'parabolics were popular and put into US homes in the 1980's, each collector being 2 by 8 feet with a 1 inch internal diameter target tube, achieving a concentration ratio of about 22 suns'. However, with time these systems either failed to operate correctly or the mechanical linkage that tracked the collectors became fouled with ice, dirt or grime and consequently broke or froze. Flat plate collectors arrived on the market and these systems were under half the price of their parabolic equivalents. The article concludes with the comment that 'parabolic systems are too complex and expensive to compete with flat plat collectors in making 140 °F domestic hot water'.

Colorado Solar Electric<sup>[37]</sup> advertise a 'single axis active tracker, 2000+ watts'. This is for a PV electric system. No details on the technology or the type of tracking system used by the system have so far been found.

Heliodynamics Ltd<sup>[38]</sup>, a UK based company have refined and are in the process of commercialising a further refinement of the parabolic trough reflector in which a number (depending on model and heat requirements) of flat mirrors are mounted in the shape of a parabolic trough. The 'facets', as they are called, are mounted on a frame which then tracks the sun and focuses the sun's energy onto an array of 'mirror collectors' which then focus the sun's energy further onto either liquid filled pipes (for heat) or onto a high yield PV array which is then water cooled to give combined power and heat. Despite attempts by the author to contact HDSolar, no replies or correspondence has been established with this firm.

Wright<sup>[39]</sup> mentions that CSIRO researchers are utilising the sun's power to achieve a high temperature which is then used to chemically change any hydrocarbon-containing gas. The article states that this would for example be used for turning coal-seam methane or natural gas into an enhanced synthetic gas called 'SolarGas'. This 'SolarGas' contains 'about 26 % more energy than coal-seam or natural gas, produces about 26 % less CO<sub>2</sub> during production and can be used for solar

electricity generation as well as a feedstock for either SolarDiesel or hydrogen generation'. Of interest is the method CSIRO use for the collection and concentration of the solar energy, which is a heliostat, with a flat mirrored array. This was also reported by Orchison<sup>[40]</sup> and 'Environ'<sup>[41]</sup> magazine. 'Environ' magazine was more interested in its architectural design and possibilities than its overall performance.

Jones<sup>[42]</sup> makes reference to the former John Howard lead government offering an A\$1000 subsidy to each of 200,000 households as an incentive to install solar thermal hot water systems. The level of subsidy is interesting as the level of subsidy in NZ at that time was \$500.

Trenkner<sup>[43]</sup> comments that in September 2007, the European Parliament had adopted a resolution with indications for 'the upcoming Directive proposal on renewable energies'. With regards to solar obligations, the European Parliament has called on the European Commission to 'accelerate the widespread adoption of such regulations in all Member States, saying "at least in the case of major renovation of buildings and new buildings ..... a minimum portion of the heating requirement [is] to be met from renewable energy sources as has already been implemented in a growing number of regions and municipalities" '. At the EU level, the decision of the 27 Heads Of State, in March 2007, set a binding 20 % target for the renewable share of total energy consumption by 2020. In Europe, domestic hot water constitutes roughly 2 % of the final energy consumption, which translates to approximately 24 million tonnes of oil per annum (MTOE). The article comments further that if buildings covered 50 % of their hot water demand with solar energy, the savings would be around 12 MTOE per year, roughly equivalent to the total consumption for hot water and space heating of almost 10 million European homes. This is of interest when comparing the subsidies offered by overseas governments with those offered by the NZ Government, via the Energy Efficiency and Conservation Authority (EECA).

Welch<sup>[44]</sup> comments on the future role of parabolic trough type CSPs stating that these will be used to generate steam to drive electric generators. The article also mentions that nine new CSPs are

planned. The article also contains a table stating that ethanol (from corn, etc.) will produce 3 to 4 kW per acre in terms of power captured, whereas for wind turbines this figure is 12 to 16 kW per acre, for photo-voltaics the figure is 240 to 730 kW per acre, and for CSP the figure is 1600 kW per acre. This comparison supports the continued refinement and development of the SET.

The National Renewable Energy Laboratory (NREL)<sup>[45]</sup>, details the types of concentrating technologies available which use mirrors as a core part of their process. It mentions that using concentrators in power plants means a lower overall operating cost, and an ability to produce power during high demand periods. The US peak demand is different to that in NZ, with a higher demand for daytime electricity which is predominantly used for cooling. Further mention is made that concentrators will help to increase US energy security. Dual axis collectors using dish and Stirling cycle engine or PV modules and associated systems are discussed. The concluding comment for this section then states that concentrator systems are not as yet commercially available (2001). The article states that early indications on demonstration systems indicate good potential with each dish capable of producing 5 to 50 kW of electricity. Several dish electric systems may be linked and so a 250 kW plant comprising ten, 25 kW dish/engine systems would occupy less than an acre of land. Other concentrating systems are also discussed including the heliostat and Solar Two in Barstow California. Mention is made that using molten salt (nitrate salt) has been trialled in Solar Two to extend the hours of electrical generation and overall usefulness of the plant past the hours of normal sunlight.

Wood<sup>[46]</sup> mentions plans by Google to produce utility-scale power cheaper than coal. This deal reportedly worth US\$10 million, has been signed with a company called, 'eSolar,' from Pasadena in California. This company specialises in solar thermal plants and the final configuration will see an array of small plants with reflectors and towers being built, much like a series of small scale heliostat plants.

Leutz<sup>[47]</sup> shows recent developments in PV tracking systems and details recent developments with concentrating PV systems using lenses. This is usually a Fresnel lens or alternatively a flat lens with a miniature sawtooth design to focus incoming light (the SolFocus system<sup>[33]</sup>), or using mirrors or a combination of mirrors and lenses to focus the sunlight onto a small amount of photovoltaic material. If the teeth are arranged in a concentric circle then light is focussed at a central point. If the teeth run in straight rows, then the lenses act as line focussing concentrators. The article further provides some definitions: 'One sun is defined as the light that falls on a cloudless day (which can vary depending upon location) as being 1000 W/m<sup>2</sup>. The 'concentration ratio' can vary; if light falls on 100 cm<sup>2</sup> and is focussed onto 1 cm<sup>2</sup> then this intensity is considered as 100 suns'. Currently in the market place, according to the article, the concentration ratios 'are around 200-300 suns with as much as 1000 suns' expected in the near future.

The SME Daily Executive Briefing<sup>[48]</sup> for the 19<sup>th</sup> March 2008, reports that a congressional subcommittee and business leaders met in Tucson and were talking about the potential of utility-scale solar power and how to use subsidies to make it work. The focus of the congressional subcommittee and business leaders concerned the 'proposed Solana Generating Station, a 3 square mile solar power plant that could be running by 2011, (located) 130 miles northwest of Tucson'. This plant would be based around a parabolic trough dish with a central heat pipe.

Pernick<sup>[49]</sup> mentions a recent large scale installation by the US Airforce in which the largest US photovoltaic system has been installed in the Nellis Air Force Base, Nevada. This system tracks in one axis.

The SME Daily Executive Briefing<sup>[50]</sup> for the 18<sup>th</sup> April 2008, states that Stirling Energy Systems (a Phoenix, Arizona based solar power developer) in conjunction with NTR (an Irish company) are planning to invest US\$100 million to build two huge solar energy plants, based around thousands of solar dishes in the desert driving small Stirling cycle engines mounted at the focal point of each mirror. Both 'projects together will initially produce 800 MW of power and up to 1750 MW eventually'.

The SME Daily Executive Briefing<sup>[51]</sup> for the 23<sup>rd</sup> April 2008, states that the 'European countries are expected to put into operation about 50 coal-fired plants over the next 5 years', despite the fact that 'the world's top climate experts agree that carbon emissions must be rapidly reduced to hold down global warming'. The article goes on to mention that the EU has been pressed 'by rising demand, record high oil and natural gas prices, concerns over energy security, and an aversion to nuclear energy' to return to coal, a move that alarms environmentalists. It further states that many countries, such as Germany and Italy, have little choice but to build coal plants to replace aging infrastructure, especially as they have banned the building of nuclear plants, this is in spite of recent and planned solar installations.

Martinot<sup>[52]</sup> states that the 2007 investment figures reflected a strong market growth for a number of technologies and aggressive industry expansion in manufacturing plants for wind turbines and components, conventional solar PV, thin-film PV, concentrating solar thermal components and conventional biofuels production. It further mentions that solar hot water markets continue to grow in China, Europe and some other countries. Grid connected PV continues to be the fastest growing power generation technology, with a 50 % annual increase in the cumulative installed capacity in both 2006 and 2007. With regards to concentrating solar thermal power (CSP), the article states that the CSP industry finished a 'first round of construction during 2006-2007, a resurgence after more than 15 years of commercial dormancy, with commercial plants being planned for Israel, Portugal, Spain, and the US having led to new technology development and investment'. Three plants were completed during this period; 'a 64 MW parabolic trough plant in Nevada, a 1 MW plant in Arizona, and an 11 MW central receiver plant in Spain'. There are a further twenty new CSP projects around the world currently either under construction, in the planning stages, or undergoing feasibility studies. The majority of these plants are in either the US or Spain, but increasing numbers are now occurring in developing countries, with a 200 MW CSP plant planned for Inner Mongolia by 2012, and as part of a broader commercial framework for 1 GW of CSP in China by 2020. Further comment is made about the size of the solar hot water rooftop collectors in Austria, Germany and Sweden,

with more than 50 % of the annually installed collector area being used for combined hot water and space heating systems. China represents by far the largest share of this market with 75 % of its annual solar hot water additions worldwide. Mention is also made of the legislative framework imposed by various governments worldwide, with particular mention being made of Spain. In 2006 the national building code required a minimum level of solar hot water and solar PV in new construction and renovation, which several other countries have followed in 2007, with for example, India now requiring at least 20 % of water heating capacity from solar, and Germany's 'Renewable Energies Heating Law' requiring new residential buildings starting in 2009 to obtain 'at least 14 % of household heating and hot water energy from renewables'. This law also carries requirements for building retro-fits.

Sargent and Lundy LLC Consulting Group,<sup>[53]</sup> states that trough technology is a fully mature technology, with low technical and financial risk in developing near-term plants, whereas there had been no commercial only demonstration tower power plants built up to 2003. The article states that there is a higher technical and financial risk in developing a first-of-its-kind commercial plant. The article estimates that by 2020 the cost of power from trough collectors will have fallen to around 4.3-6.2 c/kWh (US) and for towers to 3.5 – 5.5 c/kWh (US) (from a high development cost of between 11 and 14 c/kWh). It lists a number of key advantages of the newer trough technology over the older Solar Electric Generating System (SEGS) plants, including better ball joints and thermal storage media, and better mirror substrate materials. Both the National Research Council Committee (NRC) and Sargent & Lundy state that further work is required on both troughs and tower power and that both technologies have a future in power systems generation. In 2003, there were two demonstration tower power plants in the US, Solar One and Solar Two.

Solar Two for instance was a heliostat design with a molten salt receiver and storage facility, located at Barstow in California, with flat reflectors and was used experimentally until 1998. It was capable of a 10 MW output according to Teske<sup>[18]</sup>. The article further discusses trough based collectors and

then mentions parabolic dish systems, saying the future of these smaller dish based systems lies in decentralised power supply and remote stand-alone power applications, with projects planned in the US, Australia, and Europe.

Frederick H. Morse<sup>[54]</sup> features a dish-Stirling system developed at California Polytechnic University in Pomona, California. This system is then discussed in regards to meeting global market initiatives for CSP (targets, policies, tariffs, power purchase contracts, financing, and bidding).

Cohen<sup>[55]</sup> states that Nevada Solar One is a new design of parabolic trough collector and should not be confused with Solar 1 or the older style of SEGS parabolic collectors located in the Mojave Desert. This trough collector uses 760 solar parabolic reflectors focussing the solar energy to a central pipe containing oil which is heated from 350 °C to 395 °C, and occupies 300 acres of land. This is a 64 MW plant and was completed in April 2007. The parabolic trough dish has a concentration ratio of 71:1 and an optical efficiency of 77 %. Jones<sup>[56]</sup> covers the same plant and further details operational issues of trough based CSPs.

'Inhabitat',<sup>[57]</sup> and 'Environment News Services',<sup>[58]</sup> both comment on the first EU commercial Concentrating Solar Power Tower which was opened in Seville, Spain on the 30<sup>th</sup> March 2007. This plant, called PS10, uses a 300 ft tall tower surrounded by 624 solar panels which produces enough energy to power 60,000 homes, 11 MW. A secondary component which uses a photo-voltaic (PV) power plant and comprising 154 panels will generate sufficient electricity for approximately a further 1800 homes. The final project, which when completed will include a series of towers, additional PV panels, as well as a mixture of newer parabolic solar collectors, will be fully operational by 2013 and be capable of producing over 300 MW. Whilst this has no direct bearing on the SET, it is interesting to see the application of tracking technology in these now commercial generation plants.

Smartmoves,<sup>[59]</sup> and EnviroMission Limited<sup>[60]</sup>, both state that two solar tower power installations are planned in Australia, with one being located in Hobart and the other in Buronga, part of the

Wentworth Shire County, NSW. Again this is an interesting commercial application of tracking technology in commercial power generation plants, especially in the Asia-Pacific region.

The website for Solel<sup>[61]</sup> shows a new development, called UVAC2008. This development mentions the application of selective coatings to vacuum tubes, along with improvements in mechanical frame rigidity and mirror alignment. It is claimed that these three improvements 'give a 40-50 % increase in electrical output relative to the original SEGS collectors'. An improved 'getter system' is also employed to prevent the so called 'hot-tube' phenomenon, which frequently occurs in many other vacuum tubes due to hydrogen permeation. In a vacuum tube system, the tubes contain 'getters,' which change colour to indicate a leak of air or a vacuum failure. A second observation is that when a vacuum tube fails, the glass becomes warm or hot to the touch, as opposed to being cold to the touch when the vacuum is fully intact. This fact has been observed in the testing conducted at CPIT in 2007, when a sponsor's evacuated tube heat pipe system experienced multiple evacuated tube failures over a period of six months.

## **2.4 Texts reviewed**

Masters<sup>[62]</sup> book, which is written from a power systems perspective, details the fundamentals of power, the power industry, distributed generation, the economics of distributed resources, wind power systems, and photo-voltaic systems. However, in Chapter 4, Section 4.2.4 the author mentions in detail the process and operation of a Stirling cycle engine, with Section 4.3 discussing CSP technologies. This section discusses the Dish-Stirling power system(s), with a comment being made about the efficiency of this system being greater than any other solar technology at an average efficiency of around 20 %, and a measured peak of 30 %. Other technologies such as the parabolic trough and heliostats are mentioned later in the same chapter. Masters concludes, with comments that a Dish-Stirling engine system requires no cooling water and therefore has a significant advantage over the current designs of 'troughs and towers'. Other advantages include their relatively low profile and low noise. According to Masters, a Dish-Stirling system at 25 kW



appears to be the optimal size, with economies of scale playing a bigger role for troughs and towers that 'may be most economical in unit sizes of about 100 MW'.

Weedy<sup>[63]</sup> in Section 1.4.1 of Chapter 1, 'Renewable energy, Solar energy – thermal conversion,' discusses flat plat collectors, with the author only discussing concentrators in conjunction with larger scale (central station or heliostat) installations, where lenses or mirrors are deployed. Concentrators may be designed to follow the sun's seasonal movement or additionally track the sun throughout the day with a double axis system. The author mentions a heliostat as their central receiver system for generating electric power, stating that cost is prohibitive for two axis tracking systems and further stating that single axis trackers with water or liquid sodium as the transfer media required a collector area of 1 km<sup>2</sup> for every 100 MW of output energy with a capital cost of UKP30 /m<sup>2</sup>. The author discusses a French solar furnace in the Pyrenees, which uses two axis mirrors and has a concentration factor of 16,000 using the attached lenses. Both Wikipedia<sup>[64]</sup> and 'Time' magazine<sup>[65]</sup> cover this solar furnace. This solar furnace uses parabolic reflectors to concentrate the light to a focal point. Temperatures at the focal point 'may reach up to 3000 °C,' and this temperature is used to heat steam to generate electricity, melt steel or make hydrogen. The plant at Odeillo in the Pyrenees was opened in 1970 and was at that time considered the largest in the world. No details were given as to the tracking system.

Quaschnig<sup>[66]</sup> describes in Chapter 2, 'Solar Radiation' and Chapter 3, 'Solar Thermal Water Heating' the various types of solar absorbers and their construction along with detailed mathematical analysis, collector and pipe sizing recommendations are also discussed. Typical solar radiation and irradiance with horizontal and two axis tracking systems are given showing the northern hemisphere irradiance for horizontal and two axis tracked systems, for both the winter and summer periods at a latitude of 50 degrees. The text further expands on this stating that if a system tracks the sun, the angle of incidence is less, and the energy yield increases significantly. 'During days with high direct irradiation, tracking can achieve energy gains over horizontal orientation in the order of 50 % in summer and up

to 300 % in winter, depending on the latitude of the location. However, tracking can cause a reduction in energy yield in overcast conditions because the contribution of diffuse irradiation from behind the surface is lost. Tracking achieves the main energy gain in summer. On the one hand, the absolute energy gain in summer is higher than in winter; on the other hand the number of overcast days is usually lower in summer.' In summary, tracking appears to be of value in summer giving a higher energy gain than in winter, but the number of overcast days in summer is also lower.

Chapter 1 of the same book outlines the different types of energy systems and energy reserves available and then looks at the different systems available for capturing and making the 'best' use of the energy reserves available. In the subsection on renewable energy, solar energy systems are discussed along with Dish-Stirling, parabolic trough, heliostats and solar chimneys. This section is a useful overview of the current technology.

Sandia National Laboratories<sup>[67]</sup> in a 'News release' dated 12<sup>th</sup> February, 2008, claim a new record for the efficiency of their dish/engine test system. They claim a '31.25 % efficiency rate' which topples the 1984 record of '29.4 % efficiency'. It should be noted that Sandia measure energy efficiency on a slightly different basis to the standard solar industry procedure and to that outlined in this thesis. The Sandia method for calculating conversion efficiency is to measure the net energy delivered to the grid and divide it by the solar energy hitting the dish mirrors. Any auxiliary loads, for example circulation pumps, computers, and tracking motors are accounted for in this net power measurement. Of further interest is that the test was done on a fine clear, cloudless but cold day. The test ran for 2.5 hours and a sixty minute running average was used to evaluate the power and efficiency data, thereby eliminating any transient effects. The system 'produced 26.75 kW of net electrical power'. Sandia are currently investigating ways of commercialising this system and the plant technology involved.

This shows what can be achieved with a dual axis tracking system when connected to a Stirling engine and used for generating electricity, however it is only one direct application and use of the system and technology at this stage and it is still very much in the experimental development stage.

## 2.5 Solar insolation

It is generally accepted by the solar industry that the incoming solar radiation is 'on average 1360 watts of visible, infrared and ultraviolet radiation from the sun passes through each square metre at the top of the earth's atmosphere,' as per Ben Liley<sup>[91]</sup>, Further, this article states that only about half of this radiation reaches the ground, the rest being absorbed or reflected by gases, clouds, and dust in the air. Masters<sup>(62)</sup>, and the University of Oregon Solar Radiation Monitoring Laboratory<sup>(92)</sup> also contain references to the same incoming solar radiation levels with the University of Oregon concluding on page 6 of the article 'therefore about 1000 W/m<sup>2</sup> of the incident solar radiation reaches the earth's surface without being significantly scattered'.

J O'M Bockris<sup>[93]</sup>, in chapter 6, further suggests that 'the difference between the energy which reaches the earth's surface is reduced in intensity by >25% owing to the scattering by air molecules and by selective absorption at certain wavelengths, by water and carbon dioxide molecules in the atmosphere.' On this basis, with the sun directly overhead, on a cloudless day the rate of energy arrival on the earth is about 1 kW/m<sup>2</sup>. The chapter further comments that seasonal variations will occur allowing for more or less energy to be collected on the collector or ground surface depending on whether the collector tracks the sun, is at the right angle (latitude) to the sun (for non-tracking systems) and cloud cover.

Andrew Pollard<sup>[94]</sup> states an annual solar radiation figure for Canterbury of 1327 kWh/m<sup>2</sup>. Allowing for a 25% loss in intensity, this results in a figure of 995.0 W/m<sup>2</sup>. This has been approximated, to 1 kW/m<sup>2</sup> for all seasons and used as the basis of all efficiency calculations in this thesis.

In winter this level of solar radiation drops, depending on the day, to around 800 W/m<sup>2</sup> and in December/January the level of solar radiation, as measured at 43 deg from the horizontal or as

measured by a tracking pyranometer peaks, at  $1.2 \text{ kW/m}^2$ . However, for all efficiency calculations an average of  $1 \text{ kW/m}^2$  has been assumed as being the average solar radiation for Canterbury per annum.

To further support the use of  $1 \text{ kW/m}^2$  as an average approximation of solar radiation, EECA<sup>[95]</sup> similarly state their research shows Christchurch has  $1360.5 \text{ kWh/m}^2$  per year. In section 1 of EECA<sup>[96]</sup> the primary energy source (sun) as 'reaching a maximum intensity of more than  $1000 \text{ W/m}^2$  at the earth's surface.' The Solar Industries Association<sup>[97]</sup>, state that the 'energy reaching the earth's surface with a maximum intensity of more than  $1000 \text{ W/m}^2$ '.

Gilbert Masters<sup>[62]</sup> in appendix C, lists the 'hourly clear-sky insolation tables' for all the latitudes in 5 deg increments. The yearly figures for latitude 45 degrees are listed on page 621, with the average insolation being given in  $\text{W/m}^2$  figures for horizontal (no mounting angle to the sun), and for single and dual axis trackers. In the same table the average kWh/day are given for single and dual axis tracking systems for the 21<sup>st</sup> of every month, however the figures given are only relevant for the northern hemisphere, 'where most of the population is.' However, using the figures for reference purposes only, the average kWh for a horizontal plate range from 1.79 to 8.19 kWh, for single axis tracking from 5.00 to 9.98 kWh, and for dual axis tracking from 5.37 to 11.01 kWh (from Winter to Summer solstice). By way of comparison the level of solar radiation (insolation) received at midday onto a flat or horizontal surface and a surface mounted at 40 deg from horizontal for the same period is 357 to 924  $\text{W/m}^2$  horizontal and 782 to 927  $\text{W/m}^2$  at 40 deg (with a peak of 970  $\text{W/m}^2$  occurring at 30 deg angle from the horizontal). Lastly, in appendix F, page 641 – 645, maps of solar radiation are given for the world. The maps for 43 deg latitude south list a winter (NZ summer) 'daily total solar radiation incident on a tilted surface (at the angle of the latitude) in  $\text{kWh/m}^2/\text{day}$ , of between 5.0 and 5.5  $\text{kWh/m}^2/\text{day}$  and for summer (NZ winter) between 2.5 and 3.0  $\text{kWh/m}^2/\text{day}$ .

Thus for this thesis, all calculations will be based around the  $1 \text{ kW/m}^2$  assumption.

## 2.6 Summary

In 2002, when the author first approached the original inventors of the SET, a literature search was undertaken of the solar current technologies and tracking systems available both commercially and in development at that time. A search of relevant IET (formerly IEE) and IEEE journals found some research and development activities had occurred as outlined in the early part of this literature search above, but most of the systems were for tracking in one axis with photo-voltaic panels used for electricity generation, rather than for thermal hot water, with the mini dish system being an exception for medical applications, as well as the Stanwell solar concentrator. There were thus no comparable solar thermal hot water tracking systems which were capable of both tracking the sun's position in real time, as opposed to following the sun's position via a look-up table or GPS co-ordinate system and at the same time focusing the sun's energy onto a target which then used water to cool the target and created or generate hot water as a by-product of cooling the target. This thesis thus offers a chronologically complete history of the SET to illustrate the complexity of the development process.

The original inventor's claims that their SET was capable of producing a temperature rise in excess of 20 °C at a flow rate of 4 l/m from a 9 m<sup>2</sup> dish, warranted further investigation in itself. A literature search was first conducted in 2002, and at that time the concept of tracking in two axis and heating water seemed to be unique with a limited number of commercial dish systems being used. For those that were found, their outputs were mainly for the generation of electric power. Subsequent literature searches have revealed an upsurge in the popularity of Dish-Stirling engine systems for small to medium scale power generation, with power plants being typically of the order of 25 kW in size each and occasionally being coupled together in an array of six or ten yielding an output of 150 kW or 250 kW. There is now, in 2007/8, a resurgent interest in parabolic dish thermal systems for space heating, water heating, centralised water heating plants (for domestic space heating), steam generation plants (again for electricity generation), and for desalination applications. A future development of the SET will include the development of additional plant to fully utilise its output.

### 3.0 Mechanical Design

The SET was designed to be completely self contained and to pivot in two axes, (namely X and Y axis) with a target attached to the end of the boom with mirrors focusing sunlight onto this target. The SET contained a 75 W PV (Photovoltaic) panel in the centre top of the mirror array which charged a 12 V DC lead acid or similar car battery mounted as a counterweight attached to the base of the X axis pivot. The original concept of the SET was to use solar radiation captured on a PV panel to charge the battery which in turn provided the power to drive the SET in both axes, as well as a circulation pump and a compressor (for frost protection), if required. In this manner the SET was self powered with all its functions being based around a 12 V DC supply. When development of the original SET ceased, both the PV panel and the battery were sold off to recover some of the expenditure on the SET.

The SET was mounted on a tripod arrangement with adjustable height legs attached to concrete pods, as shown in Figure 3.1. At the centre of this tripod is the base mounting plate onto which the X axis hub locates.



Figure 3.1. Original tripod mounting frame.

This hub consists of an old truck hub which has been heavily modified and strengthened. The centre of the hub formed an excellent entry point for all cables and plumbing. The tripod legs were in two sections with the first section from the concrete pod being 1200 mm in length and formed from twin 75 mm pipe sections which terminated in a 13 mm thick steel plate. From this point back to the central hub were three 800 mm by 200 mm diameter pipes. The legs are angled at 5 degrees upwards, meaning the central hub was designed to sit off the ground, as shown in Figure 3.2. The CPIT installation as it now exists does not use these extension legs and relies only on the central larger diameter pipes terminating to plates which connect to the roof rails, which connect to the central core structure of the building. Around the base of this hub is a 1 m diameter ring which provides a driving frame for the chain drive of the X axis as shown in Figure 3.3.



Figure 3.2. Central frame and hub.

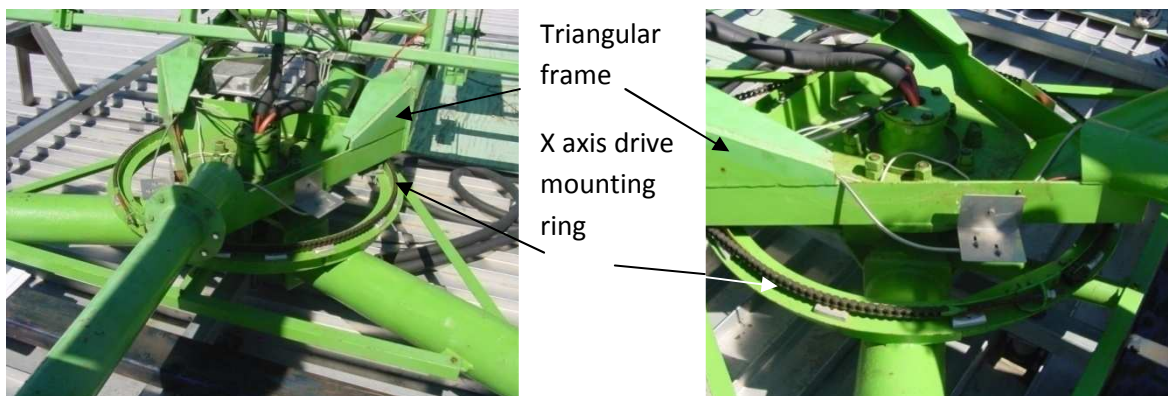


Figure 3.3 a

Figure 3.3 b

Figure 3.3 a & b. The X axis drive, triangular mounting frame, and tripod arrangement.

A thick triangular frame is welded and attached to the top of the hub (diameter 300 mm) with each side of the equilateral triangle measuring 900 mm, and being made of 13 mm thick plate steel. The counterweight boom for the battery is mounted at the point of the triangle and is attached via 75 mm diameter 6 mm thick steel pipe section with a cube box measuring 400 mm in each plane, as shown in Figure 3.4.



Figure 3.4. Battery box X axis boom counterweight.

The sides of the triangular section are further extended by the addition of twin 75 mm pipes which are welded into a vertical gusset attached to the triangular plate. These provide additional sideways bracing by running down both sides of the triangular section to the apex of the triangle and the counterweight attachment point. The vertical section of these pipes then form the mounting points for the Y axis pivots. Rear cross bracing between these two extension pipes then forms a framework for the control panel box to be mounted onto. To the rear of the triangular plate on one side is a flat plate which is designed for the X axis drive motor assembly.

A steel Y axis sub-frame measuring 75 by 50 mm is then formed to give a 2.5 m square, with two extension pieces to the frame included in this measurement. This sub-frame is mounted into the base frame using Teflon bushes and an M10 bolt which is centre taped into the base frame pivot mounting point. The Y axis sub-frame also contains a partly complete mounting ring similar in dimension and placement to the X axis but in this case for the Y axis chain drive. The Y axis chain



drive motor and support frame are a small addition to the base X axis upright support frame as shown in Figure 3.5.



Figure 3.5. The Y axis support frame drive mechanism.

Provision is made for the mounting of the boom onto the Y axis sub-frame at the bottom centre. The boom consists of a lattice framework which extends outwards by 3 m, and a further 1.4 m on an extension framework.

The boom is mounted onto the Y axis sub-frame and is secured to the Y axis sub-frame by four M8 stainless steel bolts tapering to a square box section at the end of the boom, 100 mm square. The overall length of the boom lattice is 3 m, with bracing every 1 m, as shown in Figure 3.6.



Figures 3.6 a and b. Showing two bottom attachment points for the Y axis and Y axis boom respectively.

As can be observed from Figure 3.6 b, top right corner, there is a small detachable extension to the end of the boom which contains the target. It is not sure why this extension was added by the original inventors, however it allows a more flexible mounting for larger mirrors, or mirrors with curvature, and it is easier to work on the target by removing it if required.

The boom extension is a 1.4 m length of 100 mm diameter hollow aluminium tube angled up by 15 degrees from a horizontal plane extended from the end of the main boom. The target can then be positioned at the correct focal length and spot welded to the aluminium tube section. A deflector plate is fitted primarily to protect the electrical and water pipes which service the target, as shown in Figure 3.7 a and particularly in Figure 3.7 b.



Figure 3.7. The boom extension and target with plumbing and auto-tracking head.

### 3.1 Target

The original target was made from a flat rectangular piece of aluminium with stainless steel sides, and was positioned at the focal point of the mirrors. The target measures 200 mm x 600 mm.

However this target did not have the efficiency gain that the original inventors required. In addition, the target front surface was melted and the rear water cooling pipework distorted in an accident. A new target was therefore designed, to increase the overall gain. The surface area of the target was increased by giving a raised profile to the collector plate in the form of a V. The V protruded 40 mm with the base measuring 20 mm. This increased the surface width from 200 mm to 824 mm and resulted in a much better efficiency gain for the SET. The redesigned target is shown in Figure 3.8.

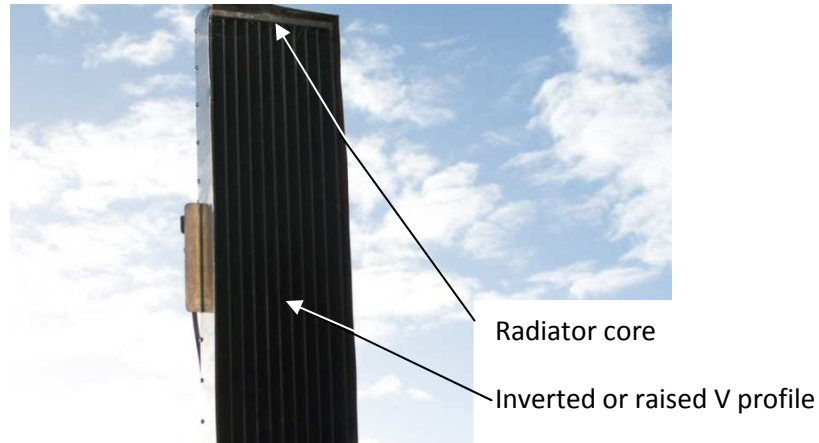


Figure 3.8. Revised target design with raised V surface profile.

The rear of the target contains all the necessary pipework for cooling of the target, including all the copper connections, ducting and copper pipework, and copper radiator surround. Cooling for the radiator comes from a circulation pump detailed in Chapter 4.2. The flow design of the target is such that water enters on one side at the bottom into a small reservoir. It is then forced up one side of the target filling the top reservoir and overflows down the other side of the target into a small bottom reservoir, leaving the target as hot water. The fins are mounted into a copper radiator frame. These fins are made from aluminium which has been anodised black. The fins are held in place by the copper radiator surround. There are nine fins in total as shown in Figure 3.8. Figure 3.9 shows the target being dismantled with the rear flat-plate removed, the fibre-glass packing on the rear of the radiator core and the stainless steel protective shrouds.

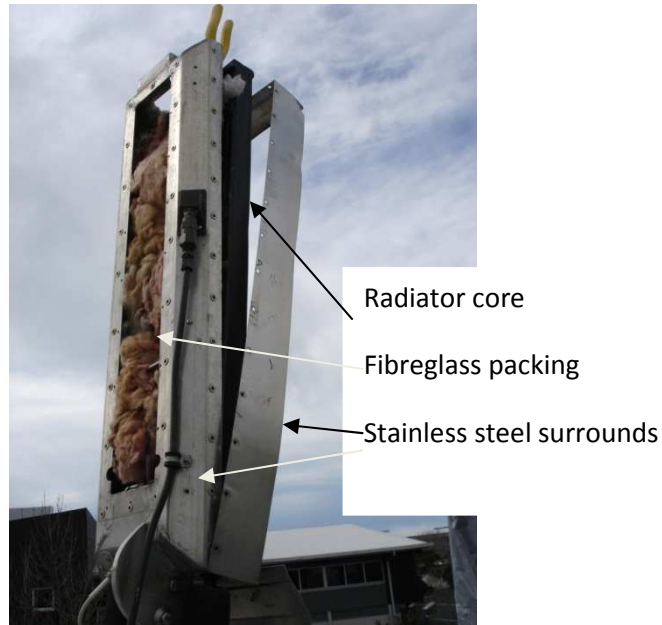


Figure 3.9. Target assembly.

The top centre of the target contains a plug which can be removed to facilitate air purging and may be used to inspect the interior of the radiator. This area also contains an additional entry point for the compressed air purge system, and two monitoring points for temperature and flow.

The target has a frost purge system, which will release 60 psi air into the top reservoir of the target, and using solenoid valves sequence this to purge the cold water supply line followed by the hot water exhaust pipes, back to a central holding tank or reservoir. The entry point for this compressed air supply is on the left hand side and midway up the target, but its entry point into the target reservoir is at the top of the target. This system was originally designed for a frost prone environment and ensured that no water was left in the target or in the cold water supply or in the hot water supply lines. Figure 3.10 shows the compressed air entry point with the copper pipe at the bottom of the picture.

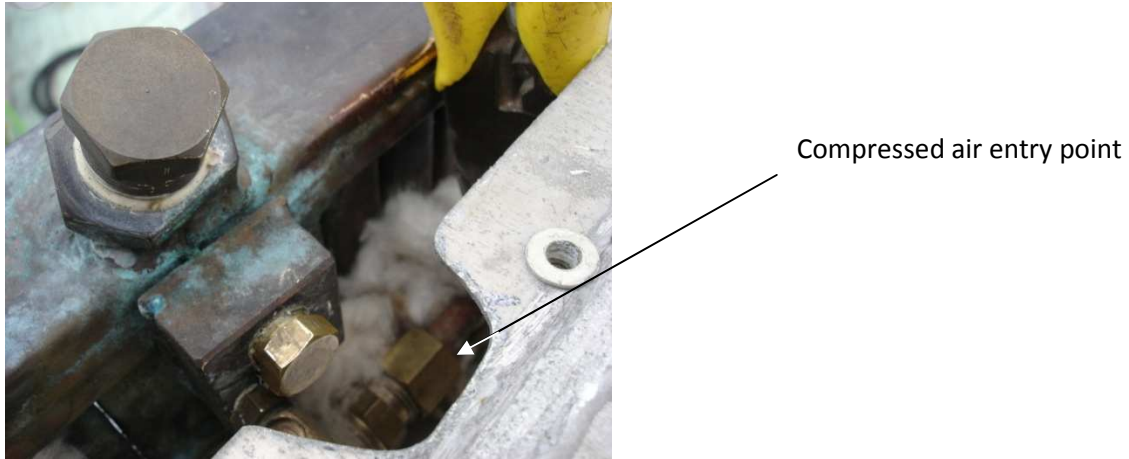


Figure 3.10. Compressed air entry point.

Originally a conductivity flow sensor and an NTC thermistor were used to sense flow and measure temperature in the target. This proved the target was immersed in water and not steam or air. However in September, 2004, both these sensors were found to be faulty and replacements sought. The temperature sensor, a National Semiconductor<sup>[68]</sup> LM335A precision temperature sensor with linear readout temperature given in Kelvin, replaced the NTC sensor and is the same type of sensor as used by the SCADA monitoring system. The temperature sensor is coupled directly into a PLC for monitoring and forms part of the safety interlock system. The conductivity flow sensor was replaced with a typical socket from a laboratory bench banana plug and socket set. The conductivity flow sensor required additional circuitry to interface it with the PLC. After several unsuccessful attempts to make this system operate it was decided to rely on a magnetic float flow proving sensor which was mounted in the exhaust or hot water side of the targets outlet, and to dispense with the target flow sensor. This revised system has performed well in all subsequent testing. The mounting positions of the temperature and flow sensor are shown in Figures 3.11 and 3.12.

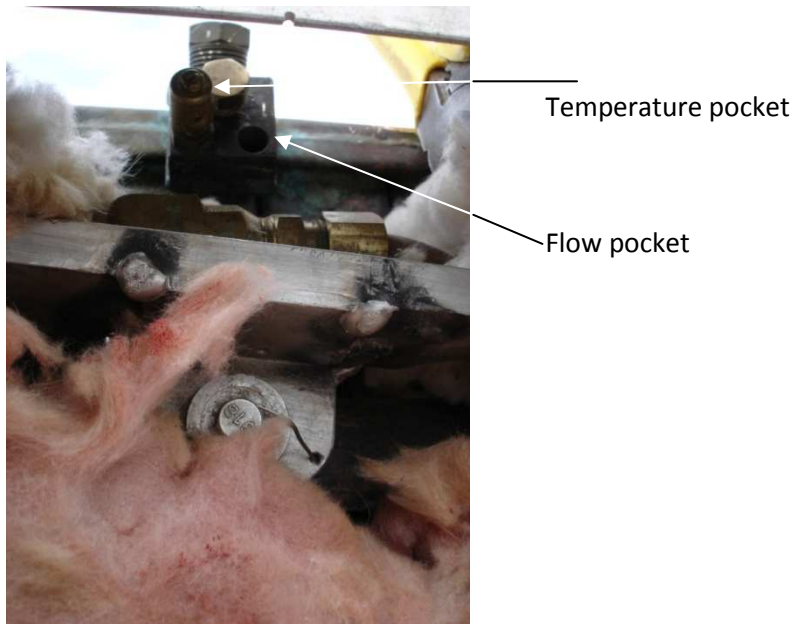


Figure 3.11. Mounting pockets for temperature and flow sensors respectively.



Figure 3.12. Showing the temperature and flow sensors as mounted.



Figure 3.13. Auto-tracking target and knuckle adjustment.

The end of the boom contains the auto-tracking sensor, which is mounted on a double knuckle arrangement allowing adjustment in both the X and Y axes as shown in Figure 3.13.

Figure 3.14 shows the configuration of the IR photo-diodes onto a reverse petal arrangement with three IR photo-diodes mounted in each of the four reverse petals.



Figure 3.14. Auto-tracking sensor head arrangement.

The original auto-tracking sensor head contained three IR photo-diodes on each of the four axes or petals, and was mounted in a double plate protective shroud painted in white, with a central M3 nut. In early testing this arrangement appeared to operate satisfactorily, but later proved unreliable and continually required adjustment.



The revised auto-tracking sensor head with one IR photo-diode in each of the four axes (petals) and a central IR photo-diode being used for the light level sensing is shown in Figure 3.15.

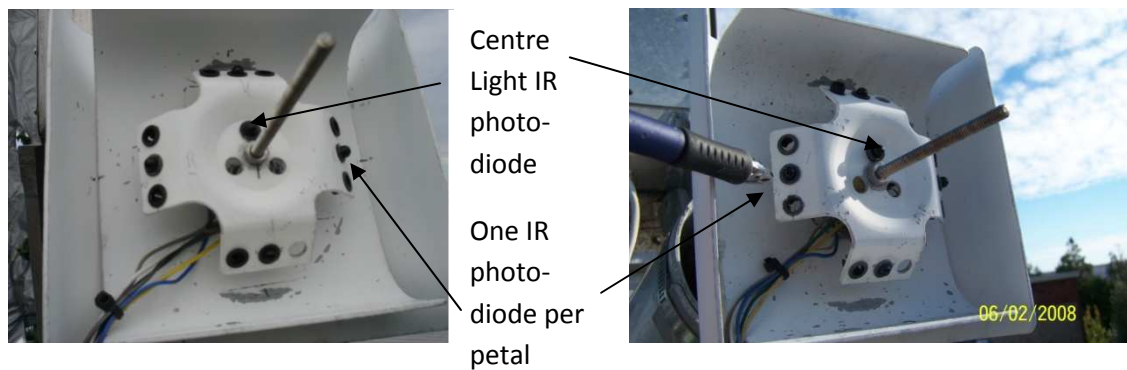


Figure 3.15 a & b. The revised auto-tracking sensor (with one IR photo-diode per quadrant) and centre mounted IR photo-diode for light sensing.

### 3.2 Mirrors

The mirrors comprise two parts, one an interface surface containing the mounting brackets and ball socket, and the other being the reflection surface. The Y axis sub-frame contains eight interface points comprising clamp bar sockets into which each mirror's ball joint fits. Some of these are shown in Figures 3.16 and 3.17.



Figure 3.16. The Y axis sub-frame with additional mounting supports for the mirror's ball joints.





Figure 3.17. The mounting support and mirror ball joint receptacle.

There are two types of mirror, based on their location in the SET. Most mirrors measure 1200 x 620 mm, and are located on the outside edges of the SET, with smaller mirrors, measuring 900 x 620 mm, being located between the hinges in the centre of the SET. However, the mirror above the hinges is also a large mirror. The mirrors are labelled by their location. From the rear of the SET the top left mirror is column A, mirror 1. The mirror at the bottom left corner is labelled A5. The central mirrors are labelled B1 to B3, and the right side mirrors are labelled C1 to C5.

Mechanically, each mirror has the same framework with the centre having a curvature from flat of 20 mm, i.e. the centre of the mirror is deflected in a concave manner by 20 mm. This slight curvature can be seen in Figure 3.18. The mirror coating or substrate is applied to this curved surface.



Figure 3.18. Mirror curvature.

The rear of each mirror contains two side panels which are then held in place by two square aluminium bars for rigidity, with a central plate forming the interface to the ball joint. The ball joint

is cast aluminium rather than being machined or milled and is of diameter 40 mm. The ball joint is cast complete with a small adaptor plate as shown in Figure 3.19 which is then attached by four M5 bolts to the central plate. The mirror's ball joint is mounted into a clamp ring arrangement in the Y axis sub-frame.



Figure 3.19. A mirror's rear mounting detail.

The mirror ball joint mounting system was useful for mounting and aligning the mirrors, however it proved to be inadequate when minute adjustments to a mirror's alignment were necessary. The mirror's ball joint mounted into a clamp bar socket system which comprised two half aluminium blocks with a small curvature and 'V' groove cut into each face to match the shape of the corresponding mirror's ball. This clamp bar socket clamped around the ball joint and was then held in place by another aluminium block secured to the Y axis sub-frame. A problem came about when re-alignment was necessary due to small amounts of movement in the mirror and its mounting interface block system. This necessitated the complete loosening in many cases of the clamp bar socket and the aluminium interface blocks to the Y axis sub-frame. In other words there was no facility to fine tune or minutely adjust the alignment of each mirror. The other issue was that the two outside bottom mirrors clashed with the Y axis sub-frame and were not able to easily align to the target.

After several attempts at aligning these two bottom mirrors, it was discovered the mounting interface blocks had to be repositioned in towards the centre of the SET to allow for the curvature on the mirror when aligned correctly for the sun. However, despite several changes in design and orientation, these outer two mounting interface blocks were still too flexible on the Y axis sub-frame, and with any vibration or wind would move out of alignment slightly. This would cause the solar radiation to miss the target in a severe vibration or wind. No amount of adjusting the position or changing the thread system seemed to be able to cure this problem. The mounting block can be seen in Figure 3.20.

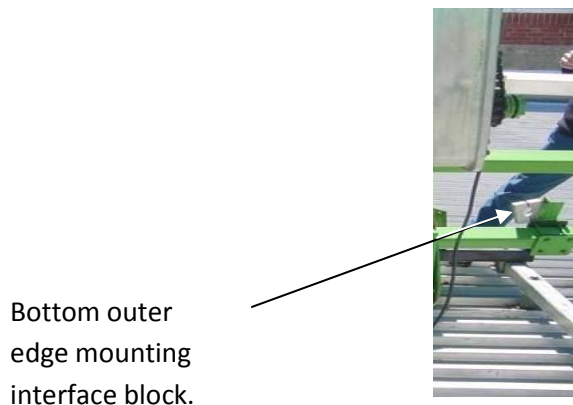


Figure 3.20. Outer edge mirror mounting interface blocks and mirror.

### 3.3 Additions and improvements

One early improvement saw the addition of steel stage lighting ties or cables. These have a high breaking strain and use a 'karabiner' type locking interface and are used in all stage performances to secure theatre lights to the clamp bar and are a backup in case the clamp holding the theatre light fails. These lighting ties were placed around the central plate as shown in Figure 3.21 and then tied back to the Y axis sub-frame. This was done such that if the mounting ball joint or socket failed for some reason in a wind, etc. then the lighting ties would hold the mirror onto the Y axis sub-frame rather than letting it fall somewhere else.

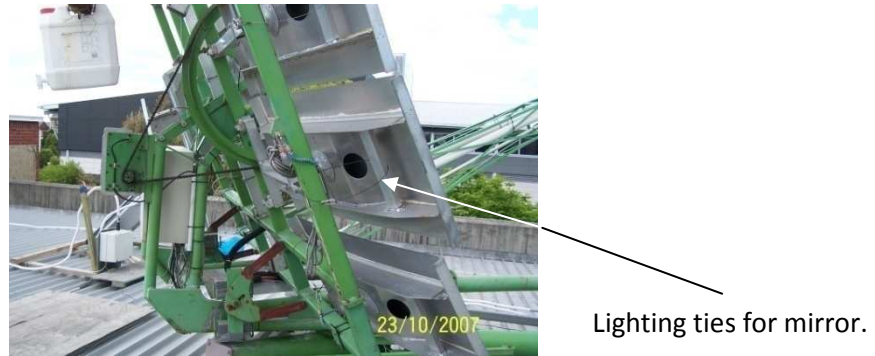


Figure 3.21. Lighting ties securing mirror to Y axis sub-frame.

A full mechanical report was commissioned on the SET, and its framework and mounting, before any mirrors were mounted onto the Y axis- sub-frame. The mechanical report, included in Appendix 1, found five areas of concern.

The first area of concern was the bolts securing the mirror ball joint to the interface blocks and the bolts securing the interface blocks to the Y axis sub-frame. These were M6 bolts and were classified as being marginal in capacity ( $<0.8$ ). The interface blocks were changed to M8 galvanised mild steel bolts for both the interface block and the mirror mounting clamp.

The second area of concern related to the method of attachment of the boom to the Y axis sub-frame. These bolts were also calculated as being marginal ( $<0.8$ ). Likewise these bolts were taped out from M8 to M10 and changed to galvanised mild steel.

The boom lattice frame was calculated as 'likely to buckle' ( $>1$ ). This has not been changed as it would be preferred that this member buckle in the event of a heavy wind or similar event. Over the years that the SET has been in service and under test, some deformation has occurred which may have in part lead to the realignment of the auto-tracking target sensor and the mirrors.

The fourth area raised by the report showed that the pivot points of the Y axis sub-frame onto the X axis frame were 'likely to deflect significantly' ( $>1$ ). This concern was valid and saw a gusset welded

to the bottom of each pivot hinge to provide additional strength to the hinge as shown in Figures 3.22 and 3.23.



Figure 3.22. Y axis frame pivot without bottom strengthening gusset.



Additional gusset fitted here on the lower flat edge of the pivot

Figure 3.23. Y axis frame pivot with bottom strengthening gusset.

Figure 3.24 shows the completed modified SET in operation in late August 2007 is shown in Figure 3.24. It is shown parked on an overcast day but still in operation, in late January 2008 in Figure 3.25.



Figure 3.24. Completed SET in operation on a fine winters day August 2007.



Figure 3.25. SET in park mode on an overcast summer's day January 2008.



#### **4.0 Motors – drives, pump, and compressor**

The choice and type of motors used in the SET are to an extent governed by the possible end uses for the SET. If for example, the SET is to be used in a commercial environment, for perhaps generating hot water as part of a boost system or preheating system, with readily available mains power, then the type of motors chosen will differ from that chosen if the SET were to be used to provide a remote supply of hot water and or power in a location where mains power is not readily available. As this was the original intended purpose and market for the SET, the inventors kept to low voltage DC. All the sensor controls, the interfaces, the control system and all the output drive systems were designed to operate from 12 V DC.

One of the advantages of using this voltage is that all electrical work can be performed without the use of a licensed person, which for a remote location may be a benefit. This has to some extent limited the choices and types of equipment which can be used for the SET. To retain the flexibility of the SET for future possible commercialisation, it was decided to stay with many of the ideals of the original inventors, namely low voltage DC, energy efficiency, flexibility of use, self-containment and easy serviceability. Whereas the original SET contained a PV panel, as has already been commented on, this was not available to the CPIT installation. The CPIT installation had the opportunity to change all the system voltages to 230 V AC; however it was decided to retain as many of the 12 V DC systems as possible, even though more energy efficient motors may be available in 230 V AC. This has meant an increase in some interface technologies (relays, etc) as the current drawn at this lower voltage is more of an issue than at 230 V AC, the cost of pursuing the 12 V DC option is more expensive, and the options for possible equipment use are fewer and perhaps more restricted to the marine pleasure craft industry or automotive industry. This has been more than offset by the fact that the SET is an experimental piece of test apparatus, and its equipment can be easily installed and commissioned without the need for a licensed electrical person.



## 4.1 Drive motor

With the original control system, the inventors had no facility to feed back the angular position of the motor or its output shaft position via a rotary shaft encoder. The only feedback which was able to be incorporated into the analogue control system of its day was the use of limit switches giving travel limits rather than continuous proportional feedback of angular position. This worked well on the original SET machine and it was decided, based on the possible end uses of the SET, to retain this feature. Much thought was given to the use of an encoder to give proportional angular feedback of position; however this increases the complexity of the processor. The only justification for using this level of complexity in the motor drive and in the associated control circuitry and controller or processor would be if the processor was preloaded with a map or co-ordinate equation based on perhaps GPS or grid co-ordinates. A typical motor with encoder from RS Components (Cat #263-6011) for example is \$520 and has an operating voltage of 24 V DC. In this case there would be no requirement for an auto-tracking system, as the processor would calculate, using an equation or perhaps a 'look-up' table, the required angular position of the drive motors and then issue a command to track to that position. The advantage of the auto-tracking circuitry is the ability to optimise the SET for the maximum solar radiation available at any time, which may not always be the fixed angular position at that time of day. This level of control, where auto-tracking and travel limit switches are used, is cheaper and easier to process and interlock within a PLC controller.

The drive motor used on the SET, is outlined in Chapter 5.4 (Electrical), and is an RS Components catalogue number #238-9670, brushed DC motor and inline gearbox with a ratio of 148:1. This motor has a torque of 0.54 Nm at its output shaft, which is further increased by the final worm-drive. The motor draws 1 A continuously at 12 V DC. Other options for the drive train system were investigated, including those with encoder feedback, stepper and servo motors, higher voltage motors and gearboxes; however nothing was able to compete in the final analysis for size, torque, and price. In 2006 and 2007 these motors sold for \$75.30 each. Spare parts for these motors are also readily available either as the DC motor or as the complete DC motor and gearbox.

In testing and operation, provided these motors are not overloaded by the SET crashing through its limit switches or 'snagging' on cables and these motors are regularly greased (perhaps a six monthly check) with White Lithium Grease (a CRC car care product), they will last for a minimum of five years. This is based on the fact that the SET has operated for this length of time, and on the history of the original 3 motors supplied with the SET. These had seen use in 1997 and 1998 and were able to survive a further 2 years of intermediate testing and setup commissioning in various forms at CPIT. The most likely cause of failure will be either of the DC motor burning out (due to brush wear or overload) or the last intermediate gear stage (prior to the output drive stage and output motor drive shaft). With this last case, the shaft 'slogs' out at the drive shaft end of the mounting plate. This is a relatively easy fix, by either 'over-driving' the offending shaft back onto the mounting plate with a pin hammer to prevent it from rotating, or simply replacing the complete motor and gearbox.

In testing it was found if there was insufficient grease on the gears, the motor 'whined' and eventually caused the intermediate support shaft to the intermediate gear before the final output drive gear, to rotate in the drive end of its mounting plate. This was treated as a sign that a new motor and gearbox should be ordered, with failure of the intermediate gear and its shaft usually occurring some thirty to forty days later.

There are two of these motors required for the correct positioning and operation of the SET. One drive motor is required for the X axis and the other drive motor is for the Y axis. The Y axis drive motor, final drive worm box and mounting frame is shown in Figure 4.1. No future modifications or changes would be made to this part of the SET.



Figure 4.1. The Y axis drive & DC motor, final output worm-drive and mounting assembly.

## 4.2 Circulation pump geared motor (CP)

Along with the drive motors, this motor is also critical to the safe operation of the SET. The function of this motor, as has already been conveyed in Chapter 3.1, is to safely and as efficiently as possible deliver water to the target, to cool it. There are various alarms such as target over-temperature shut down alarm, CP motor failure, CP over-pressure and CP tray full and target flow alarms which interlock with the operation of this critical delivery motor.

This motor is also a brushed DC motor with an offset inline gearbox, RS Components #320-590. The gearbox output shaft is 6 mm in diameter, with adaptors for 10 mm or for a tongued shaft. The tongued shaft allows the motor and gearbox to be adapted for the powering of type 303 peristaltic pump systems and applications. This motor is a heavy duty motor with a quick change brush system, sintered bronze bearings and a choice of output speeds, 100 rpm or 20 rpm. In the SET application for a flow rate of 4 l/m, the 100 rpm model was chosen. The motor at this speed has a peak and continuous torque of 1.2 Nm. At 12V DC, it draws 1A continuously in normal operation. The CP is connected via shaft adaptors to the CP pump head proper and peristaltic pump assembly, as shown in Figure 4.2 a and b. The price in 2007 from RS Components for this motor was \$457 each.



Figure 4.2 a.

Figure 4.2 b.

Figure 4.2 a & b. The DC drive motor and CP assembly.

This type of motor was originally chosen for its high efficiency and low loss in pumping, when compared to the impellor type circulation pumps. In the CPIT installation, this CP was found to be sometimes lacking in flow rate due to a poor or low head of water being used. Whilst this has been fixed by moving the low pressure tank to a position 4 m above the CP, the CP has proven itself in later testing conducted during 2007.

In 2007, the water flow through the SET was conveyed in a more controlled manner than in previous years. During these tests it was found that if the SET had ‘boomed up’ to track the solar radiation, but the water flow system was off due to there being insufficient temperature rise in the target (perhaps a dull day) and the sun appeared, the target would heat up very quickly, in turn requesting the PLC to turn on the water to cool the target. The CP solenoid (CPS) would energise and water would try to flow into the target, however, as this was pointing skywards and was close to being the same height or at the same level as the low pressure tank, the water flow was reduced. The exact reason for this has never been ascertained, however it is thought that there may be a vacuum formed which sucks in air and traps this in the target when the target ‘booms-up’.

The rationale behind this reasoning is, if all the air is removed from the CP and target systems, which is possible, and the water system is completely sealed from the low pressure tank inlet to target hot water exhaust outlet container and check valve, and the SET is allowed to operate normally for up to

three days, on the fourth day 'gurgling' noises, as is normal when air is mixed with water, can be heard in the target. There are no visible signs of water leaking anywhere in the system; there is also no audible signs of air 'hissing' as it enters the system either. All the pipework joints and couplings have been overhauled and checked for water and air tightness.

Initially the target hot exhaust outlet was left to drain directly into the spouting on the roof, however in an attempt to reduce the air in the target, the end of this pipe was upturned. After this failed to prevent air from entering back into the system, a check valve was fitted to the upturned pipe. This likewise failed and so a container was installed with the upturned pipe inside and a check valve to complete the assembly. Thus the target hot water exhaust discharged via a check valve into a container which always had water in it, as shown in Figure 4.3 a & b. This latter development greatly reduced the occurrences of and amount of air in the system. However, it in no way totally eliminated the air in the system. Likewise, all the pipework and joints were inspected and in many cases the pipework joints were remade, often with thread tape. This further reduced the amount and frequency of air entering into the target.

It was also thought air may be entering via the CP head assembly, so this has been completely overhauled and refurbished, with a modified flow design being used from 2007. Every attempt has been made to try and reduce the air in the target, including disconnecting the air compressor pipework. Another attempt may be made in the future with the total removal of the air compressor pipework for a longer period of time and the sealing of all associated surrounding pipework, including the checking of all pipework in the target proper or inner. Based on this, it is thought that at the height of the C block building and the added height of the boom, that may be water was being forced over 30 m in height and therefore pulling a vacuum, and pulling any trapped air out of the water or through otherwise sealed pipework joints into the target, as this is now the highest point. However, this theory is as yet unproven.



Figure 4.3 a & b. Hot water exhaust dumping container.

The issue in 2007 involved turning off the water to the target for lengths of time. When the target temperature increased and the PLC then called for CP flow, it was found an air lock had developed in the target and the time required to clear the air lock was outside what could be pre-determined by the flow switch proving timer, without damage being caused to the target through a lack of cooling. However, with the CP and the CPS and the open bypass arrangement in the CP head assembly, the time delay as set for the flow proving timer was always met. This was observed on the pressure gauge as fitted to the outlet of the CP assembly, with operating pressure with CP, or CP and CPS, or CPS being 2.5 psi. However, with an airlock in the system the pressure required to clear the air lock rose to 5 psi.

Throughout testing, this CP motor has proven to be reliable, with the only problem being the method of coupling between the peristaltic pump and the CP gearbox output shaft. This coupling is currently a grub screw which has with time worn loose (on a number of occasions) and has almost 'slogged out' the keyway on the gearbox output shaft. The CP motor and gearbox are the original components from the inventor's development. In the middle of 2006 an hours run meter and a pressure gauge were fitted to record the hours of operation and monitor pressure on the CP outlet and later of the CPS outlet or CPS and CP combination. At this time, a complete overhaul, brush inspection and gearbox check and grease were performed. No maintenance issues or concerns were noticed. The brush wear pattern was normal and no brush replacements were needed. The gearbox

was greased and resealed. Since this time the CPS, or CP or CPS and CP (from 2007) have recorded over 2270 hours of operation.

For the future, a revised coupling for the peristaltic pump and motor gearbox should be considered, as should the possibility of using the PLC's analogue output to allow the CP to be variable speed controlled. This would be easily accomplished with the purchasing of a current to voltage or voltage to voltage step up power transducer to interface between the PLC's low current analogue voltage or current output and the CP motor. Another cable would be required, along with the purchase of another 12 V DC power supply. This would allow a continuous flow of water through the CPS, and the water flow through the CP to be varied in accordance with a setpoint as entered into a PID (Proportional, Integral and Derivative) control block in the PLC controller which would have as its primary sensor the target temperature. This would further increase the efficiency of the SET. Another target flow switch would be required to allow a lower flow rate through the hot water exhaust pipework, perhaps a flow switch which activated if the flow fell below 2 l/m.

### **4.3 Air compressor**

This is of the type normally found in car auto shops and is powered off 12 V DC. This type of air compressor is intended for home car use or roadside use wherein the car owner takes the air compressor and plugs it into the car's 12 V DC electrical system, usually via the cigarette lighter or as it is called nowadays, the 12 V DC auxiliary power socket. This model comes complete with pressure gauges, hoses and all fittings and has only been slightly modified for this application. As such these units are noisy and are perhaps not intended to charge a pressure vessel of the type and volume as used on the SET. No catalogue number and type is given for this air compressor as it is a readily available item from any car parts retailer.

When in operation, the air compressor will draw 1 A continuously at 12 V DC. The air compressor and pressure vessel is shown in Figure 4.4.



Figure 4.4. Air compressor and pressure vessel.





## **5.0 Electrical Design**

### **5.1 Introduction and battery box counterweight**

When the SET was developed it was designed to operate from a 12 V DC battery charged by a 75 W PV (Photo-voltaic) panel. This worked well in 1997, however with the PV panel being sold off to recover some of the development costs; this meant that when the SET was shipped to Christchurch in late 2003 the only method of operation was a 12 V DC battery with battery charger top up. In the initial testing performed on the reassembled SET, the only source of power was a car battery (12 V DC). In the testing performed at that time the current drawn by the SET when it operated successfully was such that within a short time another battery was required. This may have been partly due to the age of the battery used, however the current drawn by the four motors (X and Y axes, circulation pump, air compressor), each drawing about 1 A continuously when in operation, and the fact that at that time it was possible for the SET to track in both axes at the same time, meant standalone operational time was relatively short lived. Eventually, in 2004, this system was replaced with a range of power supplies sourcing their supplies from the single phase mains.

This meant that the car battery located in the battery box counterweight could be removed, however the fusing and circuit isolation wiring systems were left in place for any future developments. With the battery removed this meant the box could be sealed and repaired from the damage caused by battery acid and fumes escaping from the battery on charge. A bag of shingle was substituted for the weight of a typical lead acid battery. Additional holes were drilled in the bottom of the counterweight box to allow for drainage should any water enter the box and to allow the box to 'breathe'. The battery counterweight box was then locked and checked only on a yearly basis for signs of decay, rust, water tightness, and correct weight.

## 5.2 Analogue Controls

The original control system, designed to be self-contained and to operate from low voltage (12 V DC), was based on analogue technology and hard wired logic with relays being used for switching heavier loads or to offer a set of clean contacts to a circuit. A wiring diagram of 'sorts' was supplied with the control panel along with a brief operational description. The wiring diagram was more of a connection block termination schedule; however when read in conjunction with the operational description an outline of the circuit's operation could be obtained.

The control cabinet at this time contained a bottom row of terminals, which acted as the termination point for all field wiring, as shown in Figure 5.1 a. To the right of the cabinet were all the circuit boards for light level, target temperature, and frost protection. The bottom front edge was additional termination sockets for wires from the PV panel, with the PV panel charge controller being mounted behind the circuit boards and on the rear of the control cabinet. Also to the right side of the cabinet and at the rear outside of the cabinet were mounted all the controls; start, stop, and system on keyswitch. There was no provision for an emergency stop or any other external operator inputs, other than start, stop or reset and a keyswitch as per Figure 5.1 b.

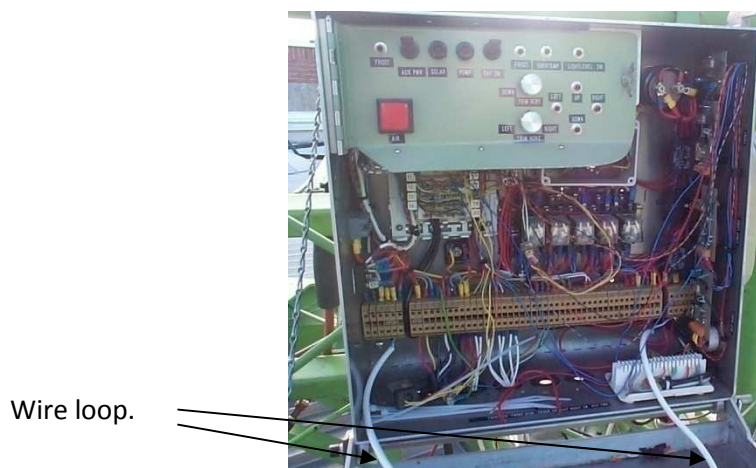


Figure 5.1 a. The original SET control panel.

Pushbutton controls.



Figure 5.1 b. The original SET control panel side controls.

As can be seen from Figure 5.1 a, there is a loop in the wiring linking the two sides of the panel. The wire link connected the battery located in the counterweight box and the PV charging circuit on the right side of the control cabinet in Figures 5.1 a and 5.2 with the rest of the control panel on the left side. The output of these terminals then fed the rest of the controller via the keyswitch and start circuits. When this control box was received, some restorative work was required to replace all the wires that had worked loose, for which some specific details had been lost. In order to make the SET operate without a PV panel, this wire connection was now essential and is shown in Figures 5.1 a and 5.2. The main power control and circuit supply for the operation of the SET entered the control cabinet on the left side.

From the supply terminals, electrical feeds were taken to the various circuits and to the main 'Krone' termination or patch panel which is partly obscured in Figure 5.1 and more visible in Figure 5.2. The rear of the control panel contained heavier current switching relays, the auto-tracking sub-board, and the 'Krone' patch panel. The connection between the 'Krone' patch panel and the auto-tracking panel was by way of a modified 11 pin adaptor plug. All diodes necessary for direction control were mounted directly on the 'Krone' patch panel which further stressed the termination points as they are designed to take small diameter wires rather than component leads of a larger diameter or size. It was thus too easy to dislodge wires when performing any operation on the control system.

Removal of the auto-tracking sub-board from the container it was in, or the removal of the box the

auto-tracking circuit was located into, was more than sufficient to cause dislocation to the surrounding wiring and caused many hours of troubleshooting and replacing wires and components into the patch panel.

The rear of the front gear plate with all the associated wiring.



Figure 5.2. The original SET control panel with the front gear plate removed.

When the SET was first restored at CPIT, the system was trialled without mirrors, and after extensive work in the controls cabinet the SET did successfully track for a short period of time. The photographs in Figures 5.1 and 5.2 are of the first successful attempts at making the SET operational (July 2003) with all the associated ancillary wiring required.

The original SET used magnetic Reid switches for both the X and Y axis travel limits. The X axis travel limit switches are mounted on a magnetic base and can be easily moved. The Y axis travel limit switches were mounted on the X axis support frame with the Y axis frame and boom closing onto these. The Y axis frame, and the boom move through an arc of 80 degrees.

The first light level sensor was a Light Dependent Resistor (LDR), but this failed to operate due to age and was replaced with another LDR which failed during the first six months of 2004, due to water damage. A third LDR was then installed, but this failed after the first heavy winter rain, despite sealing around the leads, the clear plastic top and the coloured plastic bottom. This was replaced with a set of five IR photo—diodes mounted in the auto-tracking sensor head of which one IR photo-diode sensed light level, which has worked reliably and is discussed in Chapter 6.1.

The relays in the centre of the rear panel were for frost protection compressor solenoid dump valves, frost protection start and compressor, light level okay (and start tracking), night and day switch (which drove the park circuit), and power on (to the complete SET).

The front gear plate shown in Figure 5.1 a comprised a number of switches which were also present in the control panel: Frost mode dump pushbutton, Auxiliary power isolator switch, SET solar system on, circulation pump on, day night timing circuit, other pushbuttons for frost protection (a second one), over-temperature alarm, and light level latch on bypass. The two trim potentiometers, shown in Figure 5.1 a, allowed fine tuning of the bias on the auto-tracking X and Y axis circuits, and pushbuttons for manual adjustment of the X and Y axes.

The large pushbutton (red) was of the latching illuminated type and started the air compressor which started and charged up a reservoir of air to 60 psi and then switched off the compressor but left the lamp illuminated to inform the operator the system was in operation and charged, as shown in Figure 5.3.

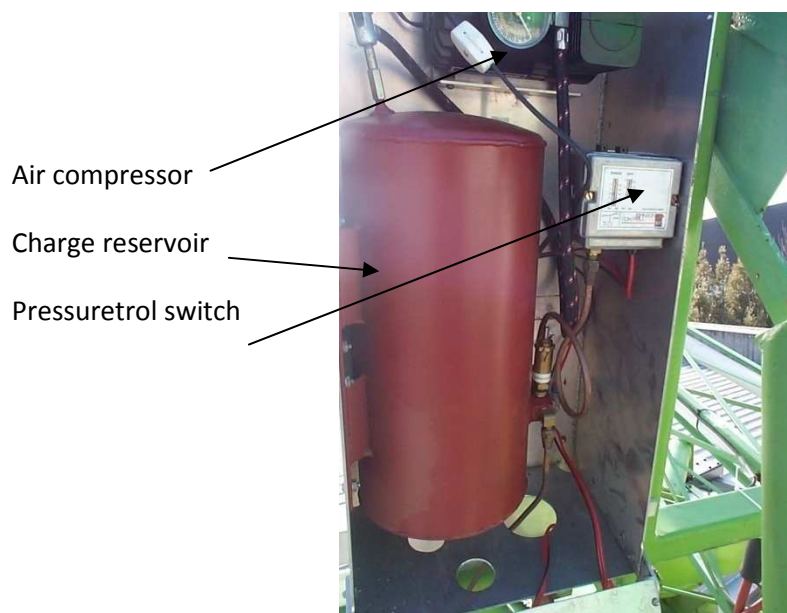


Figure 5.3 Air compressor (top), charge reservoir and pressuretrol limit switch.

The air compressor is of the type used for charging a car's tyre with air. The system takes about thirty minutes to charge the cylinder. It is noisy. The system was not fully commissioned when the SET was re-started in 2003, nor when the SET was operated in 2004. This was due in part to the noise and length of time of operation and the belief that frost would not affect the second story roof of a building. In conditions where frost was likely, the SET circulation system was drained and left for periods of time.

The X and Y axis drive motors and associated drive control interface PCB were located in the same cabinets as the drive motor. Figure 5.4 shows the Y axis motor, gearboxes, and control interface PCB.

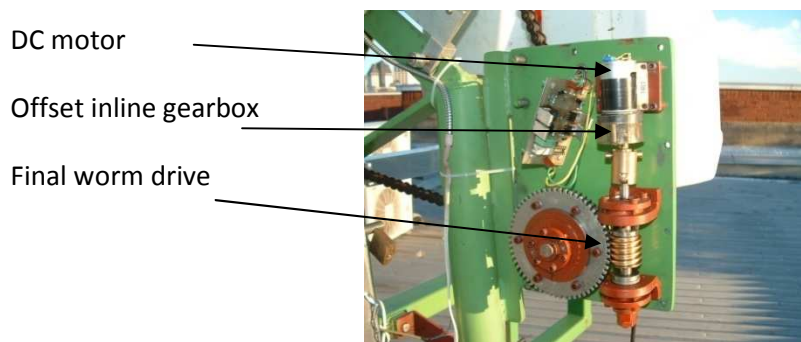


Figure 5.4. Y axis motor and gearboxes, and drive control interface PCB.

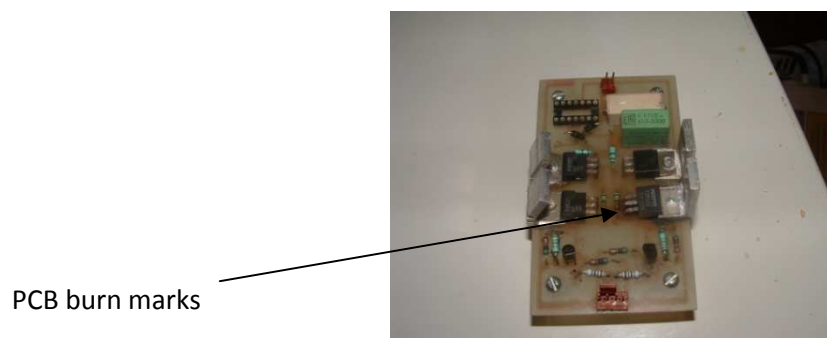


Figure 5.5 Drive control interface circuit board – component side.

PCB burn marks



Figure 5.6 Drive control interface circuit board –track side.

The drive control interface circuit used four TIP31c power switching transistors in an H bridge circuit. However, these transistors were not able to handle the currents and back EMF's generated by the DC motors and so failed regularly as shown by the burn marks on the PCB's in Figures 5.5 and 5.6. Faults with the circuit and the TIP31 transistor included the size of the heatsink and the lack of electrical isolation of the TIP31. The heatsink was too small for the intended task, and reached a high temperature very quickly. Also, if the heatsink came into contact with the chassis of the SET, then the transistor would short out and consequently fail. Whilst performing evaluation testing on the re-assembled SET in 2003, this happened several times and resulted in the PCB becoming totally burnt and not salvageable or useable in any way. A new circuit board was fabricated based on the old circuit board design to allow continued testing and proving of the SET.

### 5.3 Digital control

At the start of 2004 a decision was made to purchase a digital controller to perform all the necessary control and alarm monitoring. CPIT has traditionally used Allen Bradley PLC's, however for this application with forty digital I/O and three analogue I/O, with DeviceNet interface, there was no readily available and cost effective solution. Omron were asked to quote which included support and software. At that time this PLC was under half the price from the first supplier, which was an element in the final decision. This quote was subsequently accepted and has introduced to CPIT a more modern brand and type of industry PLC. This will allow monitoring, via DeviceNet, the status of the SET remotely. The PLC uses 230 V AC mains power. The inputs are rated at 24 V DC and may be



fed from a 24 V DC power supply. The outputs are a clean contact relay type and switch, a 12 V DC supply feeding interposing relays and the appropriate motor being controlled.

#### **5.4 Motor drives and gearboxes**

The DC motor selected by the original inventors came complete with an offset inline gearbox as shown in Figure 5.4. Here the term offset inline refers to the final output drive shaft being in a different alignment (offset) to the motor input shaft. The final drive is still inline with the motor input shaft as opposed to being at 90 degrees. The DC motor is capable of operating from a range of voltages (4.5-15 V DC), with a drive reduction ratio of 148:1, or a final shaft output speed of 106 rpm. This is further reduced by the worm drive following, offering a 12:1 reduction. These motors are readily available from RS Components, catalogue number #238-9670 and offer a torque of 0.54Nm which, when coupled to the offset inline gearbox, has a final available torque from the worm-drive output of 6.5Nm. The gearbox features all metal gears.

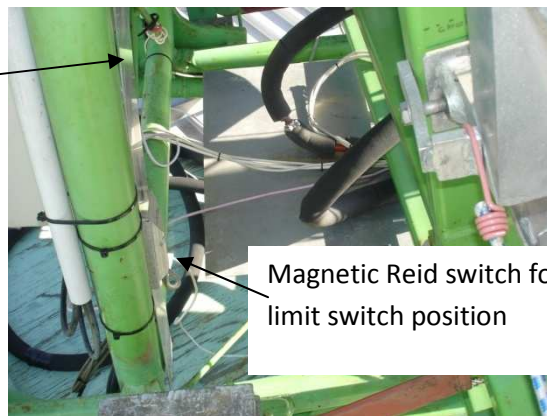
These DC motors and gearboxes have the necessary speed and torque required for the task of moving the SET in either the X or Y axis, only because the overall reduction ratio is about 1776:1, which improves the overall torque transmission figure, but decreases the total efficiency of the drive train.

The individual components of the DC motor and gearbox have proven themselves to be reliable with two exceptions. The first problem with these motor drives and gearboxes relates to how the final output gear or drive stage and shaft couple into the end faceplate. With time and use, the shaft can become loose in its mounting onto this end faceplate and with the movement, cause the final output drive stage gear to come out of alignment. which if not fixed will result in failure of the gearbox. This will also cause a noise in the gearbox. This has occurred on the two original motors installed onto the SET and tested in 2003 (repaired) and 2004 (finally failed) for the Y axis and 2005 for the X axis (finally failed).

The second failure mode of these motor drives and gearboxes is burn out due to excessive brush wear or gearbox overloading. To prevent this from occurring a safety feature in the new PLC control system was designed (to be discussed in more detail in Chapter 7. However, it is still possible to cause a motor to fail before the safety shut down override system initiates and isolates the drive motor(s) due to the safety travel time margins allowed for full system travel and shut down (refer Chapter 7.0 for details).

Another failure of the Y axis drive motor occurred in 2005 which related to the incorrect positioning of the Y- travel limit switch and the SET booming down in response to a SW wind change and storm. The consequence was the Y axis drive motor trying to place the boom below the normal park position and into a classroom below it. However, due to the mechanical design of the SET, the boom was brought hard-up against the X axis frame and jammed. This was caught in time as it was one of the first days that the SET had been left to 'its own device' for any period of time (2 hours). Although this did not cause any damage at that time to the Y axis drive and motor, it did however weaken the gearbox on the Y axis drive motor sufficiently that it failed some two months later. This resulted in the re-working of the SET control system code, which up until this time had not incorporated any latching of field limit switches and a re-design of the Y- down travel limit switch, incorporating a back plate to reinforce its position and prevented it from being moved by the boom on a fast downwards transition, as shown in Figure 5.7.

Back-plate for Y-  
limit switch



Magnetic Reid switch for Y- travel  
limit switch position

Figure 5.7. Rear support bracket for Y axis down travel limit switch.

## 5.5 Drive control interface circuit board

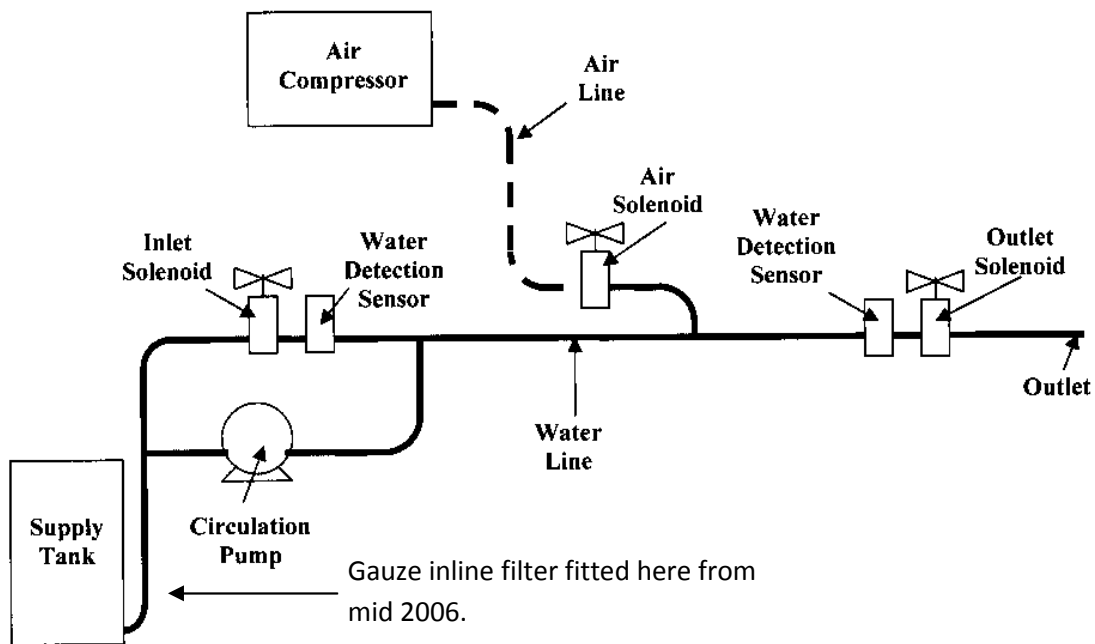
In 2004 it was decided to progress with a further upgrade for the drive motor control and interface circuit using the Intersil HIP4081A<sup>[69]</sup>, to drive a final H bridge MOSFET stage. The circuit was developed and rigorously tested on the laboratory test bench using a mains power supply with dummy loads. It operated correctly. When installed in the SET after the first move, the back emf from the DC motor caused a failure of one of the MOSFET stages in the H-bridge. Diodes to prevent back emf were then installed and the MOSFETS replaced. The circuit was trialed again on the test bench and worked, but when installed in the SET again, resulted in failure of the driving MOSFET stage and the HIP4081 IC. Further investigation revealed under certain conditions it was possible for the switching speed on the HIP4081 IC to be too fast for the outputs. This caused failure of the MOSFET stage as this was not sufficiently fast to cope with the sudden and frequent direction changes which caused the previously 'on' output MOSFET to pull down the output drive stage on the HIP4081 IC and latch the previously 'on' and the 'new on' stages on together. Further investigation showed that this was a problem that other users had also experienced and was an acknowledged short coming of the IC. At this point another type of faster MOSFET was envisaged, however the decision was made to use relays as the final power switching and drive stage instead. This has worked reliably and there have been no further failures.

The relays are interlocked electrically so that the PLC can control them or they can be manually actuated. An operator may press the direction pushbutton in the revised control panel and this manually locks out the other relay pair from operation (i.e. if the Y plus relay is activated manually by an operator and the PLC activates the Y down output or another operator depresses the Y- pushbutton for some reason, the first push-button locks out the other relay circuit from operation).

## 5.6 Circulation pump (CP)

A water flow diagram for the flow of coolant water is shown in Figure 5.8. Critical to the correct and safe functioning of the SET is the flow of cooling water through the target. The circulation pump method chosen originally was to minimise head losses and to make the movement of water as

efficient as possible for as little effort as was achievable. In 1997 there were few available pump options for 12 V DC, however after investigating impellor types and finding these not to be very efficient, as regards energy transfer, the inventors settled on using a peristaltic pump driven by a DC motor. Further mechanical details of the peristaltic pump are given in Chapter 4.2 of this report.



Note: The above plumbing configuration is as the system was first installed and operated at CPIT up to 2007. From 2007 the inlet solenoid and gauze line filter were before the CP and 'Tee' section.

Figure 5.8. Water flow diagram for SET.

The CP DC motor is 12 V DC and has the ability to be speed controlled. This feature has been retained throughout the SET's re-development. The DC motor selected is a heavy duty DC motor available from RS Components, catalogue number #320-590. It rotates at 100 rpm. The motor comes complete with an offset inline gearbox and 1.2 Nm of final drive output torque. Figure 5.9 shows the circulation pump complete with its mounting frame, and controller as it first arrived at CPIT.



Figure 5.9. The original circulation pump.

In the inventor's installation the CP was connected to a hot water cylinder and an intermediary tank and was run in a closed loop arrangement. However, for the CPIT installation this was not possible. For the CPIT installation mains pressure water was taken into a low pressure intermediary tank, with a 'ballcock' float level controller. The low pressure tank measures 400 mm square and has the float level set at 630 mm and is shown in Figure 5.10 a and b. This feeds a 25 mm clear soft plastic pipe which supplies water to the header of the CP. This header has a ½" bypass pipe with a NC solenoid fitted, which until 2007 was the original configuration. The solenoid valve was meant as part of the frost blowdown protection system.



Figure 5.10 a & b. The low pressure holding tank.

The geared DC motor is coupled to an adaptor frame which is a 25 mm thick block of aluminium. The peristaltic pump head is mounted onto two 100 mm aluminium disks which are held apart by 4 25mm rollers, as shown in Figures 5.11, 5.12, 5.13 and 5.14. Underneath these rollers are five 6 mm ID peristaltic pipes. The rolling motion being created by the DC motor is transmitted to the gearbox and coupled into the peristaltic pump head. The outlet of the tubes is a common receiver head from which the following were connected: a pressure gauge (added early in 2007), flow measuring devices, pressure measuring sensor, bypass bleed pipe and the 25 mm outlet pipe which supplies water to the target.



Figure 5.11. The CP controller upgrade in progress.



Figure 5.12. CP mounting assembly for peristaltic pump.



Figure 5.13. Peristaltic pump roller assembly and bypass pipework in background.

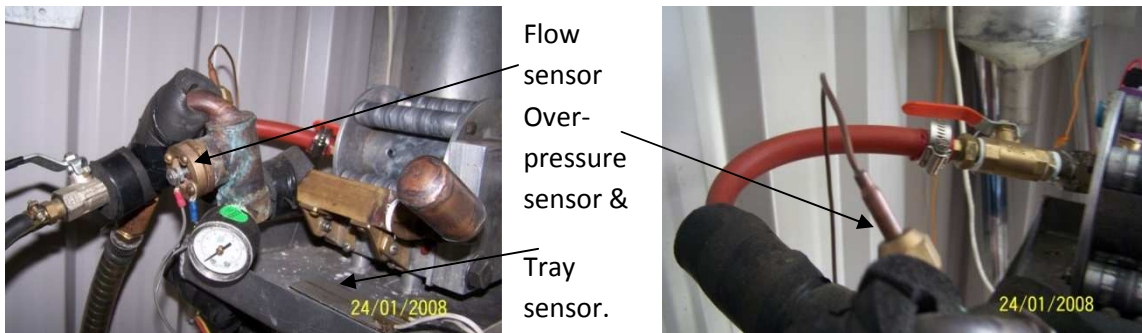


Figure 5.14 a & b. Over- pressure, no flow in the outlet header, tray full sensors and bypass for CP.

The CP control panel contained electronics to sense the flow of water through the head, and signal a 'no flow' shut down to the analogue controller, as shown in Figures 5.14 a and 5.16 for the flow sub-circuit interface board. Also, fitted was an over-pressure switch, as shown in Figure 5.14 a and b, such that if the pressure in the head of the CP became too great it would signal the analogue controller to shut down. There was a tray mounted underneath the CP to capture any leaks from the peristaltic pump pipes or associated connections. This tray contains a 'tray full' conductivity sensor which if covered by water will signal the analogue controller to shut down, as shown in Figures 5.14 a and 5.17.

In 2004, after limited success at interfacing with the CP controller, it was decided to replace the CP controller and upgrade the CP control interface to match the new PLC control system. The seven core cable connecting the main control cabinet and the CP control cable was retained.

During this time, it was realised that the flow rate through the CP was insufficient with the CP in operation. This was addressed by increasing the size of the pipes both to and from the target, which had only a nominal effect (it increased the flow rate by about 0.8 l/m), and lifting the low pressure tank by 4 m to a mezzanine platform above the shed roof. This provided sufficient head for the CP and the flow rate was now 4 to 4.2 l/m reliably, all the time.

As part of the upgrade, the flow sensors located in the CP header and in the target were found rusted beyond the point of recovery, as shown in Figure 5.15 a. These were replaced in the target and the CP header with banana sockets which sense flow by electrical conduction. However, in both cases the accompanying circuitry proved to be too unreliable and unable to differentiate between water flow and air. These sensors were subsequently discarded when the additional flow sensor inline had been fully commissioned, as shown in Figure 5.15 b. With the ever present danger of damaging the target, an additional flow switch was critical to the safe operation of the SET in its re-commissioned state. The Crydom<sup>[70]</sup> flow switch used is from RS Components, catalogue number #257-082 and is rated at a flow rate of 3.5 l/m. It is temperature rated (up to 85 ° C) for this environment, has 22mm adaptor fittings, is installed horizontally, and operates by a float rising up on a stem containing a magnetic Reed switch. This magnetic flow switch has operated well and has reliably shut down the SET under low or no flow conditions. It has only been inspected once in 2007 as part of overall system checks and SET maintenance.



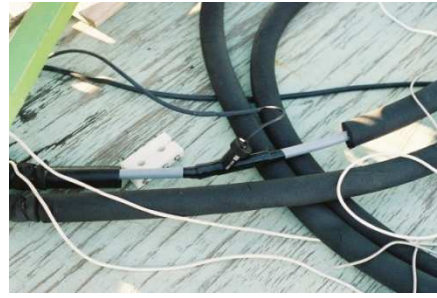


Figure 5.15 a & b. a) The rusted flow sensor from the CP outlet header, b) the inline magnetic float replacement.



Figure 5.16. Flow and Over pressure circuitry for CP.



Figure 5.17 a & b. a) Tray full circuitry, b) Manual reset pushbutton and resistor adjustment.

The completed upgraded controller from 2004 is shown in Figure 5.18 and shows the inlet pipe from the low pressure tank entering the right side of the CP header without any inline gauze filter. A NC (Normally Closed) solenoid valve can just be seen in the rear of the picture.

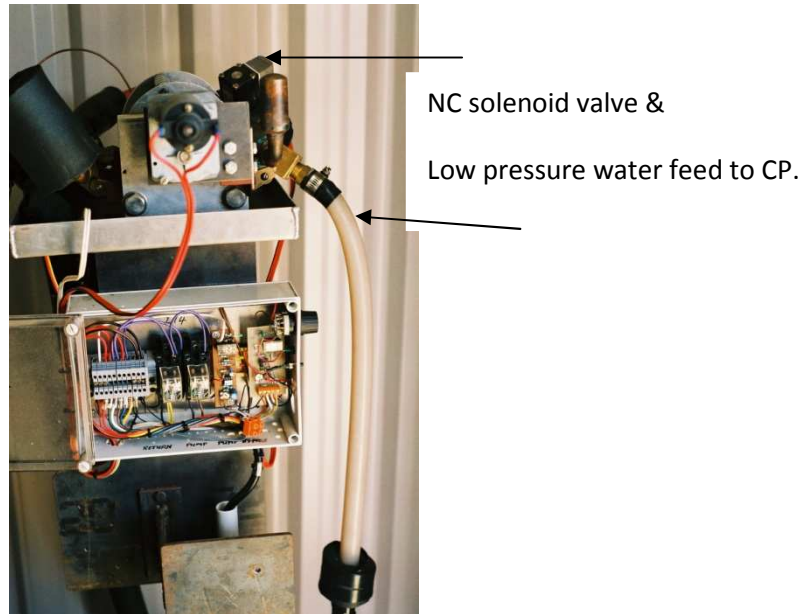


Figure 5.18. The completed CP controller panel with no input water filter.

The final version of the CP control panel after testing is shown in Figure 5.19. The only electrical additions between 2004 and 2007, were an engine run indicator as shown in Figure 5.20, a CP manual override switch to allow test running of the CP following any overhauls, or in the event of manual frost prevention or maintenance, as shown in Figure 5.21, an inline solenoid valve to control water as shown in Figure 5.23, and the addition of a SCADA monitoring point which records pump runtime directly into a PC. Figure 5.22 shows the CP inlet layout prior to 2007.



Figure 5.19. The 2008 CP controller version.



Figure 5.20. The CP engine runtime indicator.



Figure 5.21. CP manual override bypass switch.



Figure 5.22. CP and inline filter with solenoid on bypass loop (up to 2007).



Figure 5.23. Inline filter and solenoid switch (from 2007).

The SET, with a 4 m head from the re-positioned low pressure tank, would always have a flow of water at a rate of 2 to 2.2 l/m continuously, whether the CP was enabled or not. For this additional reason it was thought frost protection was un-necessary. The only addition between 2004 and 2006 was an inline gauze filter to prevent the build-up of algae, and solids from progressing into the CP header and blocking the flow of water, as had happened every two months during 2005 and the early part of 2006. When the system blocked under these conditions, it was a simple matter of cleaning the filter rather than having to disassemble the CP and peristaltic units. The algae were building up on the inside of the opaque pipe-work exposed to the UV light. In early 2006, this section of exposed pipe-work was covered and the maintenance requirement on the inline filter has reduced to a six monthly check.

In 2007 an approach was made to try and reduce the water usage. To this extent the plumbing was changed. The plumbing system to 2007 comprised the inlet pipe feeding an inline gauze filter before splitting into a ½" bypass pipe with a NC solenoid valve and the other branch feeding the CP header as shown in Figure 5.22. The NC solenoid valve was for frost protection and used in conjunction with the air purge system. The revised system was now the inlet pipe through an inline gauze filter to a NC solenoid valve (CPS), which then branched to a ½" bypass pipe with manual isolator valve and the other branch feeding the CP header and is as shown in Figure 5.23. The solenoid valve was then connected to the CP and the engine run hour's indicator. More will be commented on this in the PLC section, Chapter 7.0.

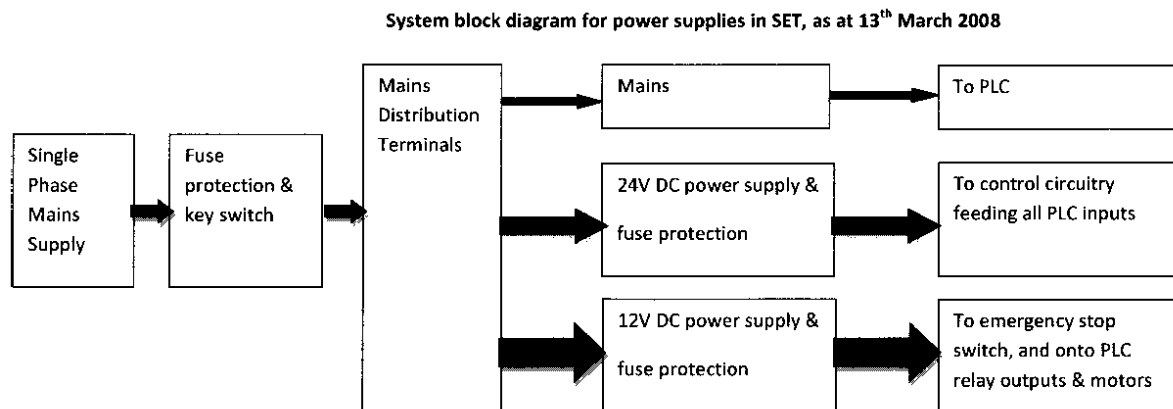
As a consequence of the above changes, this necessitated a change in the PLC code. No longer was water flowing through the CP on a continuous basis, water now had to be turned on based on either a rise in target temperature or a fall in target temperature due to frost. The PLC code was amended, turning the CP and CPS on at the same time, based on either a temperature rise in the target which exceeded the ambient conditions by 5 °C, or based on ambient air temperature falling below 0 °C (later amended to 1 °C).

Once all these changes were performed, the SET was returned to automatic tracking mode. Whereas before the performance of the target temperature graph was smooth, now temperature spikes occurred, as would be expected due to the time lag in the system and length of pipes used. This was substantially overcome by amending the PLC code further such that the differential between the ambient and the target temperature was reduced, as was the proving time, at the same lengthening the delay time to turn off the CPS and CP. This lessened the amplitude and the frequency of the spikes and was done to try to prevent the target from becoming too hot quickly, on exposure to direct sunlight, and then cooling as the sun went behind a cloud but in the meantime turning the CPS and CP on. Various configurations of flow were also trialled at this time. The first flow trial used the CPS only in conjunction with the manual bypass valve. The flow rate was 3.5 to 3.8 l/m depending on boom position. This was somewhat unreliable and more usually the inline safety flow switch would trip out under low flow alarm. The next step used only the CP with the bypass isolated, was well proven with a reliable flow rate of 3.8 to 4 l/m. Finally, the combination of CPS and CP with manual bypass valve open, gave a flow rate of 4 to 4.2 l/m reliably under all operating conditions. With both the CP and CPS in operation no matter what position the boom was in, the safety inline flow sensor would always sense the correct flow of water before the safety function timer in the PLC timed out.

## **5.7 Power supplies and panel loading**

The SET was converted from battery supply to a mains power derived 12 V DC and 24 V DC supply. A number of other changes were made to the SET control and interlock system at this time. It was decided, to change the form of control from an analogue control system to a digital means of control and so an Omron CPM2A PLC was selected. This model of PLC controller comes with forty I/O (Inputs/Outputs), comprising 24 inputs and 16 outputs. To allow the analogue temperatures to be measured, a MAD01 unit was also purchased which has two universal analogue inputs and one universal analogue output. For further flexibility and teaching purposes in the future, a DeviceNet module was also purchased for later interfacing with other CPIT DeviceNet equipment. This would

be configured for monitoring only rights, i.e. no changes would be able to be made to the PLC programme or to any I/O status bit.



Note: The size of the arrow is proportional to the current flowing in that path.

Figure 5.24. System block diagram.

The input switching level for this model of PLC is 20 to 21 V DC. A 24 V DC power supply was purchased for all the control wiring and input wiring to the PLC. This included the start, stop, emergency stop, reset and key switch isolator PLC inputs. The outputs on this model of PLC were of the clean contact relay type. A 12 V DC power supply was used to power all the existing 12 V DC motors, compressor, motor drive axes and circulation pump. Figure 5.24 show the system block diagram.

The motors consume 0.8 to 1.2 A at 12 V DC depending on loading. With the redesigned control panel it is possible to trip out the power supply when two drive motors come on together and with the CP and CPS operating at the same time, this is still possible if for example the PLC issues the track up command and an operator manually starts the track left or right push-buttons. Under trip conditions, removal of the power to the 12 V DC power supply for 5 seconds will normally clear the fault.

The rating on the 12 V DC power supply is 5 A. When this power supply was initially installed, a number of failures were recorded and a number of fuses were blown. The power supply came with

on-board 3A fuses which were progressively upgraded after reading the manufacturer's data sheets to a 5 A slow blow fuse. Finally, the remaining issues surrounding the use of the 12 V DC power supply were resolved with the relays being interlocked to prevent simultaneous operation of motors in both axes. There are two status lamps on the left-hand side of the new control panel, one for fault (red) and one for 'system normal' (green). It is however very difficult to observe the lamps status in direct light, as shown in Figure 5.25.



Figure 5.25. Control panel with pushbuttons and status indicators on the left-hand side of the revised control cabinet.

The 24 V DC power supply also suffered during commissioning and it likewise blew fuses and occasionally needed resetting, however this fault was traced to a wiring error and remedied.

The 12 and 24 V DC power supplies were sourced from Condor<sup>[71]</sup> and come complete with fused outputs to protect the switch mode power supply electronics.

The 230 V AC mains in the cabinet is fused and reserved for the power supplies and the PLC, as shown in Figure 5.26. The key switch now isolates the entire cabinet and the latching twist release emergency stop, isolates the 12 V DC supply to the outputs on the PLC.

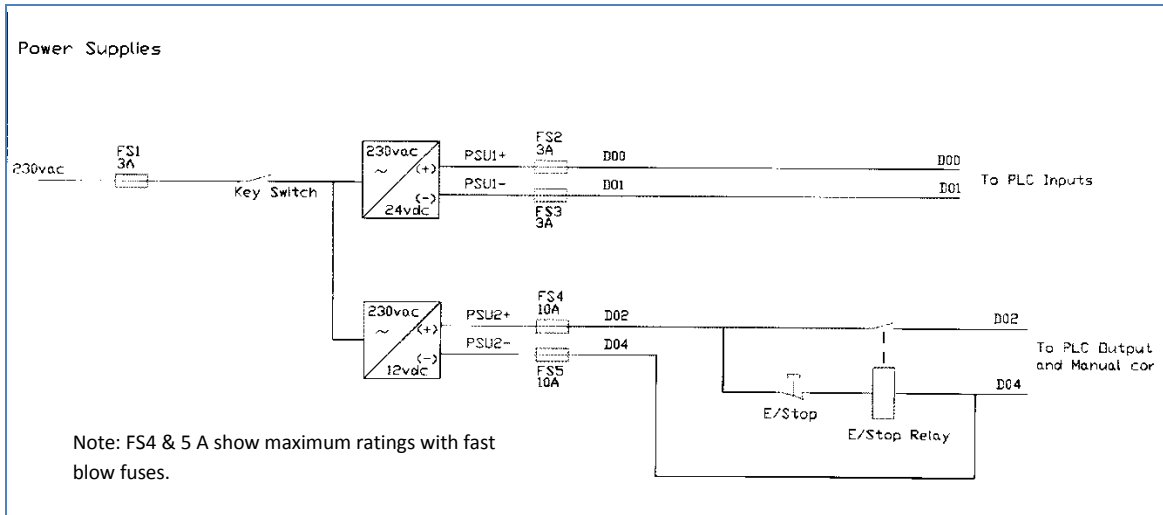


Figure 5.26. Mains power supply and distribution for control panel.

The layout of the electrical services to the remainder of the controls cabinet is shown in Figure 5.27.

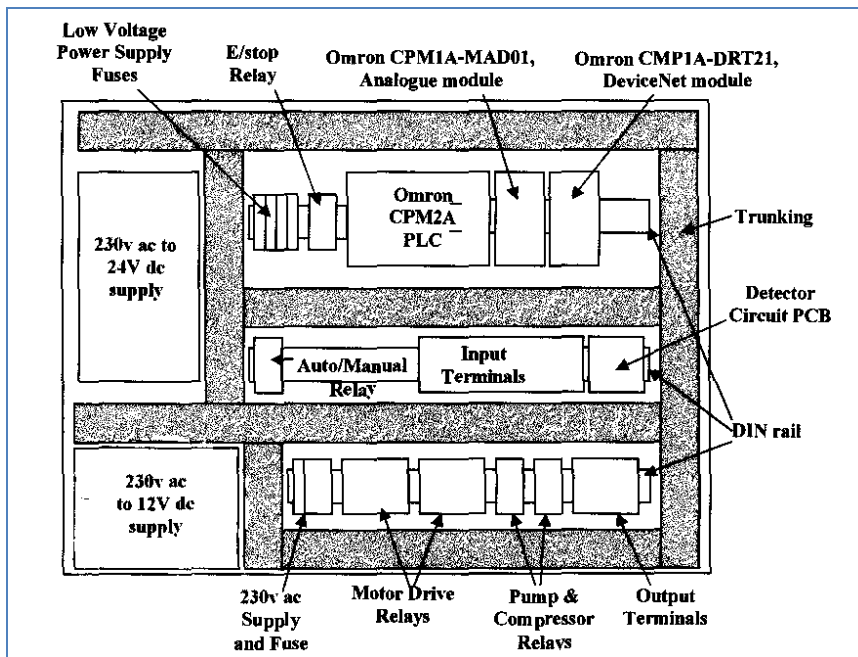


Figure 5.27. Control cabinet back gear plate layout.

Figure 5.28 shows the cabinet as built and tested in July 2005.





Figure 5.28. The control cabinet July 2005.

During testing in 2005 when the SET was allowed to operate by itself, it quickly became apparent the only indication as to the status of the SET was by visual inspection. As this was not easily possible except via an open door onto the roof area, a remote display unit was designed. Affectionately nicknamed 'the Smiley face' by students and staff 'the Smiley face' became a quick visual method for key staff and interested students to know the state of the SET. Initially designed as a pair of flashing red lights, a central green light and two amber lights at the bottom, 'the Smiley face' is shown in Figure 5.29.



Figure 5.29. 'The Smiley face'.

When connected at first 'the Smiley face' caused one of the outputs on the PLC to latch on as the grounding was not correct for the lamps. Once this was fixed, the remote monitor panel has operated flawlessly and further use has been made of 'the Smiley faces' ability to show additional

status information. In 2006 the red flashing sub-circuit of 'the Smiley face' was disconnected as this was being controlled already by the PLC. Several lighting combinations were programmed into the PLC, to alert to various critical or status events occurring on or with the SET PLC. Appendix 2 shows the information sheet as provided for 'the Smiley face' on the hallway wall and in the outside shed. Inside the control cabinet proper are several switch selectors, for auto/manual (in automatic mode the PLC takes full control and in manual mode the operator controls the SET), compressor switch, circulation pump auto or manual, and four motor drive pushbuttons to over-ride the SET position, these being X+, X-, Y+, and Y-.

## **5.8 Electrical control cabinet additions**

In 2005, an addition was made to the cabinet to allow the monitoring of the auto/manual switch. Also, the CP had been hardwired and so had no off facility. This required an extra relay to be fitted next to the auto/manual relay. This allowed the CP to be manually controlled, and meant the overall safety of the control panel and motors was no longer compromised. The operator had the ability to isolate and control motors manually as well as the PLC system having full automatic control. In 2006, following IR photo-diode problems, a UPS (Uninterruptible Power Supply) was fitted to the mains power supply of the SET. This had the facility for an output signal which was fed through a spare core in the CP supply cable to an additional relay and PLC input. This was likewise located next to the auto/manual relay. This alerted the SET to a mains power failure and allowed it sufficient time to move off axis before the UPS shut down. This system is another safety feature designed into the PLC and SET to prevent damage from occurring to the SET and target. Under conditions of mains power failure and shut down, the SET must be manually restarted.

Additional travel and park limit switches were required for NW and SE park positions, making a total of four limit switches fitted to the SET. Figure 5.30 shows the completed control cabinet in operation in December 2006. There was one more minor addition after this which was to couple the analogue output of the PLC MAD unit to the SCADA system to allow comparison of the target temperature

with the temperature monitored by the SCADA system from the exhaust or hot pipe exiting the target.



Figure 5.30. The control panel complete and in operation December 2006.

## **6.0 Daylight & auto-tracking controls**

### **6.1 Daylight controls**

#### **6.1.1 A brief history**

To prevent the use of the SET outside sunshine hours, the original inventors proposed three primary solutions, which are also mentioned briefly in the auto-tracking section (Chapter 6.2) of this thesis, as the final solution was interlocked with the development of a new auto-tracking sensor assembly.

The original solution was to use Light Dependent Resistor's (LDR's) for auto-tracking and sensing whenever there was sufficient light to allow the SET to track brightness. The second attempt used a time clock which was discarded, as the SET would track or move when nothing was present in the sky, wasting energy. The third attempt was a combination of the LDR and time clock which was later extended to include the PV panel. The idea was to use the time clock to adjust or 'kick' the SET when there was insufficient solar radiation, and use the PV panel's rising voltage to trigger, at a certain voltage threshold, the SET's auto-tracking sensor to 'take-over' tracking. The exact function of the LDR in this arrangement was not clear, but it is suspected that this may have acted and functioned more as an initiation of the park mode for the SET at sunset and sunrise, with the time-clock only being used during daylight hours, but there are no notes to detail this, nor indicate whether this had been tested on the original SET.

The fourth attempt was to use IR photo-diodes as part of the auto-tracking circuit in conjunction with a daylight switch. The daylight switch was an LDR coupled with a small op-amp circuit operating in a comparator mode using a fixed reference source, which then initiated and switched a pair of relay contacts, signalling the SET to commence operations and auto-tracking. This was the final configuration and iteration from the original inventors and was the configuration delivered to CPIT in 2003.

### 6.1.2 Current research & developments

Initial testing of the IR photo-diodes and the daylight switch at CPIT, showed the system did work and was worthy of further testing and evaluation. In early testing, the LDR had an intermittent fault and so was replaced. The LDR was positioned on the front of the SET in the PV panel slot above mirror B1 and to one side as shown in Figure 6.1. In this location it not only received full sunlight, but all the weather when the SET was parked in a NW park position (which was the park position at this time). In this position, the replacement LDR failed after a very short duration due to water ingress.

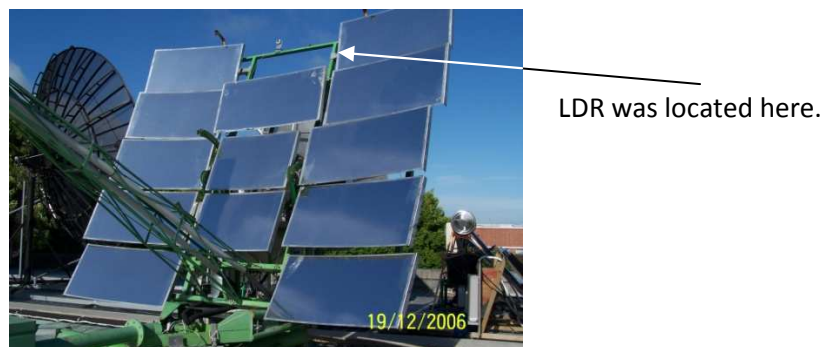


Figure 6.1. LDR position on SET.

Another LDR was trialled, with the LDR being surrounded in RTV Silastic sealant, and heatshrink protected soldered leads and lots of insulation tape surrounding all vulnerable parts and wires. However, after only a few months, this second LDR had failed as well. A more permanent fix was required. It was resolved to change the light sensor to an IR photo-diode as per the auto-tracking circuitry. Chapter 6.2 gives the details on the aspects surrounding the use of this circuit and testing.

With the IR photo-diode sensor and circuitry functioning as a light level sensor, an on/off signal is sent to the PLC. This circuit is shown in Figure 6.2. The circuit operates on the basis of an op-amp comparator circuit with a voltage reference signal which is adjustable by a trim-pot.

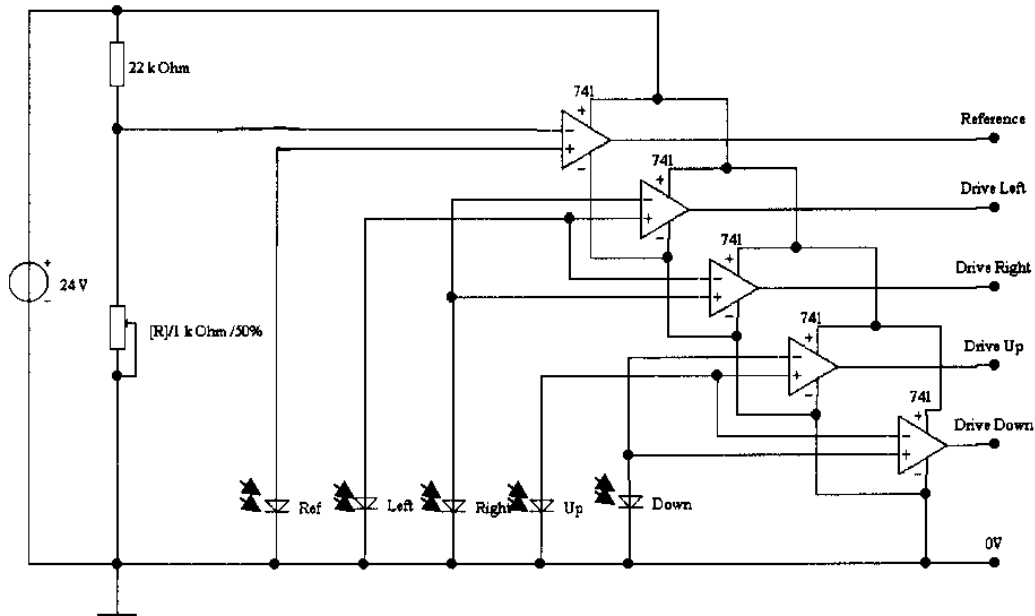


Figure 6.2. Light sensing and auto-tracking circuit first iteration.

The PLC receives the 'sufficient light' signal into the light level subroutine section of the PLC programme. If the light level is above the threshold set by the fixed reference, the light level circuit outputs a signal to the PLC. The 'light okay' signal, when received by the PLC, is proven by a delay timer which ensures the light level is sufficient or adequate and of sufficiently prolonged period for the SET to follow. The length of this delay timer has been iterated to three minutes. Likewise an 'insufficient light' signal has a delay timer, which was finally set to a value of six minutes.

It was found that additional timers were required for status indication and CP control, relating to low light after six minutes, and the ability to hold the SET in a position in low light rather than allow it to return to its park position and later find it has to perform a larger track or move to achieve its new position for maximum solar radiation. This 'extended low light' scenario is governed by a real-time clock and delay timer which can be reset at any point based on increasing solar radiation levels.

In testing it was found necessary to have both the low light and the extended low light functions from the point of view of the remote status indicator ('the Smiley face'), but, and more importantly, from the point of view of shutting down the CP under conditions of low light and to reduce the time

to track when the sun reappears. This increases the overall efficiency of the SET allowing it to come on-stream faster, and it reduces the maintenance aspects on the drive motors and the CP motor.

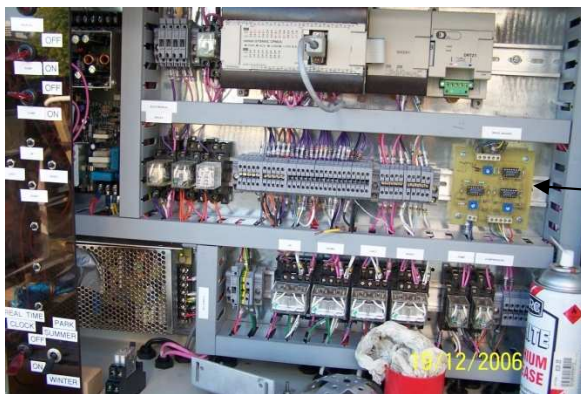
If after midday there is still insufficient light then the SET clears the X+ position limit (in case this has not been cleared due to the SET having not moved for the morning). This will then cause the SET Y axis to boom down, followed by activating the X axis drive motor to re-position the SET into the SE park position. This will cause a slow flash to occur on the amber lights on the 'the Smiley face'.

As a further modification to this, if the SET is either in the park position after midday or hasn't moved from any position in the morning due to low light and the sun appears in the afternoon, then provided it is after 1400 and the SET is on the X+ limit switch and the auto-tracking sensor, circuitry and controls are trying to move the SET further to the right than is allowed by the limit switch, the PLC will initiate a 'left kick' after a short proving time.

In this 'left kick' mode, the X motor is driven such that the SET moves to the left (i.e. in a counter clockwise direction) for a pre-determined period of time and is designed to take the SET out of being locked into the 'going further right' mode. This situation arises when the sun comes out in the late afternoon and the SET will try to take the shortest possible route to track the sun. In many cases the SET would boom up first and depending on the sun's position, would either receive an auto-tracking signal to track left and then move left, or in some circumstances it would receive an auto-tracking signal to try to track right, whilst already on its X+ limit switch and being interlocked and unable to move based on the X+ limit switch being satisfied. In this case the SET was observed to be booming all the time, i.e. the boom would transition up and then down again in a vain attempt to find the maximum solar radiation, whilst not moving in the X axis due to the X+ home limit switch interlock. With the timer value in the PLC, it is sufficient time for the X axis drive motor to reposition the SET from the X+ home limit switch to being slightly left of due north or the mid-point of the SET X axis travel arc.

This situation, where the SET became 'stuck' and 'boomed' was first observed in October 2006. A 'left kick' addition was made to the PLC code. This was subsequently tested and PLC timers fine tuned. Whilst, the situation only occurs occasionally, the solution further increases the SET's ability to maximise the use of all available solar radiation.

Overall this system has worked exceptionally well, with the light level trim-pot (RV1 in Figure 6.2) requiring only minor adjustment. The switching threshold level on the trim-pot of the light level circuit is currently set at 350 lux, which seems adequate and able to cope with most conditions encountered during testing. A higher lux level has been trialled, however this meant the SET was not able to react fast enough to changing light levels and would prematurely shut down due to low light. As a test, a lower lux level was also tried (200 lux). At this value, the SET became too sensitive to cloud and light conditions and would track continually for no extra gain or rise in target temperature, as observed on the SCADA recorder system. The value of 350 lux appears to be a suitable compromise. Figure 6.3 shows the final location of the light sensor circuitry which is now part of the light sensor and auto-tracking circuit board in the new control panel.



The light sensor circuit board is part of the auto-tracking control circuitry.

Figure 6.3. Location of light sensor circuit board on the control panel.

### 6.1.3 Outstanding issues and recommendations

Under 'white-out' conditions it is possible for the light-level circuit to trigger, (i.e. the light level is above the required setting) which may cause the SET to appear to behave erratically and perform sudden movements. However, this could be easily remedied. One of the recommendations for the



future deployment and development of the SET would be to use a day/night switch or an LDR mounted to the underneath of the control panel and in addition to the light sensing IR photo-diode. This not only offers weather protection but has the added benefit of providing the SET with the ability to ignore these 'white-out' events and conditions which occur from time to time.

## **6.2 Auto tracking**

This section discusses the development of the auto-tracking system for the SET, detailing the auto-tracking sensor and interface circuitry through to the performance testing of the completed sensor and circuit on the SET.

### **6.2.1 A brief history**

The original SET used four LDRs which were configured in a bridge to allow easy sensing and determination of tracking direction. Each of these four LDRs was mounted in a quarter circle frame and trialled both with various shapes of top hat or top covers. The intent of this setup was to ensure that each of these LDRs and their respective quarter segments received the correct amount of solar radiation, as each was shaded to the same extent or amount. Although this arrangement worked reasonably well when fed through an op-amp bridge circuit; it proved unreliable and the solar tracker chased the clouds.

The inventors' second attempt was made using a time clock, but once again this failed and was discarded. A third attempt was made using IR (infrared) photo-diodes. The exact reasoning and logic behind this choice has been lost as there are no records of this decision, nor any design details.

The understanding gained from various discussions with the inventors was that they decided to use three IR photo-diodes in series to allow them to follow the sunlight and solar radiation under a wider range of weather conditions, including cloudy conditions. The original configuration of IR photo-diodes was three in series on each of the four axes, thus giving X+, X-, Y+, and Y- signals. These three IR photo-diodes were then mounted onto a metal plate and into a metal frame with a central M5 mounting screw and bolt arrangement. For mounting, the metal plate with the IR photo-diodes in

them was then inserted over the M5 screw and onto the target. The mounting plate has four edges which are pushed back at an angle of 45 degrees from the horizontal flat front surface. Hence the IR photo-diodes are mounted on petals, which instead of facing the sun, face the SET control panel, a reverse of the 'flowers' in nature.

There are two possible modes of operation of an IR photo-diode, forward bias mode and reverse bias mode. In forward bias mode the IR photo-diodes produce a voltage and in reverse bias mode they allow a leakage current to flow. Either output can be coupled to an op-amp circuit. From the documentation obtained and the circuitry associated with the original auto-tracking module, it appears that the original IR photo-diodes were connected in reverse bias mode.

The IR photo-diodes appeared to have been matched in their characteristics for each of the four axes. Using natural light and a voltmeter, various attempts were made to characterise the IR photo-diodes and to subsequently try and match them, however, with the ever changing solar radiation this task proved to be too difficult to achieve reliably. However, for the task at hand, namely to prove the concept and to prove whether the SET would actually track or not, this simple test proved satisfactory. The SET managed to track, if only erratically and unreliably. Three mirrors were then mounted on the SET (A3, B2 and C3) and a temperature rise of 0.5 to 1 °C was observed in the water coming from the target. The SET proved to be so unreliable at this point and would repeatedly stop without notice; it proved easier to track the sun manually.

The interface cables between the SET control panel and auto-tracking interface were a nine pin EIA232 plug and a special eleven pin adaptor plug. This cable interface and the cable termination points onto the 'Krone' blocks proved to be one of its weakest points, as any movement of the cables would cause the cables to lose contact on the 'Krone' termination blocks, but it did allow the auto-tracking module to be easily removed for servicing and repair, which was a frequent occurrence. Unfortunately, in the process of removing and replacing the auto-tracking module, all the associated control wiring on the nearby 'Krone' termination panel was also disturbed and this

further exacerbated the SET's reliability problems. However, the concept was proven and the SET was therefore worthy of further investigation, research, and development, by CPIT.

The original inventors did however revisit the time-clock concept. The thought was to use the time-clock in conjunction with the PV panel and the auto-tracking module. The idea was that when the PV panel is producing electricity and charging the 12V DC battery, that this would activate the IR photo-diodes and engage the auto-tracking mode. However, in low light the PV panel's output would reduce, the auto-tracking and IR photo-diodes would disengage at a predetermined PV voltage threshold and then the time-clock would engage and 'kick' the X and Y axes drive motors at a predetermined time (no records have been found on the value of this time, but it was probably six minutes, this being the period for the sun's arc in the southern hemisphere and the South Island of New Zealand).

It is not sure whether this was actually trialled, as no records or documentation can be found detailing any results, etc. With the X and Y axis motors not having any encoder feedback, but using limit switches instead, the reliance on pulsing of these drive motors may cause the position of the SET to exceed its limit switches unless properly interlocked. This may have caused unnecessary movement and operation of the SET boom (Y axis), and would not have allowed the correct shut-down under low light or alarm conditions.

It is thought, based on conversations with the inventors, that this may have been tried, but its shortcomings realised and the concept abandoned, as the next entry in the operations manual is that the photo-diodes were being used in conjunction with a low light level circuit which, when initiated, parked the SET. About this time mention has been made of the SET successfully tracking the heat trail of the exhaust of a passing Boeing 737-200 aircraft on its final approach to Queenstown airport. This resulted in one of the inventors, in whose backyard the SET was located, receiving a visit from the Civil Aviation Authority (CAA), enquiring about 'a device that appeared to track' an Air New Zealand Boeing aircraft. Apparently the Air New Zealand pilot had raised a concern

about this device which looked like a missile launcher and followed 'his' aircraft. At this time the SET auto-tracking circuit was set-up to find the maximum source of infra-red radiation and it wasn't able to distinguish between a passing aircraft's IR or heat radiation and the sun's solar IR radiation.

Following that visit, the sensitivity on the auto-tracking circuit was reduced and no more incidents were recorded. However, on a dull overcast day, when conditions are marginal for tracking anything, if an aircraft does happen to pass overhead, the SET will still be able to see the 'hot' exhaust of the passing aircraft and will try to track it. When this did happen at CPIT, fortunately there were no complaints from the pilots or visits from the CAA. However there have been several low flying small aircraft and helicopters which have observed the SET in operation.

### **6.2.2 Auto-tracking sensor and circuit developments**

A control system, as defined by De Stefano III, et al<sup>[90]</sup> is an automatic system whereby its major function is to dynamically or actively command, direct or regulate plant. An example is then cited of an adjustable mirror angle using an adjustable screw (Figure 1-2 in De Stefano, page 1). In control systems terminology a classical negative feedback control system is shown and detailed in Figure 2-1, page 13 of De Stefano. In the case of the SET though, the negative feedback sensor is not tachometer or encoder or GPS or look-up table but the sun's position itself. The intent of the SET is to accurately sense the sun's position and to then instruct the control system the direction to track in to achieve the optimal level of solar radiation.

In 2004, attempts were made to refine the auto-tracking circuit and mechanism. Once again several different technologies were investigated, including LDRs, photo-transistors, and different types of photo-diodes. Each of these was tried in various forms and arrays with the resulting conclusion that IR photo-diodes were still the best option for this application. A top hat design using LDRs and later photo-diodes was tried, with the thought that the shadow cast by the top hat might assist in the tracking. This proved not to be the case, as on cloudy days the light levels could still be quite high, but no shadows would be cast over the sensors from which a signal could be obtained to allow for the SET to track.

One of the reasons for using IR photo-diodes was based on the fact that IR radiation makes up 49 % of the light transmitted from the sun. IR photo-diodes have proven themselves to be more sensitive than any of the other devices tried, and are more sensitive to a wider range of weather patterns than the other devices investigated.

The first attempt was made using IR photo-diodes in reverse bias mode due to the relative responsiveness of the devices in this mode and the ability to have more control over the output of the IR photo-diode by passing a current through a resistor. The value of the resistance was adjusted, to change the voltage drop across the resistor and to achieve an output voltage signal. This was fed into an operation amplifier comparator circuit which subsequently drove the drive motor in the appropriate direction, via the PLC.

Once again various mounting configurations were tried, including a top-hat and an array of four photo-diodes on each of the four quadrants or segments. The biggest problem was again the inconsistency of the sun as a source of calibration. A more consistent light source was required. A combination of 100 W incandescent and 20 W halogen light bulbs was used to overcome this problem.

The first type of IR photo-diodes used were mounted at 10 degree increments on a specially developed convex piece of metal, with four being used on each of the four quadrants, with a centre reference IR photo-diode being used to determine the light level. This set-up worked well on a fine day, with the SET aligned approximately in the right direction of the solar radiation. It was later found that this restriction was in part due to the 10 degree angular capabilities of the first choice of IR photo-diodes (Osram Opto Semiconductors<sup>[72]</sup> type SFH213FA). This type of photo-diode had a too narrow detection band, with an angular range of 20 degrees and a half angle of 10 degrees. In lower solar radiation levels this resulted in total failure, the light level circuit requiring repeated adjusting and trimming. This proved to be the case every day this circuit was used. Thus this configuration was considered to be too temperamental to be of any real use. Further attempts were made to adjust

the angles of the petals to try and overcome this issue and whilst this helped it did not alleviate these issues. It was later found that this model of photo-diode was at the end of its linear characteristics which made it too sensitive for this application.

Operationally, this meant that the SET was unable to determine which direction to move or track to, especially if the light levels became too low. The reason for this was because the IR photo-diodes were used in parallel and in this combined mode would pass a higher leakage current than if used as single reference photo-diode and connected in series. In this parallel mode of operation, one photo-diode was used as reference photo-diode for light level. This meant the circuit was able to lose its reference and was partly a fault of the circuit used at this point with the reference IR photo-diode determining the switching level for the tracking photo-diodes.

After further research, another model of IR photo-diode was found and procured. This had an angular range of 45 degrees, or a half angle of 22.5 degrees. This model was an Osram Opto Semiconductors type SFH203PFA<sup>[72]</sup> and was marginally more expensive than the earlier version. One IR photo-diode was mounted on the original target head with the reverse petal design and one IR photo-diode on each of the four quadrants, using the centre reference IR photo-diode for determining light level. The SFH203PFA photo-diode's characteristics make it less sensitive when compared to the SFH213 variant and this gives the photo-diode some apparent deadband when pointed directly at the sun, i.e. when pointed directly at the sun the IR photo-diode's output is constant for a longer time period when compared to the earlier SFH213 variant.

With reference to the SFH203 photo-diode's datasheet, it can be concluded that with a petal angle of 45 degrees, the half angle to the sun is 22.5 degrees which is still in the linear portion of the device's characteristics, as can be seen from Figure 6.4.

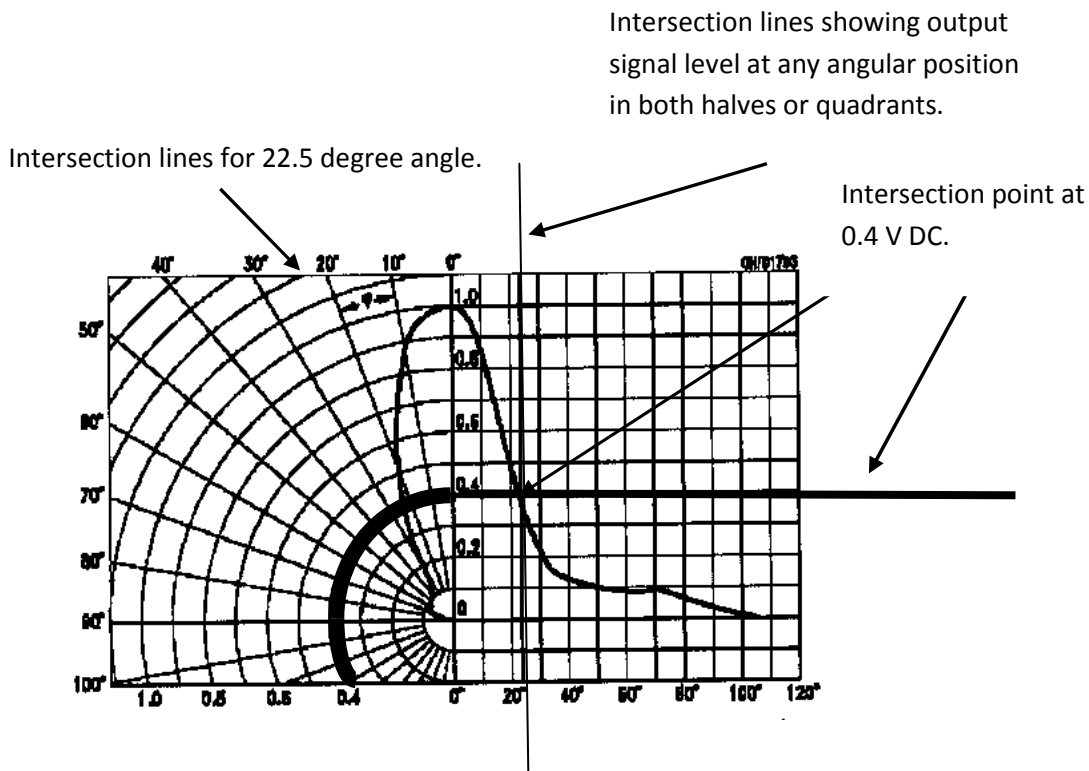


Figure 6.4. SFH203PFA photo-diode directional characteristics<sup>[1]</sup>.

The output of the photo-diode is about 40 % at a half angle of 22.5 degrees. At this point, the photo-diodes were still operating in reverse bias mode with a series resistor and interfaced with an op-amp comparator circuit with a calibrated voltage reference resistor.

The theory of operation of the circuit was such that the voltage drop across the resistor could be used for the control signal. The greater the angle the photo-diodes were away from the sunlight, the less leakage current flowed and consequently the smaller the voltage drop across the resistor, and vice versa. The comparator circuit used is shown in Figure 6.5. This circuit gives an output signal for Y+ (boom up), Y- (boom down), X+ (tracker left) and X- (tracker right). Only one axis is shown in Figure 6.5. All directions are given from the rear of the SET looking out towards the boom or sun.

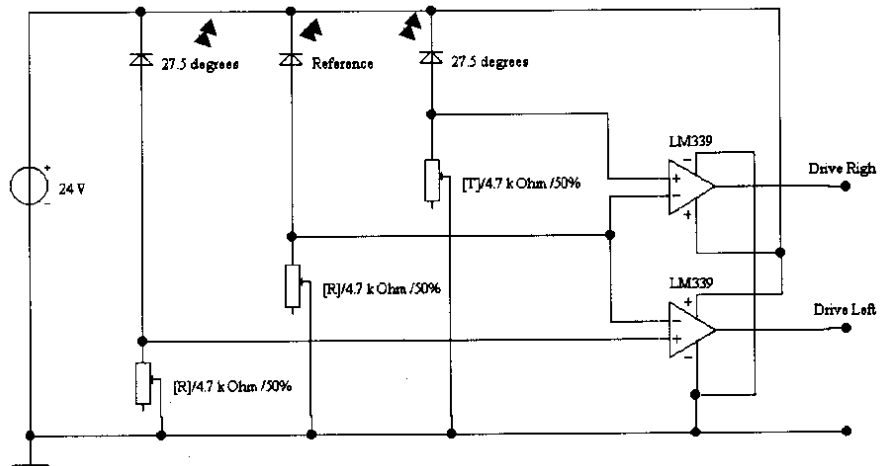


Figure 6.5. Photo-diode and comparator circuit for reverse bias mode, version 1.

These signals or direction commands were compared to the central reference level photo-diode (or light level IR photo-diode) to ascertain which direction the SET should move in. The reference level photo-diode was used at this time so if the light levels changed, the reference did as well; this was instead of having a fixed reference. At this point in the re-development process of the auto-tracking module, it was thought a fixed reference was not able to be used due to the changing characteristics of the photo-diodes. These characteristics changed quite dramatically with slight changes in weather conditions, for example cloudiness.

This revised auto-tracking system worked well on the test bench under constant light levels, from either the 100 W incandescent or the 20 W halogen bulbs. However, when this system was installed on the SET it was found the photo-diodes were very sensitive at some angles, i.e. they were on the edge of the characteristic curve for the photo-diodes and some were faulty. Adjustment of the petal angles on each of the four quadrants to the same angle reduced occurrence of the sudden and dramatic changes in photo-diode output levels but did not totally cure the problem. Subsequent testing showed that the angle of the petals was critical to changing the characteristics of the photo-diodes, thereby making them impossible to balance and to achieve stable direction control with. A



new petal head design was contemplated with less of an angle of incidence from the sun, however it was decided to try the photo-diodes in the forward bias mode.

When used in the forward bias mode it was discovered that an amplifier circuit was required.

Further testing revealed how stable the photo-diodes were when used in the forward bias mode.

Initially an adjustable amplifier circuit was built, developed and tested with the photo-diodes. The concept quickly proved to be a success. It was found that a gain of ten was sufficient to increase the signal output levels sufficiently be used by the following circuit and from these tests a full PCB (Printed Circuit Board) was developed for all the axes.

The 10:1 amplifier gave an output voltage of approximately 5 volts from each photo-diode which was stable. A 741 op-amp was used to compare the two signals, as the LM339 op-amp which had been used up to this point, and had been used by the original inventors, wasn't able to saturate fast enough unless there was 130 mV offset between the two signals.

In this circuit, the opposite direction photo-diode was used as the reference level for tracking in the other direction and for determining the sun's location. When tested, this circuit was able to track the sun but always appeared to be slightly out of alignment in its direction. This was fixed by adjusting the amplification factor on one of the photo-diode array signal amplifiers until both signals were balanced again. Different levels of hysteresis were tried with the circuit as it tended to hunt back and forth around the point of maximum solar radiation on a fine day. The feedback resistor on the amplifier was set to 470  $\Omega$  as this was found to provide the best results when used in conjunction with a short time delay (100 ms) added to the subroutine in the PLC which controls the motor drive and tracking of the SET. The larger this delay the less the SET hunted, but also the less response the SET had to the sun's change in position.

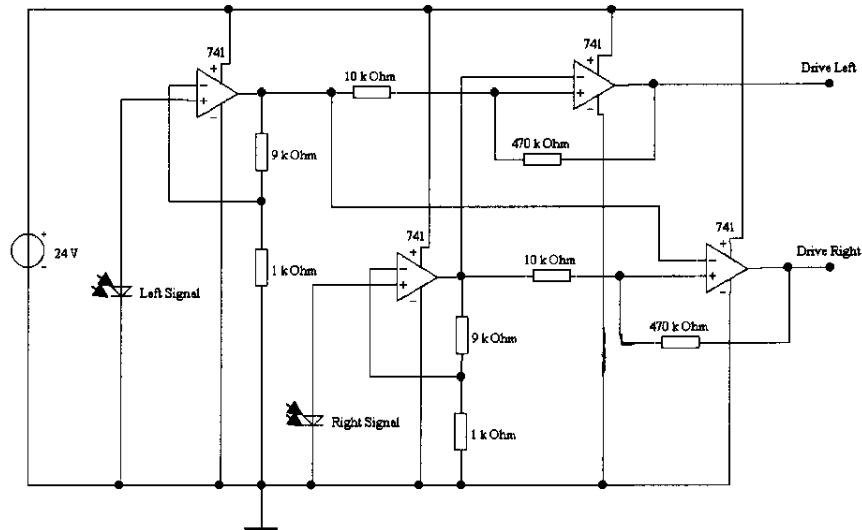


Figure 6.6. Amplifier and revised circuit.

Figure 6.6 shows the revised circuit as tested. Operationally, this circuit also proved unreliable in different light level conditions with any error in the photo-diodes or their characteristics also being amplified. In order to get the system to operate correctly the circuit required to be trimmed for the light level conditions on each day. This was clearly not feasible or practical. A further test was conducted, by disconnecting the amplifier and hysteresis and feeding the photo-diode signal as a raw signal into the PLC directly. This resulted in the PLC continually hunting no matter what time delay was used in the PLC between position updates. This setup was then quickly changed to prevent any damage from occurring to the SET.

Following this a decision was made to design a circuit which detected the position of the sun in the sky directly and to compare the boom up and down signals along with the SET left and right position signals, both being accomplished independently from the light level signal. This circuit operated correctly by pointing the IR photo-diode sensors at the sun without the SET hunting and with minimal time delay required in the PLC. The time delay in the PLC was also changed, from a PLC output direction control signal delay, to one having the requirement for the direction control signal to be on for a preset period of time (60 seconds on both axes, later decreased to 30 seconds for the

X axis and 50 seconds for the Y axis). With the 60 second time delay, the SET was able to successfully track the sun until the detector started to oscillate. The SET then stopped in that position until one of the direction control signals stayed on for the 60 second (or other pre-set) time as outlined above, which was caused by the sun moving and shining on one of the other photo-diode detectors. This caused the SET to track to this new position and follow the sun until the signal dropped out.

Of all the approximately twenty circuits and combinations tested, this circuit seemed to operate and perform the best with the SET in all weather conditions experienced in 2004. Subsequent testing in later years has resulted in only fine tuning of the light level activation and PLC direction signal timings. The only downside of this circuit is that in conditions of snow or 'white-out', the SET, if triggered by a high 'white' light level and receiving a signal to commence tracking operations, will try to hunt for the highest level of IR radiation. This may be overcome by changing the light level photo-diode detector to a day-night sensor, such as an LDR or similar. However in its present location, (Christchurch) it may snow twice in any one calendar year. For the intended final location (around the equator or lower latitudes than 43 degrees South) of the SET these conditions may not prevail at all. Under 'white-out' conditions, if the SET has been operational, it has been parked manually to prevent excessive wear and tear on the motors and motor drive mechanisms caused by continually hunting, and damage due to the weight of snow on the mirrors or SET.

All the testing performed to April 2006 was undertaken largely during the day time. From May 2006 the SET was left on overnight as well. During this time there were no real issues which appeared from the auto-tracking circuit or PLC sub-routine. By December of 2007, the SET had been in full time operation (24 hours per day 7 days a week) for a period of twenty months, with only minor adjustments being made to the values of the direction timing delay in the PLC and light level trim-pot RV1 in Figure 6.7.

It has however been noticed that in conditions of heavy cloud, the SET will appear to track the edge of the cloud where the sunlight now appears to be at its brightest. However, every time the sun



later amended to being a combination of real time clock and time, i.e. a time after 0930 plus an additional 2.25 hours delay for the shut-down timer (i.e. midday), and a shortened stayput timer of six minutes.

The reasons for using this combination of real time clock and delay timer triggering were two fold. In initial testing, it was noticed that the SET would shut-down by 0830, which was too early to determine if the day was going to develop into a day with any solar radiation. Thus the real time clock trigger point was adjusted to 0930, another hour further into the day. Secondly, it was then noticed that on some occasions the morning would experience a rain shower with the afternoon becoming fine and dry. The delay timer concept was then added to the real time clock trigger to allow the SET to stayput for a longer period of time. The delay time concept was chosen as this can be more easily altered by any user without having to re-program the PLC ladder rung, as would happen with the real time clock trigger in its present ladder rung construction.

The shut-down and park function is likewise determined by low light, the lowlight shut-down and stayput delay timer timeout and an additional timeclock requirement. The timeclock requirement ensures that the SET doesn't shut-down before midday. This has been programmed in this manner in case there is a morning rain shower and then weather conditions improve in the afternoon. If however there is insufficient solar radiation to activate the light level detector after midday, provided there is still a low light signal, the SET will shut-down and park. There is very little to be gained by tracking for only part of an afternoon; however this can be changed to reflect the conditions of the environment the SET is installed in.

Under conditions where the sun re-appears, there is a short proving delay (three minutes) built into the PLC programme to ensure the sun's reappearance is not a 'fleeting occurrence'.

There is one other shortcoming of this circuit, shown in Figure 6.7 when compared with that of the original auto-tracking circuit. The original auto-tracking circuit had trim-pots associated with each

axis allowing for a positional fine-tuning ability within each axis. The circuit as outlined above does not have this facility and all fine tuning and adjustment must be performed manually by adjusting the physical alignment of the target with the boom and sun. The auto-tracking sensor containing all the photo-diodes is mounted on a two axis knuckle below the target. This two axis knuckle allows for the auto-tracking sensor photo-diode array to be positioned in both the horizontal and vertical axes. This means that the only method of checking position of the auto-tracking sensor is to observe the shadow cast by the target on to the mirrors of the SET. When the target's shadow is in the middle of the B3 mirror as a column and occupies up to  $\frac{3}{4}$  of mirror B2 in vertical height in the middle of this mirror, then the auto-tracking sensor may be said to be calibrated for position.

Initially, this alignment was performed in early morning conditions with the alignment consisting of placing the target's shadow onto the B3 mirror. However this was found to result in a progressive error which resulted in the SET being off target at midday. In this case, off target refers to the reflected light from the mirrors missing the target. After several attempts, all with the same result, it was decided to calibrate the auto-tracking sensor for the midday position as this was the midpoint in the sun's arc for the day and the mirrors should at this point be at 90 degrees to the incoming solar radiation. This proved to be the correct method with the winter sun (2005). After three days of further adjustment the SET was reliably able to track the sun throughout any given day. On the fourth day the SET was able to reliably find the sun and to position the solar radiation correctly onto the target.

At this point the adjustment nuts on the knuckles for the auto-tracking sensor were tightened and the position recorded and marked. For the next few months the system worked well on a daily basis and then two events occurred almost simultaneously. One day the SET suddenly decided to point skyward regardless of the sun's position. Initially it was thought one of the knuckles had worked loose and so the boom was lowered and knuckle nut rechecked and found to be loose. When this was re-tightened it was found to be out of alignment; however no amount of adjustment of the

knuckle in the Y plane managed to effect any change to the auto-tracking sensor's direction output which was to still boom up.

Further investigations revealed that the Y+ direction photo-diode had gone short circuit under all light conditions and was therefore causing the auto-tracking circuit to output a boom up command. Replacing the Y+ sensor immediately fixed the problem; however the alignment was now effected. Recalibration of the alignment of the auto-tracking sensor head required another fine and cloudless day.

Some months later it was again noticed that the SET appeared to be out of alignment to the target and to the shadow cast onto the mirrors. This was fixed by tightening the nuts on the X and Y axes in the knuckle. However within a short period the same problem surfaced again. Over time these knuckle nuts had loosened with the constant movement of the SET, its boom, the wind and other prevailing weather conditions, causing deflections on the boom and the auto-tracking sensor head. This time the knuckle was stripped, cleaned, and spring washers or star washers were installed to prevent the knuckle nuts from working loose again.

Once again the position of the auto-tracking sensor was checked for calibration at midday using the shadow cast onto the B series of mirrors as outlined previously and also by checking the bright shadow cast by the mirrors of the sun's rays onto the target. With the final position reached and checked, markings were made onto the knuckles and then recorded. No further adjustments have been made to this alignment since.

With cloud, the SET will sometimes track to the edge of the cloud and in early mornings or late afternoons will be seen to be slightly off target. In this latter case, it can be seen that in any season, the position of the end of travel (west) and start (east) limit switches interfere with the first and last operations of a day. Whilst these may be able to be moved slightly, there are physical limits which prevent this from occurring. In the early morning when the sun appears over the buildings on

the east side of the campus, the SET wants to try to put the boom into a lower position than is mechanically and physically possible. In the late afternoon sun, again the boom wants to go into a lower position than is possible. There is also a problem with a nearby tracking satellite dish which blocks any further westward tracking.

### **6.2.3 Failures and final comments:**

The IR photo-diodes seem to be prone to failure, not so much from the weather but from voltage spikes and fluctuations. Whilst these failures may not always be apparent nor are they immediate, they manifest themselves some time later with the SET trying to go to the extreme of one axis despite the position of the sun.

The IR photo-diodes are prone to failure due to voltage spikes, which may be caused by any number of reasons ranging from power supply problems, shorts and surges, to supply rail shorts, to grounding faults, to mains supply fluctuations. Once the potential susceptibility of the IR photo-diodes to 'voltage fluctuations' was realised all IR photo-diodes were replaced as a precaution to ensure reliable operation of the SET. IR photo-diodes were selected, matched and installed so as to have similar characteristics to those currently in use. As an additional precaution, a UPS and line filter was installed on the mains supplying the SET to help filter out any possible spikes originating from other users in the building and to provide a provision to take the SET off axis in the event of a mains power failure.

No other failures of the IR photo-diodes have occurred in the auto-tracking sensors. Likewise there have been no failures associated with the auto-tracking control circuit or with the PLC auto-tracking control sub-routine. Relatively minor adjustments were made to the PLC auto-tracking deadband timer in late 2006, in an attempt to reduce the amount of deadband and improve the overall sensitivity of the SET, which resulted in the SET beginning to hunt too much.





## 7.0 PLC code

This chapter outlines the highlights and features of the PLC software developed rather than systematically reviewing four years of PLC code development. The PLC code is divided into a number of subroutines which best describe the task they control, for example lighting subroutine, auto-tracking sub-routine, etc. The PLC code was segmented early in its development in this way to allow easy change, modification and troubleshooting as well as allowing for easy future additions, etc. The selection of the PLC has already mostly been covered in the electrical chapter, with technical support and price being the primary motivations. Future expansion capabilities and a small footprint having secondary roles in the decision. As stated in Chapter 5.3, the PLC chosen was an Omron CPM2a forty I/O with a MAD01 analogue unit containing three I/O and a DeviceNet module.

The PLC code was first developed and trialled in 2004. When first successfully tested by the student it operated under full sunlight. However, on an overcast day, in early 2005, the PLC system decided to boom down. At this point the PLC programme allowed the boom to transgress or over-ride the Y-travel limit switch and permitted the boom to transition well past the Y-travel limit. Had the author not been walking past 'the Smiley face' and decided to check on the SET, the boom may have transitioned further. As it was, it had become engaged and locked into the X axis support frame. Upon discovery of this mishap the SET was immediately isolated by the use of the emergency stop (which isolates all the outputs on the PLC by disabling the 12 V DC power supply). Following this, the cover on the Y axis motor was removed, and the motor gearbox quickly inspected for any damage without removing the motor drive. The emergency stop latch was then released (enabling the 12 V DC power supply) and immediately the Y axis drive motor re-started and tried to continue to boom down. At this point the stop button was pressed and the Y axis drive motor ceased operation. An attempt was made to use the manual over-ride pushbuttons to try and reverse the direction of the motor and thereby release the Y axis frame from the vertical X axis support frame. However this was not possible and it was required to be released by another means. At this point the Y axis motor was

disconnected from the 12 V DC electrical supply and removed from the mounting frame. This released the drive motor from the coupling and allowed the Y axis sub-frame to be manually separated from the X axis support frame. After some effort this was accomplished. The Y axis drive motor was given a complete check-over and grease before being run on the test bench. No damage was obvious, however, it was apparent that the gearbox and motor had been stressed, based on the noise the motor made when operating in one direction. Some four months later, the final output drive stage of the gearbox failed, with stripped gears. The Y axis motor drive was subsequently replaced.

The problem was found to be twofold, the movement of the Y- axis travel limit switch, and the failure of the PLC code to react to a travel limit switch being triggered. The PLC code was further investigated and it was found that all the travel limit switches on all the four axes exhibited the same problem, namely it was possible to trip the travel limit switches and to continue to track or move. The PLC code was changed from non-latching outputs on travel limit switch activation to a latching type of travel latch output. Further problems were immediately apparent in that if the output travel limit switches were activated based on a travel limit being exceeded, then a reset mechanism was also required to prevent continual operator intervention. This led to a lot of extra PLC code being developed such that the PLC was able to 'un-latch' a travel limit provided the auto-tracking sensor requested that the direction of travel was in the opposite direction. For example, if the Y- travel limit was latched then this could be reset by the auto-tracking system issuing a command to track or boom up.

Throughout the rest of 2005, further development of the PLC code proceeded with various systems checks being performed with the system in manual mode in August 2005. Only after acceptance of these manual mode tests was the system allowed to run in automatic mode. During this investigation it was also found that it was still possible for the PLC to output both X and Y motor drive commands simultaneously which would trip out the 12 V DC power supply. This was fixed by



The Omron PLC chosen has a total combination of twenty four digital inputs and sixteen digital outputs, or what is called a forty I/O PLC. The digital inputs are words zero and one (i.e. 0.00 through 0.11, and 1.00 through 1.11). Analogue inputs in this configuration are words two and three. Digital outputs are ten and eleven (i.e. 10.00 through 10.07 and 11.00 through 11.07). Analogue outputs for this configuration are word twelve.

For this project some of the basic rules observed from 2005 onwards were: all PLC outputs for travel limit switches and important safety control functions and alarms, etc, were to be latched; all PLC code developed would conform to sub-routines, based loosely around the operational area it controlled; all PLC code would be fully documented at both symbol and instruction level and would also be commented on at ladder rung level; and all PLC inputs would be time delay proven.

As has been mentioned in Chapters 5.7 and 6.2, the PLC code is divided up into nine sub-routines dealing with separate areas of the operation of the SET. A brief description and overview of each sub-routine block follows:

#### **7.1.1 Start sub-routine**

This section is the core of the project and comprises twelve ladder rungs in total. It controls the emergency stop, start, stop and reset pushbuttons, all safety interlocks for operation and safety shut down operation, the green status lamp, and sets up the PLC's configuration.

#### **7.1.2 Light level sub-routine**

This section is eleven ladder rungs in length and establishes the light level conditions necessary for the SET to operate in. The ladder rungs also decide the necessary conditions for low light stay-put conditions and, based on real time clock and delay timers, for extended low light shut down operation.

#### **7.1.3 Water pump sub-routine**

There are four ladder rungs in this section which prove flow, CP motor fault status, CP over-pressure status and tray full status. The CP controls are derived from these ladder rungs, being controlled on

shut down and over-temperature conditions, normal operation over-temperature condition, frost condition, CP motor fault lock-out condition or tray full or over-pressure lockout conditions, CP flow switch and lockout condition, and finally from 2007, CP start and stop control action based on target and air temperature comparison.

#### **7.1.4 Auto-tracking sub-routine**

These forty four ladder rungs are the 'brains' of the SET. The first two ladder rungs deal with shut down conditions, and preliminary conditions required for auto-tracking to occur. The next eight ladder rungs detail the interface between the auto-tracking sensor and interface circuit and the PLC, dealing with proving delays and interlocks for Manual Park and start modes and safety shut down interlock conditions. The next twenty four ladder rungs are the travel limit latch bits, time proving delays and the conditions for automatic and manual resetting of these travel limits based on the depressing of the reset push-button, or the auto-tracking sensor request to travel in the opposite direction, or a real time clock clearing or resetting pulse. This is followed by ten ladder rungs pertaining to the NW park position, its selection switch and travel limit switch selection latch and reset bits and the motor drive conditions to force the X+ motor drive to track to the X+ travel limit switch for 0600 hour automatic timed restart.

Following on from this and having set up the conditions necessary for the auto-tracking mode are the ladder rungs necessary for the control of the motor drive of each of the four axes (up, down, left and right), and the various interlocks for auto-tracking and automatic timed modes, manual over-ride modes, safety shut down over-ride modes, automatic timed restart mode, parking position modes (NW verses SE) and the PLC code for left kick mode.

#### **7.1.5 Analogue temperature sub-routine**

These nineteen ladder rungs primarily set-up the reading of the target and outside air temperature, the necessary conditions for target over-temperature (CP on and shut down), frost protection mode (CP on at 1 to 2 °C), and the conditions necessary to set and unset latch bits for CP control action. All are time delay proven. The basis for the set and unset latch bits for CP control action is a 15 second

sampling, followed by an offset addition to the air temperature, then a comparison of the target and the offset air temperature to initiate delay timers to either commence CP operations or to suspend CP operations. CP target over-temperature or frost protection latch protection bits are based on a set threshold value being exceeded and are time delay proven, before any control action occurs.

The target temperature is corrected for offset values and is copied to the analogue output for display on the SCADA system.

#### **7.1.6 Alarms sub-routine**

These thirteen ladder rungs set up the alarm and status conditions for red (shut down alarm), amber (yellow status), and UPS mains power failure shut down alarm (based on a time delay proven input).

The alarm code word, based on the actual fault generated) is loaded into the flash sequence for the red shut down alarm lamp to alert operators to the fault code condition as currently on the SET.

Although the amber light is not shown on the control panel, it is shown on 'the Smiley face' along with the red fault and green status lamps.

#### **7.1.7 Air Compressor sub-routine**

These five ladder rungs deal with the operation of the air compressor. The air compressor's operation is based on the SET system running (or in normal operation), the air compressor selector switch being on, and the pressuretrol switch on the air cylinder not being satisfied. This starts the air compressor, which will operate until the air cylinder pressure switch preset condition is met, and turns the air compressor off. Should the air cylinder pressure switch become unset due to either a slow discharge or a rapid discharge, at this point the air compressor will restart. However, this condition may be amended with the real time clock such that a discharge of compressed air from the air cylinder and the consequent air compressor starting at say 0200 in the morning doesn't 'wake the neighbours'.

### **7.1.8 Auto morning start sub-routine**

These sixteen ladder rungs detail the real time clock park and real time clock restart conditions, the manual and manual re-start over-ride modes and their resetting, and additional timer delay interlocks for resetting and unlatching of some latch states.

If in real time clock mode and the SET is in fully automatic mode, at 1800 the SET is put into a park mode, and will automatically park itself into the predefined park switch position (i.e. NW or more usually SE). At 1815 this latch bit will reset itself and set the 'night-time' shut down bit. In automatic real-time mode at 0600, this 'night-time' shut down latch bit clears, the CP starts and operates for 15 minutes to prove water flow and clear any flow problems which may have occurred over-night, and the SET repositions itself to the X+ travel limit (with blanking on the SE park limit for 60 seconds allowing the SET to move off the SET SE park limit). At 0601 the park travel limit resets itself and clears, and at 0615 the 6am restart latch bit resets. The manual over-ride park and manual over-ride restart operations are dealt with further in the PLC code description.

### **7.1.9 Park (position) winter sub-routine**

These six ladder rungs deal with the conditions necessary for the SE park position latch bit and some minor timing issues on clearing interlock latch bits, etc. in both the fully automatic, partially or interrupted automatic mode, and manual or partially interrupted manual modes.

## **7.2 Parking, safety shut down and frost mode**

During testing the requirement became clear for a set park position. Up to this point the SET had been manually positioned for a day's testing and tracking, and at night parked with the boom facing the NW. It was decided this NW position represented the path of least resistance to the prevailing and gusty NW gale and the SW storm which usually follows (the SET would be sideways on to a SW storm). In this position the boom faced the NW gale and was slightly elevated above the Y- lower travel limit switch. This presented the NW gale with a path for the wind gust to dissipate through the SET mirrors or be deflected over the top. A decision was made to automate this manual process and



the necessary PLC code was entered and tested. This testing went well and the SET responded correctly to the command to park in the NW.

Throughout the re-commissioning of the SET the OSH representatives for CPIT have been involved and consulted and advised on relevant events before and as they occur. For this reason a sign was erected in 2004 warning of the dangers of the SET and its movements, etc. However in late 2005, just as the PLC code was being completed for automatic timed parking and restarting, a refrigeration contractor was walking along the ridgeline of the roof and 'bumped' his head on the lowered boom and complained, fortunately to the CPIT School of Engineering (SOE) Electrical technicians, and threatened to lodge a complaint about an OSH work related safety issue on the roof line of C block roof in a restricted access area. A decision was quickly made to park the SET with the boom facing the Port Hills, or as it is known, the SE park position. This has meant a lot of extra PLC coding to facilitate the two different parking positions.

At this time of development (2005), it was noticed the PLC code would prematurely shut down the SET on low light and was not be able to restart the SET. This PLC code was improved to allow the SET to shut down and stay put, as well as being able to shut down and park. The PLC code also had to recognise the two different park positions. This gave rise to the low light shut down and stay put condition (amber light slow flash – refer Appendix 2 or Table 7.2). This required several iterations of the PLC code and much fine tuning of the delay timers associated with the extended low light shut down and park commands to ensure correct operation.

By January 2006, testing had commenced on the automatic SE parking PLC code in conjunction with the low light and extended low light code conditions. The SE parking PLC code eventually operated correctly and reliably, but necessitated the addition of another limit switch to enable an extra step in the PLC code to position the boom past the normal X+ travel limit. The SE park position is further to the right of the X+ travel limit switch.

Having resolved this issue, the next question was to determine if the SET could operate without an operator continuously. The particular model of PLC used has a real time clock which could be accessed. The PLC was subsequently coded to allow the SET to correctly park, correctly clear and reset non-critical alarms, to provide remote monitoring and display of conditions, and to provide the SET with the ability to perform a morning restart to the X+ travel limit switch, with non-critical alarms being cleared. The problem in restarting at 0600 was the requirement to blank out the X+ travel limit for a period of time to allow the SET to move off this travel limit switch, as shown in Figure 7.1.



Figure 7.1. The X+ travel limit switch and the SE park limit switch.

When the PLC coding was completed, comprehensive testing was undertaken. During one of these daily test sessions it became apparent that an operator also needed to have the ability to over-ride these commands and to be able to reset them. This saw yet further additions and changes made to the PLC code such that an operator may be able to hold down the reset pushbutton and cause the SET to perform a SE (or NW) park manoeuvre, but then at 0600 (i.e. the next morning 'wake-up') commence tracking in the normal manner, provided there was sufficient solar radiation, the CP was operational, and there were no critical alarms, as has already been commented in the PLC section.

Likewise the SET had to have the ability that should someone perform a SE park manoeuvre during the day, to perhaps perform some maintenance on the SET, the operator should be given the ability

to re-start the SET or at least return it to the start (X+) travel limit from the SE park position. When the auto-tracking sensor causes the SET to commence auto-tracking in the X axis (i.e. the SET X axis motor drive) this event will reset any latch bits pertaining to the manual restart requirement.

Further to this was the requirement that an operator should be able to cancel either of these two modes of operation manually at any time.

The final iteration for manual over-ride process saw operators with the ability to hold down the start pushbutton for 20 seconds to initiate the manual over-ride restart mode and re-position the SET to the X+ limit switch ready for auto-tracking to commence. Holding the reset pushbutton for 20 seconds likewise will initiate the park mode (usually the SE position), with an 0600 automatic restart the next day, provided the other conditions as already mentioned are met. Momentarily depressing both the start and the reset pushbutton would clear any of these modes of operation and stop the SET in the position it was currently in.

Another feature was added at this time, which was that if either the reset or the start pushbuttons are depressed, the X and Y axis motor drives are momentarily disconnected, but the CP and air compressor operation continues as normal. This was done to prevent movement during manual operator interventions, and to allow any person to stop any movement of the SET if required without having to press the stop or the emergency stop, or having to open the control cabinet to control any of the motor drives.

By April of 2006 the SET was being reliably parked, but manually restarted. By May of the same year the SET was able to restart by itself on an automatic early morning restart (0600). By June the SET was being increasingly left alone for weeks at a time, which soon developed into months. By July all remaining issues with some alarm conditions and latches, which wouldn't always reliably reset, were resolved and the SET was in full-time operation.

In October of 2006, the project supervisor was invited for an inspection, and as luck would have it this day the filter on the CP inlet was blocked with the result that the SET shut down under low flow fault. However, data captured by the SCADA system was shown to reinforce that the SET had successfully been in operation up to that point. At this meeting, a problem had revealed itself in testing, whereby the SET would shut down due to low light in the morning, however, the sun would appear in the afternoon and the SET would try to follow this by taking, in some cases, the shortest route, i.e. by tracking right. However nothing would happen with the position of the X axis as the SET was already parked on the SE and the X+ travel limit switch was still true or latched, the SET would 'boom' up and down. This seemed to happen only occasionally and under conditions where the SET had shut itself down due to low light as might happen of a morning, but the solar radiation improved later in the day, i.e. a fine afternoon. In some cases the SET would boom up first and then receive a command to auto-track left, whilst in other cases it would receive the command to auto-track left then boom up, i.e. the problem was intermittent in its occurrences. This was partly corrected by amending the extended low light timer in the PLC light level subroutine.

This necessitated a further addition to the PLC code, with a 'left kick'. In this case the PLC code was modified to allow for the condition of the SET being 'stuck' in the X+ travel limit position and continually wanting to track right but being unable to do so because of the X+ travel limit PLC latch code. In this case, if the SET auto-tracking sensor and associated PLC code decided to track right in the fully automatic mode, the real time clock recorded a time in excess of 1400 hours (this seemed to be the most common time for fine weather to appear after a wet or overcast morning), and a short proving delay then the X drive motor would receive the command to drive left for a preset period of time. This time limit was set to five minutes to allow the boom to be positioned just past its midday point. The auto-tracking sensor would then reliably take over and correctly instruct the SET to continue to track left. After the PLC code was programmed it proved very difficult to simulate or perform any test on the SET, without the aid of personnel, a cardboard box and the forcing of several travel limit switches. When all the conditions were simulated, some minor fine tuning of the

values of the timers was found to be necessary. Shortly after this fine tuning occurred, the right conditions happened naturally for a 'left kick' which resulted in a successful test of the 'left kick' modification being observed.

Another safety feature was added to the PLC code in early 2006, with the addition of a 450 VA rating UPS. The interface to the PLC code, being by way of a failsafe input and in the event of a mains power failure, alerts the PLC to perform a shut down park manoeuvre on the SET. The primary aim is to ensure the SET is off the sun's axis, and preferably parked before the UPS battery power runs out. The UPS power is designed to last about fifteen minutes.

A minor addition to the PLC code occurred in June 2007, which saw the target temperature sensor connected to the SCADA system. This allowed comparison of the inner target temperature (as monitored by the PLC) with the exhaust hot water temperature as measured by the SCADA system when the hot water pipe from the target just leaves the SET.

### **7.3 Safety shut down**

In testing during 2006 it was noticed there was no safety cut-outs on the drive motors. PLC code was developed to allow the PLC to monitor its own outputs and to shut down these outputs if either the travel limits were not engaged or if the auto-tracking sensor signal for that direction was not satisfied within a pre-defined timeframe. The philosophy here was to try to prevent a drive motor from burning out due to a mechanical failure or due to being overloaded. The problem with this was that the safety over-ride was required to be the longest move for any given axis plus a small safety margin to prevent false triggering. This was determined as being eight minutes for the X axis drive motor to travel from the X- travel limit to the X+ travel limit and then to the SE park position. For the Y axis, this time was three minutes to go from boom up to boom down. As if to reinforce the correctness of the requirement for this safety shut down PLC code, during the testing of the PLC code for park position in late 2005, the Y axis drive motor coupling came loose and the safety shut down code prevented the Y axis drive motor from operating continuously for the period the SET was

left unattended. The safety shut down PLC code has been tested at other times with other motor drive and gearbox transmission failures and the timer values are correct for the SE park position, but will require adjustment if the NW park position is to be used.

In 2007 the safety shut down PLC code failed to prevent the burnout of the X axis drive motor. In this case a new data cable had been connected to the SET and had worked loose from its mounted position and become stretched on one of the tripod feet. With the SET not having reached the X-travel limit due to a loss of solar radiation in the early afternoon, this left the X axis drive motor with too much time on the safety shut down delay timer before the output was disabled by the PLC. This caused the 12 V DC drive motor to burn out. The drive motor was removed and gearbox inspected. The gearbox proved to have survived the ordeal. A new DC motor was purchased and fitted to the gearbox. The new motor and old gearbox was then fully tested and is held as a spare. The power supply required a power off reset as no fuse blew on this occurrence. With the drive motor removed, the X axis had to be moved manually by manipulating the worm drive input to release the tension on the stretched cable. The cable was then repaired and tied more securely to the X axis sub-frame to prevent a repeat occurrence.

Other events have occurred such as axis motor drive coupling failure, Y axis motor drive coupling failure and Y axis motor drive gearbox failure due to stripped gears or due to the intermediate shaft having worked loose on its end mounting plate, which reinforce the decision to institute a safety shut down over-ride mechanism in the PLC was correct.

#### **7.4 Frost & water saving modes**

Up to January 2007 the SET water circulation system always had some small amount of water passing through it. In January, CPIT facilities management requested a reduction in the water usage for the solar thermal experiments on the C block roof. This meant another change to the PLC code to allow the CP to be turned on only when the SET was functioning. This change necessitated a physical alteration to the pipework as well as to the PLC code.

The change made to the pipework meant the cold inlet water pipe from the low pressure tank on the roof above entered the isolating valve, the inline gauze filter, followed by the NC solenoid valve (CPS), then split into a bypass with an isolating valve (left open) and entered the CP inlet header. In some SET system and flow tests, only the CPS and hours run meter were enabled. In later testing, the CPS, CP and hours run meter all came on together with the bypass isolator open.

The reason for the change in operation was due to some situations whereby if the SET had been off for some time due to a lack of solar radiation, and was either in a shut down park mode or an auto-tracking mode, and trying to find any source of solar radiation. In this condition the boom could be in any position, but if the boom was up, then on resumption of solar activity and the CPS turning on, there was sufficient air leakage in the system which prevented a flow of water which meant the SCADA system recorded a temperature 'spike' and the SET PLC recorded either high target temperature or no flow and consequently shut down under a red fault alarm. It was thought part of the problem may also have been a partially blocked inline gauze filter. However, this proved not to be the case, and although the flow rate only increased marginally using the CP and CPS, the SET would never shut down due to a 'no flow' alarm or 'target over-temperature' alarm during testing with both CPS and CP in operation. The flow rate with CPS was 3.0-3.5 l/m and with CP and CPS together the flow rate increased to 4.0-4.2 l/m. Attempts were made to lengthen the flow timer delay switch, using only the CPS, but this proved not to be a reliable solution, with a blockage or restriction sometimes occurring in the pipework making clearing the blockage directly proportional to the time the CPS had been off. Using the CP in conjunction with CPS meant that there was more pressure and therefore more force to overcome any restriction or blockage in the water supply pipes to the target.

The PLC code was amended to sample the air temperature and target temperatures every fifteen seconds, store these values and then add an offset of 1 or 2 or 4 Binary Coded Decimal (BCD) to the air temperature, and if the target temperature was still greater than this, to turn on the PLC CP

output after a short proving delay. Likewise, if the offset air temperature exceeded the target temperature, after a preset time, the PLC CP output was turned off.

The results observed on the SCADA screen saw a very high target temperature 'spike'. Further investigation revealed the timer values were incorrect and after several iterations of timer values were finally amended to the CP having a fifteen second delay timer to turn on and a six minute delay to turn off, with a fifteen second sample time and an offset value of 1 (about 5 ° C) between the air temperature and the target temperature. It was noticed during this testing an error would occur occasionally in the PLC instruction code for the offset addition. This was found to be a function of the type of instruction used. This was corrected and the PLC error code disappeared with more reliable SET control being obtained.

The SCADA system also required a PLC offset correction before it was able to correctly display the results on the SCADA screen. Once this had been accomplished, reliable data was obtained. It was noticed that the inner PLC target temperature was very sluggish compared to the exhaust SCADA temperature that had traditionally been used, however, both read the same temperatures. In other words there was no temperature loss or delay in the temperature readings by measuring the SCADA target exhaust temperature at the point where it left the SET and joined into larger diameter pipes feeding into the roof system guttering, when compared to measuring the inner target temperature. If anything, the exhaust pipe recording point was marginally quicker to record a temperature change.

Some 'temperature spiking' can still be observed occasionally on the SCADA recording system, however the amplitude and frequency of these 'temperature spikes' is reduced using the delay timers and settings mentioned above.

During an early winter's frost in June of 2007, which saw many homes in Christchurch experience frozen water pipes for the first time ever, (it was recorded as a 7 ° C frost), the SET frost mode initiated and failed. However, the failure was due to water freezing in the target exhaust pipe. This



occurred before the CP and CPS turned on at 0 °C. The exhaust pipework remained frozen for 48 hours. With the CP and CPS both on, there was a sufficient increase in pressure which caused the hose clamp holding the smaller diameter pipe from the flow switch outlet on to a larger diameter exhaust and dump pipe to release and fail. Thus water was released from the SET target which prevented the target from freezing. Once repaired and the cause of the failure analysed, a decision was made to raise the frost trip point in the PLC code to prevent the pipework from freezing and the frost trip point in the PLC code is now 1.5 °C.

## **7.5 Alarms, pushbuttons and other controls**

In early testing in 2005, it became apparent there were 2 alarm levels, one a caution (amber) status type, the other a shut down (red) alarm. With the development of 'the Smiley face' (remote operator interface) in 2005, came the clear separation of these alarms.

Yellow or amber status alarms were events such as: travel limits – which would be reset by the SET itself upon the auto-tracking sensor detecting an opposite tracking direction; low light and extended low light; manual park with automatic reset at 0600; and frost protection mode initiated. All these events were non-critical and the SET would take the appropriate action and reset the alarm when conditions improved. No operator intervention is required for yellow status alarms.

Red alarms were for critical events such as: no flow in target or CP; target over-temperature; CP over-pressure or tray full or motor fault; mains power failure; and safety shut down due to a failed auto-tracking move. These alarms are critical and require operator intervention to check and take any remedial action before resetting and clearing the fault condition.

The green lamp is used to indicate: standby mode; travel limits; and to indicate the heartbeat of the SET, i.e. all systems normal and operational. Appendix 2 gives details on 'the Smiley face'. Table 7.2 lists details of the indicator lights.

**What do all the lights mean?**

| GREEN                                | AMBER                               | RED                       | ACTION REQ'D  |
|--------------------------------------|-------------------------------------|---------------------------|---|
|                                      |                                     |                           | <b>Please help me !!!!!!!</b>   |
| <b>Solid</b>                         | <b>Solid</b>                        | <b>Solid</b>              | <b>SYSTEM SAFETY SHUT DOWN.</b>   |
|                                      |                                     |                           | <b>Please see below for how to help me!</b>   |
|                                      | •                                   |                           |   |
| <b>Solid</b>                         | <b>Solid</b>                        | <b>3 quick flashes</b>    | <b>Target over temperature. System will shut down and go to park position.</b>      |
|                                      |                                     | <b>&amp; a long pause</b> |   |
| <b>Solid</b>                         | <b>Solid</b>                        | <b>4 quick flashes</b>    | <b>Circulation water flow fault. System will shut down and go to park position.</b> |
|                                      |                                     | <b>&amp; a long pause</b> |   |
| <b>Solid</b>                         | <b>Solid</b>                        | <b>5 quick flashes</b>    | <b>Circulation water pump fault. System will shut down and go to park position.</b> |
|                                      |                                     | <b>&amp; a long pause</b> |   |
| <b>Slow flash</b><br>(60 sec on/off) | <b>Slow flash</b><br>(60sec on/off) | <b>Off</b>                | <b>System in standby mode &amp; system parked.</b>                                  |
|                                      |                                     |                           | <b>System parked.</b>   |
| <b>Slow flash</b>                    | <b>Solid</b>                        | <b>Off</b>                | <b>Manual Park mode initiated, will reset 6am next</b>                              |
| <b>Solid</b>                         | <b>Slow flash</b>                   | <b>Off</b>                | <b>Frost protection mode engaged.</b>   |
| <b>Off</b>                           | <b>Slow flash</b>                   | <b>Off</b>                | <b>Low light level mode engaged.</b>  |
| <b>Fast flash</b><br>(1 sec)         | <b>Fast flash</b><br>(1 sec)        | <b>Off</b>                | <b>System normal and on one of its travel limits, it will reset.</b>                |
|                                      |                                     |                           |   |
| <b>Fast flash</b>                    | <b>Off</b>                          | <b>Off</b>                | <b>System Normal.</b>   |

Table 7.2. Sign 'What do all the lights mean?' on notice board.

### 7.5.1 Pushbutton functions

In 2004, a decision was made on the operator functionality required for the control of the SET. This saw important operator control pushbuttons mounted on the side of the control cabinet, in 2005.

These important operator control pushbuttons are shown in Figure 7.2 and listed as follows:

- Key switch, system on, master control, supplies power to the control panel.
- Emergency stop – latching type, twist release, isolates the 12V DC power supply effectively disabling all motors.

### 7.5.2 Start and stop pushbuttons, start the SET or stop the SET.

The Reset pushbutton is used to clear any and all fault conditions for red or yellow (amber) alarms.

This will also clear most latch circuits in the PLC, resetting these to the unlatched state. Should this occur, when perhaps the SET is on a travel limit, the travel limit latch will reset and clear for one programme scan and latch again due to the proximity of the magnetic Reid switch. The maximum time delay for this to occur is two programme scans or 240 ms. The DC drive motor output will never be able turn on in this time and certainly the DC drive motor won't be able to start or turn in this time frame.

## SET Definitions and orientation guide.

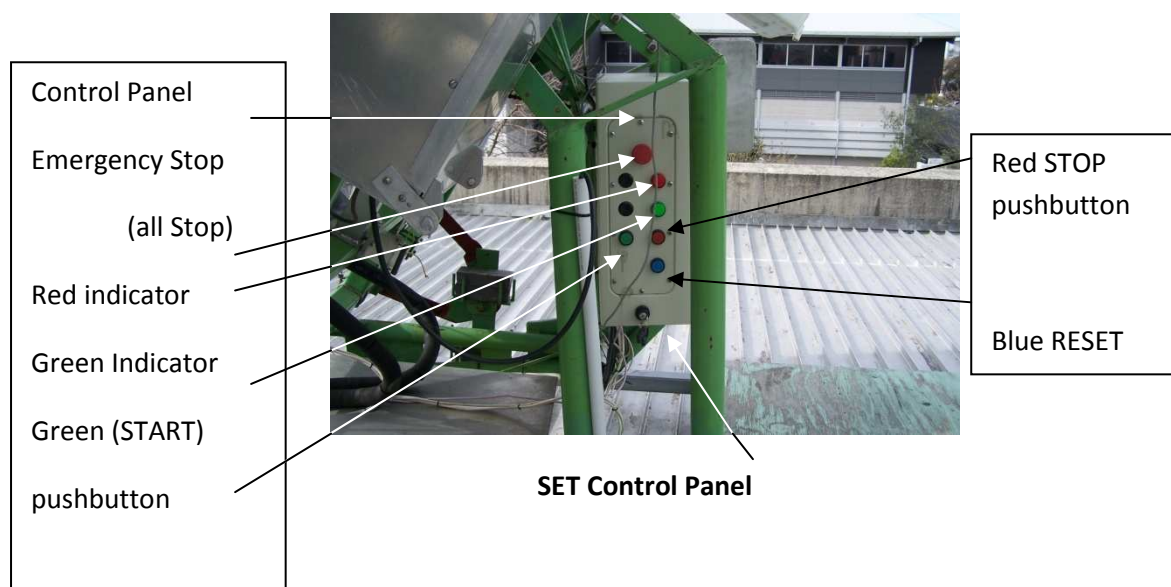


Figure 7.2. SET definitions and orientation guide.

Inside the control panel, a front gear-plate contains a number of selector switches for Auto/Manual (is the SET operating in operator manual mode, or in full PLC automatic mode – auto position is normal –obscured in Figure 7.2), CP control off or on (on is normal and in Manual mode {above} means the CP will operate manually), and air compressor off or on (off is normal). Next are four pushbuttons for Y+, X+, Y- and X-. Depressing a push-button activates the appropriate drive motor independently of the PLC, i.e. it allows for manual over-ride. The next three pushbuttons are not allocated or used. Lastly there are two selector switches for enabling the real time clock (off and on – on is normal) and a selector switch for Summer (NW) or Winter (SE) park position (SE park position is normal), and is shown in Figure 7.3.



Figure 7.3. The control panel complete and in operation December 2006.



## **8.0 Mirrors and mirror substrate testing**

This chapter details the research and testing undertaken to procure a replacement mirror substrate for the original substrate that is currently on the mirrors of the SET. This original substrate is no longer manufactured and very little is known about it other than what can be found in the inventors' notes on the subject. This chapter details the attempts to replace the mirror substrate with comparable newer substrates and to research other more recent technologies such as a spray on coating. Investigation into other methods of application and types of substrates (such as vacuum coatings and the application of substrate in a vacuum) are not discussed. The primary focus of this section is to review current mirror coatings and substrates and simple methods of application of these substrates. This is in part due to the size of each panel on the current SET, the type of construction and mounting, and the desire to 'keep it simple' for long term maintenance and repair purposes. Cost was also an issue. A brief summary of the findings and results of this section and testing is detailed in Section 8.5 Future Solutions.

The approach used was to select three possible substrates and then to mount these on a piece of aluminium. Initially, three such aluminium panels were constructed and the mirror substrate applied with different adhesives. Once, the adhesive had cured, the panels were mounted in their test locations and subjected to the weather. The rule which was observed in all cases and which has been followed throughout this project is that once per month photographs would be taken of the test panels. These would then be compared and any deterioration observed and commented upon. This has been followed through with over five years of data now archived. This 'rule' was further extended to capture more relevant data. Thus all solar thermal hot water systems and SET panels were photographed once per month and at any other time during the month if any substantive or relevant changes were made to any of the solar thermal hot water systems.

This chapter is sub-divided into, mirror coating selection, the first three test panels, the Antarctica test panels, the SET test panels, and future solutions.

With the large amount of data to select from, an attempt is made to present the status of the same test panel at six monthly intervals, throughout the testing process, and with comments added where relevant.

## **8.1 Mirror coating selection**

With some of the original mirror substrate still available, but insufficient for a complete SET mirror panel, attempts were made to try and find the supplier. The original mirror substrate was manufactured by 3M in America. However, with the retirement of the head of that particular division sometime during 2002, 3M withdrew the product from the market. This left a void in the market, with very few other products available that could compete with the quality and consistency that is traditional for a 3M product. 3M do have other reflective coatings, but these are designed for indoor applications, and have no UV resistant outer coating. It is possible to add a UV coating, but the cost escalates. A recent search of the 3M website by product, 'reflective Mylar films or coatings' reveals that 3M still do not manufacture anything in the way of reflective coatings.

In 2003, a German company, (Solkote, [www.solec.org](http://www.solec.org)), offered a flexible aluminium sheet, coated with pure aluminium in order to increase reflectivity. This product could be shaped to suit the focal point of a reflector; however the product was withdrawn as there were problems with the UV resistant coating as applied to the product.

In the search, two other options presented themselves. The first option was a product called 'Clear Dome Solar Flex' which had a 97.4 % reflectivity. It appeared to be extremely durable in that the foil can be folded, creased and flattened many times, cannot be torn easily but can be cut with a pair of scissors. This company is an off shoot of the NASA space shuttle research into how to reflect heat away from the shuttle. A sample of this product was procured.

The other product is from Nielsen Enterprises<sup>[73]</sup>. This product comes in a wide variety of thicknesses, reflectivity options and is made as a Mylar film for applying as a coating to mirrors or windows. From the testimonials on the website, the product appears durable, available in up to 7 mil thickness and

be reflective on both sides of the Mylar film. The product is available only in a 56" wide, 10 ft roll. In 2003 the supplier was reluctant to cut a sample and was also reluctant to reduce the width of the roll from at that time 48". A compromise was however reached and an additional fee paid for a smaller quantity which had been cut down. In 2003, this cost USD\$50 plus a shipping charge of USD\$85. In 2008 this same product is 56" wide, and costs USD\$60. A sample of this product was procured for testing and evaluation purposes in 2003.

When both products arrived they were cut into strips and tried in the direct sunlight, with the 3M product and the Nielsen product comparing very well in initial acceptance and reflectivity testing.

## **8.2 The first test panels**

In order to fully test these mirror coatings or substrates, a method of testing had to be developed.

The mirror substrate was placed onto a piece of aluminium which was at a fixed angle (this being the angle to the sun for the latitude of the installation – 43 degrees). Three of these test panels or frames were made to allow for two panels to be put into the field and one to be held in the research laboratory at CPIT as a control. Each test panel was to be square with a side of 300 mm and be manufactured from a 2 mm thick piece of aluminium sheet which was fabricated with the outer edge being folded back to allow the provision of a mounting support frame to give the correct angle, as shown in Figure 8.1. In the assembly of these test panels, three substrates were laid out on the aluminium panels in the same sequence, namely the 3M product, the Clear Dome product, and finally the Nielsen product. Each mirror substrate measured 75 mm by 250 mm.





Rear support bracket mount for test panels to maintain 43 degrees from horizontal.

Figure 8.1. Mirror edge fold-back for correct angle support.

A 3M product called Super 77 adhesive<sup>[74]</sup> was used to glue the substrates to the aluminium panel. This product is a spray on adhesive and is suitable for bonding lightweight materials such as foils, plastics, papers, foams, metals and cardboard. The manufacturer's instructions were followed as to the application method.

It was found that after the mirror substrate and the aluminium surfaces were brought in contact the two surfaces would stick together for a short period of time and then the mirror substrate would curl away from the aluminium backing or mounting plate. This was particularly the case for the original 3M mirror substrate, which had been stored in a rolled format.

Once this was realised, the panels were removed from the assembly environment and placed in a temperature controlled room, with a protective material being placed on a bench top followed by the mirror substrate and aluminium panel complete with a heavy weight (in this case reference books) which covered the entire area of the panel. This was left for three days to allow for a full cure. On removal, on some panels the protective cover had become stuck to the aluminium panel. This was removed by soapy water and scalpel. The panels were then fully cleaned to remove any surplus adhesive or any adhesive which may have become smeared onto the mirror substrate. The three test panels were then distributed to their test locations.

Figures 8.2 to 8.4 show panels on test.



Figure 8.2 a & b. The first test panel (TP#1) on top of the old boiler chimney C block roof CPIT  
September 2003.



Figure 8.3. The second test panel (TP#2) in the author's garden on a seat underneath a Scarlet Oak,  
September 2003.

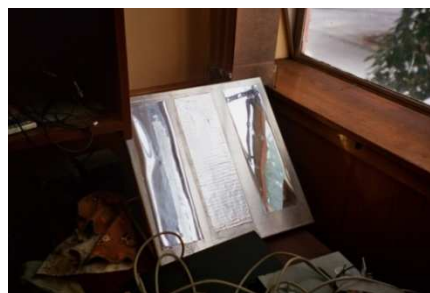


Figure 8.4. The third test panel (TP#3) as located in the research laboratory (C206a) at CPIT,  
September 2003.

The Scarlet Oak, in Figure 8.3 is significant in that it provided a consistent reference point, shade and filtered sunlight in summer and full exposure to the weather in winter, and 'bird' deposits. All of

which the final mirror substrate selected must be able to tolerate without any adverse affect. From Figure 8.4 (TP#3), it may be seen that the 3M product has lifted along the left edge, nearest the book case. This was the case almost immediately after the weights were removed.

Figures 8.5 to 8.37 chronicle the same test panels at six monthly intervals, with yearly photographs of TP#3 as this is the control panel.

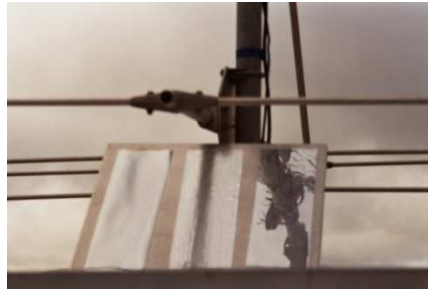


Figure 8.5. TP#1 in December 2003, showing lifting on left hand edge and top right edge of the 3M substrate.

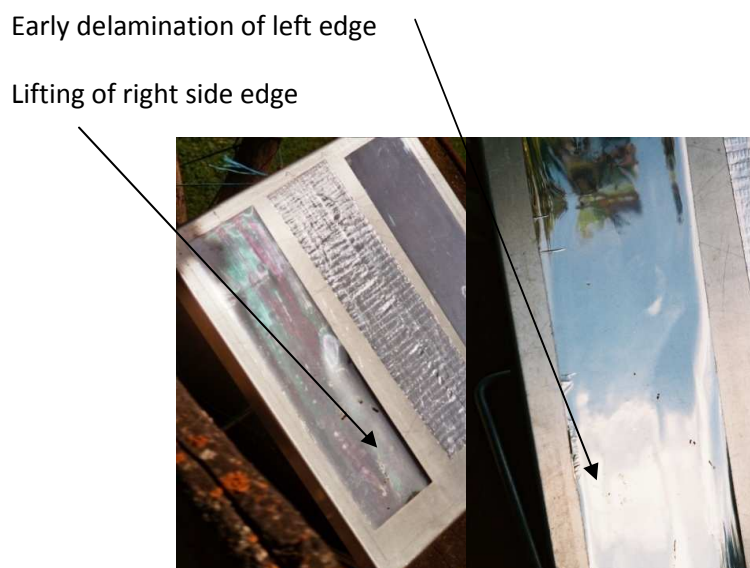


Figure 8.6. TP#2 in December 2003, showing the lifting of the 3M panel on the lower right side and delamination on the left side.



Figure 8.7. TP#3 in January 2004, showing the lifting of the 3M panels on the left side of the 3M substrate.



Figure 8.8. TP#1 in June 2004, all mirror substrates still all intact.



Figure 8.9. TP#2 in June 2004, showing all the mirror substrates still intact, (but with signs of lifting on the 3M panel (right side edge)) and showing signs of weathering, i.e. all substrates are dull.

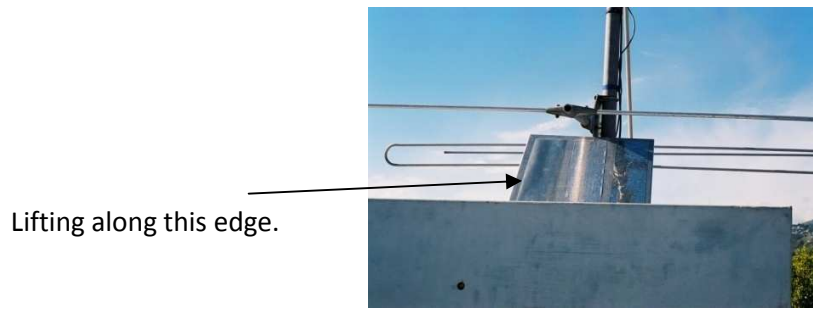


Figure 8.10. TP#1 in November 2004, showing an increase in lifting along the left edge of the 3M substrate.



Figure 8.11. TP#2 in November 2004, with all mirror substrates all intact, but some lifting on the 3M substrate right lower edge.



Figure 8.12. TP#1 in 23<sup>rd</sup> January 2005.

Figure 8.12 taken on the 23<sup>rd</sup> January 2005, shows that some degradation in the original mirror substrate due to delamination of the mirror layer has occurred on the left hand edge of the first test substrate on the first test panel – now fifteen months old. This left hand edge weathered first due to the folded nature of the original substrate causing some lifting on this edge when first glued to the aluminium test panel. The same delamination occurred and is more obvious in Figure 8.13.

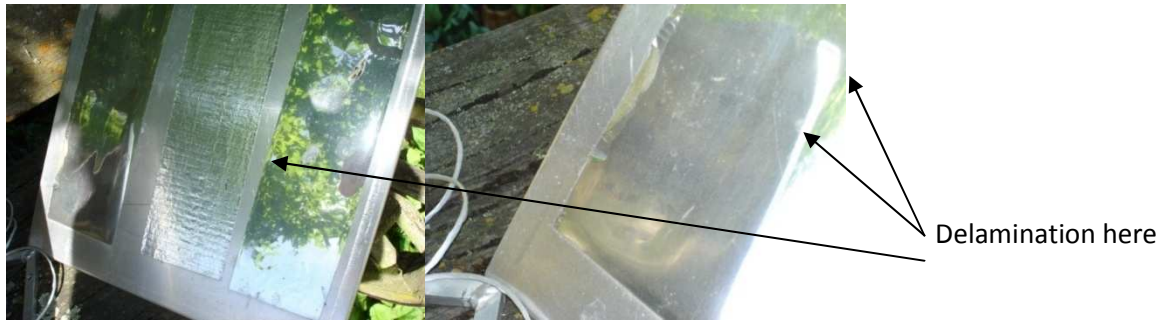


Figure 8.13. TP#2 in 23<sup>rd</sup> January 2005, showing early delamination of the left hand edge which had lifted away from the aluminium panel in earlier figures.



Figure 8.14. TP#3 on 23<sup>rd</sup> January 2005

Figure 8.14 shows all the mirror substrates are intact, but some lifting of the left edge of the 3M substrate from the aluminium panel has occurred.

The common modes of failure of these mirror substrates appeared to be either a failure of the adhesive holding the substrate to the aluminium panel, caused in part by the substrate's natural tendency to retain its rolled shape, or a failure of the front protective Mylar plastic cover due to an impact or a scratch caused by wiping with any object sharper than a 'blunt finger nail' hereafter called a 'blunt object failure mode'. Figure 8.15 shows the effect of the first failure mode, which results in water entering between the substrate and the aluminium panel which causes further separation, then in the event of a strong wind the top plastic layer snaps off taking the entire mirror substrate with it.



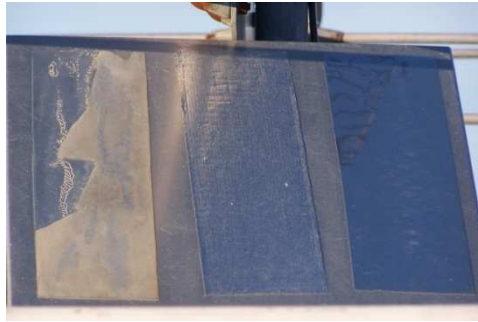


Figure 8.15. TP#1 in 25<sup>th</sup> June 2005, showing a failure of the 3M panel due to the ingress of water, and then wind snapping off the top plastic layer.

With the second mode of failure the edge of the substrate fails due to a blunt object being run along the edge or near to the edge of the substrate. If this is carried out with sufficient force it will cause the top Mylar plastic layer to lift away (delaminate) from the silverised backing paper. With time and water ingress, this silverised backing paper then tarnishes as with all silver when left exposed to the atmosphere. The early stages of the delamination process and the combination of air and water causing the left edge of the silverised layer to commence tarnishing, can be observed in Figure 8.16.

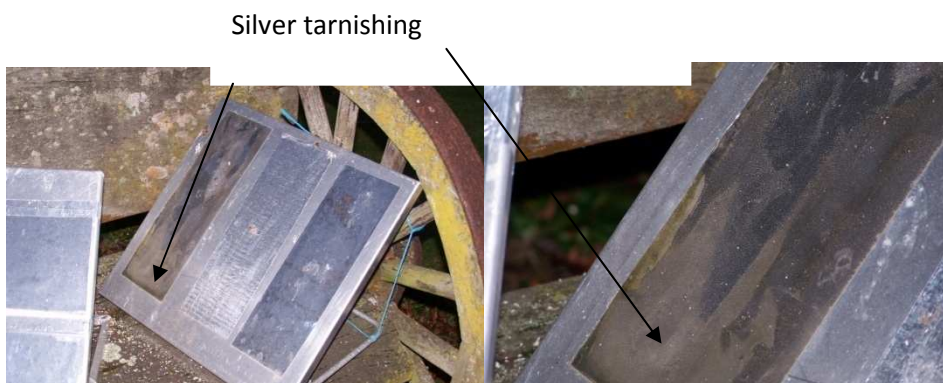


Figure 8.16. TP#2 taken 25<sup>th</sup> June 2005, showing tarnishing of the 3M substrate.

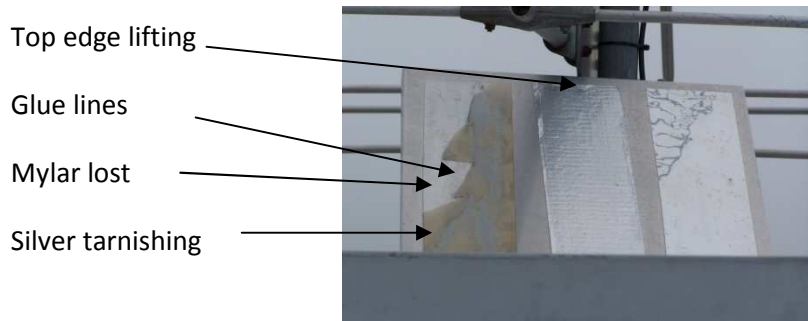


Figure 8.17. TP#1 taken 16<sup>th</sup> December 2005, no further loss of Mylar, only silver tarnishing of the 3M substrate.

As can be seen in Figure 8.17, some lifting of the Clear Dome substrate top edge has occurred, underneath the antenna mast.



Figure 8.18. TP#3 in March 2005.



Figure 8.19. TP#2 taken 16<sup>th</sup> December 2005.

Close-ups of TP#2 from the same date are shown in Figures 8.20 a, b, c and d. The delamination continuing of the left edge of the 3M substrate and new lifting and delamination of the lower right



corner of the same substrate is shown in Figure 8.20 a. Figure 8.20 b shows tarnishing of the left edge of the 3M substrate, while Figure 8.20 c shows some lifting of the Clear Dome substrate on the top edge, and Figure 8.20 d shows normal weathering of the Nielsen substrate.

It should be noted that throughout the tests with these three test panels, no cleaning of the substrate occurred other than that caused by the weather, i.e. no rags or cleaning products of any sort were applied to the test panels, with the exception of a light spot clean to see how the surface cleaned up which occurred in January, 2008.

3M substrate delamination (right edge) followed by the tarnishing of the 3M substrate.



Figure 8.20 a. Delamination and lifting of 3M substrate right front edge.

3M substrate delamination (left edge) followed by the tarnishing of the 3M substrate.



Figure 8.20 b. Tarnishing of left edge of 3M panel.



Figure 8.20 c. Clear Dome substrate top edge lifting.



Figure 8.20 d. Nielsen substrate, showing weathering only with no other damage.

No photographs were taken of the third test panel at this time, as no further visible deterioration had occurred.

### 8.2.1 Mirror substrate testing from 2006

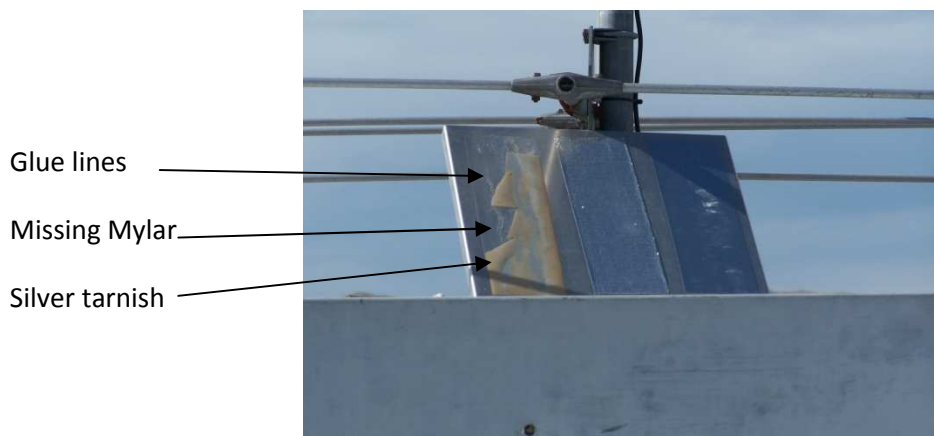


Figure 8.21. TP#1 taken 25<sup>th</sup> January 2006.

The full effect of the top Mylar layer failure and the consequent tarnishing of the silver layer can be seen in the enlarged photograph as shown in Figure 8.21.



Figure 8.22 a & b. TP#2 taken 25<sup>th</sup> January 2006.

Figure 8.22 shows the progressive failure of the 3M substrate with the close-up photograph in Figure 8.22 showing failure of both edges of the 3M substrate, and tarnishing. In this case the silver layer has oxidised away and left the top clear plastic Mylar cover or layer.



Figure 8.23. TP#1 taken 24<sup>th</sup> July 2006, showing the almost total failure of the 3M substrate with wind causing the clear Mylar top layer to break-up, and showing failure of the Clear Dome substrate top right edge.

Lifting top edge    Cracking Mylar



Figure 8.24 a & b. TP#2 taken 22<sup>nd</sup> July 2006, showing the 3M substrate Mylar cracking failure and some lifting of the Clear Dome substrate top edge.



Figure 8.25. TP#3 taken 25<sup>th</sup> May 2006, showing only limited deterioration with some lifting of the 3M substrate side edges.



Figure 8.26. TP#1 taken 19<sup>th</sup> December 2006, showing the lifting of the Clear Dome substrate, and total failure of the remaining 3M substrate.

Total failure of the 3M substrate occurred in October 2006, as shown in figures 8.27 a, b, c, and d.

Shortly before this TP#2 was shifted from the location underneath a 45 year old Scarlet Oak tree as

this was being removed from the author's parents garden, and the test panels are now mounted under the eave of a house, still on the wooden seat and facing due north as opposed to due west and partially being sheltered by the oak.



Figures 8.27 a & b. TP#2 enlarged taken 26<sup>th</sup> October 2006, showing total failure of the 3M substrate (follow the finger).



Figures 8.27 c & d. TP#2 enlarged showing top Mylar layer separation from the silver and backing material.



Figure 8.28. TP#2 showing no further deterioration to the other substrates.



No photographs were taken of TP#3 at this time as no further visible signs of deterioration were observed, except a build-up of dust.

### 8.2.2 Mirror substrate testing from 2007



Figure 8.29. TP#1 taken 18<sup>th</sup> January 2007.

No further deterioration was observed of the 3M substrate, as shown in Figure 8.29, but more lifting of the Clear Dome substrate's top right edge has occurred.



Figure 8.30. TP#2 and AP#2 taken 18<sup>th</sup> January 2007.

The 3M substrate, as shown in Figure 8.30 has continued to deteriorate with the silver layer tarnishing and then wearing away with weather, however the top Mylar layer has just peeled back and is still intact. A further peeling of the Clear Dome's substrate's top edge has occurred however this is still only a slow deterioration in comparison to the 3M substrate.



Figure 8.31. TP#3 taken January 2007.



Figure 8.32. TP#1 taken 19<sup>th</sup> July 2007.

As shown in Figure 8.32, elements of the 3M substrate are still on the test panel, and more lifting of the Clear Dome substrate has occurred.

No photographs are available of TP#2 for July; however as can be seen with Figure 8.33, very little further deterioration occurred, except the final break down of the clear Mylar top layer as evidence by the cracking and upwards curling. Figures 8.34 and 8.35 further show the amount of 'curling' which has occurred on the 3M substrate and how brittle this Mylar top layer has become in January 2008.



Figure 8.33. TP#2 taken November 2007.



Figure 8.34. TP#2 taken in January 2008, as viewed from the rear of the panel.



Figure 8.35. TP#2 taken January 2008, as viewed from the front.

The cracked top Mylar layer is obvious in Figure 8.35. Figures 8.36 and 8.37 show TP#1 and TP#3 in January 2008. The total loss of the 3M mirror substrate is evident in Figure 8.36 as is the lifting of the Clear Dome substrate's right upper edge. The control panel shows only minor deterioration of the 3M panel following gluing and the accumulation of 4 years of dust on all mirror substrates.



Figure 8.36. TP#1 from January 2008.





Figure 8.37. TP#3 from October 2007.

### 8.3 Antarctica test panels

In late 2003, and after discussion with the Project Supervisor, a decision was made to further test the range of new and old mirror substrates and their adhesive coatings in a cold and windy environment, namely Antarctica. For this purpose two additional test panels were manufactured and shipped to New Zealand's research base in Antarctica (Scott Base) for testing, with one test panel being left for twelve months and the other test panel being left for the duration of the summer research season. Two more test panels were manufactured from 400 mm square 2 mm thick aluminium. In this instance, because of the potential for strong winds, the rear brace was made out of a piece of strip aluminium, for robustness, as shown in Figure 8.38. These two test panels were called AP#1 (summer season only), and AP#2 (twelve months). Both panels were shipped to Antarctica with test panel assembly instructions.



Figure 8.38 a & b. AP#1 rear aluminium strip bracing. (13<sup>th</sup> November 2003).

For this test, it was decided to make up six substrates (200mm squares) and try different adhesives. Consideration was given to the possible different rates of expansion of the mirror substrate and the

aluminium mounting or backing plate, to wind and wind chill and to the extreme low temperatures these panels would be subjected to. On this basis, the first three mirror substrates were the 3M substrate, the Clear Dome substrate and the Nielsen substrate applied using Permabond F245 adhesive<sup>[75]</sup> which has an 'excellent resistance to high impact or peel loads, and stresses caused by differential thermal expansion, making it ideal for bonding a wide variety of similar and dissimilar surfaces'.

The second adhesive trialled was Dow Corning Silastic 1080<sup>[76]</sup> (neutral cure), as this had a good temperature rating for the environment and offered some flexibility of movement between the mirror substrate and the aluminium panel. The completed test panels are shown in Figures 8.39.



Figure 8.39. The completed AP#1 and AP#2 test panels following the gluing process – no edge sealing has yet occurred.

As a further test, reflective aluminium silver tape was also applied to the top edges of both of these panels, with the bottom edge being left un-taped. This was done to see if there was any advantage in sealing the edges of the mirror substrates, and is shown in Figure 8.40.

Aluminium self adhesive sealing tape applied in a strip to seal the top edges of the mirror substrates

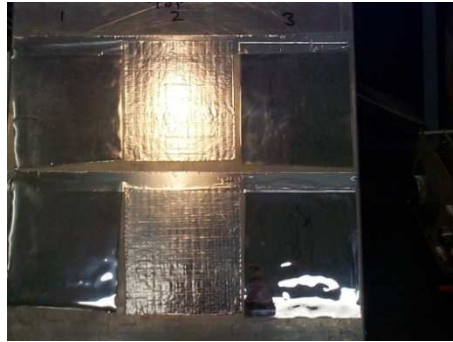


Figure 8.40. Sealed top edge of the mirror substrates.

The two test panels were then sent to Antarctica for mounting and testing as shown in Figure 8.41 a, b and c.

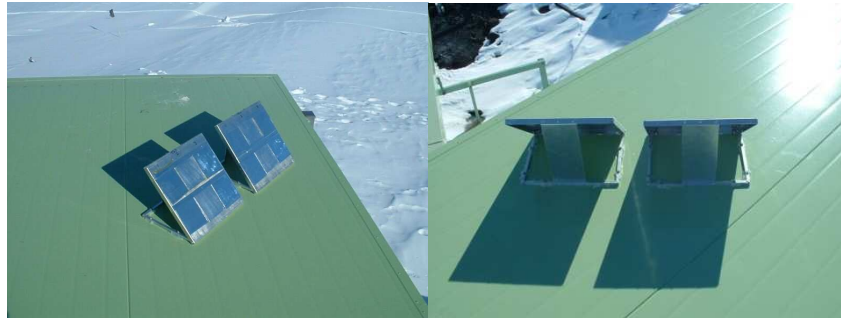


Figure 8.41 a & b. AP#1 and #2 on test in Antarctica.

AP#1 and #2, on the roof of the 'wet lab,' facing north, at Scott Base.



Figure 8.41 c. Scott Base sign post.

AP#1 was returned in March 2004 on the last flight out before aircraft movements ceased for the winter season. The panel had survived the summer and showed signs of dirt around the edges of the

panel and on any raised surface, as shown in Figure 8.42. The returned panel was mounted on the satellite extension platform at C block in April 2004 and was rinsed off following installation.



Figure 8.42. AP#1 on satellite extension platform C block roof, April 2004.

During the winter of 2004, Scott Base experienced its worst storm in forty years of recordings. AP#2 survived this event and was returned to Christchurch in November 2004, and is shown being unpacked in Figure 8.43 in late November 2004.



Figure 8.43 a & b. AP#2 returned November 2004.

On unpacking this panel, it was noticed that it had rubbed against the bubble foam packing, circle marks on all mirror substrate surfaces, and had been either dropped or had an object scrapped across its surface as shown, accentuated in white, in Figure 8.44.

Scratched surface  
(highlighted in white).



Figure 8.44. Scratched surface of AP#2, November 2004.



The blunt object impact on the 3M  
mirror substrate.

Figure 8.45 a & b. Reassembled, cleaned and mounted AP#2 alongside TP#2, November 2004.

AP#2 was reassembled and mounted alongside TP#2 in the author's garden underneath a Scarlet Oak.



Figure 8.46 shows AP#1 on test at CPIT in November 2004.



No visible deterioration was noticed on AP#1 in November 2004 as shown in figure 8.46. However, by January 2005 the 3M substrate with glued backing had started to show signs of delamination particularly where the substrate was struck with a 'blunt object'.

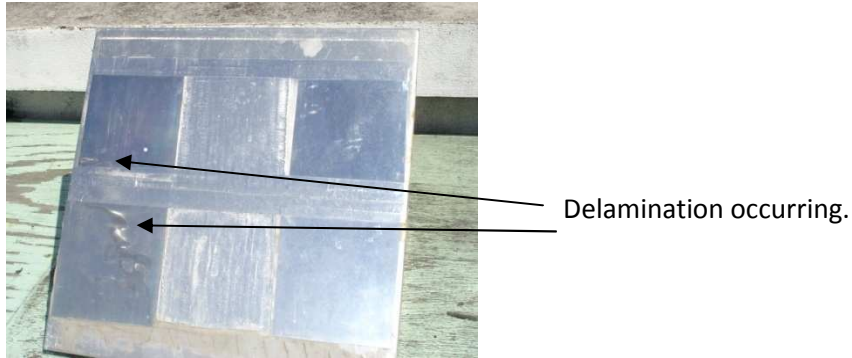


Figure 8.47. AP#1 taken 23<sup>rd</sup> January 2005.

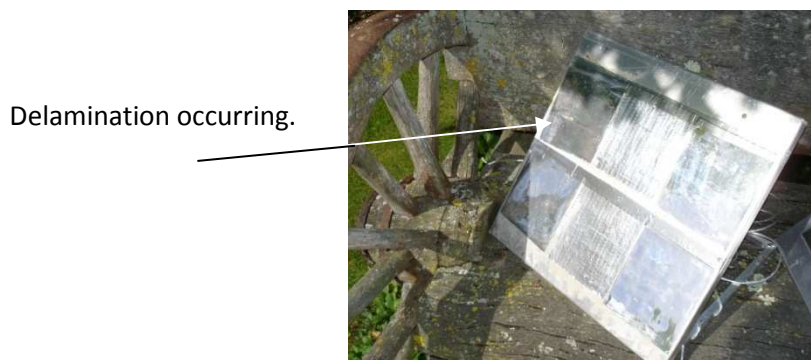


Figure 8.48. AP#2 taken 23<sup>rd</sup> January 2005.

When AP#2 was returned it had suffered a blunt impact across the front upper surface which was evident from the initial inspection upon the panel's return. However, exacerbation of this was now showing up in the photographs in Figure 8.49, from 25<sup>th</sup> June 2005.

Delamination occurring and tarnishing on AP#2.

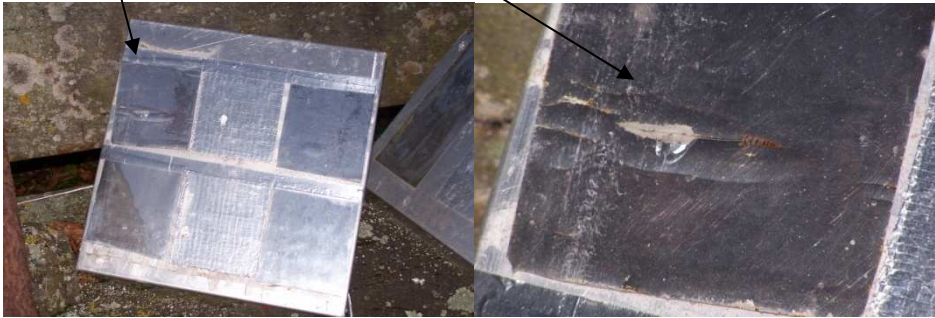


Figure 8.49 a & b. Delamination on AP#2 taken 25<sup>th</sup> June 2005.

As shown in Figure 8.49 the centre of the 3M panel has a cracked Mylar layer which has delaminated from the silver and backing layers. This has formed a bubble which then cracked and allowed the ingress of water and air to enter with the resulting decay and tarnishing of the silver layer. There is some edge deterioration on the 3M substrate. The Clear Dome and the Nielsen substrates both withstood the same environment well and showed no signs of deterioration.

Delamination and bubbling.



Figure 8.50 a & b. AP#2 taken 16<sup>th</sup> December 2005.

Figure 8.50 shows the continued deterioration of AP#2, 3M substrate.

Figures 8.51 a, b and c show AP#1 in January 2006, with close-ups of the 3M substrate deterioration, and some lifting of the inner edge of the upper Clear Dome substrate which was glued. Figure 8.51 a

also shows the RTV Silastic applied 3M substrate commencing to tarnish due to a crack appearing in the Mylar layer. This is perhaps more obvious in the Figure 8.51 b.

Earlier edge delamination due to blunt object rubbing.

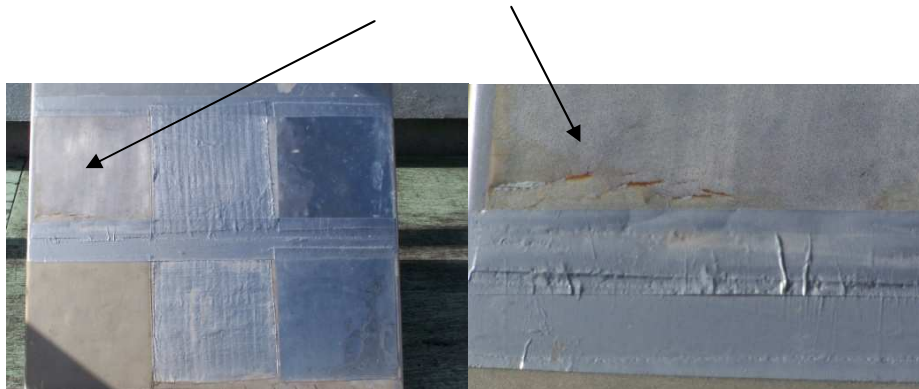


Figure 8.51 a.

Figure 8.51 b.



Figure 8.51 c. AP#1 taken 25<sup>th</sup> January 2006 showing substrate failure 3M substrate.

Figure 8.52 shows the progressive failure of the 3M substrate.





Figure 8.52 a & b. AP#2 25<sup>th</sup> January 2006, progressive failure of the 3M substrate.

Figure 8.53 is taken in July 2006 and is of AP#1 and clearly shows the total failure of the 3M substrate with both the permabond and RTV adhesives.



Figure 8.53 a & b. AP#1 taken 24<sup>th</sup> July 2006, 3M substrate failure.

Figure 8.54 shows the continuing failure of the 3M substrate.



Figure 8.54 a & b. AP#2 taken 22<sup>nd</sup> July 2006, the continuing failure of 3M substrate.

Figure 8.55 shows the total failure of the 3M substrate.



Figure 8.55 a & b. AP#1 taken 18<sup>th</sup> January 2007.

Figure 8.56 a, b, and c shows AP#2 'bubble' growing and failure of other parts of the 3M substrate. A light cleaning was performed on the RTV applied Nielsen panel as indicated.



Figure 8.56 a.

Figure 8.56 b.



Figure 8.56 c. AP#2 taken January 2007, with a light cleaning of a small area of the Nielsen substrate.

Figure 8.57 a, b, c and d shows the total failure of the 3M substrate, some lifting of the Clear Dome RTV substrate and a light cleaning of the Nielsen RTV substrate.



Figure 8.57 a.

Figure 8.57 b.



Figure 8.57 c.

Figure 8.57 d.

Figure 8.57 a to d. AP#1 taken 24<sup>th</sup> July 2007.

No pictures were taken of AP#2 in July 2007, as no noticeable change in its condition had occurred.



Figure 8.58 a, b, c, d, e and f show the six separate substrates for AP#2 from November 2007 with 8.58 c showing the effects of a 'blunt object impact' and 8.58 f showing the results of a light cleaning.



Figure 8.58 a.

Figure 8.58 b.

Figure 8.58 c.



Figure 8.58 d.

Figure 8.58 e.

Figure 8.58 f.

Figure 8.58. AP#2 taken 12<sup>th</sup> November 2007.

Lastly, Figure 8.59 a & b show AP#1 in January 2007, with the completion of testing of the mirror substrates. Of interest is the slight tarnishing which has just started to appear on the Nielsen permabond substrate, which is more obvious in the enlarged Figure 8.60.



Figure 8.59 a & b show AP#1 and the complete failure of 3M substrate and slight tarnishing on the Nielsen substrate.

Slight  
tarnishing  
on Nielsen  
glued  
substrate.

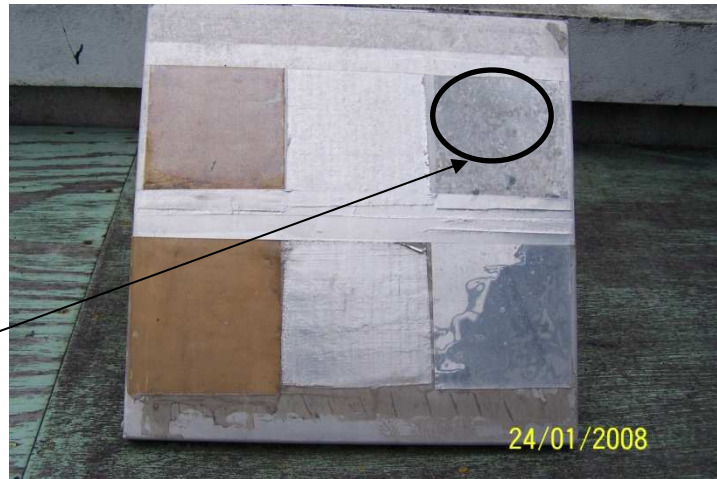


Figure 8.60. AP#1 Jan 2008.

Figure 8.61 shows AP#2 taken in January 2008 at the conclusion of mirror substrate testing showing the weathering which has taken place on the Clear Dome and Nielsen substrates and the failure of the 3M substrate.



Figure 8.61. AP#2 taken 24<sup>th</sup> January 2008.

In respect to the light cleaning which was performed in early 2007 and again in January 2008, the cleaned areas as shown in Figures 8.62 a, b & c show that the Nielsen substrate could be lightly cleaned to improve reflectivity, however it could also smear the substrate resulting in a total loss of reflectivity in the cleaned area, as seen in Figure 8.62 a & c.



Figure 8.62 a.

Figure 8.62 b.

Figure 8.62 c.

Figure 8.62 a to c. Spot cleaning of the Neilsen substrate in January 2008.

#### 8.4 The SET test panels

The original inventors decided to use the 3M substrate, as this was all that was available at that time.

The 3M substrate was applied to the mirrors as delivered to CPIT initially. These are shown in Figure

8.63 a & b.



Figure 8.63 a & b. The original substrate (3M) as was applied by the inventors.

All the mirrors were shipped wrapped in polystyrene and plastic bubble packaging and stored in a shed on the roof, only being handled when necessary. Three mirrors were test mounted onto the SET in late 2003, and later removed and stored back in the shed. In 2004, following the completion of the remedial action as outlined in the mechanical engineer's report, the remaining mirrors were installed, complete with 12 mm thick black high density foam and a cover sheet, as shown in Figure 8.64. The intention at this point was to prove the PLC tracking and safety shut down mechanism and

then to progressively lower the cover sheet. However, at this point the student who was assisting at the time decided to photograph the SET and so dropped the cover sheet, removed all the foam insulation and then raised the cover sheet once the photographs were taken. The foam insulation was never replaced by the student who in his haste to remove it tore the foam insulation rendering it useless. This has meant that the mirror substrate has become dull and lightly scratched.

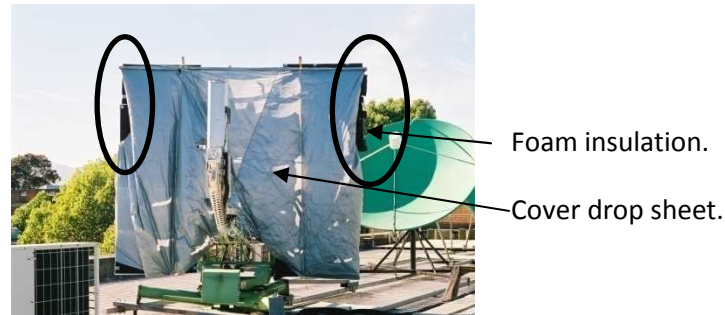


Figure 8.64. Foam and drop covers installed over the mirrors to prevent scratching and damage to the substrate surface.

Throughout the SET testing in 2005 and the early part of 2006 the only protection for the SET mirrors was the cover drop sheet. The cover drop sheet was necessary because of the NW park position in 2004 and 2005, the lack of alignment of the mirrors to the target in 2005, the variability of cooling water flow in 2004 and 2005, and the inability of the SET to shut down correctly on faults or shut down alarms.

As the PLC code was progressively 'debugged' and the SET was proven, the cover sheet would be dropped for day testing (early 2006). It was at this point that the full extent of the damage caused by the cover sheet rubbing on the mirror substrate was realised. Minute scratches in the Mylar layer surface appeared and the rubbing of the drop sheet cover on the mirror substrate left the mirror substrate with a dull appearance which reduced its reflectivity, as shown in Figure 8.65.





Figure 8.65. The dull 3M mirror substrate, January 2008.

After much research and many trials with car cleaning and polishing compounds it was found that a silicone polishing compound, called Silicone Tyre Shine<sup>[77]</sup>, which goes on as a liquid but dries quickly, provided a short term solution and restored the 3M mirror substrate to an ‘as new’ condition, as shown in Figure 8.66 with a contrasting before and after photograph. It can also be observed from Figure 8.66, that each mirror substrate panel is curved which adds to the overall parabolic focussing effect of the SET and improves its ability to focus the sun’s radiation more effectively onto a target.



Figure 8.66 a & b. 3M mirror substrate before (a) and after (b) polishing.

Throughout the test panel testing, a method of determining each substrate’s reflectivity has been sought. Attempts using reflectivity and lux meters have been tried, as have attempts by placing a piece of dry leaf or paper at the focal point of the reflected panel’s image. To date none of these have yielded any successful and repeatable results. The method which was discovered some time back relates to an ‘unscientific’ and definitely not a typical ‘engineering approach,’ is the use of the ‘back of a hand’ placed at the focal point of the reflected solar energy from the mirror substrate



being tested. Using this method the reflected energy from the Clear Dome substrate when new is minimal, the reflected energy from the 3M substrate is good (i.e. the 'back of the hand' got 'hot' after five minutes), and the Nielsen substrate is excellent (i.e. the 'back of the hand' got 'hot' after three minutes). With weathering and aging the Nielsen substrate in its 'raw' unclean state and using the same test criteria in 2008, the Nielsen mirror substrate receives a good rating with a 'hot' time of nine minutes.

## **8.5 Future solutions**

From the above testing it may be concluded that the Nielsen substrate shows promise and is worthy of purchase for any further developments. It should be noted though that the Nielsen substrate does show signs of tarnishing. It can also be seen from Figure 8.60 that the substrate is not totally immune to the effects of UV light with any 'blunt object' damage manifesting itself some time later as the top Mylar surface delaminating from the silver layer, as shown in Figure 8.58 c.

The other issue which needs to be addressed with any further development of the SET is the requirement to clean the panels. A possible solution to this has been found with the application of a pure silicone car care product (Silicone Tyre Shine – as used for applying to the rubber of car tyres, to make them 'shine'). However, the life expectancy of this product when applied to the 3M mirror substrate was 6 to 8 weeks depending on the amount of rain which fell in this period, before the mirror substrate was returned to its natural unpolished state. Before applying the Silicone Tyre Shine product, the mirrors were cleaned with warm soapy water and then rinsed off and allowed to dry. This silicone based product proved to be capable of filling in any gaps or light scratches in the substrate's surface. The Tyre Shine product was applied with a brush and then lightly polished or buffed with a clean cloth by hand.

It is obvious that the clear Mylar protective layer scratches and marks easily, is capable of being easily 'bruised,' and will deteriorate over time depending on its treatment. However, it is still capable of good reflectivity even after over four years of continuous testing.

The conclusion from this testing is that there is no issue with the choice of adhesives and sealants used. The edges of any substrate as applied to the aluminium panel must be sealed with a non-porous UV resistant tape. The Nielsen substrate appears to be the best currently available for this application, but care needs to be taken in handling, installing and cleaning it. A non-abrasive and longer lasting cleaning and polishing compound is still to be found.

Throughout this testing process attempts were made to ascertain the amount of reflectivity of each mirror substrate as have been detailed previously with the only effective method found being to test the mirror substrate on the SET or to use the 'back of hand method'.



## **9.0 SCADA System & Ancillary Controls**

### **9.1 SCADA system and selection**

Currently there are several systems for logging temperatures and events in the control systems market place. The system chosen for this installation was based on the Intech Microscan platform. The Microscan platform is a full SCADA (Supervisory Control And Data Acquisition) system. Whilst many SCADA systems are tag based and follow a 'top-down' philosophy, the key difference with this SCADA system is that it is written from the bottom up, i.e. the sensor interface is more important than the control side of the SCADA package.

This means the sensor interface is easier to configure than on many other SCADA software packages or on a typical SCADA and PLC package (for example Rockwell Micrologix with RS View 32). CPIT had purchased, many years ago, a full license for this system along with two Microscan 2000 SCADA stations. The purchase included all the ancillary software tools which are not normally included. Thus the package included recorder and mimic display, add on toolkit and remote alarm server. This allowed a recorder system to be set up and configured very quickly. The CPIT had also purchased an unusual configuration of SCADA stations at that time, namely an 8 channel differential analogue input station, called a 2000-AI station with fixed input range of 0 to 20 mA, and a 12 channel digital relay output station, called a 2000-DO station. The system had not seen use for a number of years.

Initially the SCADA system ran on an older 80486 computer, with an out of date version of software (v4.0). In 2004, in order to assist in quickly getting the system operational with the SET, it was decided to purchase a more 'universal' analogue input station called a 2100-AO which came with 8 universal inputs (current or voltage), 8 analogue outputs (current or voltage), 12 digital inputs and 2 relay (digital) outputs. The analogue inputs and outputs are configured by a combination of SCADA configuration software and dip switch settings in the SCADA 2100-AO unit. The communications protocol between the computer (PC) and the SCADA station (#1) is AIA-422A. The communications interface, between the PC and the SCADA station is an EIA-232 to AIA-422A protocol interface

converter (formerly, called an RS232 to RS422A interface). An attempt was made in 2005 to interface and use the 2000-AI station, but this failed as the student's interface PCB (voltage to current converter) was not ready in time.

In December 2005 the software was updated to version 5 which necessitated the purchasing of a new type of Dongle and software updates. In 2006, it was realised that another SCADA station was required for the additional solar thermal research projects being undertaken during that year, this was a 2100-AO and allocated as station #3 in the SCADA list. Later in 2006, with more solar thermal work expected in 2007, additional SCADA stations were purchased. These were of the 2100-AO type again and it was allocated station #9. An additional 2100-AO station was procured, station #2 in May 2007. At this point the other older 2000-AI and 2000-DO stations (stations #5 and #8 respectively) were successfully re-commissioned and reconnected to the SCADA network. These were used for the recording of additional solar thermal research and development projects conducted during that year, including research into airwalls and pool mats. The extent of the revised and updated SCADA network as at 15<sup>th</sup> March 2008 is shown in Figure 9.1.

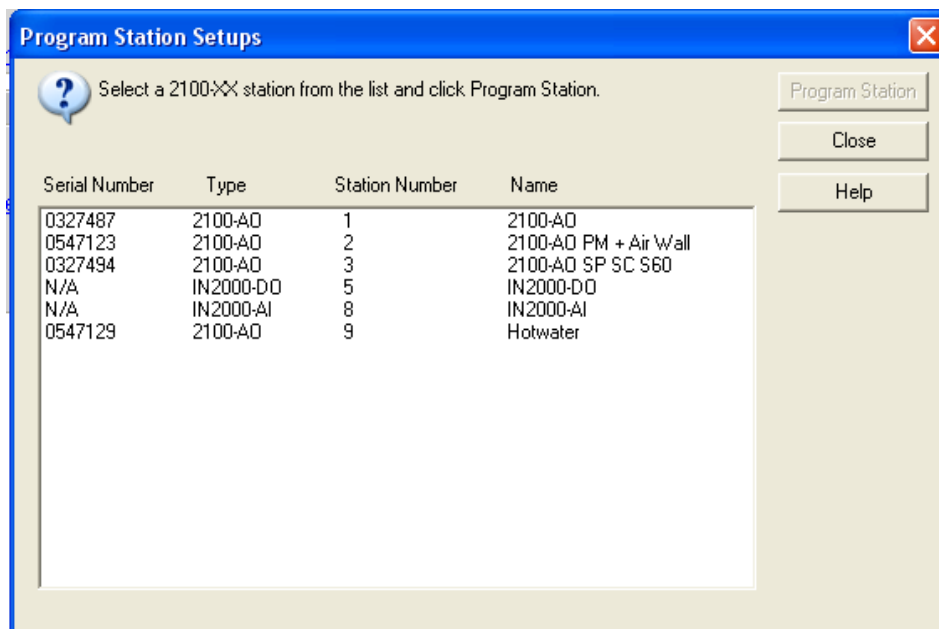


Figure 9.1. SCADA station listing.

The layout of the SCADA stations on the second story of C block and their association with the research activity is shown in Figure 9.2. The SCADA stations were progressively added as required for research and development activities, with the SCADA station being added being named and associated wherever possible with the research activity.

Thus, the SET is associated with station #1 and there are several CAT5E data cables connecting the SET to the SCADA station. In 2004 some research was being conducted into an evacuated tube thermosyphon batch collector on the mezzanine roof of C block and so the balance of SCADA inputs were at that time allocated to this solar collector. Station #3 was used for both activities. In 2005, the solar collector was moved to the second storey roof, and mounted alongside an evacuated tube heat pipe system which was purchased from one of the author's CPIT Publication Incentive Grant (PIG) funds. A coiled pool mat mounted under glass was added to this station. In 2006, the areas of solar thermal research had grown to include two flat panels and a solar trough collector; station #3 was used for the two flat plate collectors and the spare capacity from station #1 was used for the controls on the solar trough collector (this was later replaced by a small PLC). In 2007, with further research being requested into the area of solar thermal, more hot water cylinders were added to the system and thermal layering being investigated (station #9 was added for this). A pool mat system was installed; station #2 was added for this purpose. A new sponsor joined (2007) with specific areas of research and development and this saw the addition on stations #5 and #8 into the SCADA network. August 2007 saw the addition of a new type of collector, called an Air Wall (AW). In December 2007 a Transpired Air Wall (TAH) and a PV AW were later additions to the SCADA recording system. Because of a space limitation, the SS Blue system is an evacuated tube finned heat pipe system with blue coating, and the SS Black system is an evacuated tube heat pipe system with black coating.

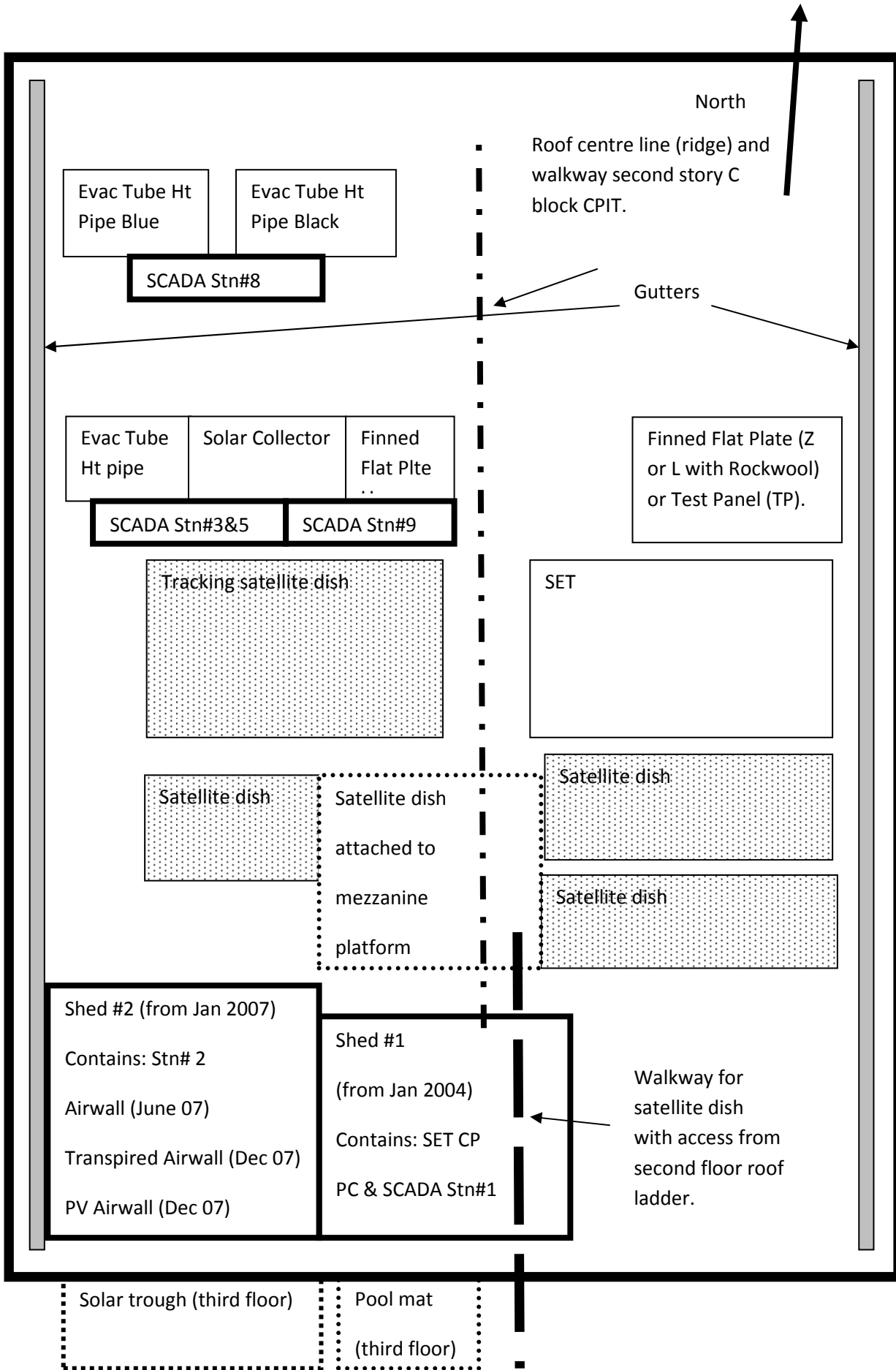


Figure 9.2. SCADA station location listing.

With the number of temperature recordings required, a cheap means of measuring temperature was required. The device had to be flexible enough to allow immersion in the water whether this be hot or cold, able to be strapped to the outside of a pipe and accurately measure the temperature of the fluid inside, to within ½ to 1 °C, as well as being relatively cheap, available and robust. Such a device was discovered in the LM335. There are three versions available, one for Fahrenheit, one for Kelvin and one for Celsius. In 2004, the Kelvin range was purchased, in 2005 the Fahrenheit range was carried in stock, and in 2007 it was decided to stock and carry only the Celsius range for CPIT student projects. The advantage of this device is it that it is robust, relatively cheap, accurate to within 1 °C, and capable of being calibrated using a single point calibration check and a fixed resistance. The device draws its power from either a 12 V DC or 24 V DC supply.

The 2100-AO station is configured to accept voltage inputs from the LM335 temperature sensors via a calibration and current limiting series resistor. The SCADA system then applies a scaling factor to this raw data. This scaled data is then presented to the display. The SCADA system has been configured such that the data is then recorded to a 'report number with day.csv' file for every fifteen seconds of each twenty four hour day. A new file is created each day. The report as it is called by the SCADA software can be configured to contain up to two hundred and fifty entries or lines. Each channel on the 2100-AO SCADA station has 12 bit resolution.

The SCADA software can be configured to log digital inputs, with four digital channels of the 2100-AO SCADA station able to be configured as counters, whilst the remaining channels record on/off event status. In 2006, these digital counter inputs were connected to digital flow sensors and used to record flow rates of the solar thermal devices. A compact flow sensor was found from RS Components (#185-9982), with a PTFE filled nylon rotor on a stainless steel shaft, suitable for flow rates from 1 to 20 l/m, with a working temperature range +5 to +50 °C and featuring a low pressure drop. This flow sensor is of the turbine type, with flow through the unit causing rotation of the



turbine which interrupts the photo-electric beam housed in the unit. The signal is then processed with the resultant pulse output being proportional to the flow rate.

The solar thermal devices used had differing flow rates ranging from 2.2 l/m up to 6 l/m depending on the attached circulation pump, the selected speed and the pipe size. At this time a problem was revealed in that the counter inputs on the 2100-AO were only capable of recording correctly up to a frequency of 50 Hz. The pulse train produced from the compact turbine flow meter used was suitable for two of the solar thermal devices it was intended for, but unsuitable for the third. For this unit a frequency divider interface sub-circuit was used with the correcting multiplier being applied in the SCADA recorder.

The 2100-AO SCADA station is also capable of performing limited control functions using its two relay digital outputs. These outputs were used in 2006 for controlling a hot water cylinder (HWC) and preventing it from becoming too hot by initiating an over-temperature dump. The digital output was configured such that when the temperature of the HWC reached 65 °C, its output would turn on for ten seconds which in turn signalled a PLC to turn on the hot water cylinder purge and dump valve for five minutes. The latter time was set to allow the layer or 'slug' of hot water in the top of the HWC to be exhausted and the remaining layers to mix with the incoming cold water and thereby reduce the overall temperature in the HWC.

The SCADA system has been reliable in operation except for some AIA-422 network communication problems with the older SCADA 2000 series stations (the newer network operates on a different wiring configuration) and, in the latter part of 2007, the EIA-232 to AIA-422 PC interface adaptor and the EIA-232 port on the computer seemed to latch-up, requiring a reboot of the computer. Initially it was thought that the interface was 'locking-up' based on incorrect line termination resistance. With the installation of line termination resistance the problem reduced, however the problem has reappeared. The only apparent means of 'clearing' the fault is for the computer to be reset. The CPIT

technicians, at the request of the author, were supposed to have enabled or scheduled regular midnight maintenance activity on this computer, but this would appear not to have been done.

## **9.2 SCADA & PLC controls 2005**

In 2005, with the advent of a coil pool mat collector and the reinstatement of the batch solar collector, a small PLC was required to control the sequencing of water. The mains powered PLC with 10 I/O (6 inputs and 4 relay outputs) was purchased from Rockwell for \$150.00. This was used to sequence the valving and circulation pump required for the coil pool mat collector and for the batch solar collector. At this point in the solar system's development, because the batch solar collector was of the low pressure type, its contents were dumped into an intermediate low pressure tank located directly beneath it. The PLC controlled the fill and dump solenoid valves and circulation pump sequence.

The batch solar collector water fill level is set by the height of the overflow exhaust pipe on a rubber bung and then inserted into the batch solar reactor's storage vessel or hot water tank. The drain and timings on the associated PLC were then set such that it took fifteen minutes for the 55 litres to drain completely and five minutes to fill back to this level with the circulation pump used. As this solar collector is a batch type and used evacuated tubes with a thermosyphon principle, it was calculated and then measured that in summer the maximum gain from this system was 10 °C per hour. Assuming a 20 °C inlet water temperature, (based on an inlet mains water temperature of 10-12 °C for winter and 15-16 °C for summer, plus a safety margin) the cycle timer for flushing the system was set to dump and refill every 5 hours provided there was daylight.

The coil pool mat plate collector used Normally Closed (NC) solenoid valves and a circulation pump controlled on timers via the same PLC. The coil pool mat system comprised three 25 mm lengths of black 13 mm irrigation pipe (alkathene) mounted and tied onto a board mounted at 43 °C and then placed under 4 mm of safety glass. Water enters on the outer edge and leaves in centre of the panel. In the absence of any temperature or flow measurement, the PLC was programmed to flush the coil

pool mat collector every 30 minutes for 10 minutes provided there was daylight. This appeared to work well, however, a failure of the pipe used in the coil pool mat collector lead to a no water condition in the intermediate low pressure tank, which caused two attached circulation pumps to fail and material damage to the other attached collectors. This was in part due to their being no level interlock on the intermediate low pressure tank, as well as the required project tasks not being completed correctly.

Connected on the same pipe-work system was an evacuated tube heat pipe system with a continuous flow manifold. This system was mounted and equipped with temperature and flow sensors, neither of which was connected to the SCADA or PLC systems. Total failure of the coil pool mat collector system caused the circulation pump to operate 'dead-ended' and overheat on the evacuated tube heat pipe system as the 'hot' side of this collector fed into the common intermediate low pressure tank. This system came as a packaged system with frame, evacuated heat pipe tubes, circulation pump, and system controller.

At this time the intermediate low pressure tank acted as a storage facility which was connected to a 290 l domestic HWC with a separate heat exchange loop. The HWC was mounted on the roof in the open atmosphere and had no other form of heating, but did have two thermometer pockets for recording temperatures. The cold side of the HWC's heat exchanger fed back via a 25 mm diameter black polyethylene pipe to a common header from which the evacuated tube heat pipe CP and/or the coil pool mat collector or the evacuated tube heat pipe and/or the batch solar collector could pump 'colder' water. This system seemed to work well once all the air was removed from the system, and until the pipe split on the coil pool mat collector.

### **9.3 SCADA & PLC controls 2006**

In 2006, following the failures of 2005, the low pressure intermediate tank level was interlocked with the PLC controls. An interposing relay was installed on the evacuated tube heat pipe circulation pump system such that on low water level in the intermediate tank, the circulation pump would be

disabled even if called on to operate by the heat pipe evacuated tube's controller. The damage to the solar batch collector system was repaired, and changes were made to the interlocks and plumbing layout including the addition of check valves, before the system was re-commissioned. The evacuated tube heat pipe circulation pump was replaced, check valves installed in the plumbing system, and the PLC interposed relay circulation pump low level interlock added to the PLC software and failsafe hardwired into the control cabinet. Finally, both the solar batch collector and the evacuated tube heat pipe systems were connected to the SCADA station for logging of the evacuated tube heat pipe's flow rate, inlet and outlet temperatures, the batch reactor inlet and outlet temperatures and much later in 2007 the circulation pump, turning on as a digital input into the SCADA station.

This year saw the arrival of the first thermal sponsor, with the sponsor supplying three collectors of differing designs. The first design was of a traditional standard design as sold by the sponsor, comprising – a flat plate of 'L' design. This design is normally mounted long ways up a roof, however in the CPIT installation, the 8' by 4' panel is mounted sideways across the roof to reduce the 'sail' effect in a strong southerly wind. The 'L' design is such that water enters in one side via a cold water header and is piped off via smaller diameter laterals to a hot water header outlet on the diagonally opposite corner of the panel. This panel was supplied complete with all plumbing, check valves, insulation for copper pipes, circulation pump and controller. It was connected to the SCADA system allowing flow as well as inlet and outlet temperatures to be recorded.

The second panel was a 'Z' design, also from the first sponsor. Once again this system came complete with all the necessary items to make it operate and was likewise connected to the SCADA system. With both systems, the inlet and outlet temperatures and flow rates were recorded as well as temperatures across the rear of the Z panel.

The focus of the investigations were: what is the optimum pipe size for maximum efficiency, what is the efficiency of the different panels and can a 'Z' panel be operated in a Christchurch winter,

successfully without failure. To simulate real-life, normal domestic draw off, the HWC was flushed every 6 hours for five minutes. Also, the HWC was flushed at 0500 every morning.

The third system was an early trough collector from Australia. This system contained three heat pipes with associated troughs connected to a modified 320 l HWC mounted sideways. The three heat pipes pierced into the HWC. In Australia, this system was called a 'Suntrac' (now obsolete) as the troughs follow the sun in one axis. The system worked from a separate set of twin pipes, one coated in black and the other being clear. When exposed to sunlight the water in the black tube heated up and expanded, and in so doing caused the piston it was attached to, to change its position causing the 'sails' or troughs which were attached to the piston by cable to also move and hence follow the sun. The HWC was also equipped with a thermostat and an electric element for providing an electricity boost or top up. In Australia, mounting a HWC on the roof is common as there is normally no room inside the dwelling, especially for this size of HWC. This system was not connected to the SCADA system, but did use its own small 24 V DC PLC to control the electric actuator which replaced the water piston which had split as the result of a severe frost. The electric actuator drives the 'sails' by means of a cable on a timer basis from the PLC.

#### **9.4 SCADA & PLC controls 2007**

Further extension of the solar thermal system occurred in 2007, with the addition of individual hot water cylinders (HWC #2 and #3) for both flat plate panels, the addition of a pool mat solar thermal system and the addition of two new solar thermal panels complete with hot water cylinders #4 & #5 from a new sponsor.

The revised and completed system with all major plumbing connections is shown in Figure 9.4. This year the focus for the first solar thermal sponsor was on determining the amount of layering in a typical HWC; determining the optimum angle for the flat plate collectors; ascertaining the optimum controller and pump settings; developing a method of quickly ascertaining the efficiency of a solar

thermal system (called the test panel, TP); and measuring the drop in efficiency with age of the existing finned flat plate collector.

With the solar thermal system revision and the addition of two more HWCs the PLC programme was modified to allow for reduced flow due to the addition of two extra HWCs. The flushing time remained at 0500, with the flush timer lengthened to twenty five minutes to allow for all three HWCs to be flushed with cold water. The flush load cycle timer was decreased to 5 hours from 6, with the five minute flush cycle timer's time remaining unchanged. As with the 2006 version, the SCADA system could still initiate a dump cycle based on excessive temperature in any of the HWCs.

The pool mat system was added with its own controller, water holding tank and radiator load (twin copper pipe with aluminium fins). This system was interfaced to the SCADA system with inlet and outlet temperatures and thermostat turn-on cycles being recorded. The goal was to determine how efficient the pool mat was. Under a domestic situation, the surface area of the pool is the area of the pool mat. However, in this CPIT situation this was not feasible (due to physical size constraints and roof accessibility), and so an area correction factor was applied. This has been reflected in the final performance calculations.

The new sponsor in 2007 presented one new solar thermal system design for testing against another solar thermal system. Both these systems were placed onto the roof and fully interfaced with the existing plumbing and SCADA system. These two systems were both evacuated heat pipe systems, one of 38 mm diameter pipes (SS Black in Figure 9.4), the other with a 75 mm diameter (SS Blue in Figure 9.4). The 75 mm diameter system was an evacuated heat pipe tube design but with a black nitride coated fin attached to the heat pipe. The research investigation was to determine how much extra energy is required for a light industrial or accommodation establishment, to boost a HWC to 60 °C once in 24 hours to meet Ministry of Health guidelines. This is in contrast to the Building Act which recommends that the HWC water temperature be taken to 70 °C once in 24 hours. Both government bodies site the same reason as the risk of Legionella being present or existing in the

HWC unless their respective temperature requirements are met. A small PLC was installed and programmed for this system as well, allowing for 0400 flush cycles, five minute flush cycles three times every day (at 0800, 1200, 1600), with the SCADA system initiating a five minute flush cycle based on an over temperature alarm with either HWC #4 and/or #5. Manual flushing was also permitted with this PLC programme.

In 2007, the SET target temperature as read by the PLC was connected to the SCADA system to allow comparison of the target temperature with the hot water exhaust temperature.

In June, another sponsor arrived requiring testing of airwall panels, where air is used as the media to cool an absorber panel exposed to the sun rather than water contained in a copper pipe. These systems were added to shed #2 and connected to the SCADA system for temperature and event logging.

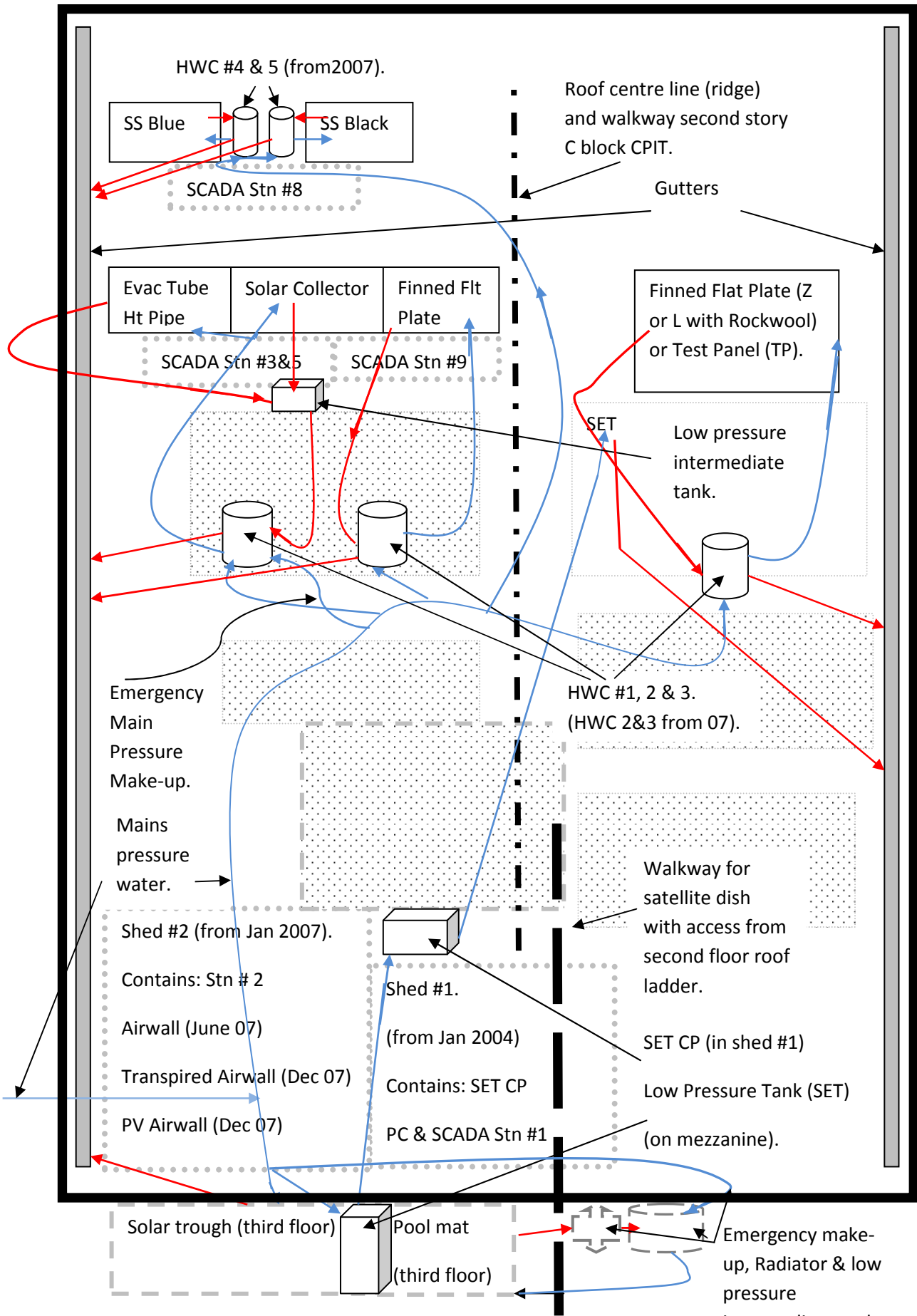


Figure 9.4. Plumbing layout for solar thermal CPIT 2007.



## 9.5 Sunlight hours

CPIT had procured a calibrated pyranometer from Kipp and Zonen<sup>[78]</sup> in 2002. This pyranometer was originally installed on the batch solar collector. However, when this experiment ceased in 2004, it was moved to the SET, as shown in Figure 9.5. This pyranometer was calibrated, by Kipp and Zonen, as having a sensitivity of  $18.42 \mu\text{V} (\text{W}/\text{m}^2)$ . Despite several attempts to interface this with the SCADA system, this proved impossible to achieve. The pyranometer was instead connected to an Agilent 34970A data acquisition instrument, which was set up to log the pyranometer directly. This data was then extracted as a CSV file every twenty one days to a PC, where it was later analysed in an Excel spreadsheet.

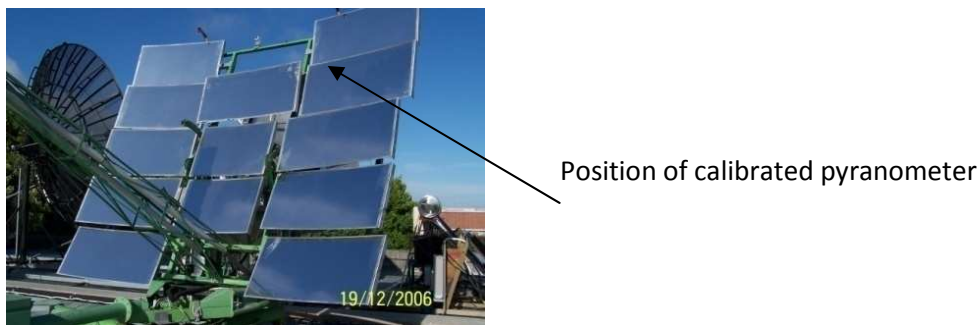


Figure 9.5. Position of calibrated pyranometer on SET.

It was thought that sunlight hours may vary between the fixed solar collectors and that as measured by the pyranometer mounted on the SET, also if the SET was parked for any length of time this would affect the results. A separate industrial grade pyranometer was purchased from Intech Instruments<sup>[79]</sup> which came with a 4-20 mA output. It was installed on one of the fixed solar collectors as shown in Figure 9.6. This allowed it to be easily interfaced into the SCADA system.

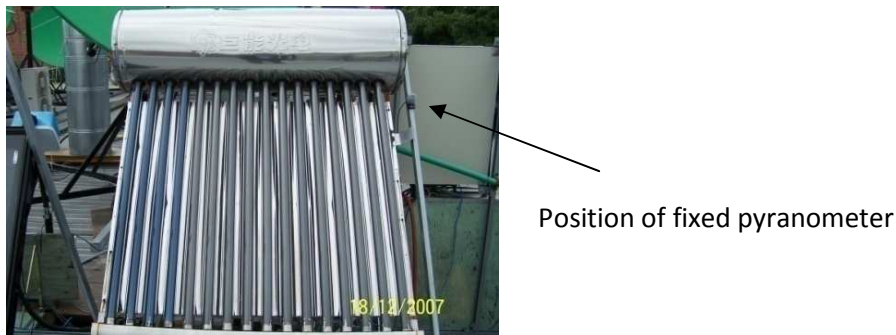


Figure 9.6. Position of fixed pyranometer

## 9.6 Wind speed

In 2004, it was decided to measure wind speed at various locations around the third floor roof space at C block CPIT. An anemometer was purchased for the project. The design centred on a PIC micro-controller (Programmable Interface Controller). The uniqueness of the design allowed for a three cup anemometer sensor with one cup having a tab on it. As the cup rotated it would slow down into the wind and speed up away from the wind. This slight change in wind speed was picked up by a specially designed chopper disk using an IR LED and photo-sensitive transistor (pTrans). This signal was then fed into the PIC micro-controller which illuminated two LED displays indicating wind direction and wind speed. The controller also logged the time, day, date, wind speed and direction to a CSV file for analysis. A specially developed piece of Lab VIEW code was developed to analyse this information and present a histogram of the wind speed and direction for that day. Figure 9.7 shows the wind anemometer in operation in March 2007.



Figure 9.7. Wind anemometer in normal operation, March 2007.

The device was checked against calibrated wind anemometers and motorcar speedometers. Several different sites around C block's third floor roof were recorded, with position changes occurring only after a year's successful data collection at one site had occurred. Unfortunately, during this time (2004 to 2008) four, one in fifty year weather bombs hit Christchurch, each destroying the anemometer cups to varying extents as shown in Figure 9.8. The wind anemometer not only logged wind position and direction data, it provided a real-time data stream to a CPIT website. The logging and web server interface underwent several changes by both the web development team and by the IT department at CPIT, resulting in several gaps or extended 'invalid data' entries.



Figure 9.8. Wind anemometer mast and cups after a weather bomb in late 2007.

Finally, in late 2007 a severe weather bomb destroyed the anemometer. It will be replaced by a more conventional system comprising two separate devices for wind speed and wind direction.

The reason for wanting to log both the anemometer output and a weather station's output was to allow easy correlation of solar activity and solar panel gain against weather events. For example, it is known and has been observed that the evacuated tube heat pipe collector is affected by southerly winds and the test panel's location is effected by easterly wind. In 2007, a CPIT weather station was set up, however this created a separate CSV file which then needed to be matched to the SCADA system data. Also this weather station did not log wind speed and direction. The addition of wind speed and direction is expected by May 2008.

It was planned that at some stage a signal could be obtained, indicating high gust or sustained high wind speed, which would then instruct the SET PLC to boom down and perform a park and shut down manoeuvre. However, this is considered a future development of the SET.

## **9.7 Air walls**

In May 2007, the author was contacted by another sponsor with regards to measuring the performance of a new product called an air wall. An airwall consists of a matt black flat plate with glass or acrylic cover and instead of copper pipes being mounted on the rear and extracting the heat by passing water through the pipes, air is moved over the rear surface of the absorber. Typically in a domestic consumer's dwelling, where the airwall attaches to the north side of the dwelling, two holes are made in the wall, one at the bottom and one at the top of the wall where the airwall absorber panel is then ducted into the dwelling. The airwall functions in much the same way as a thermal hot water absorber, with a controller monitoring the inlet and outlet air temperatures. Based on the temperature rise, the controller will start the fan to extract heat from the absorber passing this into the consumer's dwelling. The first airwall was set up and commissioned in June 2007 and interfaced with the SCADA system, which records the inlet and outlet temperatures and the controller turning the fan on as a digital event.

Two more airwalls were added in the last weeks of December 2007. These were a Transpired airwall (TAW), and a photovoltaic airwall (PV AW). These have both been installed onto or on top of the second shed (PV AW), and have only partially been set up with the SCADA systems in as much as the inlet and outlet temperatures are being recorded for both systems, but the TAW fan on event and PV AW fan speed sensors have yet to be connected to the SCADA system. The SCADA system is fully configured for these sensor inputs when they arrive and are installed. The SCADA system is likewise generating reports on the performance of these airwalls.

The first airwall suffered from poor fan speed which allowed the outlet temperature to reach 65 °C on a clear winter's day (a temperature gain of up to 54 °C over ambient, with a fan speed of 1.9 m/s).

At this point there is too much solar energy being lost through re-radiation back into the surrounding environment. The fan was changed to one with a higher speed (about double the original fan speed at 4.8 m/s). This resulted in more noise, but in a lower outlet temperature, now up to 15 °C higher than the inlet temperature on a clear sunny day in summer.

The TAW absorber is comprised of one entry point to a consumer's dwelling, as the front absorber is mounted directly into the open, and has many critically dimensioned and placed holes in its surface. This system is common overseas and is cheap to manufacture, but its performance is yet to be measured and proven in NZ. In early testing it has been observed that in winds (particularly the NW wind which it predominantly faces), the TAW fan will not operate as the wind speed is such that it forces air through the front absorber and into the outlet duct, causing the fan to rotate freely. This factor is known overseas, specifically that TAW's suffer in windy environments.

The PV AW has a preformed matt black metal plate mounted under glass with rear panel insulation and metal cover, and measures 1800 x 1200 mm. This panel is designed to bolt onto the wall of a consumer's dwelling, with two holes being drilled into the dwelling. As with the airwall, air is passed between the rear mounting plate of the panel and the back of the absorber panel. On the top of this panel is a small 300 x 1200 mm PV panel, with the fan speed being proportional to the amount of sunlight. The claim with this panel is that it will produce a temperature gain of 15 °C when in operation regardless of the solar radiation conditions. In testing so far this claim has proven to be slightly high with a 12 °C gain under partially cloudy conditions being observed on the controllers and SCADA systems. However, more data is required to formulate a more accurate assessment of the panel's performance. The possible market place for this panel is in baches or self contained remote locations where some form of pre-heating is required, or as in the case of a 'bach' or holiday home, heating may be required to remove moisture in a dwelling.

One issue which is apparent from the testing done to date is the requirement for a storage media for these devices as they all produce heat, with varying degrees of efficiency, and will heat a domestic

dwelling on a fine day, when sometimes there is no requirement for heat. For example, in the middle of summer, these panels produce a good level of heat, but heating a dwelling in summer on a fine day is not usually required. In fact it is more likely that cooling may be required. Heating the room would be required towards early evening or at sometime during the evening when these panels are ineffective.

Further research and development is being performed and the author is aware of other studies by BRANZ<sup>[80]</sup> and EcoLibrium<sup>TM[81]</sup>.



## **10.0 Solar thermal hot water and comparison**

In 2003 when the SET project was first proposed, research was performed into the type, nature and efficiency of the solar thermal systems on the market at that time. It became clear that there were a number of different offerings available with a wide range of claims as to efficiency and the amount of energy savings that could be achieved. It was also realised that if the claims by the SET's inventors were to be understood and appreciated, then a means of comparison was required.

On this basis the author developed the SET into an operating solar thermal hot water system, and simultaneously researched the technologies being utilised in other types of commercially available solar hot water systems. In late 2004, this led to the purchasing of a 20 tube commercial/domestic evacuated tube heat pipe system, (no brand names will be mentioned in this document, as all research and development is covered by confidentiality agreements with the various sponsors).

### **10.1 Typical solar system operation**

A 'flat plate' solar thermal hot water system comprises a flat plate usually painted or anodised matt black with copper pipes welded to the rear through which water is passed. A derivative of this is a finned flat plate where black nitride coated copper (or similar) fins are welded to a smaller diameter copper pipe which in turn feeds a larger diameter copper pipe, much like the rungs of a ladder. Near the outlet of the panel, which is usually on the high side of the flat plate, a second smaller diameter copper pipe pocket is welded and mounted. Into this pocket is normally placed a Platinum Temperature 1000  $\Omega$  sensor (PT1000). This temperature sensor feeds back the temperature in the collector, called  $T_c$  to a controller. The copper pipe from the panel and collector is then fed to the hot water cylinder (HWC). Figure 10.1 shows a typical flow diagram for a solar collector system, with a heat exchanger (type three) HWC.



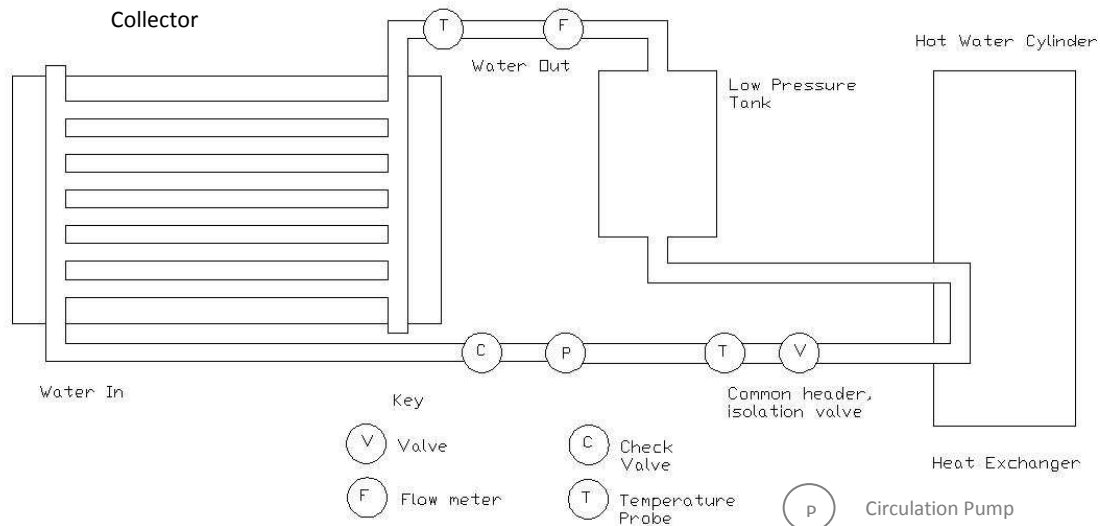


Figure 10.1. Typical flow diagram for a solar thermal hot water system at CPIT, 2006.

There are three basic types of HWC in common usage. The first type has two entries usually top and bottom of the HWC, but sometimes this may be side entry bottom and central top exit. This type of HWC is common in many older homes and is of a lower insulation grade than the more modern HWC types. This type was not able to be used or connected to a solar thermal system until 2006, when a spray nozzle was developed which fitted inside the water entry adaptor fitting and sprayed incoming hot water upwards past the electric element. However, the fitting also had to provide a means for the circulation pump to extract cold water from the bottom entry adaptor as well for circulation through the solar panel. This type of solar thermal system and HWC is seen by many in the industry as only being able to preheat the water in a HWC, or as providing boost energy.

The next type of HWC is being sold as a solar thermal type and has two side bottom entries and a central top exit. It is shown in Figure 10.2. There is no separate heat exchanger loop on this HWC. The solar thermal side entry has an upwards mounted spray nozzle, with the side entry hole being slightly above in height of the normal cold water side entry point.



Figure 10.2. HWC type 2 – two side entries and top exit.

As with the first type of HWC the second HWC has the requirement that the solar thermal system be approved for use with domestic drinking water in case a consumer drinks from a HWC.

The third type of HWC has four or more connections, a side or bottom entry and central top exit as per normal, with the extra two (or more) side connections being for a separate heat exchanger loop which is completely isolated from the contents of the HWC and is shown in Figure 10.3. This type of HWC is more expensive than the previous two, (as the heat exchanger loop sits inside the HWC and is in addition to the normal electric element) but it allows for greater thermal mass conversion. This type also allows for a consumer to connect to wood stoves or wood fires, or solar thermal systems which do not have to be drinking water approved.

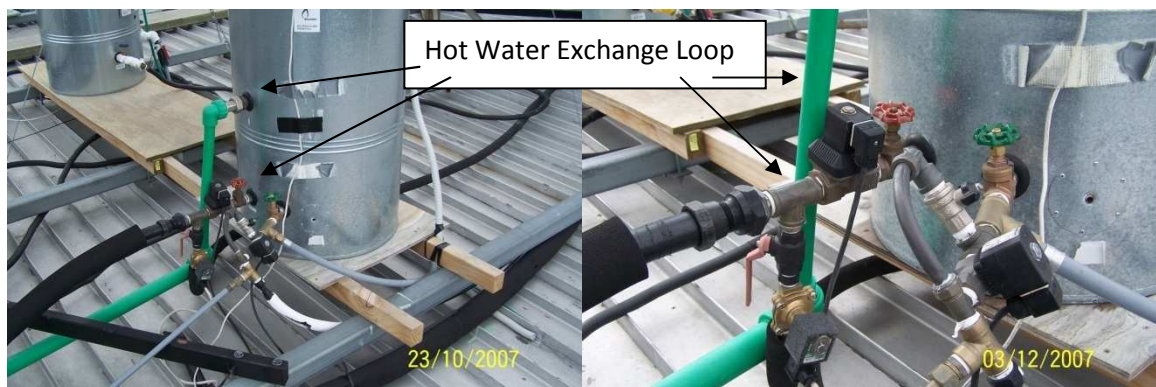


Figure 10.3 HWC type 3, heat exchanger loop with separate exchange loop.

The collector from the solar panel enters one of the above three types of HWC. The pipe connecting the two is usually either 3/8" (more common) or 1/2" (less common now). It is fully insulated. The second temperature measuring point is likewise another PT1000 (called Ts) and is positioned onto or into the HWC depending on the age of the HWC and whether there is a separate pocket for putting the temperature probe into the HWC rather than mounting it on the return water pipe. For example, on older HWCs the Ts sensor is mounted on the return water pipe to the solar panel. On newer HWCs there are two pockets and Ts is mounted into one of these depending on the season and the amount of hot water the home owner uses and requires. In this instance for summer, when solar energy is able to supply most of the hot water requirements, Ts is mounted in the upper third of the HWC or top pocket. In winter when a lot more hot water is used, Ts is mounted in the bottom pocket, where it is normally situated for most non-solar HWCs. One of the reasons for this is to do with the controllers.

The return pipe to the collector panel is usually a copper pipe but sometimes this can be a thermally rated plastic pipe of the same internal dimensions as the copper hot water pipe from the panel. This then leaves the HWC and enters into a circulation pump (CP) which is under the control of a controller. The outlet of the CP is connected to the bottom or cold side of the panel.

The final element is a controller. These range from simple solar only controllers which monitor the difference between Tc and Ts. When the temperature difference exceeds a pre-determined limit the CP turns on. Likewise the CP turns off when the temperature difference falls below a preset value. Some controllers now also feature a 'frost mode' which turns the CP on when the Tc temperature falls below a preset limit. This causes the hot water from the HWC to circulate into the solar panel to stop it from freezing. This is clearly a waste of energy, as the panel then re-radiates this heat energy into the surrounding environment.

The newer more modern controllers allow the consumer some flexibility in the setting of these preset temperatures, and will also control the HWC's electric element, such that if the temperature in the HWC is at an agreed preset temperature, the electric element will not turn on.

There is still much debate within the solar industry and suppliers about these preset temperatures. When the solar thermal project first commenced in 2005, some solar thermal manufacturers had presets of 10/6/4, i.e. 10 °C difference between  $T_c$  and  $T_s$ , CP turns on, with CP turning off when the difference between  $T_c$  and  $T_s$  falls below 6 °C, and the CP turning on in frost mode when  $T_c$  falls below 4 °C.

These controller settings, 10/6/4, have been the basis for all solar thermal systems testing performed at CPIT until 2007. In July 2007, it was realised that 10/6/4 may not be the best for all panels. The thought in the industry at that time was that it is better to turn on the CP more frequently and extract any and all solar energy from the panel rather than allowing it to re-radiate back into the environment and be lost to the system. At this time it was also discovered that finned flat plate solar manufacturers now use 6/4/4, and evacuated tube heat pipe solar manufacturers had also adjusted their settings twice in this intervening time and were currently using 8/6/2 as their controller presets.

It appears from the results obtained in the last six months of 2007 that controller preset temperatures do affect the overall performance of some panels, and in particular finned flat plate collectors. They have a smaller effect on the overall efficiency of the evacuated tube heat pipe systems.

## **10.2 Types of solar thermal collectors**

The flat plate collector comes in glazed or unglazed formats, suitable for mounting in roof or on roof.

This type is basically an anodised matt black collector (usually aluminium is used as the collector material which is then anodised matt black). Early examples of this type can still be seen on domestic roofs. The next phase in the development was the inclusion of a thick plastic cover to stop re-

radiation of the heat energy back into the environment; these can still be seen today. The newer versions of this type now feature toughened shatterproof 4 mm or thicker glass. These types are prone to frost damage.

A further refinement of this type is the use of two dimpled plates sandwiched together under high pressure, and with the air removed from them. At this point a low boiling point liquid, most likely a derivative of antifreeze (the original developer will not disclose any details on the liquid) is introduced and fills the vacuum left by the removal of the air. A 3/8" copper pipe is then welded to the rear of this panel before it is mounted into a metal frame containing rear panel and side wall insulation. A glass cover is then installed over the top to protect the panel and prevent re-radiation.

Yet another refinement is the use of copper nitride coated fins (violet blue in colour), which are welded onto 3/8" copper pipe in an L shape. The fin then becomes the absorber. These "laterals" then interface to 3/4" header pipes. The complete assembly is then placed into a metal frame with rear and side insulation and glazed with 4 mm safety glass. There is a problem with the choice of insulation used on many of these collectors, referred to as rust in the solar industry. The rust is caused by the polyurethane insulation giving off a gas on exposure to solar radiation. Whilst its effects are not immediately apparent, over thirteen months the performance of the panel has degraded by up to 15 %. To solve this, the solar manufacturer has suggested drilling holes in strategic locations to allow air to move freely between the fins and the glazing, however this has not worked. A second attempt was made by changing the panel insulation to 'Rockwool'. This is more neutral under solar radiation, and makes for a much lighter panel in handling, however in testing, the panel responds more quickly to solar radiation, but loses its temperature more quickly as well whenever the sun disappears. This panel does not have the efficiency of the older polyurethane panel, even after comparison with the older panel type after eighteen months of operation. Figure 10.4 a and b, shows the urethane flat panel and the Rockwool panels respectively with Figure 10.5 a

showing the urethane panel after five months of operation and Figure 10.5 b after thirteen months of operation from installation, with the rust clearly visible in the upper right corner.



Figure 10.4 a & b. Urethane and Rockwool insulated flat plate collectors.



Figure 10.5 a & b. The urethane panel top right corner in Sept 2006 and Oct 2007, 13 months later.

The solar manufacturer has developed a Mk3 version which uses more Rockwool insulation, but for aesthetics has added a metal cover frame around the edges of the collector header pipes when is then installed in to its outer mounting metal frame. This means that the copper pipes and fins are in contact with the cover frame which is in direct contact with the outer mounting frame. Thus any heat gain by the collector also heats the covering metal frame, the surrounding mounting framework as well as supplying heat to the HWC. This design continues in current manufacture.

A further variation of the L shape is called a 'Z' panel. The Z panel design has not traditionally been used in frost prone areas as the frost will usually cause the pipes in the lower centre of the panel to split due to water freezing at this point. The Z panel in shape resembles more of an 'M' on its side,

i.e. water enters at the bottom, is then pumped through the copper pipes with the nitride coated fins attached before leaving on the same side but 4' above the inlet pipe. In this case the investigation was to determine if the Z panel could survive a Christchurch winter and its efficiency. This panel is the same area as the L design panel at 2.88 m<sup>2</sup>. This panel used Rockwool as its insulation.

Another type of flat plate collector uses a black anodised panel mounted under either clear or dimpled glass. The output from these panels interfaces directly to a small sideways mounted roof HWC. The hot water from this system is then pumped via controller and timer function into the main HWC. This panel is also prone to rust.

The next type of collector uses vacuum flask technology, where two glass tubes are formed with a vacuum applied between the two tubes. The inner tube may, depending on its age, have only a matt black coating applied. The more modern evacuated tubes feature a black outer layer and a silver inner layer applied to the inside of the inner tube, the idea being the black coating absorbs the heat and transmits it to the inside where the internal media absorbs it. Any re-radiation is stopped by the silver layer reflecting the energy back to the medium. The medium is usually water. In some instances evacuated tubes are connected to a batch holding tank much like a small HWC. These can be temperature controlled with cyclical dumping and pumping operations. The evacuated tubes now come in a variety of sizes ranging from 38 mm diameter to 55 mm diameter, and range in length from 1200 (older type) up to 1800 mm (newer type), as shown in Figures 10.6 a and b.



Figure 10.6 a & b. Showing 38 mm diameter evacuated tubes and 55 mm diameter evacuated tube heat pipes.

There are two refinements of this technology. The first inserts a copper pipe with sealed ends and contains a low boiling point refrigerant in the centre of the inner tube. This is surrounded with naturally coloured silver aluminium as shown in Figure 10.6b, 10.7 a & b and 10.8 a & b. This type of system is called an evacuated tube heat pipe, and is designed for flow through manifold systems rather than a batch or roof mounted HWC. Some variations on this design centre around the shape and position of the aluminium spacer, and the position of the heat pipe (front or rear of the evacuated tube). In more recent examples, water is used as the media in the heat pipes and all the copper pipes were connected in parallel in the manifold. These tubes come in two types of ratings, normal and high efficiency (the manufacturer changes the refrigerant), two sizes 38 or 55 mm diameter, and are 1800 mm in length. It is this system that CPIT purchased from some monies allocated to the author in 2004, and commissioned in early 2005.

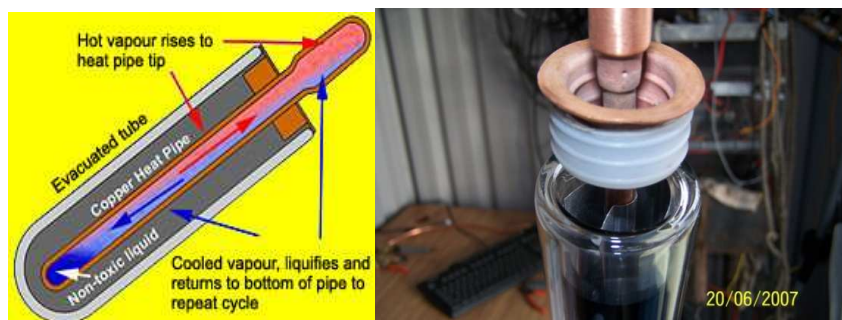


Figure 10.7 a & b. Evacuated tube heat pipe technology.



The second major refinement to this technology uses copper nitride coated fins welded to a conventional copper heat pipe, all mounted in a 75 mm diameter tube, which is then evacuated and sealed. Once again this system is designed for a continuous flow manifold. Currently, the tubes are only available in one size and one length and are shown in Figure 10.8 a & b. In 2007, initial comparative testing of the conventional heat pipe and the finned heat pipe showed the finned heat pipe to be more responsive. The test was undertaken by placing both tube samples into the sun at the same time and recording the length of time it took for the bulb ends of the tubes (which insert into the water cooled manifold) to become too hot to comfortably continue holding onto. Both tube samples were removed from a dark place and the time recorded for the same person (sometimes the same hand was used, other times the person's left and right hands were used) holding the ends of the tubes. The tests were conducted in full sunlight and at various times during the year, namely summer, winter, autumn and spring, and were completed with the knowledge that the test was an 'unscientific' comparison. In all cases, the finned heat pipe was able to produce its heat more quickly than the conventional heat pipe by a factor of approximately 3 to 1. The conventional heat pipe bulb took from twelve to fifteen minutes to become too hot to comfortably continue to hold on to, whereas the finned heat pipe bulb would take from four to six minutes to reach the same. There is however a problem with the design of the latter tube. There have been several instances brought to the author's attention of the tubes cracking or breaking, and there is a lot of pressure on the larger diameter seal of the finned heat pipe and the possibility of the seal failing is increased. The tube losing its vacuum over time is an increased risk.



Figure 10.8 a & b. Evacuated tube finned heat pipe technology.

Evacuated tube systems also feature a rear mounted reflector which ranges from being flat and dimpled in shape and of no value or consequence in its ability to reflect any energy onto the rear of the evacuated tubes, through to a partially shaped reflector and a fully shaped reflector which comes halfway up the sides of the evacuated tubes. In 2007 the investigation was to determine if a reflector added anything to the efficiency of the panel. The results indicate that the addition of a reflector adds 15 % to the overall efficiency of the evacuated tube heat pipe panel.

### 10.3 Method of calculation and comparison

The SCADA system measures every fifteen seconds, all incoming and outgoing temperatures for all solar thermal hot water collectors. Flow rates are also recorded by the SCADA system either directly or where the flow rate is known and fixed as a digital on event. The outside air temperature and solar radiation from a fixed position pyranometer are likewise recorded by the SCADA system.

The energy delivered by a solar thermal heater<sup>[82, 83]</sup> is:

$$Q = V \delta c \Delta t$$

Where V is volume in m<sup>3</sup> (of water heated),

$\delta$  is density in kg/m<sup>3</sup> (taken to be temperature independent),

c is 4.1813 J/gK which is water's specific heat capacity at 25 °C,

$\Delta t$  is the temperature gain

The formula can be simplified to:

$$\text{Energy (Joules)} = \text{Flow (in ml)} * \text{Average Temp Gain} * 4.1813$$

Also, 1 Joule = 1 Watt for 1 second and 1 Joule = 2.7778 x 10<sup>-7</sup> kWh.

Hence the energy can be translated into power per unit area measured in kW/m<sup>2</sup> by dividing the energy by time (hours) and the surface area of the collector.

An efficiency figure is then obtained by dividing the  $\text{kW/m}^2$  figure obtained by the average solar radiation arriving on a flat body on the earth's surface ( $1 \text{ kW/m}^2$ ).

#### 10.4 Mounting angle

The accepted practice in the solar industry is to mount the collector at an angle to the horizontal equal to the latitude of the location, thus giving the collector a good all year round response. After nine months of research it has been determined that angle matters for some collectors and not for others. The finned flat plate collector's performance is enhanced, especially with low solar radiation levels, by mounting it at an angle of 65 degrees from the horizontal for both summer and winter, whereas the angle has no effect at improving the performance of an evacuated tube heat pipe system, which indicates that this can be mounted at any angle. The flat plate sliding mounting frame is shown in Figure 10.9. The flat plate efficiency response graph for 22, 45, 65 and 90 degrees mounting angle is shown in Figure 10.10. The response of the finned flat plate under low solar radiation ( $50 \text{ to } 100 \text{ W/m}^2$ ) at a mounting angle of 65 degrees from the horizontal, is improved over other mounting angles.



Figure 10.9. Showing sliding mounting brackets for flat plate collector.

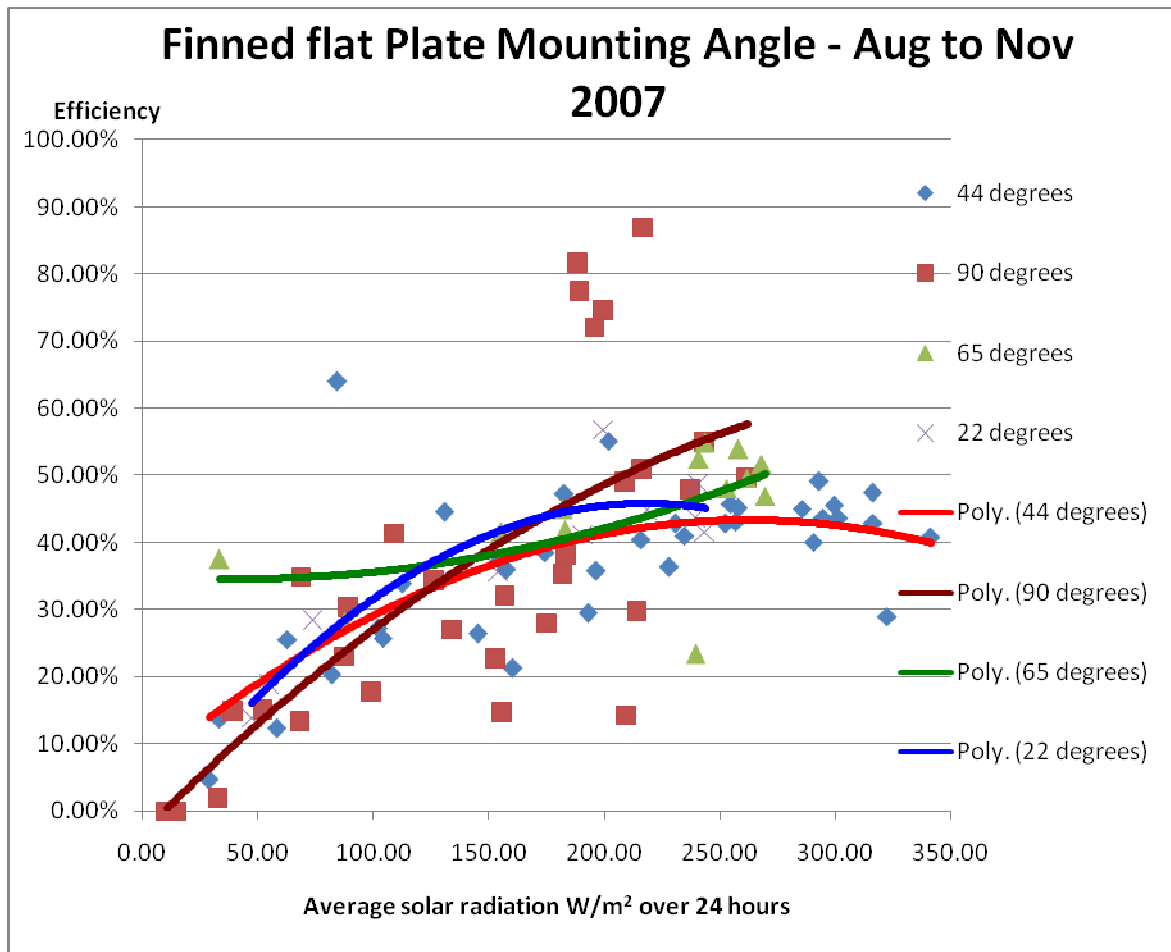


Figure 10.10. Flat plate response for mounting angle.

### 10.5 Efficiency increase

The traditional solar industry response to a customer needing more hot water has been to increase the size of the customer's collector area. Whilst this sells more panels and makes more money for the manufacturer, it does not solve the customer's dilemma, namely 'how effective is the collector?' The other reply sometimes offered to customers is that if the customer spends more money in increasing the collector area, then the customer will get more hot water, and to achieve this, the solar manufacturer will place all the collectors in series with each other.

### 10.6 Performance measures & compliance

The traditional method of comparing a panel's overall performance has been to take the area of the collector, record the temperature rise for the day, record the panel's flow rate for the day, and to calculate from this the energy in Joules, relating this to kWh and kW. At this point the efficiency is

calculated by dividing the kW produced per twenty four hour day for the collector's area by the average solar radiation arriving at the earth's surface onto a horizontal surface, i.e.  $1 \text{ kW/m}^2$  for the NZ conditions.

For a flat plate collector, the area is that of the collector or absorber and not the area of the metal case. With the round evacuated tube, is it the area of the tubes flattened out or is it the area of the outer diameter of the tubes, or is it the area of the reflector? The author has chosen for all analysis work the area of the reflector, as whilst this is not an absorber, it is reflecting energy or concentrating solar energy on to the evacuated tubes. Also, there is a gap between each evacuated tube when mounted in the support frame. This has been ignored in the author's calculations with the area of an assumed reflector being used instead.

Currently the way the solar industry operates and the way Standards New Zealand set up the area calculation, the larger the area of the solar panel the greater is the available subsidy. This has led to several solar manufacturers increasing the dimensions of their solar panels. The Standard does not help in defining how to make the measurement or on issues pertaining to the calculation of the overall panel efficiency for which a smaller collector area is advantageous.

From 2007, all solar installers have to undergo approved solar thermal hot water training and have completed the required unit standards. Recent changes in legislation (2007) require all solar panel suppliers to submit their panels for efficiency testing. This is being performed by actual testing at Applied Research in Nelson, and by University of Otago performing modelling using the TRNSYS software modelling system. There have been problems reported to the author, by two of the solar thermal system sponsors, about the first organisation and that they were performing testing in isolation and without reference to the NZ standard (NZS 4613:1986, AS/NZS 2712:2002A1 and AS/NZS 2535.1). This has been remedied late in 2007. The Energy Efficiency and Conservation Authority (EECA) now administer all solar thermal hot water systems and as such administer the governments fund for grants for households installing approved solar thermal hot water systems.

The level of grant increased in 2007 and again on the 24<sup>th</sup> May 2008 with the subsidy level now being \$1000 according to Silkstone<sup>[84]</sup> for approved solar thermal hot water suppliers, approved solar hot water installers, and households with newer compliant HWCs.

EECA<sup>[85]</sup> calculate that an average household can save \$350 to \$450 per annum of the household's electricity bill for the year. In testing this has proven to be very subjective, and the maximum saving available from a typical evacuated heat pipe system at 20 c/kWh appears to be \$420 per annum.

On a regional basis, compliance with the building code and local or regional council requirements have seen the cost of building consent (required for any alterations to the structure or 'water tightness of a building') rise and have seen lower domestic adoption rates of solar thermal hot water systems. New requirements require the fitting of relief valves to any solar hot water system. This has to be fitted at the collector hot water outlet and is designed to release any excessive pressure from the collectors due perhaps to a failure of the mains or CP. However, if the relief valve operates, it will dump potentially boiling water or steam onto the roof. Roofing suppliers have stated that their roofing material is not able to handle this temperature and on many installations with solar thermal systems they have not honoured the warranty on the roofing material. The same issue arises with the use of plastic gutters on the roof, and plastic stormwater pipes. To this extent some local councils have decided the relief valve must discharge into a copper pipe which then is connected to the household's sewage system which is not readily accessible in many cases and results in very long runs of copper pipes. Some councils will allow the relief valve to dump into the hot water cylinder where it feeds to the household's hot water tempering valve. In this case the solar hot water is tempered or cooled before being dumped or used by the household.

## 10.7 Solar thermal hot water research and results

### 10.7.1 2006 solar thermal hot water research and results

In 2006, the first solar sponsor approached CPIT with two solar thermal research projects (two finned flat plate collectors). The research questions being asked pertained to the optimum pipe size to be used in solar thermal installations, and how to stop a Z panel from freezing. A trough collector was also supplied as an interest project and is shown in Figure 10.11. As the SCADA system already had provision for recording temperatures and flow rates of each thermal system, it was thought that each solar panel system could discharge into a low pressure tank, and draw its cold water supply from a 65mm common supply header pipe, after the water had passed through a typical domestic load or the separate heat exchanger HWC. This HWC is flushed for five minutes every 6 hours during daylight hours or if the HWC reached a temperature as indicated by the SCADA system in excess of 55 °C.



Figure 10.11. Trough collector.

Analysis of the results for six months (four months from 2006 and the first two months of 2007) reveals that ‘temperature spiking’ was occurring. Whenever a controller decided to turn on a panel’s CP due to  $T_c$  in the collector, a hot slug of water was then delivered past the  $T_c$  sensor. This was being seen on the SCADA recorder system, and is shown in Figure 10.12. Temperature extremes occur where  $T_c$  reaches in excess of 65 °C and in some cases in excess of 100 °C on the evacuated

tube system. Figure 10.12 shows one such temperature spike of 75 °C. It was common to have several such spikes in one day. At the time, these temperature spikes could not be explained. However, with the change in the hot water system layout occurring, such that each solar thermal system has its own HWC, which occurred in April 2007, these high temperature spikes have disappeared. It was noticed in testing that if the CP, which was used this year for only the batch solar collector, turned on it took all the available water supply from that end of the header and reduced the flow of water through the remaining header leading to the resulting higher temperatures in all the collectors connected to this header. The batch solar collector took fifteen minutes to empty and five minutes to fill, and was flushed every 5 hours of daylight. A picture of the solar batch collector is shown in Figure 10.13. Figure 10.14, shows a corrected graph of the overall solar system's efficiency result for the period August to November 2006, using a second order polynomial curve fitting equation, with evacuated tube heat pipe systems averaging up to 16 °C, finned flat plate L type with urethane insulation averaging up to 13 °C, and finned flat plate Z type with Rockwool insulation averaging up to 13 °C.

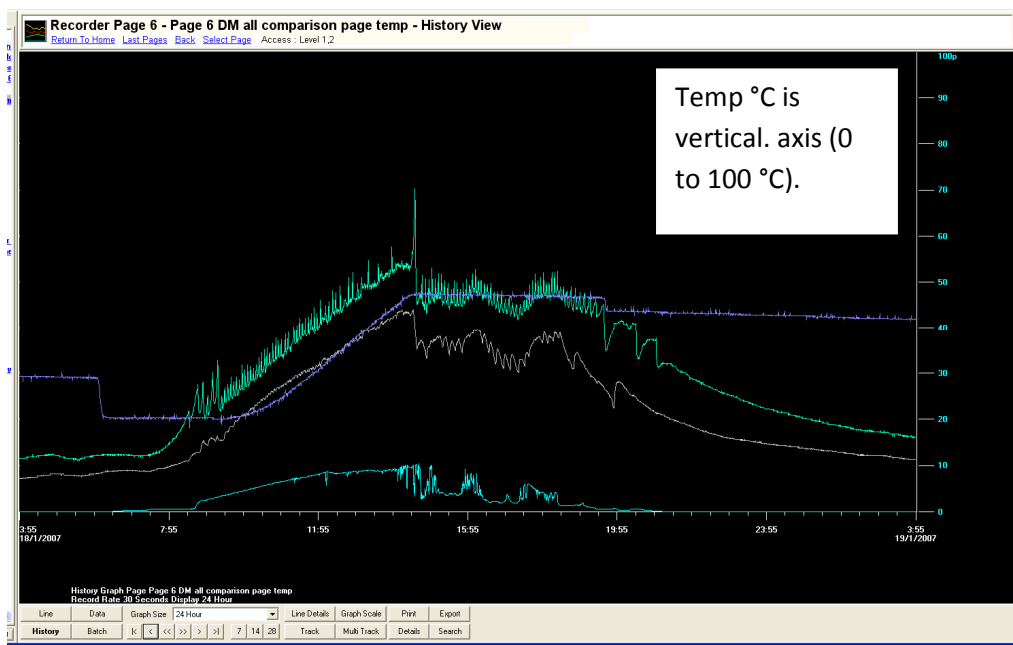


Figure 10.12. SCADA temperature spiking for evacuated tube heat pipe solar system.





Figure 10.13. Solar batch collector.

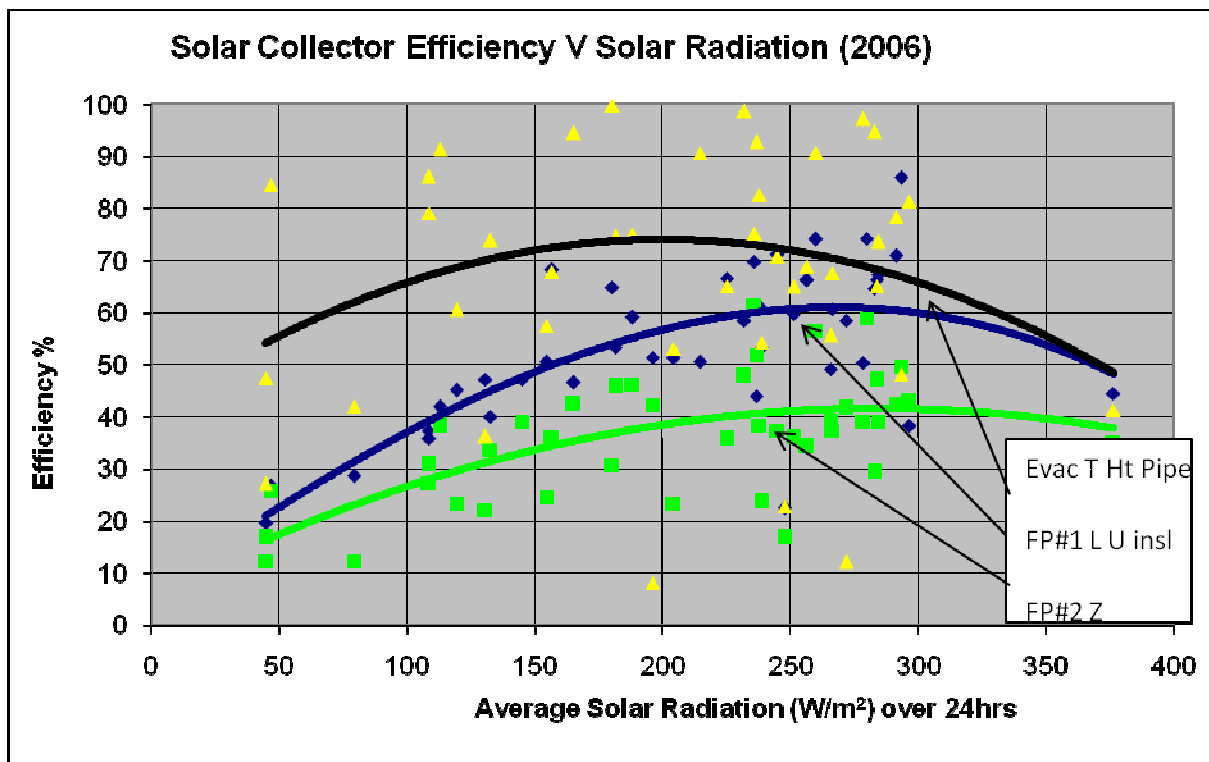


Figure 10.14. Summary graph of solar thermal system performance 2006 (Aug to Nov).

There were some other inconsistencies between days with similar solar radiation levels and it was thought that this variation may be due to wind. It was noticed from the results that easterly and southerly winds affected a solar panel's performance, and whilst this effect is still to be quantified, it has been seen on the SCADA recorder that a southerly wind or front will reduce the output temperature of the evacuated tube system. Likewise an 'onshore' easterly will affect the performance of solar panels on the east side of the building, by cooling them. The wind effect has to

do with the location of the solar thermal system on the building and the exposed nature of the panels to the weather, which would not normally be seen in a consumer installation. Typically for the evacuated tube system, the southerly wind will take 5 °C off the panel’s temperature gain, and for an easterly up to 10 °C off the temperature gain of the east mounted flat plate panel.

The results from graphing the flow performance for one flat plate collector, as shown in Figure 10.15, show the preferred pipe size for flat plate collectors is 3/8". This information has been supplied to the solar manufacturer who has changed the installed pipe size recommendation guideline for their flat plates to 3/8" from 1/2", as 3/8" gives a better efficiency at lower solar radiation levels. With an increased pipe size (1/2") the flow rate increased from 2.8 l/m to 6.5 l/m with the same speed setting on the same circulation pump. This also affected the temperature gain of the finned flat plate collector lowering the temperature gain from 12 °C to 8.5 °C.

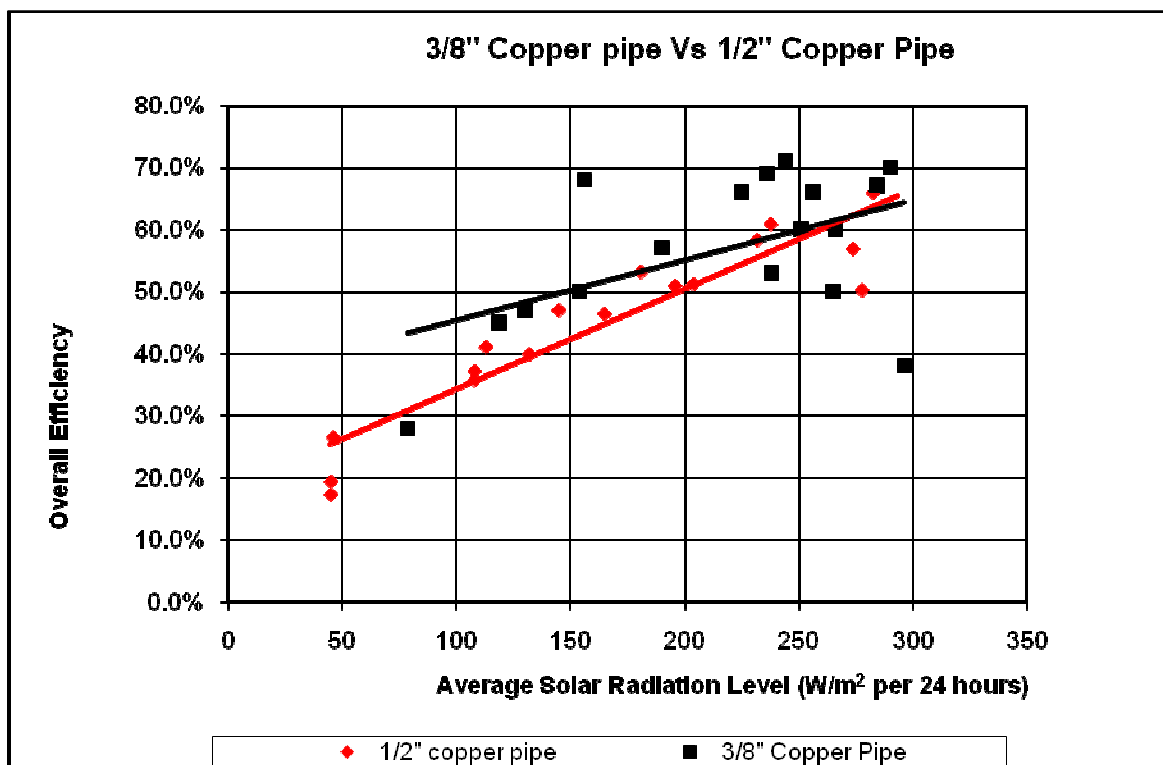


Figure 10.15. Graph of comparison of efficiency for copper pipe sizes.

It was also concluded from the testing performed, that a Z panel can be used in a frost prone environment provided the controller's frost mode initiation point has been set correctly. Much of the testing done with temperature probes monitoring the centre and outlet areas of the Z panel, have shown the coldest part of the Z panel is not, as is commonly thought, the centre of the collector pipework but is in fact the outlet point. The controller, when set to initiate the frost mode at 4 °C, does prevent the Z panel's pipes from freezing. Unfortunately time and the lack of a late frost season prevented further exploration as to how low this frost mode temperature could be lowered to without the pipes in the collector freezing. This Z collector has 1.25 l of water in all its pipework. A normal finned flat plate panel (of the L shaped design) has 1.5 l of water in the pipework.

In the environment at CPIT there was no observed swing in temperature when the frost mode was initiated. It is however known from the sponsor that a swing of 1.5 °C occurs on his 'L' flat plate collector and the controller display shows a Tc of 2.5 °C, as shown in Figure 10.16. The sponsor has a finned flat plate collector mounted on his roof, with a frost mode setting of 4 °C and regularly checks the system.

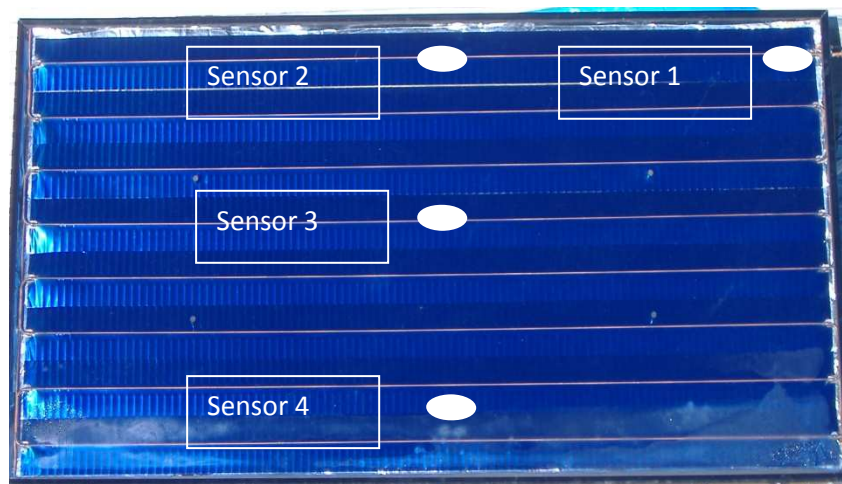


Figure 10.16 a. Z panel temperature probe locations.

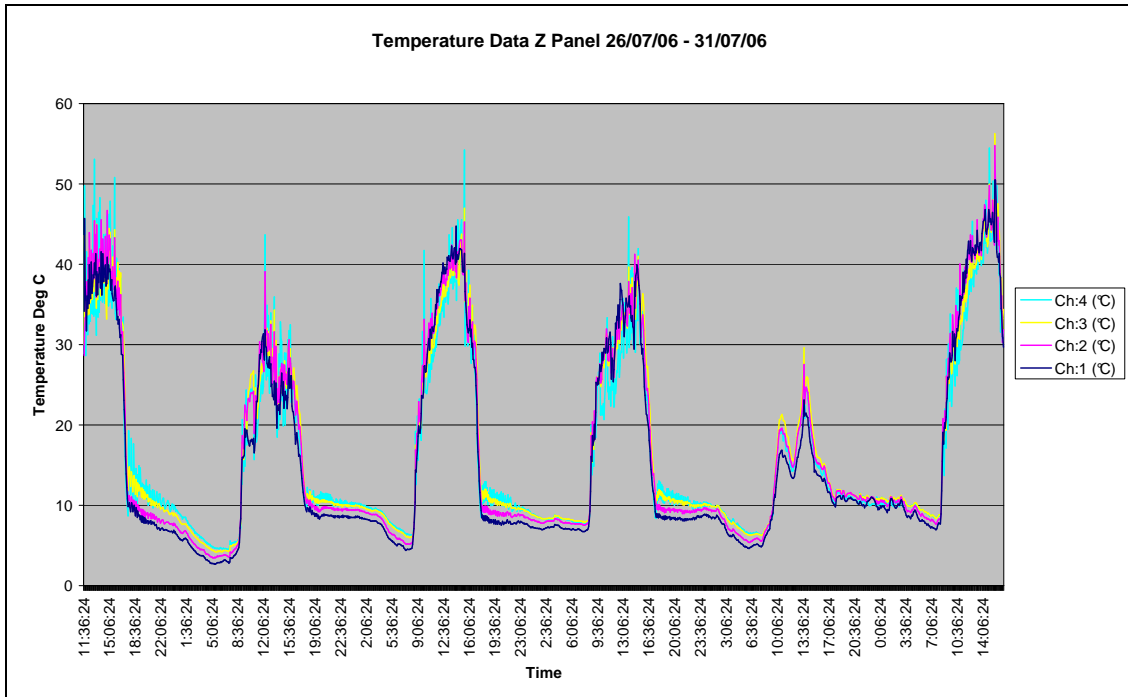


Figure 10.16 b. Z panel temperature response under frost conditions, September 2006.

During this year two other flat plate panels were submitted for testing, one using matt black painted folded stainless steel. The panel was glazed and was supposed to be cheap to manufacture and only contain 2 l of water. However, it contained 6 l of water and when empty weighed 72 kg and had an area of 1.44 m<sup>2</sup>. It is shown in Figure 10.17. The panel also failed to provide a sensor pocket for T<sub>c</sub>. Under testing, the panel failed to match the instantaneous performance figures of the finned flat collectors. Over a period of two weeks of testing in September 2006, it was found to produce between 15 and 30 % less energy depending on ambient conditions and with only a few samples. Further investigation showed the average temperature gain of the panel was 2.8 °C per square metre, whereas the sponsor's flat plate panel produced 4.2 °C temperature gain per square metre.



Figure 10.17. Matt black folded stainless steel glazed flat panel under test 6<sup>th</sup> September 2006.

Later, in December 2006, an approach was made by another supplier of a different design of cheap flat plate panels claiming frost resistance. This panel had an area of 2.37 m<sup>2</sup> and contained two matt black plates which were supposed to be seam welded but which were only spot welded and leaked under high (>65 °C) temperature and moderate pressure. This panel contained a clear polycarbonate cover instead of glass, which was one of the reasons for its cheapness. Using similar controller settings (10/6/4) and ½” pipework, the system was commissioned in wet conditions prior to Christmas 2006 and is shown in Figure 10.18. In performance testing in January 2006, investigation revealed that the Ts sensor was located in the wrong place and so all previous results were discounted. For the last part of January and up to the 20<sup>th</sup> of February 2007, this flat panel managed 80 hours of operation, compared to the evacuated tube heat pipe panel’s 189 hours. It was observed that the temperature rise at the collector of the panel was on average 9 to 10 °C as seen on the controller’s display and SCADA, whereas for an evacuated tube heat pipe, the collector rise under the same conditions was 14 to 16 °C. A test was conducted in which the panel’s polycarbonate cover was removed and the temperature gain from the collector dropped to a 7 to 8 °C rise. By way of qualifying these figures, a temperature rise figure can be observed directly on the front of the controller, this figure varies as the solar radiation levels varies, for instance with changing cloud cover. The author has observed by recording manually these temperature gains on the controllers for minute periods through the day these test results were made.



Figure 10.18. Cheap pressed steel & welded frost proof polycarbonate covered panel, December 2006.

A report on the panel's efficiency and performance was written for the sponsor and his investors. However, the original inventor obtained a copy and amongst claims of improper testing and bias, the inventor insisted that CPIT redo the tests, which was later revised to the inventor claiming his system was a pressurised system and that it did work at a much higher efficiency than CPIT was stating. CPIT offered to redo the tests on payment of monies, as was the basis for the original commission, however the original inventor declined. The average efficiency for the cheap flat plate for the short period of late January to mid February (i.e. four weeks) was 33 %, whereas the efficiency for the evacuated tube system for the same period was 81 %. The extended analysis for the entire period of testing, including the period of late December to the temperature probe location correction in January is shown in Figure 10.19. The author acknowledges that the inclusion of some of these results affects the final outcome (average efficiency for the period and graph), however, the design of the panel appeared from testing to only respond well to full direct sunlight which occurred in February 2007. The panel was removed in March 2007.

The evacuated tube heat pipe system results, as shown in Figure 10.19, produced efficiencies exceeding 100 % during this analysis period. This was found in 2007 to be due to the common plumbing and common HWC configuration. In other words the contribution made by the evacuated tube panels and the other flat plate panels took the temperature in the HWC to a level higher and

more quickly than the cheap flat plate was itself able to produce. This had a flow on effect, with it being easier and requiring less heat energy to heat already warm water, due to thermal inertia than it does to heat cold water. For example, a temperature rise of 15 to 30 °C takes more energy than say a 15 °C rise from 40 to 55 °C due to thermal inertia. It was also observed in later testing that under some circumstances, when the solar collector circulation pump was executing a fill cycle for the solar collector, the hot water temperature in the manifold of the evacuated tube heat pipe system rose and peaked as there was not sufficient water flowing through the evacuated tube heat pipe manifold due to the operation of the nearby solar collector circulation pump.

From the testing conducted in 2006 (and latterly in 2007), the evacuated tube heat pipe systems offer a greater temperature rise and have higher temperature gain, especially in low light, than the comparative finned flat plate systems of the L and Z designs.

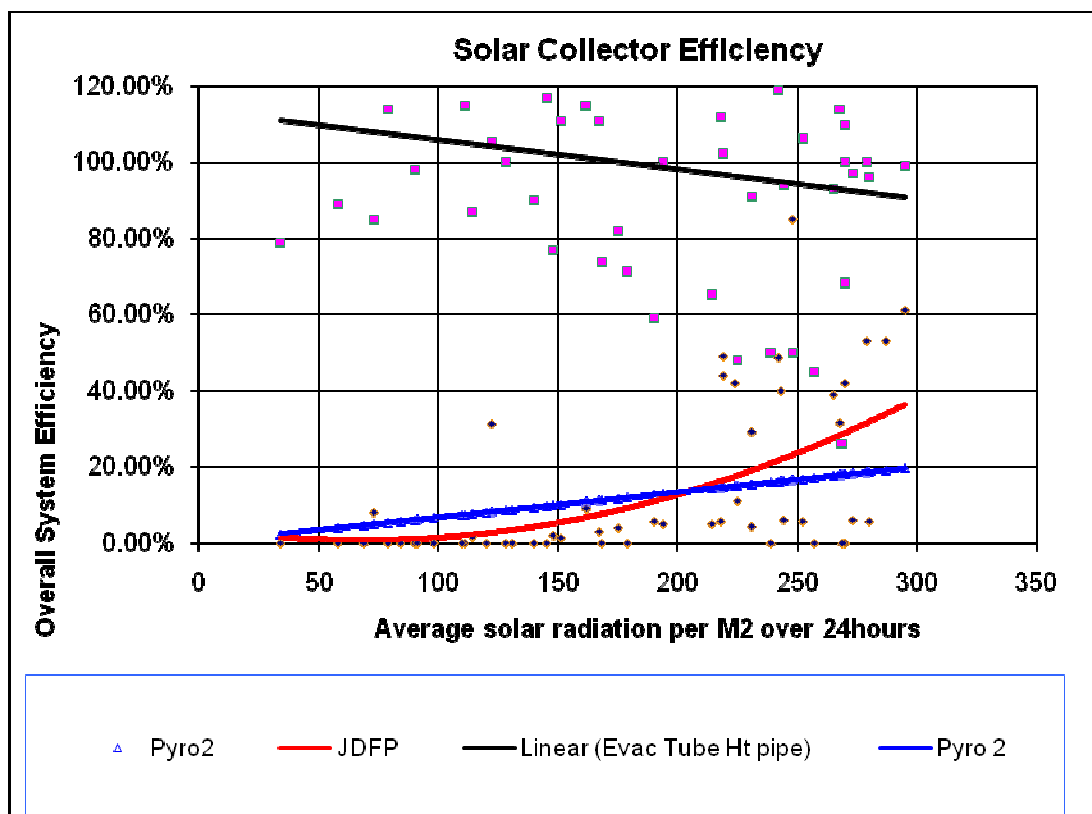


Figure 10.19. Cheap flat plate panel's performance.

In Figure 10.19, the term 'pyro2' refers to a fixed pyranometer for measuring solar radiation, with 'JDFP' referring to the cheap flat plate, and linear (evacuated tube heat pipe) referring to the linear regression analysis applied to the results for the evacuated tube heat pipe.

The Solar Industries Association (SIA) and EECA have both expressed interest in the results CPIT has obtained and has requested access to these results, however CPIT's contractual obligations are with the sponsors for whom the testing, research and development work is being done. Any findings and results will be made public, but only with the sponsors prior knowledge and approval. SIA and EECA both expressed interest in becoming part of the testing team. A proposal was made by CPIT, however nothing has as yet eventuated and with the recent changes in the structure of EECA this seems less likely now.

### **10.7.2 2007 solar thermal hot water research and results**

In 2007, following presentation of the results to the solar sponsor, it was decided to separate the solar thermal panels, with each having their own HWC. Thus the research was to determine whether the angle a panel is mounted at affects its performance, how efficient is unglazed pool mat, how much thermal layering occurs in a HWC, and to develop a method to allow a quick comparison of a solar panel's performance and efficiency, while at the same time continuing to record the deterioration in performance of the existing 'L' designed finned flat plate panel.

A new sponsor provided two evacuated tube heat pipe systems, one a conventional heat pipe, but with 38 mm tubes, 1800 mm in length, with black coating, and with an area of 0.607 m<sup>2</sup>, and the other system being a newer finned heat pipe, diameter 75 mm, 1800 mm in length, with blue nitride coated copper piped fins, and with an area of 0.997 m<sup>2</sup>. The research involved determining how much extra energy is required to make up the HWC to 60 °C to satisfy Ministry of Health guidelines (for a minimum of one hour during any twenty four hour period), the method of heating hot water as used in the motel/hotel and light commercial industries, and is having a reflector a necessity for evacuated tube systems.



The setup for this second 2007 sponsor has two individual HWCs and collectors with a common flush connection, and separate solar controllers (10/6/4 settings) and PLC sequencer for over-temperature, flushing at 0400, and 5 minute commercial load simulation every 4 hours (between the hours of 0800 and 2005). Flow rates were checked and adjusted to ensure equal flow rates to all HWCs.

A pool mat system is comprised of a header pipe of 50 mm diameter, with 6 mm laterals falling (in this case) 2 m to a 50 mm diameter footer pipe at the bottom. In the CPIT case this is then passed through a twin pipe radiator of 2 m in length which simulates the load of a pool. The water then enters a water mains pressure level controlled tank (600 mm diameter and float water height set to 430 mm) before being re-circulated by the CP. In a typical domestic pool installation, this system is driven not by a standalone CP, but by the pool's pump and interfaces with the chlorination system.

In both cases with the CP operating, it generates pressure in the lateral pipes sufficient for it to expand the lateral pipes and prevent any water escaping from the system. Thus when the CP turns off, the pipes contract in size and air is allowed into the system. This drains any water from the lateral pipes. In this way there is no water in the lateral pipes to freeze.

The pool mat system is shown in Figure 10.20. The pool mat has a filled system thermometer with the bulb coated with matt black heatshrink. When the system is exposed to sunlight, the temperature increases and the liquid expands and trips a thermostat which in turn starts the CP.

The findings for the first sponsor in regards to the unglazed pool mat are shown in Figure 10.20. The pool mat has an efficiency of 20 %, which is 5 % higher than was expected based on industry experience. This is shown by the graph and linear curve analysis in Figure 10.21 and Table 10.1. The thermal layering in a HWC is up to 5 °C depending on how recently the HWC has been disturbed by water dumping or flushing as shown in Figure 10.22. The test set up was changed for both the test panel and for the fixed finned flat plate to allow for changes in mounting angle. From the results

obtained, the angle matters for a finned flat plate panel. The best performance for a flat plate appears to be at an angle of 65 degrees for winter and with the limited testing conducted to December 2007 the same appears to be the case for summer. A quick study was also conducted into the optimum controller settings. These appear to be 6/4/4 for a finned flat plate, however this study needs more time to prove these values.



Figure 10.20 a & b. Pool mat solar thermal system, radiator and storage tank, January 2008.

| No. of days of usable data: | Efficiency | Average solar radiation<br>W/m <sup>2</sup> |
|-----------------------------|------------|---|
| 73 out of 122               | 20 %       | 214   |

Table 10.1. Summary data for the pool mat system, Sept to Dec 2007.

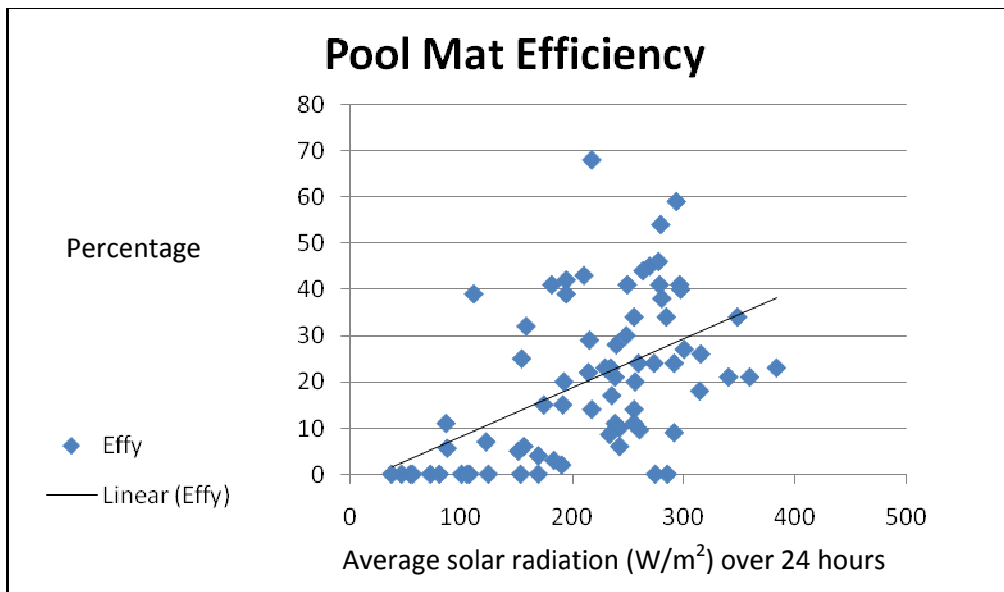


Figure 10.21. Pool Mat efficiency for the period September to December 2007

To record the thermal layering in a type two HWC, a special probe was manufactured which contained four LM335 temperature sensors equally spaced along a copper rod which was then inserted into the centre of HWC #2. Another probe was manufactured for HWC #3 with the two temperature sensors located at the top and halfway points of the HWC. These HWC were connected to the PLC load system with five minute flushing every 4 hours and a 0500 complete HWC flush.

The results indicate that when the HWC is left un-disturbed, a 4 to 5 °C layering occurs across the complete HWC, with the top of the HWC being up to 2 °C cooler than the middle layer created by the incoming solar hot water discharge nozzle. The bottom of the HWC is up to 5 °C cooler than the middle layers, as shown by Figure 10.22. Figure 10.22 also shows the collector Tc has a temperature gain of 13.4 °C, which is slightly higher than the normal 12 °C for this panel.

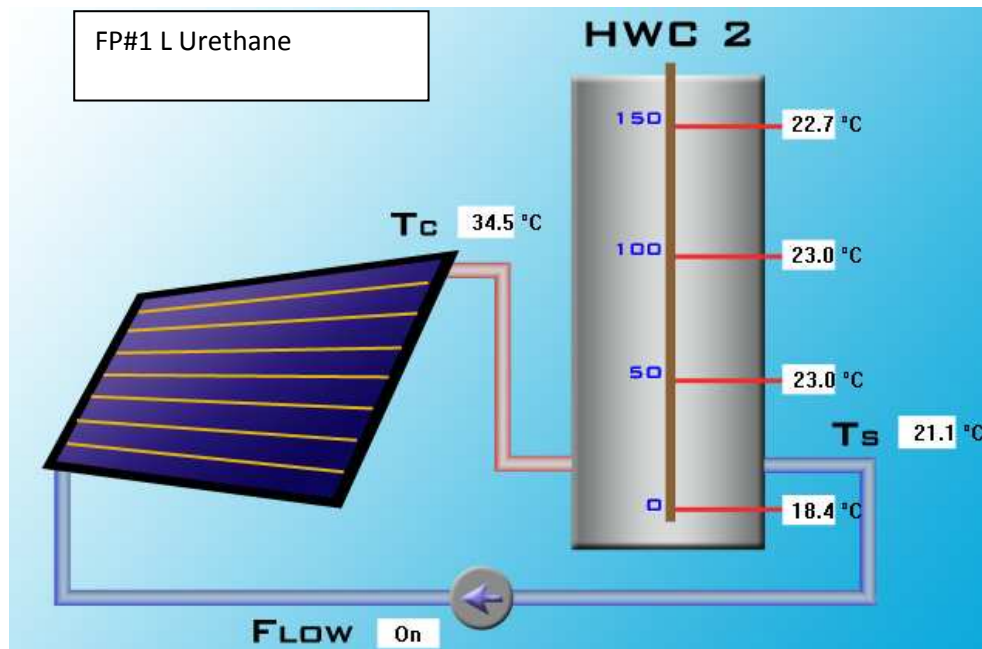


Figure 10.22. Solar thermal finned flat plate layering in type two HWC #2.

Several observations were made during the thermal layering tests, which will lead to further research. It was noticed that wind for example, particularly an easterly wind, has an effect on only one of the type two HWCs and its associated connections, despite these connections being lagged and insulated. This HWC is the middle of three HWC's. Other areas of ongoing research include analysis of the efficiencies of the two different types of HWCs and the level of insulation as recorded by the SCADA system, when the HWC is left undisturbed for periods of time, and the maximum temperature achievable in a HWC with and without flushing.

During the winter of 2007, a severe frost occurred. This had very little effect on any of the collectors on the roof of C block. All but one of the controllers had initiated their frost mode with display readouts of  $T_c$  of 3 to 4 °C, however, the display readout for the evacuated tube heat pipe controller was showing 1.5 °C and the controller had not initiated its frost protection mode. It was found that the manufacturer of this collector doesn't normally set frost mode, and if they do they set it to 2 °C, but only in highly frost prone areas. The controller's frost protection mode was then set to engage at 2 °C. A full system check was performed later in the same week on the tubes. No leaks were found in

the manifold or any pipework. There was however, a need for a fresh application of thermal transfer paste to the bulbs (top end of the evacuated tube inserted into the manifold), which had either not correctly been applied on installation or had become dry and worn off when the tubes were removed. The evacuated tubes heat pipes were also cleaned following this event. This was the first maintenance that had been performed on this system in two years. A small incremental improvement in the overall performance of the panel was noticed immediately following this maintenance, (the Tc temperature was observed to have increased by 1 to 2 °C on the controllers display).

A comparison of the finned flat plate panel performance for 2006 and 2007 over the same period in each year shows the panel had suffered a 15 % drop in performance, as shown in Figure 10.23 where a second order polynomial curve fitting algorithm has been applied to the graphed results. Figure 10.5, shows the deterioration which has occurred on the nitride coated fins which is now tarnished in the upper left and right corners of the panel. On some of the fins there is white speckling, the urethane insulation on the sunny side is cracked and pitted, and there is a green discolouration on the left side of the panel. Water from outside the panel has also entered into parts of the panel and caused further discolouration on the right side of the panels, copper pipes and nitride coated fins. This 'rusty panel' syndrome is common to this type of flat plate and to one other flat plate batch system which is also manufactured in part or whole in NZ. Further information on other sites with 'rust panels' can be seen on a web site set up by Gary Moller<sup>[86]</sup>. Currently BRANZ (Building Research Association NZ), have been contracted by EECA to survey seven flat plate collectors with falling flat plate performance, with the aim of identifying the extent of the physical deterioration. The report titled BRANZ EC1301<sup>[87]</sup>, speculates little in terms of the effect the deterioration may have on performance and only really does so in a qualitative customer satisfaction way.

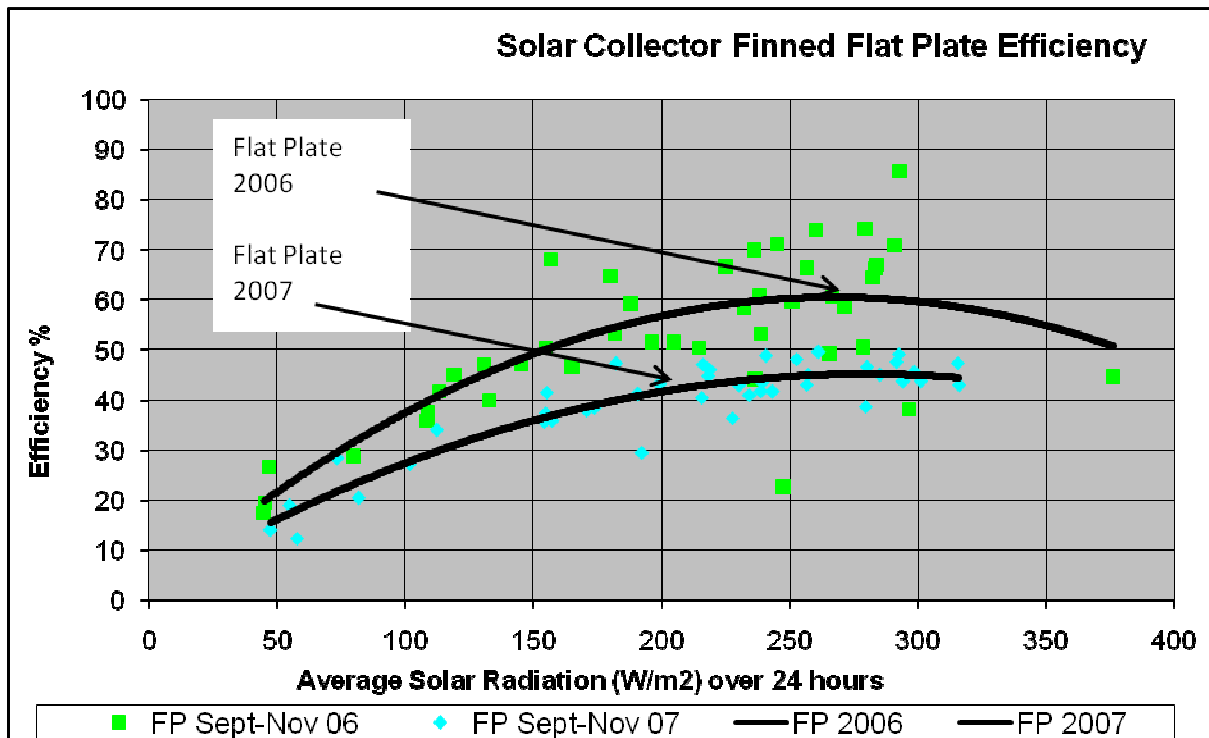


Figure 10.23. Flat plate panel efficiency performance August to November 2006 and 2007.

The overall system results for the first sponsor's solar thermal systems for the period of August to November in 2007 is given in Figure 10.24, with the finned plate being the original (2006), the second panel (ET in the graph) being a new type of evacuated tube heat pipe system, and panel three being the conventional evacuated tube heat pipe (purchased 2004, installed 2005, maintained early 2007).

Figure 10.24, shows that in low solar radiation, evacuated tube system heat pipe systems out performs the finned flat plate systems when compared on an energy produced per square metre, (kW/m<sup>2</sup>) and at higher radiation levels peak at between 55 % (older type evacuated tube) and 60 % (newer technology evacuated tube) efficiency respectively. A second order polynomial algorithm has been applied to the graph in Figure 10.24.

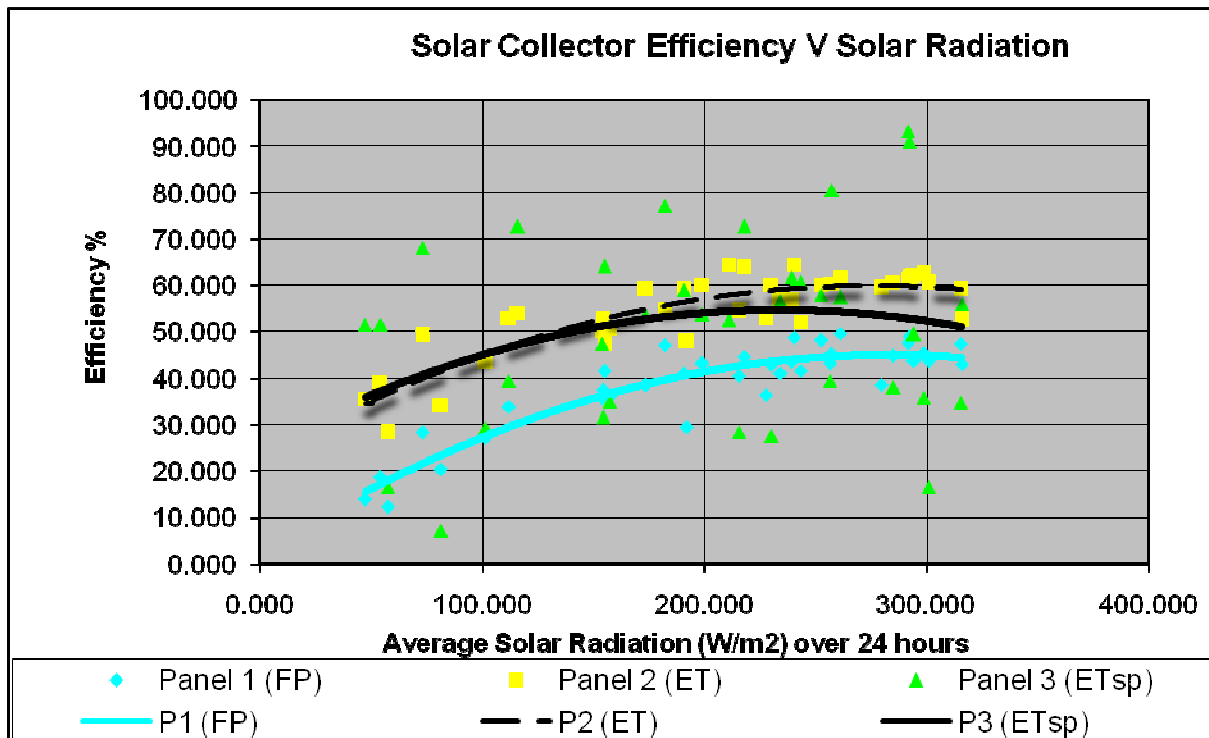


Figure 10.24. Summary graph of solar thermal systems response for 2007.

Investigation into controller settings is reported here, but is only preliminary at this point of time, with further ongoing and more testing being required. The results are shown in Figure 10.25, with a comparison being made between the finned flat plate and the conventional heat pipe at controller settings of 10/6/4 and 6/4/4. The graph shows an increase in both flat plate and evacuated tube solar systems performance with lower controller settings, with experimentation being performed on controller settings on a week about basis from July to December 2007. A second order polynomial algorithm has been applied to the graph in Figure 10.25.

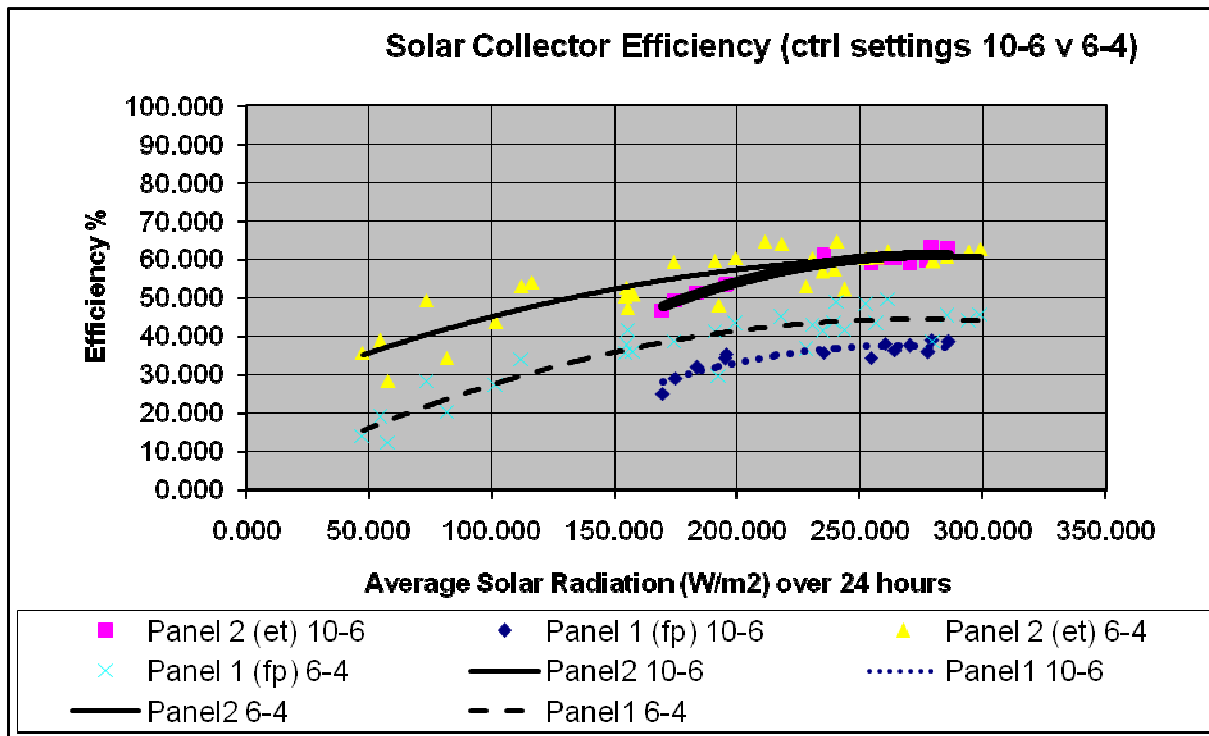


Figure 10.25. Solar controller settings for finned flat plate and evacuated tube heat pipe.

The results for the collectors from the second sponsor showed the inconsistencies currently in the solar industry and with Standards NZ in regards to the area measurement of collectors, that on average the gain from an evacuated tube finned heat pipe thermal solar energy will save \$410 per annum (extrapolated from results for the period of August to the start of November 2007, as shown in Table 10.2, i.e. for three months), and \$340 per annum for a conventional small tube heat pipe thermal system (for the same 3 month period). EECA's suggested figure per annum was \$350 to \$450. The results also indicate that a shaped reflector does matter and will give up to a 15 % increase in the performance of an evacuated tube finned heat pipe system, when compared with the results of the finned heat pipe system without a reflector, and with a flat non-reflective pressed aluminium sheet.



| <b>Evac Tube Finned Heat Pipe</b>          | <b>Averages</b> | <b>Accumulated Totals</b> |
|--|-----------------|---------------------------|
| Total Temp Gain (in °C)                    | 7201.           | 532865.                   |
| Average Temp Gain (in °C)                  | 8.46            | 626.                      |
| Total Flow (in l)                          | 203676.         | 15072000.                 |
| Ave Solar Radiation (in W/m <sup>2</sup> ) | 188.            | 13917.                    |
| Energy (in Joules)                         | 7234288.        | 535337281.                |
| Power (in Watts)                           | 83.7            | 6196.                     |
| Power density (in W/m <sup>2</sup> )       | 84.0            | 6221.                     |
| Efficiency (per unit)                      | 0.45            | 33.3                      |
| Efficiency (in %)                          | 45.             | 3329.                     |
| Extra Energy Req'd (in Joules)             | 33675921.       | 2492018182.               |
| Extra Energy Req'd (kWh)                   | 9.35            | 692.                      |
| Heating Time 2 kW element (hrs)            | 3.12            | 231.                      |
| Energy Req'd (in Joules)                   | 54696777        | 4047561475.               |
| Extra Energy Req'd (kWh)                   | 15.2            | 1124.                     |
| Heating Time 2kW element (hrs)             | 5.06            | 375.                      |
| Saving                                     | \$1.17          | \$86.40                   |
| Outside Temp                               | 10.80           | n/a                       |
| <b>Evac Tube Ht Pipe dia 38 mm</b>         |                 |                           |
|  | <b>Averages</b> | <b>Accumulated Totals</b> |
| Total Temp Gain (in °C)                    | 4701.           | 347855.                   |
| Average Temp Gain (in °C)                  | 8.87            | 657.                      |
| Total Flow (in l)                          | 125390          | 9278880.                  |
| Ave Solar Radiation (in W/m <sup>2</sup> ) | 189.            | 13989.                    |
| Energy (in Joules)                         | 4722557         | 349469211.                |
| Power (in Watts)                           | 54.7            | 4044.                     |
| Power density (in W/m <sup>2</sup> )       | 90.7            | 6711.                     |
| Efficiency (per unit)                      | 0.46            | 35.                       |
| Efficiency (in %)                          | 47.60           | 3522.                     |
| Extra Energy Req'd (in Joules)             | 42259464        | 3039264168.               |
| Extra Energy Req'd (kWh)                   | 11.4            | 844.                      |
| Heating Time 2 kW element (hrs)            | 3.80            | 281.                      |
| Energy Req'd (in Joules)                   | 57788418        | 4276342930.               |
| Extra Energy Req'd (kWh)                   | 16.0            | 1188.                     |
| Heating Time 2kW element (hrs)             | 5.35            | 396.                      |
| Saving                                     | \$0.93          | \$68.70                   |

Table 10.2. Energy savings per quarter in spring for evacuated tube thermal systems.

A limited survey was also conducted at this time of motels and hotels to understand their reactions to solar hot water heating and to ascertain their primary form of heating. Several motels and hotels were canvassed in both the central city and Riccarton Road, Christchurch. The age of the accommodation largely dictated the primary form of hot water heating, with larger, older complexes having diesel, coal or electric boilers with larger storage tanks, and the slightly more modern units having centralised electric hot water heating. However, the more modern approach is to have individualised electric hot water in each unit or for shared units, or for the newest motel with a gas main outside, instantaneous gas hot water heating with no storage. Moteliers and hoteliers had all heard of solar, but most thought it was too costly and offered no security of supply. The trend in the motel industry is for the developer to build the complex then maybe sell it off to operators, who may in turn, when the complex is fully operational, sell an operating lease to a new lessee. Therefore any capital expenditure for the complex is governed by the builder or complex owner, who is less likely to spend money on capital additions or alterations without any significant direct payback or saving to them. The second sponsor also conducted a survey and found the same results.

The airwall system connected in June 2007 was further expanded and added to in December, with a transpired airwall and a PV airwall. Whilst indicative results for the first airwall installed in June were available, some problems with the first airwall panel's fan necessitated a redesign of the system by the sponsor. A photograph of the combined systems is shown in Figure 10.26. It is too early for any results or trends to be presented as some of these panels have had only a few weeks of operation with the author leaving CPIT on study leave in February, 2007.

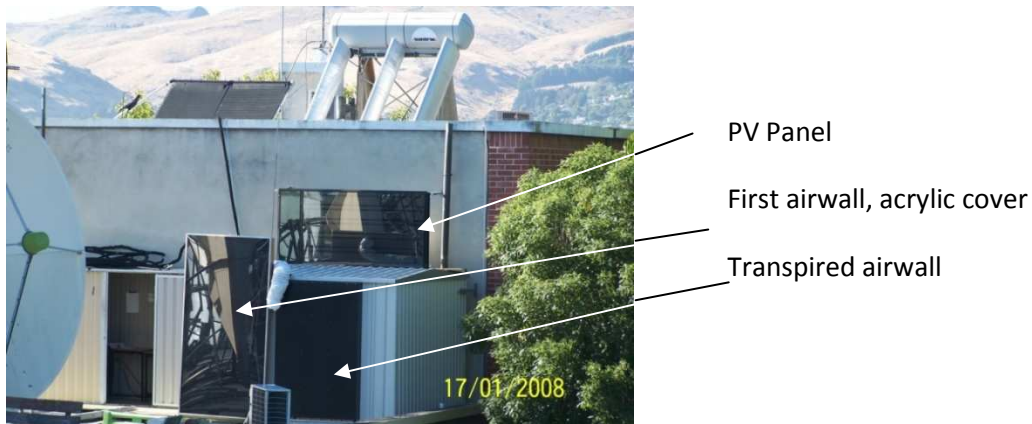


Figure 10.26. Airwall testing CPIT January 2008.

### 10.8 The economics of solar thermal hot water systems

A finned flat plate collector thermal system (one 8' x 4' panel) typically costs from \$2500 to \$3000, and is generally recognised as being sufficient for a household of up to three adults depending on hot water usage and householder age. Complete with installation into an existing HWC for a domestic consumer, the total cost is about \$5000 to \$5500 depending on location, mounting, the local council's building consent, and the length of copper pipework required to connect the solar collector to the HWC. If the consumer then wishes to upgrade the HWC to include a separate loop or heat exchanger, this will add \$1200 for the HWC plus a small additional cost for installation, plumbing and a tempering valve if there is none currently installed.

A twenty tube evacuated tube heat pipe or evacuated tube finned heat pipe system, recognised as being suitable for up to three adults as per the above comparison, costs \$2300 to \$2600 depending on suppliers. There are installation costs of up to \$1500, plus building consent costs which range from \$165 for Christchurch City Council to \$450 for Waimakariri District Council, plus in some instances a tempering valve to meet council requirements. Some central city solar hot water suppliers will include the tempering valve and the building consent in the total installation cost. This is for a straight forward and simple installation where the HWC is no more than twenty metres from the location of the HWC and there is no electrical work required for an additional plug power point for the solar controller and CP.

EECA will offer a domestic consumer a subsidy off the cost of installation of an approved solar thermal collector into a domestic dwelling, using an approved solar thermal hot water installer and provided certain criteria are met. In 2006 the subsidy was fixed at \$300, this was increased in 2007 to \$500, and as of 24<sup>th</sup> May 2008, it increased again to \$1000. After the first increase, additional qualifications on the grade, type, level of insulation, position of hot water element and age of HWC criteria being added to the assessment for subsidy process in 2008. EECA believe a domestic user can save between \$350 and \$450 per annum off their electricity bill using a solar thermal hot water collector system.

These cost savings are overly optimistic, as has been shown in Chapter 10.0. It is agreed that the solar hot water system can in many cases take over the heating of a consumer's HWC in summer, however, in winter the solar collector is at best a water pre-heater rather than providing a reliable supply of continuous hot water.

Using EECA's figures and assuming a typical installation cost structure for an evacuated tube heat pipe system (\$2500 for the collector, \$1500 for the installation, less an EECA subsidy of \$1000) results in a capital cost to the consumer of \$3000. Based on EECA's estimated per annum electricity saving of \$450, this means it would take a domestic consumer 6.7 years to pay off the complete system.

This has perhaps been the reason for the slow uptake of solar thermal systems in NZ. This analysis assumes that the price of electricity is fixed at 20 c/kWh (current electricity day rate prices, depending on consumer's electricity plan this can be up to 24 c/kWh), and that the HWC is heated with electricity during the day rather than at night when cheaper electricity is available. For some domestic installations, for example, a household may be on a 'night and day 8' plan (night rate 12 c/kWh and day rate 24 c/kWh). With two HWC's (say 290 l each) supplying hot water to different areas in the house (such as a laundry and kitchen for the first one, and showers and bathrooms for the second HWC) and the HWC load being connected to the night rate, the payback period for such

an installation will be thirteen to fifteen years, based on an estimated annual electricity saving of \$200 to \$225 pa.

## 10.9 Summary

In brief, a summary of the two years results is as follows:

- 1/. 3/8" pipe is more efficient for flat panels, in Christchurch.
- 2/. A finned flat plate Z panel design can operate in a frost environment with a controller whose frost mode setting is 4 °C.
- 3/. The average efficiency for an evacuated tube heat pipe (55 mm dia) is 55 % at a solar radiation level of 250 W/m<sup>2</sup> per 24 hour period, with 53 to 55 % in 2006 with a slightly higher level in 2007, at 55 to 57 % following maintenance.
- 4/. Evacuated tube heat pipe systems perform better than flat plate systems especially in low light and low solar radiation (a solar radiation level of 50 W/m<sup>2</sup>/24hr), with 35 % for evacuated tubes and 15 to 20 % being for flat plate collectors.
- 5/. A conventional finned flat plate L panel design with urethane insulation on installation has an average efficiency of 58 % at a solar radiation level 250 W/m<sup>2</sup>/24hr, falling by 15 % to 43 % in 2007 over the same period.
- 6/. A finned flat plate Z design panel with Rockwool insulation has an average efficiency of 40 % at a solar radiation level 250 W/m<sup>2</sup>/24hr. No further testing was conducted on this panel in 2007.
- 7/. Pool mat, unglazed, has an average efficiency, of 20 %, and at a solar radiation level 250 W/m<sup>2</sup>/24hr and efficiency of 24 %.
- 8/. The energy savings level as promoted by EECA is optimistic, based on extrapolation of the energy savings as measured for spring time solar thermal performance.

9/. Thermal layering in a type two HWC, when fed by a finned flat plate solar system and left undisturbed, is a maximum of 5 °C top to bottom of the HWC.

10/. Newer technology evacuated tube heat pipes of 38 mm diameter have a greater efficiency than larger diameter evacuated tube heat pipes and a more efficient manifold design resulting in an overall system efficiency of 60 % at a solar radiation level 250 W/m<sup>2</sup>/24hr.

11/. The best mounting angle for a finned flat plate collector is 65 degrees to the horizontal, in Christchurch, not 43 degrees which is the latitude. The mounting angle for evacuated tube systems doesn't make any significant difference.

12/. The solar controller's settings for turning on and off the circulation pump appear to matter for both systems, with preliminary data indicating that a finned flat plate collector's controller settings of 6/4/4 is best and for an evacuated tube heat pipe controller, settings of 6/4/2 seem best, especially in low solar radiation levels.



## **11.0 Results for SET**

The standard solar industry approach of calculating the efficiency of a solar collector as the energy it produces over a twenty four hour period, and then translating this figure to an efficiency figure based on area, is only one measure of a solar system's performance. There are other perhaps more important factors such as flow rate, instantaneous energy gain at the collector and temperature rise at the collector. The actual temperature the solar unit is capable of may be more important.

For this reason, as many parameters as were feasible and capable of easily being monitored and recorded by the SCADA or other systems, were recorded.

### **11.1 Operational**

In early testing, flow rates through the SET not only affected the SET system performance and temperature gain at the target, but also triggered the low flow sensor alarm and shut down the SET. It was found that the float flow switch used had a low flow switching threshold of 3.5 l/m. Although these units are supposedly sealed for life, the float will sometimes stick on the shaft (as occurred in 2007, with a flow rate of 2.2 l/m). Any vibration will free the float on the shaft. After a period in early 2007, when the SET would shut down with what seemed a slightly low to normal flow rate of 3.3 l/m, the float flow switch was pulled apart for checking. The float was found to periodically stick on the float shaft, despite the later being smooth. The float shaft was then lightly greased and put back into service with no further problems being noticed. Following this, the inlet water gauze filter and CP peristaltic pipes and header were overhauled and cleaned, with a peristaltic pipe needing replacement due to perishing. The perished peristaltic pipe was indicated by the CP tray full shut down alarm being triggered. Upon completion, air was bled from the CP header and target before the SET was allowed to operate again. It was found after this testing that if the SET target booms up and then the SET enters the shut down and stayput mode waiting possible solar radiation, which arrives some time later, that an air lock would prevent the flow of water through the target and the SET would then shut down under a no flow fault condition. After reluctantly altering the flow sensor



delay proving timer, the final solution to this problem came with the realisation that the pressure in the CP header required to overcome the air blockage rose to 3.5 psi and the CPS with its associated header tank could only manage 2.5 to 2.8 psi. The solution was to use both the CPS and CP, in which case the CP was able to boost the pressure in the CP header to just over 5 psi. This would immediately overcome any air lock or air blockage in the SET target, and would do so within the 90 seconds allowed for by the flow sensor delay proving timer.. This problem had not previously been observed, however it was only in 2007 that the water flow to the SET was modulated and controlled to the same extent. This issue will also effect the future developments of the SET, especially when the flow rate is modulated and a different type of flow switch will be required.

In previous year's testing, the flow rate through the SET varied between 2.2 l/m and 4.5 l/m depending on whether the CPS or CP or CPS and CP were on. In testing during 2006, the CPS was used by itself, and as there was always a trickle of water flowing through the SET, there was never any possibility of an air blockage occurring. In 2007, after the issues outlined above, further flow testing was carried out using a bucket and timer, under conditions of normal operation, shut down and stayput for extended periods and forced manual starting of the CPS and CP. The results of all this additional testing revealed that the float flow switch would reliably shut down the SET if the flow rate dropped below 3.5 l/m. Because the water flow was modulated (turned on and off), the chance of an air blockage occurring was increased and that because of this risk, increased pressure at the CP header was required to overcome this air blockage and prevent the SET from shutting down due to either a no flow or target over-temperature alarm.

## **11.2 Calculations**

The flow rate in the revised SET flow system (2007) varied between 3.8 l/m and 4.2 l/m depending on the time of the test and the position of the Y axis boom and target, i.e. immediately following an air blockage the flow rate would be 3.8 l/m, however in normal operation the flow rate with the CPS and CP both in continuous operation was 4.2 l/m. For all calculations, the flow rate is therefore averaged and assumed to be 4 l/m for the 2006 results and 4.2 l/m for the 2007 results (when both

CP and CPS were used). All flow meters and temperature probes were checked to ensure accuracy in all results and data obtained. Calibration has been performed to the best of the equipment available and to the limits of the surrounding environment.

Using the specific heat formulae as given by Wikipedia<sup>[82]</sup> and Steve Tomsett<sup>[83]</sup> as presented in Chapter 10.3, the energy in Joules and kWh can be calculated. This is then translated into kW per square metre. An efficiency figure is then obtained by dividing the kW/m<sup>2</sup> figure obtained by the average solar radiation arriving on a flat body on the earth's surface (1 kW/m<sup>2</sup>), as presented in Chapter 10.3.

Example 1: The solar trough collector, as shown in Figure 11.1 a & b, holds 320 l of water in its sideways mounted HWC. Over a twenty four hour period in Summer it is heated by 13 °C, this being the difference between the water inlet temperature at 0800 one day and the outlet temperature measured at the same time the next day, when the contents were emptied out of the solar trough HWC.



Figure 11.1 a & b. Solar trough in operation Dec 2006 (midday) and Feb 2007 (1500 hrs).

As 1000 millilitres of water equates to approximately 1000 grams in weight, (at 25 °C) the energy calculation is:

$$Q = 17.39 \text{ MJ}$$

Since 1 J is equivalent to  $2.78 \times 10^{-7}$  kWh then:

$$Q = 4.83 \text{ kWh}$$

Assuming an eight hour heating period, which for the solar trough is governed by the associated PLC that controls the timed operation of the three sails or troughs, this translates to a power input of 604 W of instantaneous power averaged over 8 hours.

Example 2: For the SET, assuming a flow rate of 4 l/m for a period of 8 hours, at a constant or an average 17 °C target temperature rise:

$$Q = 136.48 \text{ MJ}$$

This is equivalent to = 37.9 kWh

Or an instantaneous power value of 4.74 kW averaged over 8 hours.

Relating this to efficiency requires the division of the kW by the area of the collector.

As the area of the mirrors on the SET totals  $9.318 \text{ m}^2$ , this means the efficiency for the SET is 51 % for the 8 hour period under consideration, (assuming a solar insolation of  $1 \text{ kW/m}^2$ ).

Example 3: For the SET, assuming a temperature rise of 20 °C for the same conditions as in example 2, this gives a Q value of 160.56 MJ or 44.6 kWh and a power of 5.58 kW, and 60 % efficiency for the 8 hour period.

Example 4: For the SET, assuming a temperature rise of 22 °C and a flow rate of 4.2 l/m, this gives values 185.45 MJ or 51.51 kWh, and 6.44 kW and 69 % efficiency for an eight hour period.

By comparison using the same basis, the theoretical efficiency of the other solar devices is:

- solar trough (delta t of 13 °C, 320 l, 10 hours), is 12 %,
- solar batch collector (evacuated tube thermosyphon with a delta t of 31 °C, 112 l, 10 hours), efficiency is 30 %,
- evacuated tube heat pipe (delta t is 13 °C, 1600 l, 9 hours), efficiency 60 %,
- finned flat plate L type (aged) (delta t is 10 °C, 1200 l, 9 hours), efficiency 47 %,
- finned flat plate Z type (delta t is 11 °C, 756 l, 9 hours), efficiency 40 %.

From 2007, the actual results for the second sponsor's solar thermal systems, namely the finned evacuated tube heat pipe (blue tube) and the conventional evacuated tube heat pipe (small diameter) which have used a different measurement system, were 45 % and 46 % efficient respectively. These results are about 10 % to 12 % lower than what was expected. The exact reasons have still to be ascertained, however, possible reasons may be the physical location, the impact of wind, HWC limitations, or just poor quality evacuated tubes – the black system has experienced four evacuated tube failures as evidenced by the tubes being warm to the touch rather than cold. The new style of conventional evacuated tube heat pipe, with smaller diameter tubes, submitted by the first sponsor in 2007 for evaluation and test panel achieved an actual efficiency of 61 %.

### **11.3 Results as tested**

In testing it has been observed that there is a difference in the average operational hours per day for the evacuated tube heat pipe and SET. The actual results from August 2006 and February 2007, when the SET mirrors were freshly polished, were for the evacuated tube heat pipe, 3.92 hours per day average, and for the SET, 4.78 hours per day (this contrasts with the theoretical allowance of 9 hours and 8 hours respectively). For the summer month of February 2007, the actual hours of operation were 6.44 hours for the evacuated tube heat pipe and 8.5 hours for the SET.

The average temperature gain for the two systems for a twenty four hour period was 5.4 °C for the evacuated tube heat pipe and 3.5 °C for the SET in August 2006, and 7.3 °C (evacuated tube heat pipe) and 2.5 °C (SET) respectively for February 2007.

By contrast, the peak temperature gain achieved for the evacuated tube heat pipe in August 2006 was 32 °C, and 60 °C in February. This figure should be tempered by there being only one HWC, whereas for the SET, the maximum temperature gain was 30 °C per twenty four hour period and an average of 32 °C over the month. The temperature gain for the month on average for the evacuated tube heat pipe was 8.5 °C (August 2006) and 17.3 °C (February 2007), and for the SET 15.3 °C (August 2006) and 12.4 °C (February 2007). The slow fading of the mirror polish with age and consequently the poor quality of reflected image on to the target for September 2006, are shown in Figure 11.2 a, b and c, i.e. spring. Figure 11.3 a, b, c and d shows the polished state of the mirrors and the reflection onto the target in February 2007 i.e. summer.



Figure 11.2 a & b. Reflected image to the target in September 2006.



Figure 11.2 c. The polished state of the mirrors in September 2006.



Figure 11.3 a & b. The target with polished mirrors on 14<sup>th</sup> February 2007.



Figure 11.3 c & d. The polished state of the mirrors on 14<sup>th</sup> February 2007.

A temperature gain of 21 °C for a period of up to 4 hours in the afternoon is shown in Figures 11.4 and 11.5 for the 9<sup>th</sup> February and the 14<sup>th</sup> February 2007 respectively. The weather on both occasions was cloudy in the mornings, with clearing fine conditions in the afternoon. A four hour time period is shown on the SCADA display system in Figure 11.4.



Figure 11.4. SCADA system data recording for 9<sup>th</sup> February 2007.

Figure 11.4 shows a peak temperature of 40 °C and an average temperature rise of 37 °C target outlet from 16 °C inlet water temperature for period 1230 to 1630 (resulting in an average temperature gain of 21 °C gain for 4 hours).

The trend for the 14<sup>th</sup> February 2007 is in part shown on the SCADA recording system in Figure 11.5. The SCADA screen printout in this figure and those featured throughout the remainder of this chapter, show time on the x axis and temperature on the y axis. The temperature gain was 8 °C in the morning for about one hour. The afternoon conditions cleared, as indicated in Figure 11.5 on the SCADA spreadsheet report. A further rise in solar radiation levels occurred around 1630 to 1700 (not shown in Figure 11.5) with the average solar radiation for the day being 405 W/m<sup>2</sup>, a peak solar radiation of 1693 W/m<sup>2</sup> (which, despite the pyranometer being calibrated, is above the theoretical maximum of 1367 W/m<sup>2</sup> and is therefore anomalous) and target temperature levels peaking during this time at 43.4 °C (the inlet water temperature at this time was 20.8 °C, i.e. an instantaneous temperature gain of 22.6 °C). The average temperature gain for the period of operation from 1430 to 1800 (3.5 hours) was 15.1 °C and 3.6 °C, evaluated over the twenty four hour period. By 1810 the SET had automatically parked and the target had cooled off. The SET operated for a period of 6 hours on this day.



Figure 11.5. The peak temperature gain for the 14<sup>th</sup> February was 43.4 °C, the average temperature gain was 21.6 °C. The SET operated for 6 hours on this day.

A polished mirror substrate is shown in Figure 11.6, on 21<sup>st</sup> August 2007. Figure 11.7 shows the temperature gain as recorded on the SCADA system for the same day, with the rise in the target's temperature being interrupted for mirror polishing. It can be seen from this figure that the unpolished target outlet temperature peaked at 17 °C. After polishing, the target outlet temperature rose to on average 30 °C. The morning water inlet temperature was 8 °C and the afternoon water inlet temperature was 12 °C. This results in a temperature rise of 9 °C for the morning and an 18 °C temperature rise across the target after polishing. The peak temperature spike was 40 °C or a 28 °C rise. The hours of operation for the peak onwards are 1130 to 1530 or 4 hours of operation at this level of temperature rise. This resulted in an average temperature rise for the day of 14.6 °C, with a peak of 40.5 °C, and a run time of 7.3 hours according to the SCADA report for the day.





Figure 11.6. A polished mirror with light condensation on the substrate, camera incorrectly stamped at 22<sup>nd</sup> August 2007 (should be 21<sup>st</sup> August 2007).

The average temperature rise for the evacuated tube heat pipe system for the day was 17.4 °C, with a peak average temperature rise of 33.2 °C, and an operational time of 5 hours for the CP.

Relating both sets of performance figures for the two solar devices to the same twenty four hour period, results in the findings as detailed in Table 11.1. The solar radiation for the day peaked at 1316 W/m<sup>2</sup> and averaged 358.3 W/m<sup>2</sup> for the 24 hour period. Figure 11.7 shows the effect of mirror polishing with the dip being the time taken to polish the mirror substrate.

|  | SET                         | Evacuated tube heat pipe    |
|--|-----------------------------|-----------------------------|
| Average delta T gain per 24 hours                                | 5.5 °C                      | 4.7 °C                      |
| Peak delta T difference per 24 hour (outlet – inlet temperature) | 27.9 °C                     | 7.5 °C                      |
| Runtime (CP in operation time) hrs                               | 7.3                         | 5                           |
| Power per 24 hour period   | 0.46 kW (5 % efficiency)    | 0.41 kW (14.8 % efficiency) |
| Power produced in operation & therefore efficiency in operation  | 1.54 kW (16.5 % efficiency) | 1.97 kW (71 % efficiency)   |

Table 11.1. Summary of results for SET and evacuated tube heat pipe.

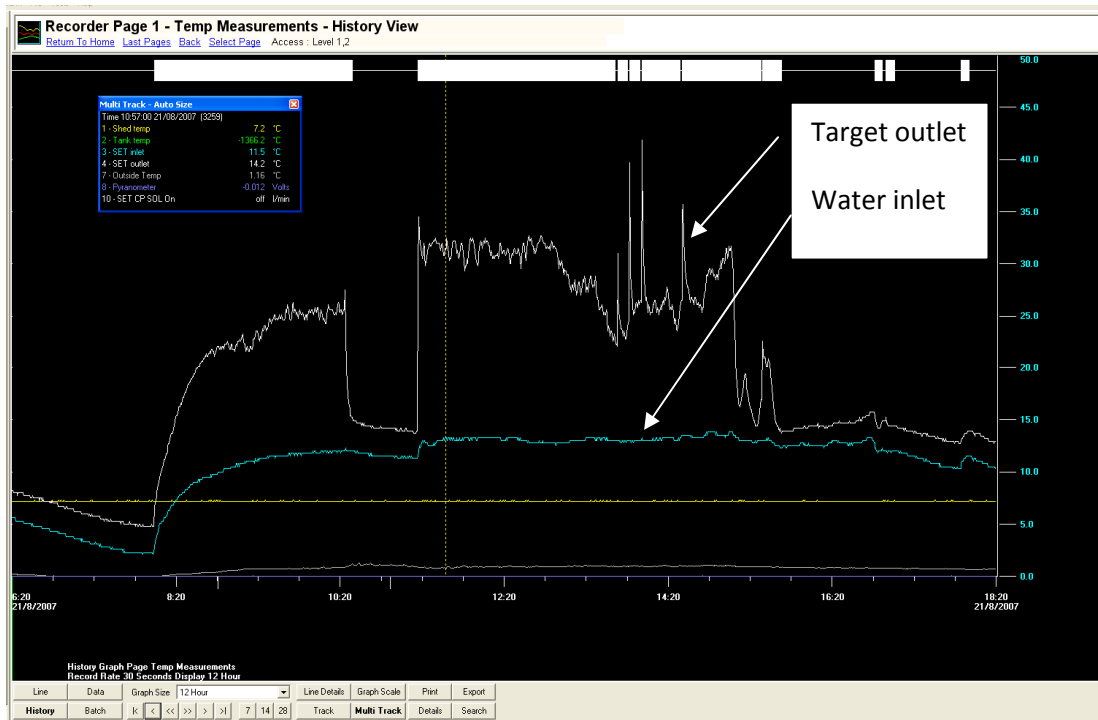


Figure 11.7. The temperature gain as shown on the SCADA system for the 21<sup>st</sup> August 2007.

Figure 11.8 shows the temperature gains produced by the SET in daily batch data format for the period from 19<sup>th</sup> August to 25<sup>th</sup> August 2007.

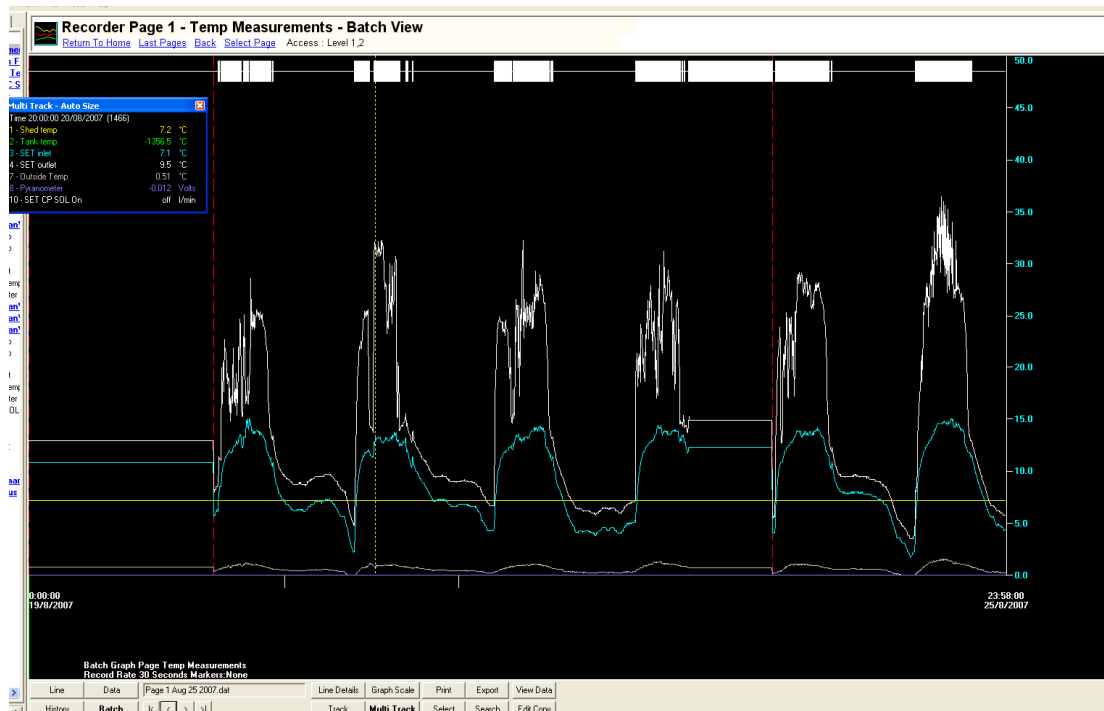


Figure 11.8. SET target temperature gains for 19<sup>th</sup> August to 25<sup>th</sup> August 2007.

With unpolished mirrors, the instantaneous readings of temperature gain from the SET drop from 22 °C on average, a temperature gain of between 10 to 13 °C depending on ambient conditions. This is shown by way of contrast in Figure 11.9. This shows the target with unpolished mirrors on 20<sup>th</sup> June 2006 (the shortest day), where the temperature gain was 7 °C at 0830 rising to 10.0 °C by 1130, peaking at 11.4 °C rise between 1130 and 1545 before falling away again in the late afternoon sun, i.e. an average for the period 0930 and 1600 of 10 °C rise for the day. Figure 11.9 c shows the SCADA display screen for the period 1130 to 1545.



Figure 11.9 a & b. The target with dirty or unpolished mirrors, 20<sup>th</sup> June 2006.

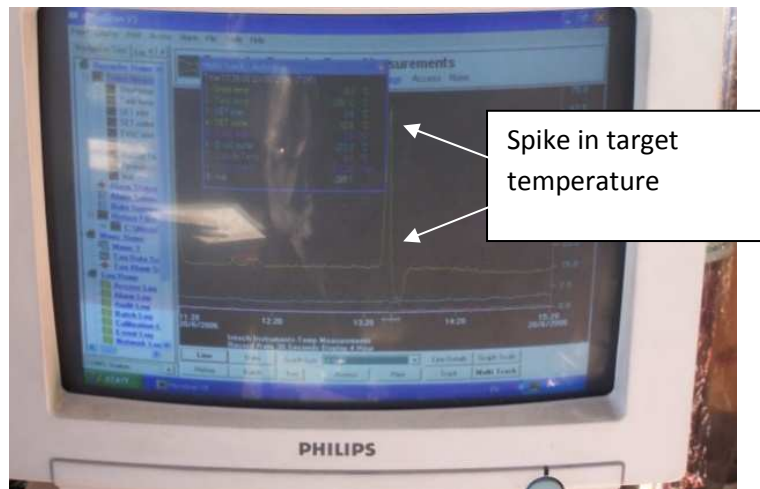


Figure 11.9 c. SCADA display readout for period 1130 to 1530 on 20<sup>th</sup> June 2006.

For the period of 2 to 6 weeks after the polishing of the mirrors in late August 2007, the average temperature gain has fallen to a 14.5 °C temperature rise for the month of September.

Some of the other factors affecting the performance of the SET relate to its:

1. Operational characteristics, i.e. it sometimes does not seem to perform well under certain types of cloud and high cloud situations, which is believed to be a function of the characteristics of the IR photo-diodes chosen, and is evidenced by SET's low performance on cloudy or overcast days.
2. Operational limitations relating to the surrounding environment limitations, i.e. being unable to track the late (past 1700) winter sun and track the early morning winter sun due to nearby buildings.
3. Detailed analysis of the performance figures for the SET on the 6<sup>th</sup> September 2007 reveals that the hours run meter and the SCADA report (#10) both showed 16 hours of CP operation. This was not thought possible with the SET being restricted in operation by the PLC's real time clock to 0600 to 1800, a maximum of 12 hours. However, investigation showed that the overnight temperature dropped below the frost protection threshold and engaged the frost protection mode for a period from 0130 to 0140 and then from 0200 to 0800 when the SET

commenced normal auto-tracking operations and immediately produced a small temperature rise across the target. Therefore, ignoring the hours run meter readings, except where there was a temperature rise in excess of 5 °C across the target, the hours runtime is reduced to 10.4 hours resulting in an average temperature rise across the target for the day of 16.6 °C, a peak rise across the target for the day of 35.5 °C, and power produced (for the twenty four hour period) of 0.97 kW (10.8 % efficiency). If the actual runtime efficiency method is utilised, then the SET has a power level of 2.23 kW (23.9 % efficiency). By comparison, the evacuated tube heat pipe has a 16.7 °C rise, a peak of 36.3 °C, a power (24 hour) of 0.4 kW (14.3 % efficiency) and a runtime power of 2.4 kW (86 % efficiency).

From these results it is determined that the SET is capable of producing a 10 to 13 °C temperature gain with dirty or unpolished mirrors, but with polished or cleaned mirrors the temperature gain increases to over 20 °C, and sometimes up to 24 °C. It is desired that the SET maintains this power output under a broad range of solar conditions. However, further analysis of the results for 6<sup>th</sup> September 2007 showed that whilst the SET achieved a temperature rise across the target of greater than 20 °C, it only did so for one SCADA sample period (15 seconds). A filter was applied to the results to ascertain how long the target temperature exceeded the 18 °C limit. This was 2.5 min. The next filter level applied was a 15 °C limit. The target temperature exceeds this for fifty five minutes.

The standard solar industry means by which all solar thermal units are judged, is the amount of energy produced per unit area of the collector in a twenty four hour period. For the SET, the average output over a twenty four hour period is lower than that for the comparative solar thermal devices, being less than 8 %. However, if analysis is restricted to calculating the efficiency for the period of generation, and without any further temperature constraints (i.e. the target rise must be greater than 5 °C over the inlet water temperature for the SET to be considered operational and ignoring frost events), then the comparative solar device's efficiency improves, as does the SET's figure to between 15 and 20 %.

This is then a measure of the device’s generation efficiency as opposed to its efficiency which includes idle periods or when it is physically restricted due to nearby equipment or unable to track during early or late afternoons due to the physical limits of the machine.

Wind also affects the performance of the SET, especially the Easterly as it tends to cool the target more quickly, by up to 3 °C. A strong North Westerly will cause the target to move about in the wind and therefore reduces the overall target heating as the target moves about the focal point of the mirrors. There is a consequent loss of up to 5 °C in the target temperature rise.

Figures 11.10 and 11.11 show the temperature gain from the target as recorded on the SCADA system on 13<sup>th</sup> December 2006 and the 19<sup>th</sup> December 2006, with the period of operation being from 0800 to 1300 and 0800 to 1700 respectively. The average temperature gain during both of these periods is 18 °C.

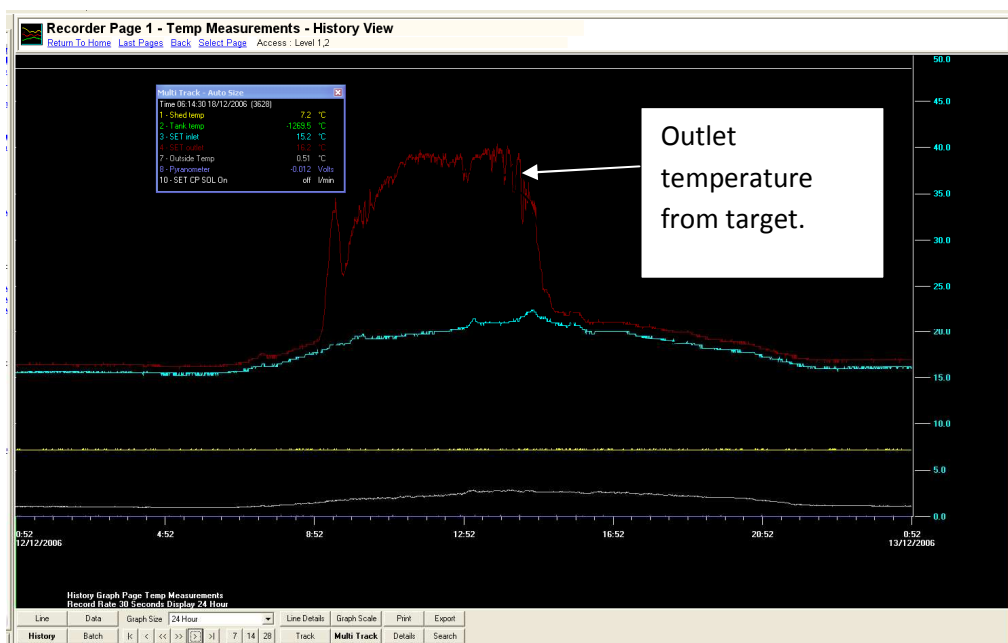


Figure 11.10. SCADA system temperature gain response curve for 13<sup>th</sup> December 2006 (light red coloured line in the centre).

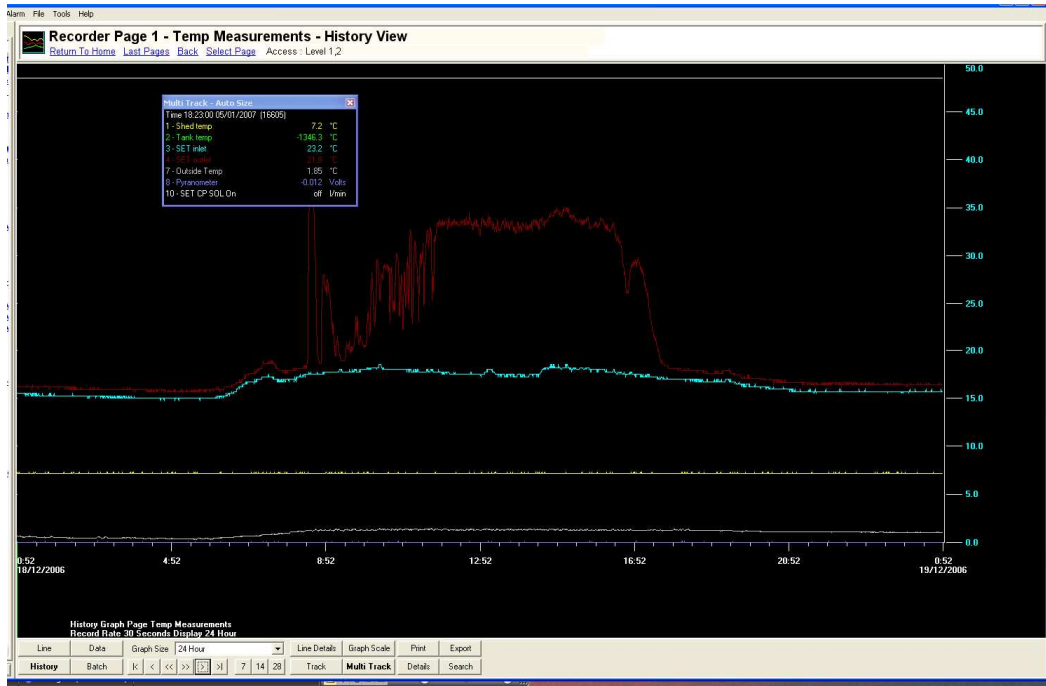


Figure 11.11. SCADA system temperature gain response curve for 19<sup>th</sup> December 2006.

Figures 11.12 and 11.13 show the maximum period of temperature gain for the SET is 0800 to 1630 in November 2007.

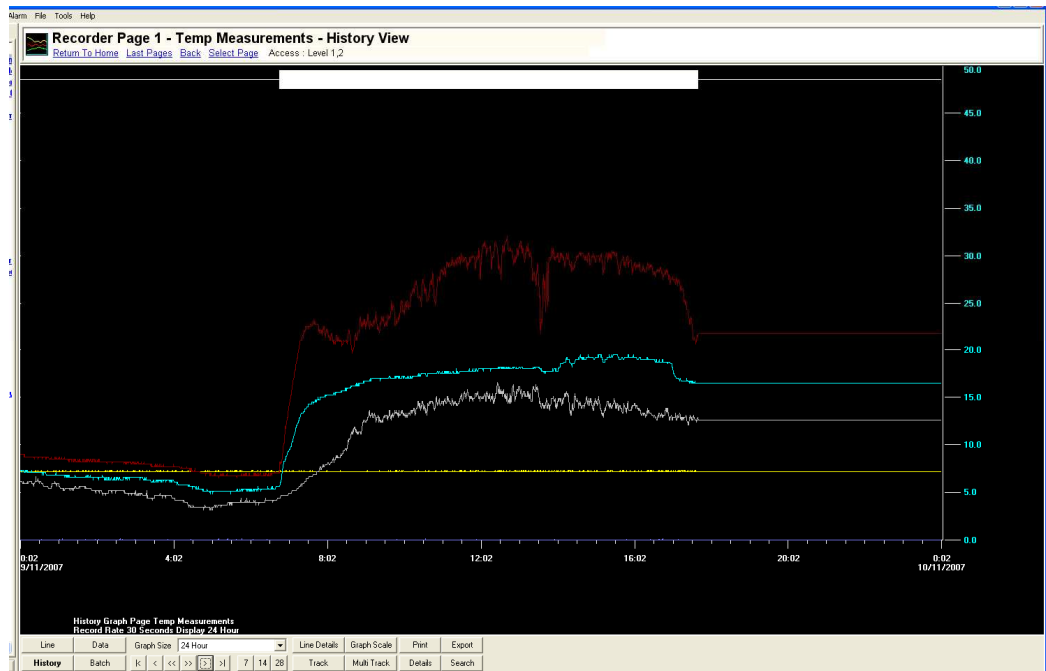


Figure 11.12. SET SCADA temperature response with an average 14.5 °C temperature gain for unpolished mirrors, early November 2007.

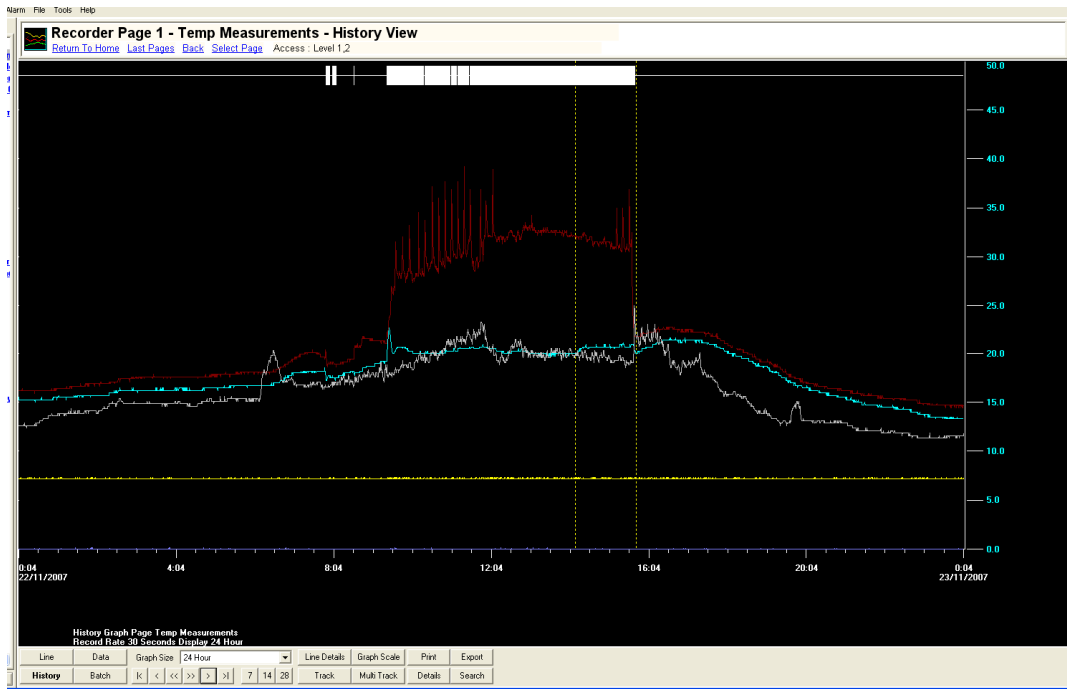


Figure 11.13. SET SCADA temperature response with an average 13 °C temperature gain for unpolished mirrors, late November 2007.

In 2007, a refinement to the water supply side of the SET (now modulated on/off reducing the amount of water wasted) and to the combination of the CP and CPS all being controlled from the PLC based on air temperature and target temperature, a change was observed in the SCADA output for the SET. This resulted in temperature spikes being recorded in the target outlet or exhaust pipe. An attempt was made to reduce this temperature spike, in both amplitude and frequency. To check whether this temperature spike was due in part to the 20 m long exhaust pipe, a test was performed on the calibration of the temperature probe attached to the exhaust pipe, i.e. where it leaves the SET and joins the flow meter and becomes a larger diameter pipe. The readings observed between the temperature sensor and the test probe were consistent within the margins of the equipment measured against. A further check was performed in which the analogue output from the PLC was reassigned to the SCADA station #1 and then compared with the temperature sensor as described and located above. The target temperature sensor was found to exhibit the same temperature spike characteristics but delayed slightly in frequency and at a reduced amplitude. It was therefore



decided to focus on using a different approach within the PLC to try and reduce the amplitude and frequency of these temperature spikes, shown in Figure 11.14. This was partially overcome with the adjustment of the time delay to commence CP and CPS operations and the lengthening of the time delay to turn off the CP and CPS, but also by adjusting the differential between the target and outside air temperature such that this differential was reduced from an offset of #4 BCD to #1 BCD. The BCD count corresponded to temperatures of 9 °C and 3 °C respectively. The start delay timer was changed from 40 seconds out to 1.5 minutes (on) and the off delay timer setting increased from 4 minutes to 6 minutes. A small PLC coding error was also remedied at this time in regards to the addition of Binary data rather than BCD data addition. Figure 11.15 shows the result with the amplitude and frequency of the spikes being reduced.

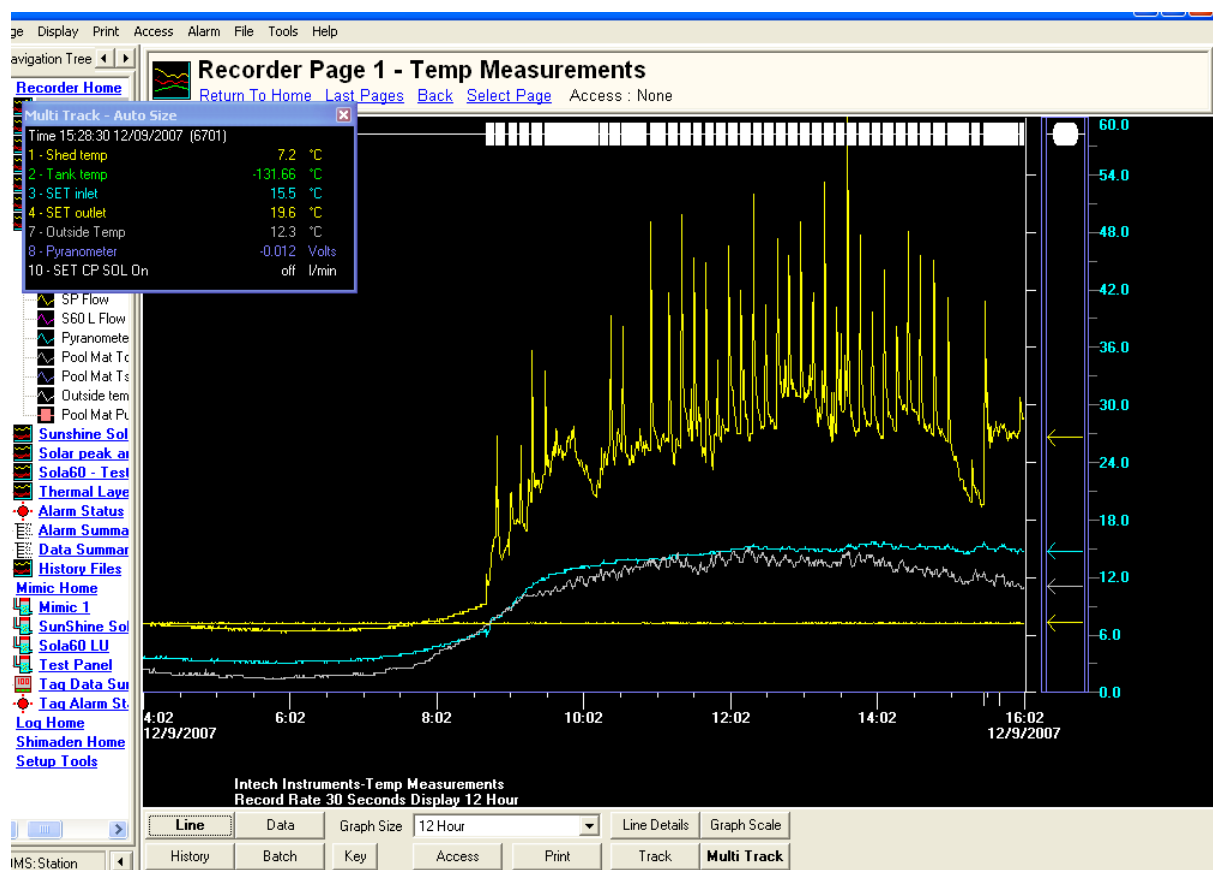


Figure 11.14. SET temperature spiking as recorded on the SCADA system, mid August 2007.

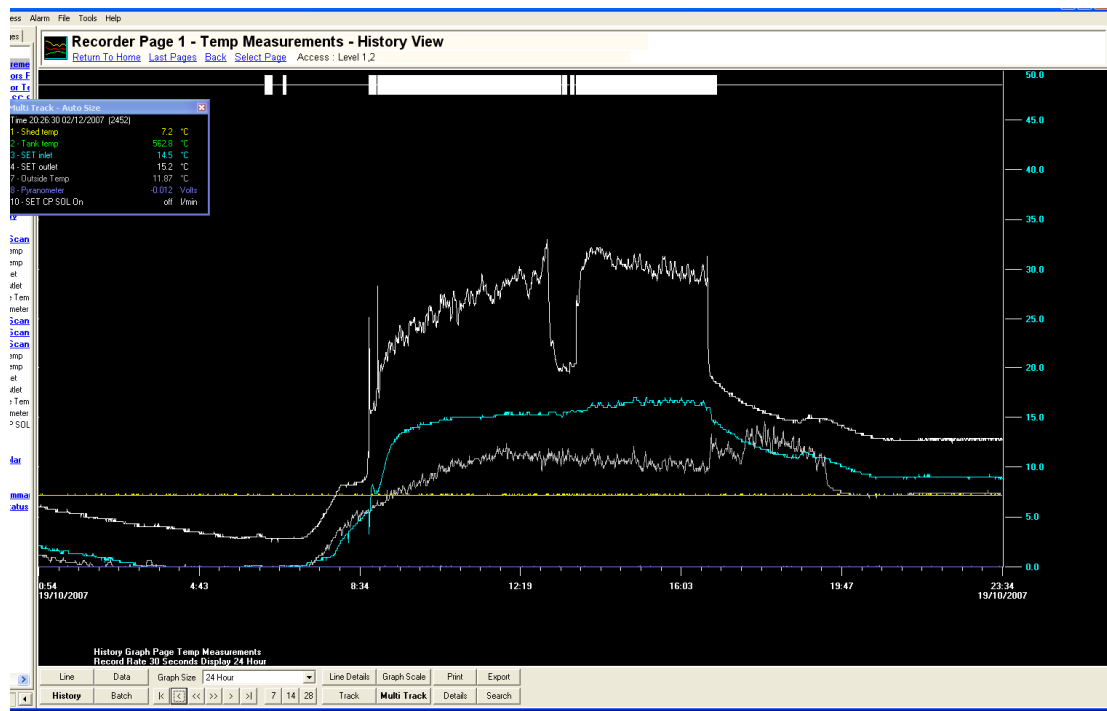


Figure 11.15. SET temperature spiking as recorded on the SCADA system, late August 2007.

An analysis of the results for September, October and November 2007, shows in Figure 11.16 a reoccurrence of the temperature spiking for the last week of October and first week of November 2007. The amplitude of these temperature spikes is however, greatly reduced (now up to 55 °C, but typically up to 45 °C) from when they were first observed (peaking at 60 to 70 °C or occasionally higher). In this case the x axis of Figure 11.16 is measured in days not hours.

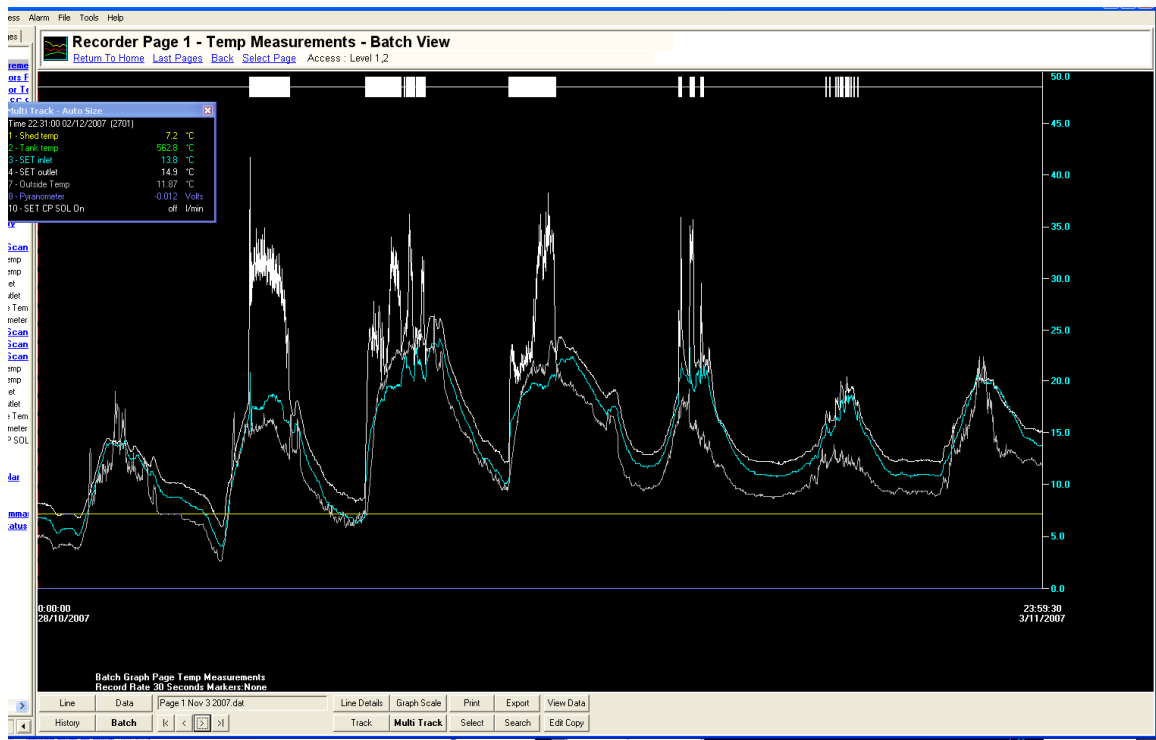


Figure 11.16. SET temperature spiking as recorded on the SCADA system, for the last week of October and first week of November 2007.

Figure 11.17 shows the light level, the evacuated tube heat pipe and the SET's performance averaged per day and then graphed for the month of August 2007. The SET's overall performance for three selected months is shown in Figures 11.18 through 11.20. From these results it is observed that the SET should not be compared to the evacuated tube heat pipe on the basis of a twenty four hour performance as it has a much lower efficiency. Figure 11.18, however shows the same graph with the addition of the average daily peak temperatures (the average of several days of peak temperatures) and shows the influence, in the second half of the month, of a light polishing of the mirror substrate by way of an increase in the average daily peak temperature rise.

The mirrors had also been lightly polished in February 2007, and the resulting performance graph is shown in Figure 11.19 with the overall performance falling off towards the end of March as the polishing compound wears off the mirror substrates and the mirrors return to their dirty, cloudy unpolished state.

The last graph, Figure 11.20, shows a peak of 90 °C in the evacuated tube heat pipe, which it is thought occurred when the CP for the solar batch collector turned on at the same time as the evacuated tube heat pipe CP turned on, which reduced the flow of water through the evacuated tube heat pipe giving rise to the sudden sharp increase in temperature in its manifold. The other graph of interest in this figure is the downwards trend in the SET overall performance for the latter part of September 2007, which is due to the mirror substrates returning to their dirty unpolished state following a polishing in early August 2007 as shown previously. The gap in data for Figure 11.20 is when the SCADA system ceased recording.

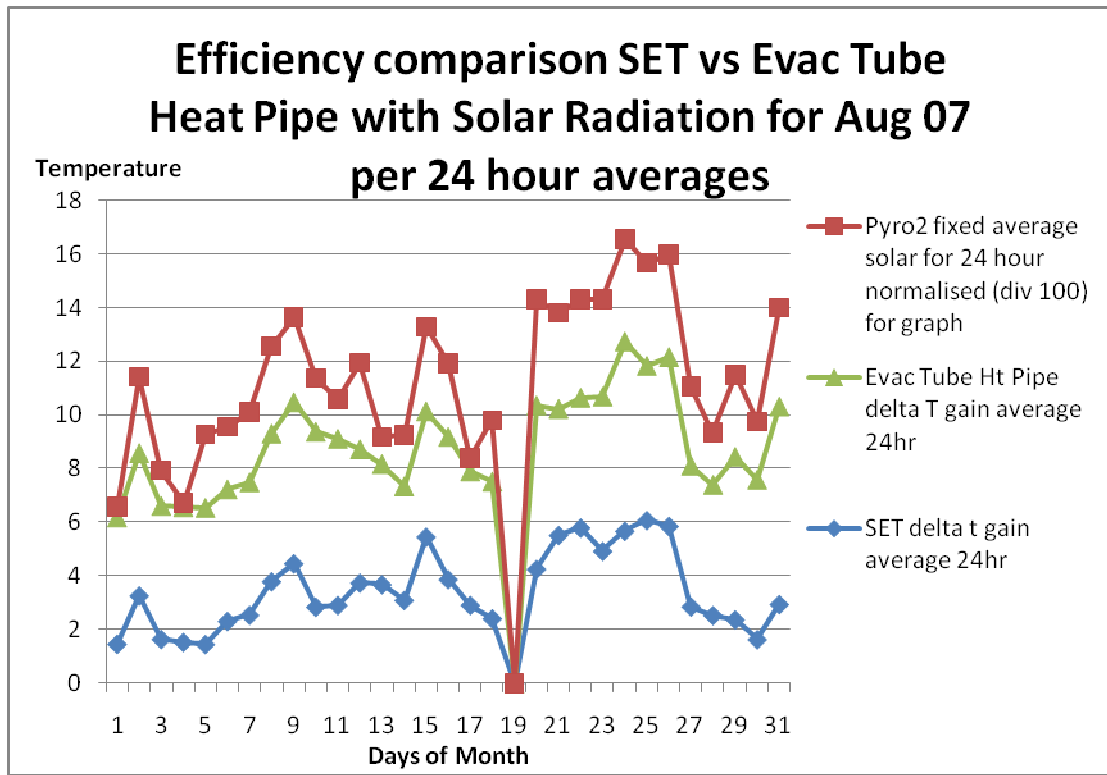


Figure 11.17. SET, Evacuated tube performance averaged for a twenty four hour period and plotted for August 2007.

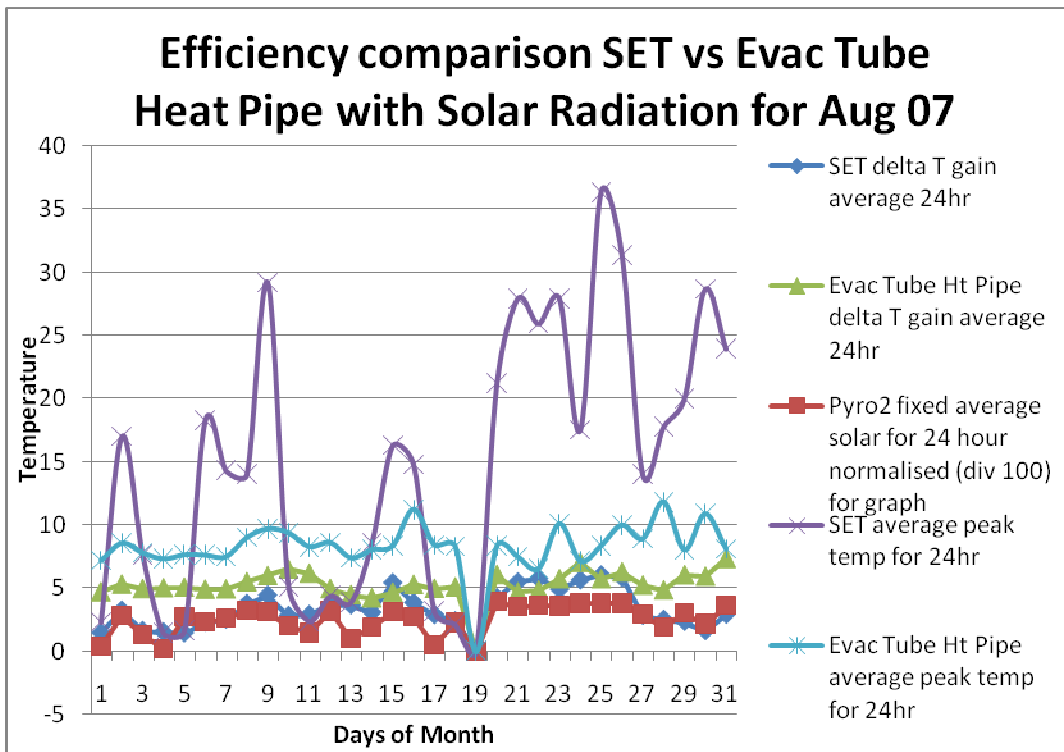


Figure 11.18. SET, Evacuated tube heat pipe performance when average peak daily temperatures are taken into account for August 2007.

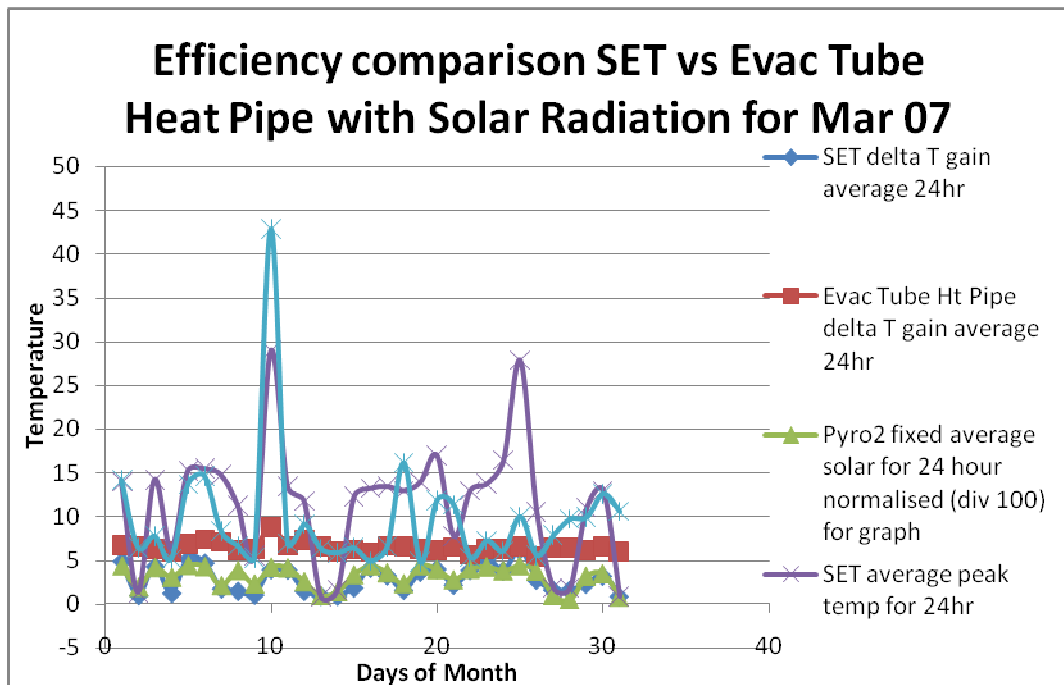


Figure 11.19. SET, Evacuated tube heat pipe performance when average peak daily temperatures are taken into account for March 2007.

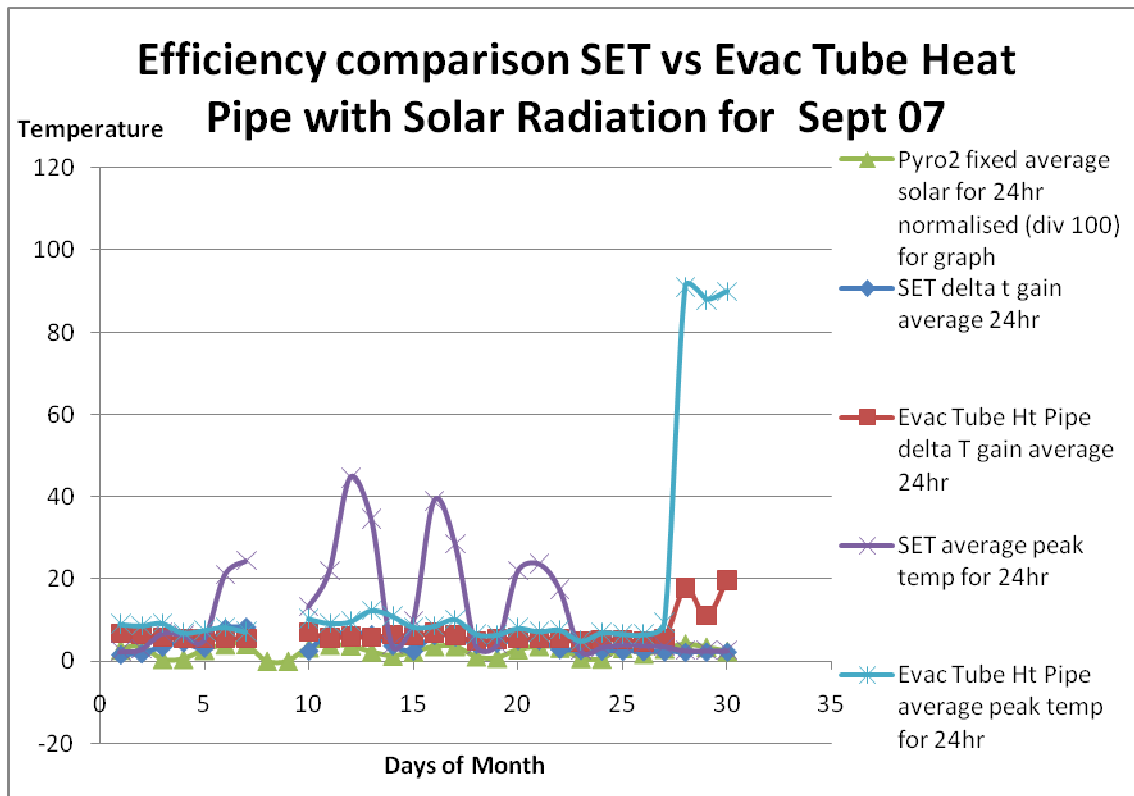


Figure 11.20. SET, Evacuated tube heat pipe performance when average peak daily temperatures are taken into account for September 2007.

#### 11.4 Summary

Whilst the SET is capable of achieving a 20 °C rise in temperature across the target, the ability to sustain this for any long period of time is required for the SET to be considered of any real commercial use.

The standard industry method of comparison of a solar thermal system's response, by relating the energy gained to area over a twenty four hour period, is not a suitable means of comparison for the SET as it is only capable of producing heat energy during daylight. Therefore a means of analysing the SET's performance for the period it is generating should be used, especially if the SET is to be used for electricity generation or other purposes or plant requiring hot water.

The SET is affected by the condition of the mirror substrate, by wind and by cloud cover. The SET in its current location is also physically limited in its travel ability in the early morning and late

afternoon positions. The results achieved may also be affected by the current method of operation, i.e. operating the SET in open loop mode, whereas in a typical installation it would be operated in closed loop mode and may be able to achieve a sustained higher average temperature rise across the target.

The overall efficiency of the SET with polished mirror substrates and using the instantaneous SCADA readings and averages is encouraging. More work will be done on trying to increase the temperature rise and into lengthening or extending these spikes into longer periods of higher temperature rise. This may possibly be achieved by closing the loop from the target hot exhaust back into the low pressure storage tank and by modulating the speed of the CP rather than turning it on and off. It is envisaged that this will improve the overall efficiency of the SET and achieve performance figures closer to those indicated at the start of this chapter.

## 12.0 Conclusion and recommendations

### 12.1 SET

In Mother Earth News December 07/January 08<sup>[88]</sup> reference is made to the way forward as being 'using concentrating solar power which uses parabolic mirrors to focus the solar heat (energy) and generate steam to drive electric generators' as is currently happening in the utility power marketplace in the USA. It can be seen from the research and development and testing performed on the SET, that it is possible to develop a two axis solar tracker which is capable of following the solar energy in real time, rather than following GPS coordinates or a look up table of locations. The SET can continuously optimise its position to ensure the maximum possible solar energy is reflected onto the target. With clean and polished mirror substrates, the SET is capable of producing a temperature rise in the target in excess of 20 °C, which, according to Masters<sup>[62]</sup> and Quaschnig<sup>[66]</sup>, makes the SET suitable for power generation and other commercial and industrial applications requiring hot water. The current limitation of the SET is related partially to its physical location, to the state of its mirrors and to the plumbing setup.

The SET has been transformed from a kitset of parts into a fully functioning two axis solar energy tracking machine capable of achieving a temperature rise of up to 15 °C across the target at a flow rate of 4 l/m, with dirty or unpolished mirrors. This translates to an efficiency of 8 % in this case but in general terms the efficiency ranges from 5-10 % when related to energy produced per 24 hour time period. If the efficiency is calculated for the actual 'generation period' then this efficiency rises to between 16 and 24 %. However, with polished mirrors the temperature rise across the target can be in excess of 20 °C, but this has only been for short periods of time.

By comparison, the testing performed on the other solar thermal hot water systems have shown that the efficiency of an evacuated tube heat pipe system can be up to 65 %, and for a finned flat plate collector the efficiency can be up to 43 %, fourteen months after initial installation.



The SET has proven itself capable of automatically tracking the sun's radiation and in being able to successfully optimise the solar radiation onto the target. It is more than capable of shutting itself down at a day's end and restarting itself at the commencement of a new day. It is capable of monitoring itself and performing all safety actions required. It is also capable of being able to clear minor status and alarm conditions itself without reference to any human intervention.

The control system developed for the SET has therefore proven to be reliable over the twenty month period from April 2006 to December 2007, when only relatively minor adjustments were required to either the PLC code or to the mechanical operation of the SET. The SET has proven to be a reliable test platform from which other developments associated with this technology can be made.

In order for the SET to be considered for a commercial operation, the temperature rise is required to be sustained for longer periods of time rather than being just spikes or momentary peaks. The basis of comparison of the SET efficiency should also be changed to that related to the efficiency during operational hours rather than being related to a twenty four hour period. This is especially the case if the end commercial use or end purpose of the SET relates to an application where overall efficiency doesn't matter, but the temperature of the final medium (water) produced is what is important and decreasing or varying the flow rate may help in achieving this result. This for instance may be the case in electrical generation where the SET heats water or natural gas or oil in a closed loop arrangement which is then used to generate electricity, perhaps via a Stirling cycle engine as is the case in the USA<sup>[26][88][89]</sup>. Increasingly, the trend overseas is to link the output from a solar thermal plant (parabolic trough or heliostat types) with a steam turbine, with water or oil or molten salt as the transfer and storage medium, and thereby improve the electrical generation capacity, when there is no solar activity, and improve the efficiency of the complete system. It is this conversion efficiency which is important.

## **12.2 Future developments**

In its current form with unpolished and dirty mirrors, in its present location and operating in open loop mode, the SET is not really suitable for further development.

The future development of the SET will focus on achieving a closed loop operating environment and improving the circulation pump controls to allow modulation of the CP speed using the temperature rise in the target as the primary variable in a PID cooling operation mode within the current PLC setup.

New mirror substrates will be purchased allowing for higher temperature gains to be achieved all the time without having to rely on regular polishing of the current scratched and dirty substrate. It is envisaged that with the move of the Faculty of Design and Engineering to a new campus in 2009, that a larger area can be set aside without some of the current physical constraints, allowing the SET to operate for longer periods during the daylight hours without its performance being affected by surrounding buildings, trees, satellite dishes, and associated equipment shadows. The present target's raised profile is the best design for converting reflected sunlight into heated water as it offers the largest surface area available at the focal point of the present mirrors.

It is proposed to trial a recently released new type of IR photo-diode, and a different type of mirror mounting framework, which resembles that more commonly found in satellite dishes.

It is planned to continue the research, development, testing and evaluation of the solar thermal hot water systems with the current sponsors and with any interested new sponsors in 2009.



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## **14.0 Acknowledgements**

The author would like to express his gratitude for their support and assistance throughout the duration of this research project and thesis:

Paul Wilson, Chief Executive Officer, Tai Poutini Polytechnic, West Coast, formerly head of School of Engineering CPIT, then Dean of School of Engineering and then Deputy CEO CPIT.

Prof Pat Bodger, Head Of Department, Electrical & Computer Engineering, University of Canterbury. (Masters project supervisor).

CPIT technicians, Bob Cross, Ross Weir (retired), and Caillyn Benbow.

Dr Dirk Pons, Head of School of Engineering, CPIT.

Mike Brown and Steve Tomsett, Mechanical Engineering Tutors, School of Engineering, CPIT.

CPIT research committee for funding via the Publication Incentive Grants (PIGS) given to the author for peer reviewed publications by the author.

The author of this thesis would like to publically thank the various Bachelor of Engineering Technology final year project students who over the years have all contributed in one form or another to the solar projects at CPIT and towards the success of the SET.

The 2006, and 2007 solar thermal hot water system sponsors, who have offered their products for research and development purposes as well as supporting the B Eng Tech project students and the author.





## **Appendix 1 – Mechanical Engineering Assessment Report.**

### **Mechanical analysis of the SET.**

**Performed as a classroom exercise under supervision of Mike Brown (Mechanical Engineer).**

**Report compiled and completed by Mike Brown, 5<sup>th</sup> Dec 2003.**

### **STUDENT CALCULATIONS**

Based on wind loads calculated to NZS4203 (40-50m/s or 140-180 kmph) the students noted a number of critical areas shown in the following photos.

Using an interaction formula which sums all the various actions on a member, e.g.....

$$\frac{\text{Bending Action}}{\text{Bending Capacity}} + \frac{\text{Buckling Action}}{\text{Buckling Capacity}} + \text{etc} \leq 1$$

.....then any member in which this total exceeds 1 is likely to fail if the wind gets to these velocities.

There was obviously a bit of variation in the students calculations, but the areas shown were found to be over 0.8.

As discussed, the areas most likely to cause a hazard would be the mirrors, which could detach and cause injury. Your precaution of additionally securing these to the frame is a good idea.

As someone involved in the marine field, I am extremely nervous about using stainless steel fasteners with other metals in damp environments. This is especially true of threaded fasteners and in particular the use of threaded rod in differential aeration conditions (partly exposed to air, partly hidden) Whilst this rig probably won't be in marine conditions??? it is still an issue.

Galvanised mild steel bolts are more reliable in this situation, but the galvanising means that 10 mm is the smallest size available.

Other areas may cause collapse of the rig but are unlikely to be so catastrophic.

THESE BOLTS WERE  
CALCULATED AS  
MARGINAL (0.8)



THESE BOLTS  
WERE  
CALCULATED AS  
MARGINAL (0.8)



THESE MEMBERS  
LIKELY TO BUCKLE  
( $>1$ )

THESE MEMBERS  
LIKELY TO  
DEFLECT  
SIGNIFICANTLY  
( $>1$ )



## Appendix 2 - 'The Smiley face'.

Solar Energy Tracker

Lights Matrix

V1.3 08 Aug 2006

### What do all the lights mean?

| GREEN                         | AMBER                        | RED                               | ACTION REQ'D  |
|-------------------------------|------------------------------|-----------------------------------|---|
|                               |                              |                                   | Please help me !!!!!!!  |
| Solid                         | Solid                        | Solid                             | SYSTEM SAFETY SHUT DOWN.  |
|                               |                              |                                   | Please see below for how to help me!  |
|                               | •                            |                                   |   |
| Solid                         | Solid                        | 3 quick flashes<br>& a long pause | Target over temperature.<br>System will shut down and go to park position.      |
|                               |                              |                                   |   |
| Solid                         | Solid                        | 4 quick flashes<br>& a long pause | Circulation water flow fault.<br>System will shut down and go to park position. |
|                               |                              |                                   |   |
| Solid                         | Solid                        | 5 quick flashes<br>& a long pause | Circulation water pump fault.<br>System will shut down and go to park position. |
|                               |                              |                                   |   |
| Slow flash<br>(60 sec on/off) | Slow flash<br>(60sec on/off) | Off                               | System in standby mode & system parked.<br>System parked.                       |
|                               |                              |                                   |   |
| Slow flash                    | Solid                        | Off                               | Manual Park mode initiated, will reset 6am next                                 |
|                               |                              |                                   |   |
| Solid                         | Slow flash                   | Off                               | Frost protection mode engaged.  |
|                               |                              |                                   |   |
| Off                           | Slow flash                   | Off                               | Low light level mode engaged.   |
|                               |                              |                                   |   |
| Fast flash<br>(1 sec)         | Fast flash<br>(1 sec)        | Off                               | System normal and on one of its travel limits, it will reset.                   |
|                               |                              |                                   |   |
| Fast flash                    | Off                          | Off                               | System Normal.  |

To clear any fault, proceed as follows:

1. Press the blue RESET button on the side of the white control cabinet on the rear of the solar energy tracker, for 1 second, this clears the fault condition. The solar energy tracker will then move and respond to light and commands in the usual manner.

### **SYSTEM SAFETY SHUT DOWN**

**ONLY when all lights are permanently lit (solid) is there a problem and should the contact list be used or the following action be taken if no one is available.**

If all the lights are permanently illuminated this is a sign that the solar energy tracker has exceeded one of its safety limit conditions and needs to be shut down (eg one of the limit switches may have come off). This safety alarm condition is designed to stop the Solar Energy Tracker from destroying itself or 'strangling' itself.

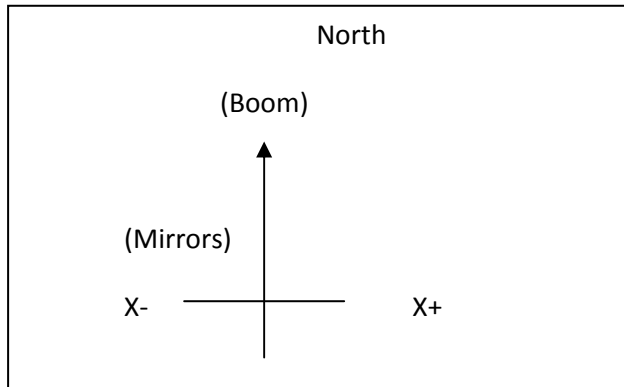
Check that all the four limits are still intact. See photographs following and if ALL the limits are still intact then proceed as follows:

1. Next press and hold the blue RESET button for 60 seconds, and **upon release** of the RESET pushbutton, the SET will move to the safety park position. This is different for each season based on the suns path. Summer position is boom NW, Winter position is boom South-East  
Please notify either David or Bob or Caillyn.

### **SET Definitions and orientation guide.**



**SET Control Panel**



A **Plan View** of the SET



**Summer Park Position**

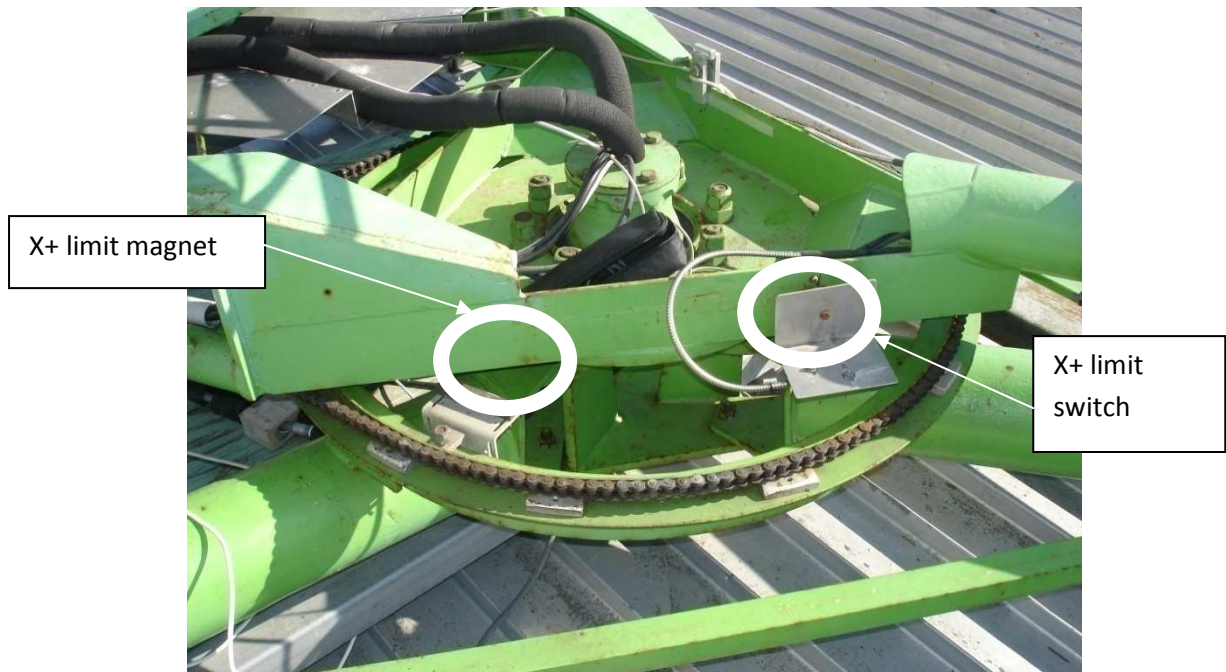


**Winter Park Position**



## Limit Switch - Position Check

X axis – rotation (horizontal) limit switches



Y axis – vertical boom axis limit switches

