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Development and testing of an advanced photovoltaic receiver

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DEVELOPMENT AND TESTING OF AN ADVANCED PHOTOVOLTAIC RECEIVER

by

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ABSTRACT

Development and Testing of an Advanced Photovoltaic Receiver

by

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In August of 2004, the SAIC solar concentrator located at UNLV was retrofitted with a 24 module photovoltaic aperture in hopes of producing a new type of solar electric concentrator. After the initial solar testing began, it became very apparent that the receiver design did not supply adequate cooling of the silicone cells, leading to module deformation and eventual failure. Through investigative studies of the failure and the possible solutions to the problem put forth at NREL and UNLV, a second phase array of mechanically sealed photovoltaic modules was constructed and tested. With a new methodology implemented in phase two, the module design was validated. Highly instrumented on-sun evaluation ultimately followed. The instrumentation included flow meters, thermocouples and a pressure transducer. A period of performance was carried out in the field. This paper summarizes this work and the performance of the system. Included is the diagnostic work related to the initial failures and how the perceived problems were corrected. Some qualitative evaluations of this approach for solar power generation are made.

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ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

UNLV and Science Applications International Corporation (SAIC) completed the construction of a 25 kW dish-Stirling system at the UNLV test facility in late 2001 [1]. At the time, the system used stretched membrane facets to concentrate the available solar energy on a central receiver, a Stirling engine/generator. This setup was used somewhat successfully for approximately a year and a half until engine reliability issues stopped operations. See Figure 1.

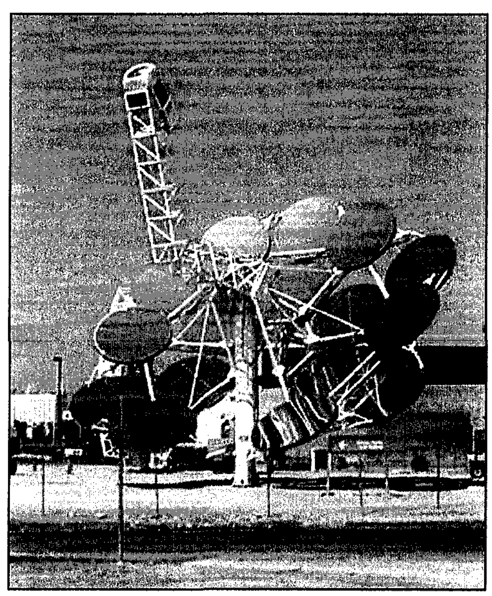


Figure 1 SAIC dish-Stirling system at UNLV

With the desire to explore cutting edge technology, the SAIC concentrator was redesigned for a photovoltaic (PV) receiver, Figure 2, in hopes of producing a new type of PV concentrator.

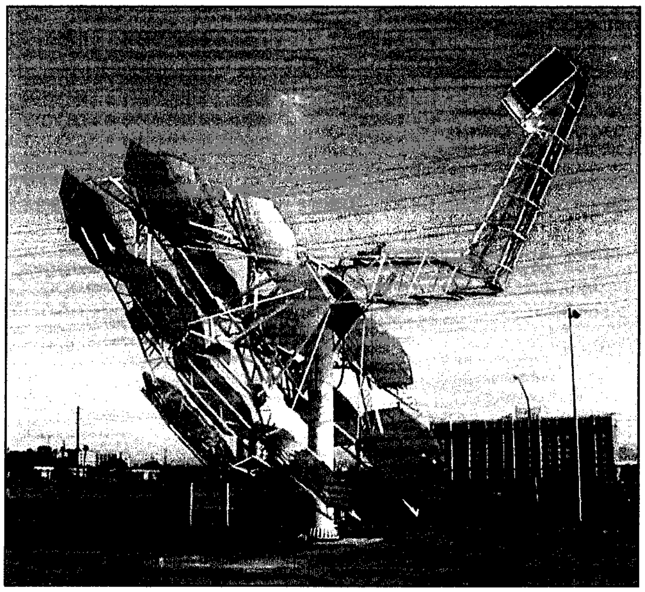


Figure 2 SAIC fixed focal length, PV concentrator at UNLV

The retrofit to the system involved replacing the old engine/generator package with an array of single crystal silicon PV cells and a heat rejection system. In addition to this, the stretched membrane facets were replaced by fixed focal length glass mirrors. Figure 3 shows a general schematic of the system.

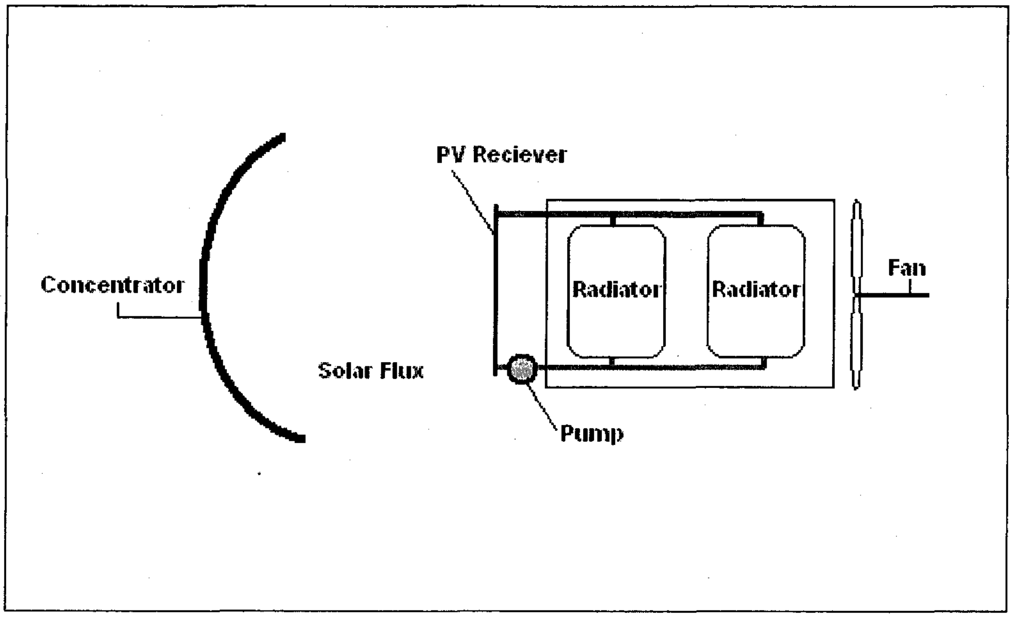


Figure 3 PV system schematic

The available solar flux is collected and concentrated by the mirrors mounted at a fixed distance from the central receiver. The PV panels within the receiver unit convert a portion of this energy into electrical energy. The remainder of this energy must be dissipated by the cooling system. This is accomplished using automotive type radiators mounted in a steel square tube frame. A single fan is used to pull air through the heat exchangers and coolant is circulated through the system using a centrifugal type pump.

Before a receiver could be constructed, extensive research and design began. The design was constrained by available solar cells and their characteristics, the flux pattern of the dish, available electrical inverters, and cooling constraints and requirements of the receiver and heat rejection system. SAIC chose the solar cells to use from the manufacturers available, as well as a preliminary module design and the inverters. The module design was refined by UNLV [2]. The heat rejection system was designed and evaluated by UNLV as well [3].

The PV aperture was made of a 24 module, 60cm (24in) high and 54cm (20in) wide, array. Each 5cm (2in) by 27cm (11in) module was comprised of a receiver plate and a cooling housing.

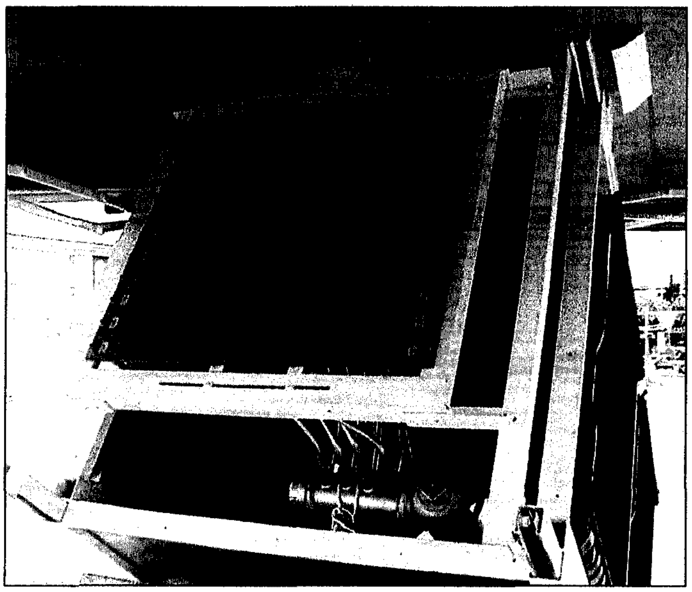


Figure 4 SAIC fixed focal length PV concentrator at UNLV

The receiver plate started out with a 0.25cm (0.1in) thick copper plate. The copper was then covered with a dielectric. A copper electrical substrate was etched into the dielectric, and the photovoltaic cells were soldered on using a compression process. Each module contained 88, 1cm square (0.15in square), Amonix single junction cells. The cooling housing, 0.65cm (0.25in) thick, started as a plate of copper. 15 heat transfer fins were then machined into the plate forming cooling channels that ran the length of the receiver. Two compression fittings were soldered onto the opposite ends of the cooling plate (inlet and outlet). The two surfaces were joined by solder, creating the coolant cavity. Module assembly was done at NREL.

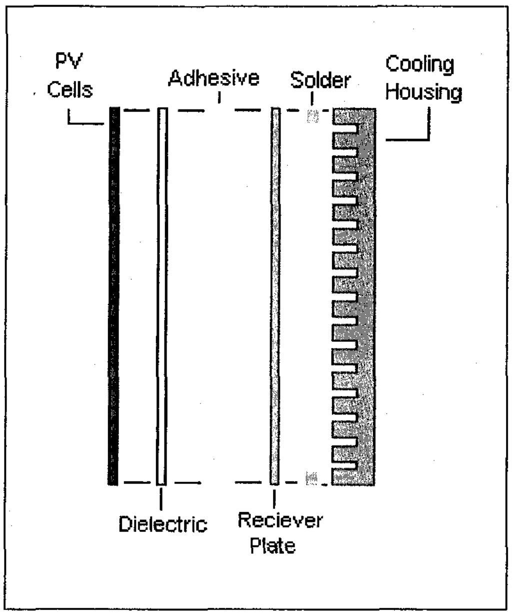


Figure 5 Module schematic

When the receiver was installed on the SAIC system, the modules were plumbed in series pairs. That is, coolant would flow through one module, then immediately into a second below it, and then return to the radiator bank. To ensure all of the incoming flux fell on the receiver, four secondary reflectors were positioned around the modules. The secondary reflectors were made from 0.10cm thick (0.04in) aluminum covered with thin glass mirror. The secondary reflectors were shrouded with aluminum air dams to channel air behind them, removing excess heat. See Figure 6.

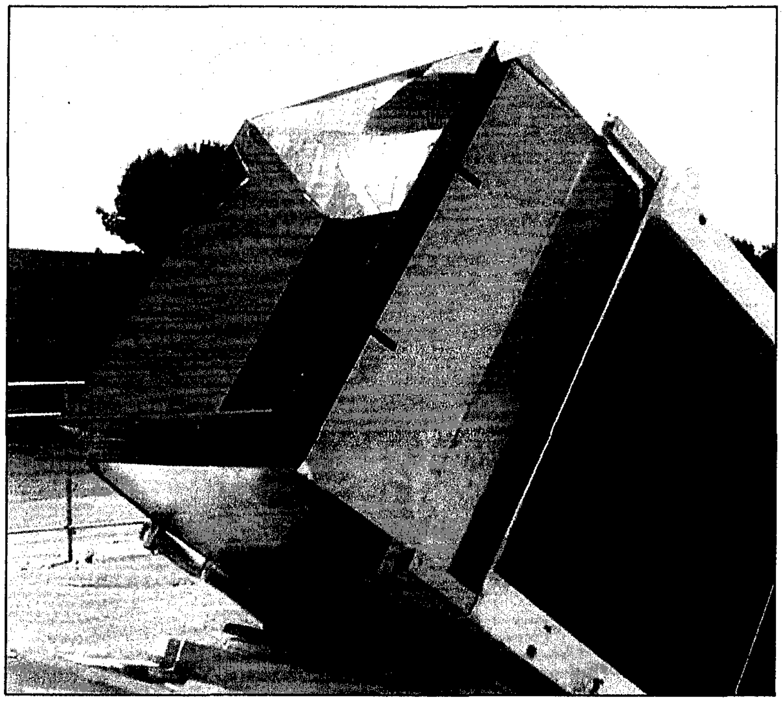


Figure 6 Secondary reflectors and air dams

The heat rejection system for the PV receiver was designed to use off-the-shelf parts. The package started out with a square steel tube frame. The frame held four automotive radiators, two each on the left and right sides of the PV receiver. The top and bottom walls of the package were sealed using aluminum honeycomb. Inside, coolant was circulated thought out the system using a single centrifugal pump. The radiators were plumbed using 5cm (2in) rubber fuel hose. A single, 91cm (36in) puller fan was mounted at the rear of the package. See Figure 7.

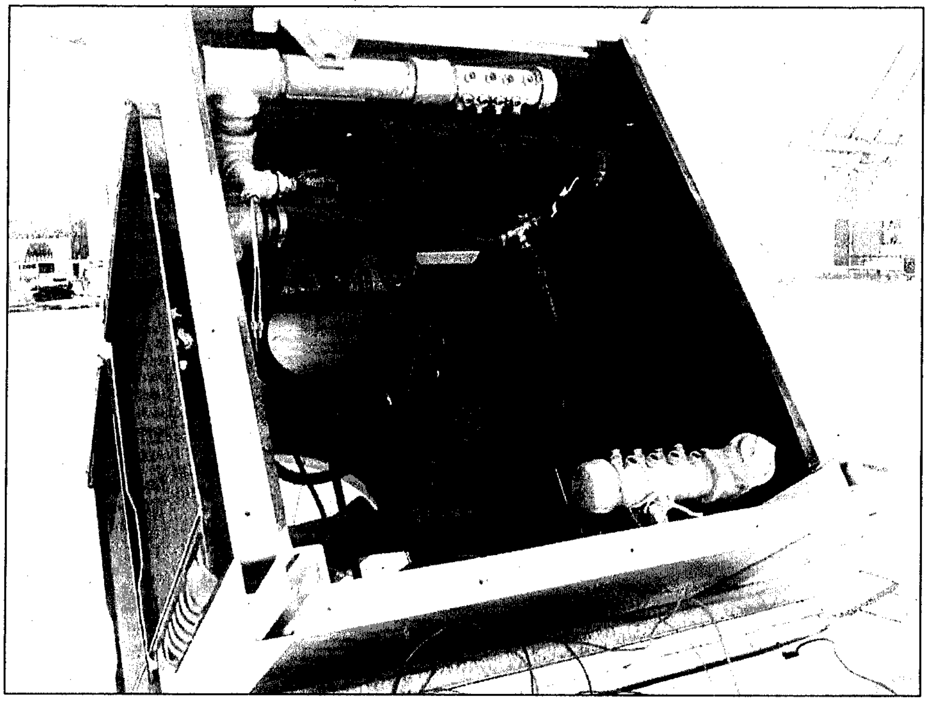


Figure 7 Heat rejection system from the back of the receiver point of view

After the receiver was installed and the subsystem checkout was completed, the process of attempting to get and keep the full system operating on sun began. Several problems arose during operation, including coolant leakage through the modules, overheating of cells, and short-circuiting.

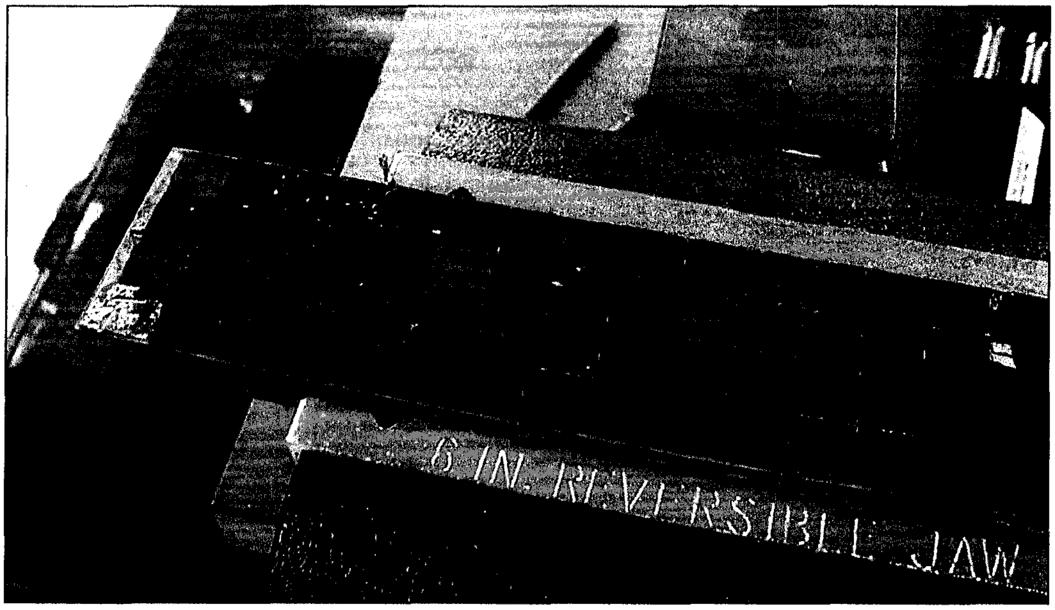


Figure 8 One of the modules with overheated, delaminated cells

The solution to the module leak problem, and ultimate cause of thermal deformation, was a sandwich design that involved removing the receiver plates from the cooling housings and brazing a copper plate to the cooling housing to form a sealed cavity. The receiver plates were then soldered to the cavity. This method of sealing provided excellent integrity of the joint, and solved the leak problem.

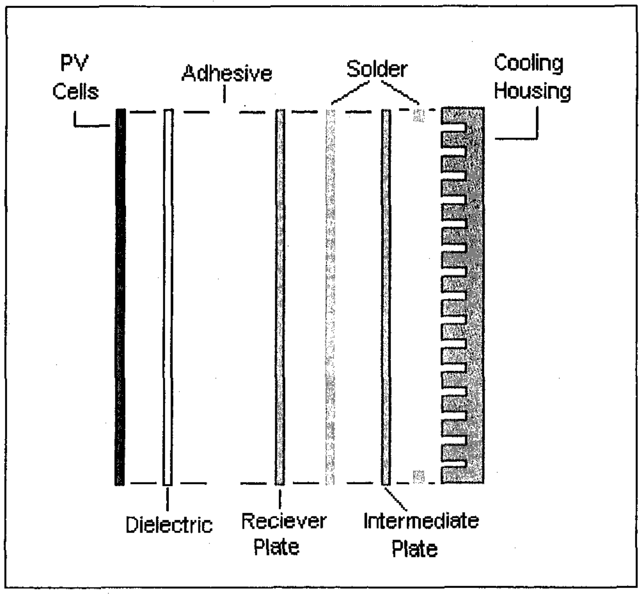


Figure 9 Module schematic with intermediate plate

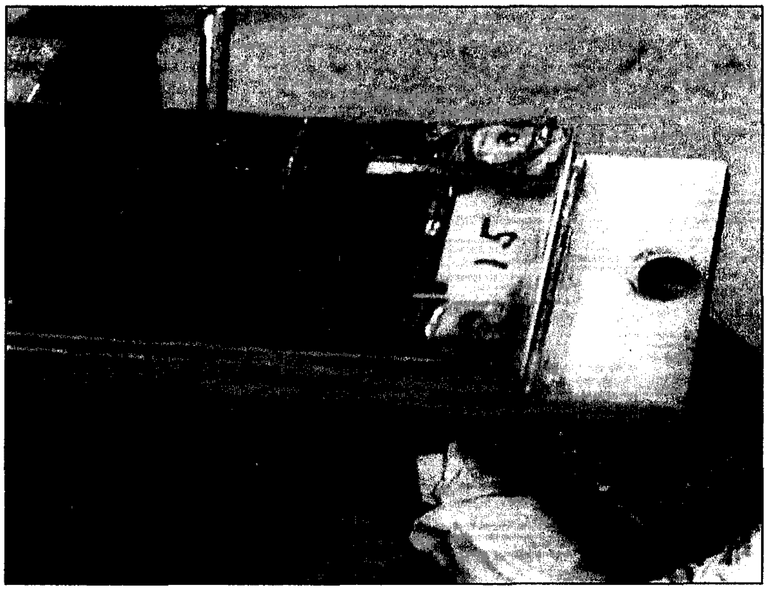


Figure 10 Module with intermediate plate

In late 2004, a representative from Amonix came to UNLV and made measurements on the receiver modules. It was determined that most of the modules were functional, but that the combination of solar flux variation at the left and right edges of the receiver and poor cooling efficiency were leading to poor performance.

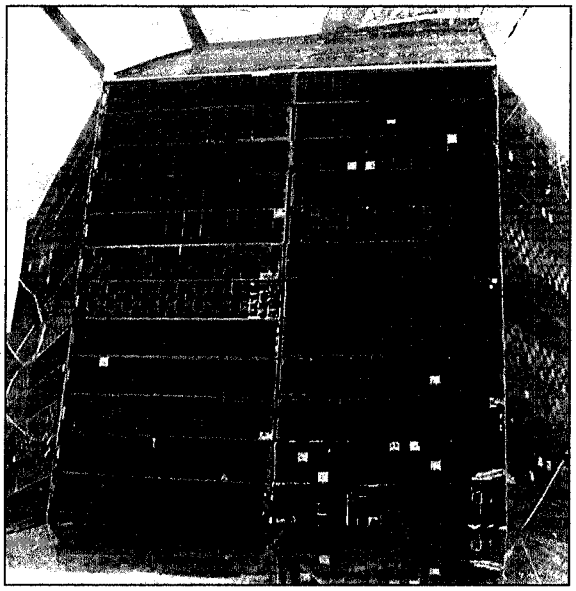


Figure 11 PV receiver after delimitation and overheating

The investigation into the source of module heat inefficiencies revealed the sandwich design was a major weak point in the heat rejection system. The design required that the receiver plate be soldered to the intermediate plate.

Upon inspection, it was noted that only sections of the receiver plate had bonded with the intermediate plate, reducing the amount of contact between the two. The cause of the solder gaps resulted from an inadequate amount of heat during the soldering process. The heat was limited because the solder used on the PV cells had a slightly higher temperature than the solder used to attach the receiver to the intermediate plate. Too much heat would have de-soldered all of the PV cells on the receiver.

Between the combination of the poor flux distribution and inadequate cooling, the design failed. As a result, NREL, UNLV, and SAIC decided to push forward with an advanced receiver design. Points to be considered included the revision of the cooling cavity seal, the flux distribution, and the validity of the cooling systems heat load capacity.

CHAPTER 2

NEW MODULE DESIGN

After the first phase module design failed, the process for a second phase module began. The first step in the process was the detailed development of a design and test plan.

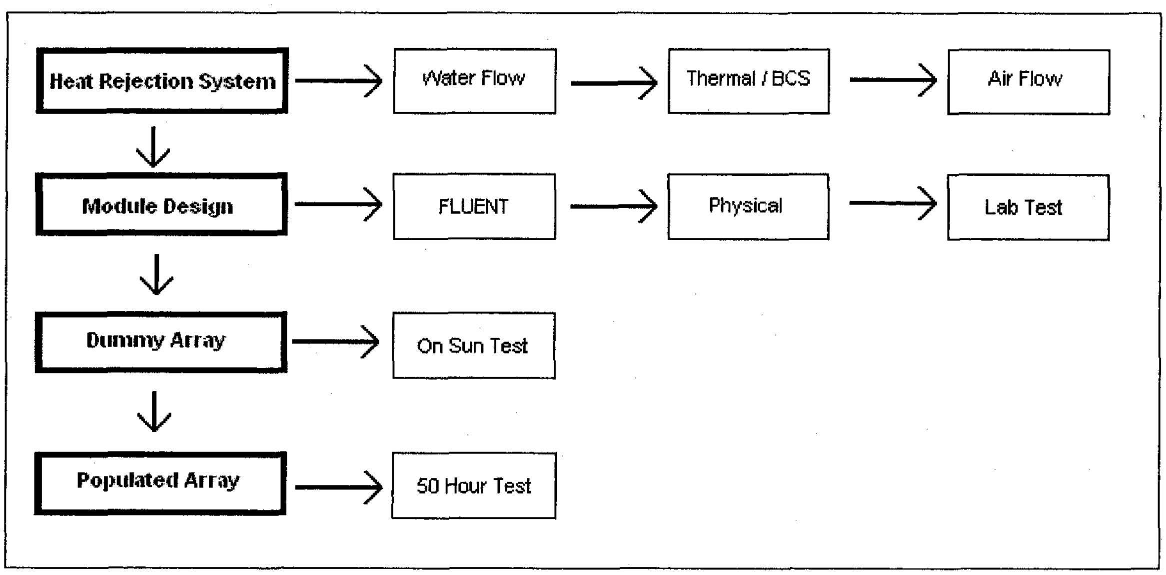


Figure 12 Development flowchart

The design process began with research involving the heat rejection system. Because the previous PV receiver was subjected to poor heat rejection, a thorough set of measurements were made to validate the previous data [3]. First, the volumetric flow rate of the pump/system was made by placing a calibrated flow meter inline with the pump.

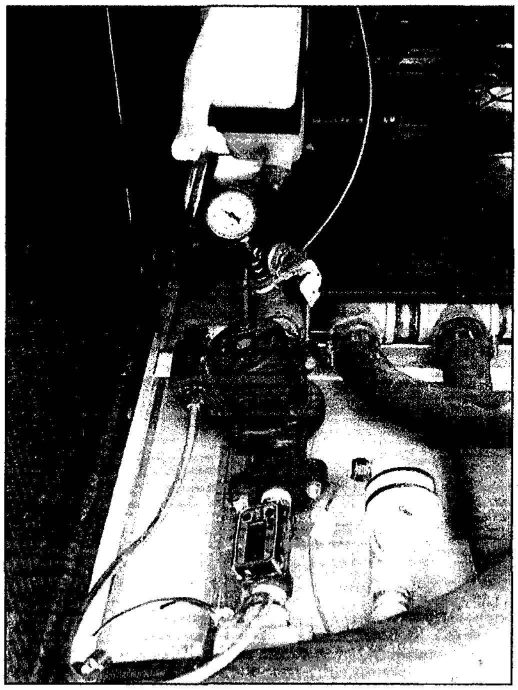


Figure 13 Flow meter inline with the pump

With the system down in a maintenance position and the cooling system at the standard operating pressure, the cooling system was turned on and allowed to reach a steady state. Once the system had reached steady state, the flow meter measured a flow of approximately 1.8L/s (28gpm), the expected value.

Next, the desire to measure the cooling efficiency of the radiators was requested. Using the SAIC Beam Characterization System (BCS) target, solar flux could be used to evaluate the heat rejection system. In Figure 14, the BCS target was painted black and mounted in the receiver position on the concentrator.

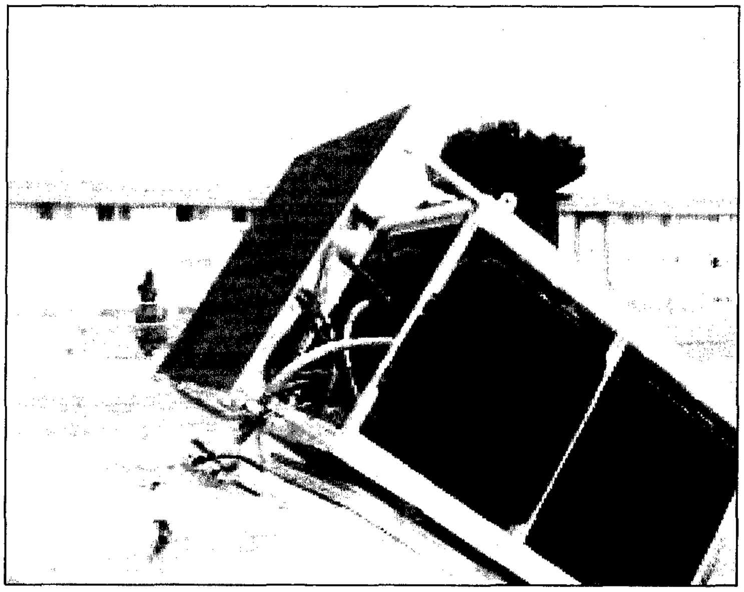


Figure 14 Black BCS target mounted on heat rejection system

Each radiator was then wired with two type K thermocouples, measuring the inlet and outlet temperatures of each radiator. These thermocouples were measured using an Agilent HP 34970A Data Acquisition System. The BCS target was painted black to absorb as much radiation as possible, allowing for the measurement of the maximum heat dissipation of the heat rejection system. The secondary air dams were also mounted to limit the amount of air bypassing the radiators.

Figure 15 BCS target with air dams mounted on the heat rejection system

When the BCS mounted system was positioned on sun for thermal testing, the system operated shortly until there was an excess of expansion in the system, causing the BCS target to blow out and loose all of its coolant.

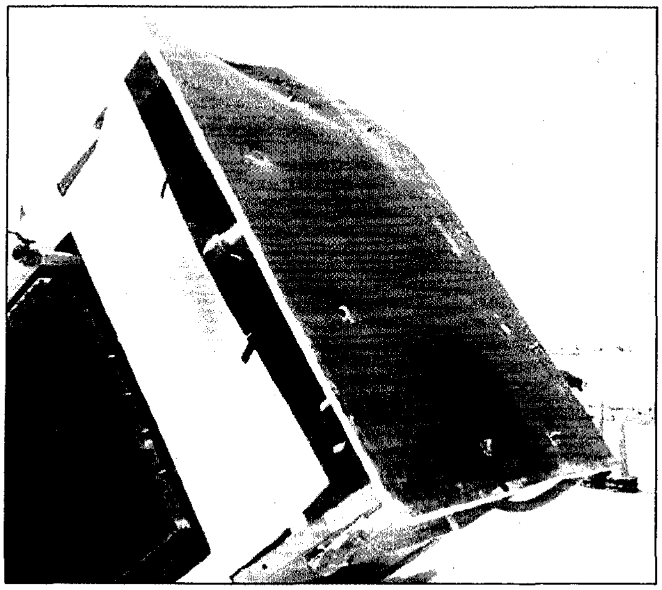


Figure 16 Damaged BCS target

Analysis of the data revealed a system trend. The data, Figure 17, showed that the front radiators did not cool the incoming fluid as much as the rear ones. This imbalance called for the airflow and individual liquid flows to be measured. By balancing the liquid and air flows, the heat rejection system could be optimized.

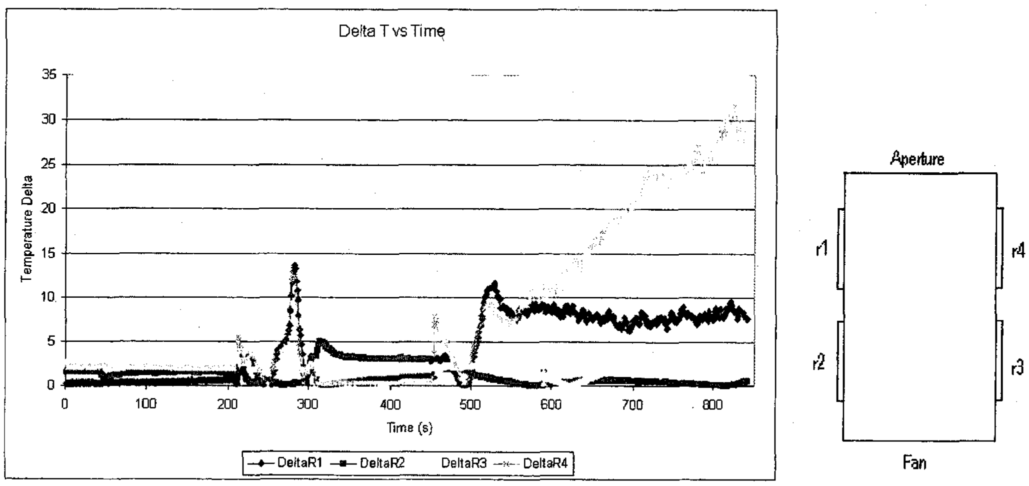


Figure 17 Radiator temperature delta

For the radiator airflow measurements, the front aperture was sealed using heavy plastic and duct tape. Measurements were made three ways. First, the radiators were divided into six equal sections. Then, using a hot wire anemometer, the velocity at several points in each section were measured to find an average for that section. This method proved to be very troublesome because the hotwire section of the anemometer was very sensitive to orientation. The next method of measurement used an HVAC flow hood, as seen in Figure 18.

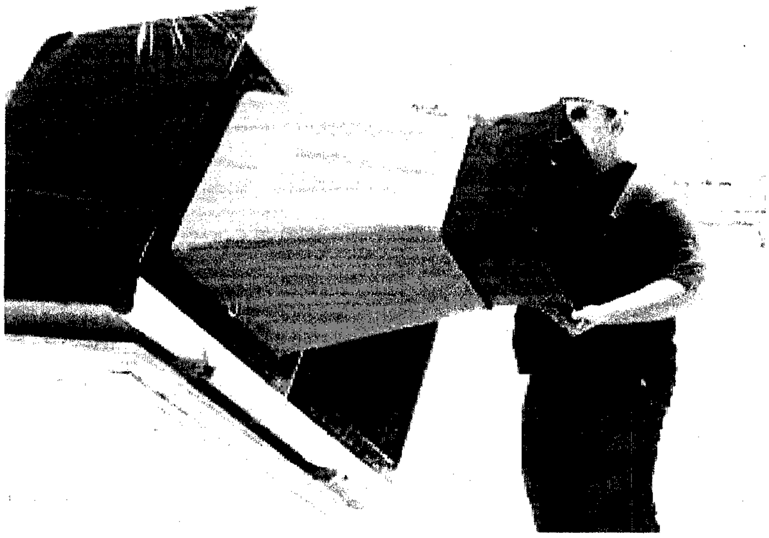


Figure 18 HVAC hood used on the system

The flow hood was positioned over the radiator while the cooling system was operating. The flow measurements were recorded and validated by repeating the process multiple times. This method of measurement was an accurate one, in that it gave a very good value for the overall flow of the radiator, however, it was not able to measure small sections of the radiator.

The third method used a handheld windmill anemometer. The radiators were sectioned off the same way as when the hotwire anemometer was used. This method was very effective in giving consistent measurements in each of the sections. The following plot, Figure 19, was generated using the windmill anemometer data.

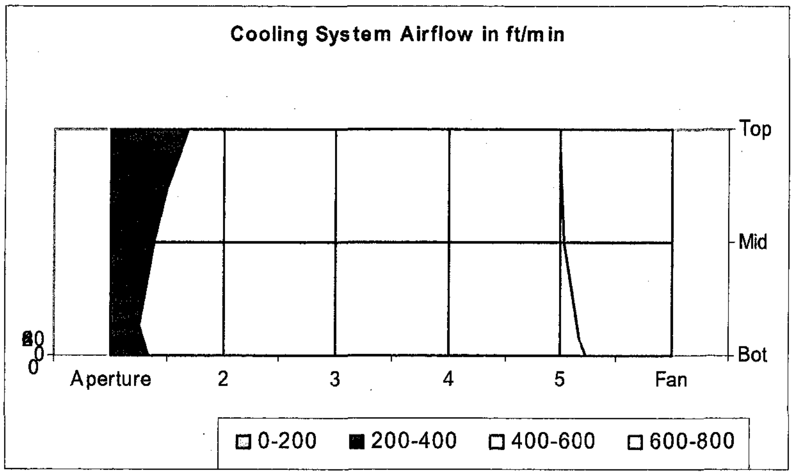


Figure 19 Airflow through radiators

Figure 19 shows the airflow in ft/min as a function of position on the side of the heat rejection radiators. The aperture of the receiver is to the left, and the system fan is to the right in this figure. It was noted that more air was flowing through the rear radiators than the front, resulting in less overall efficiency from the cooling system.

To rectify the airflow discrepancy, supplemental fans were installed on the front radiators using two off-the-shelf 120VAC attic fans. The fans in combination with some fabricated sheet metal shrouds resulted in a significant boost to the front radiators.

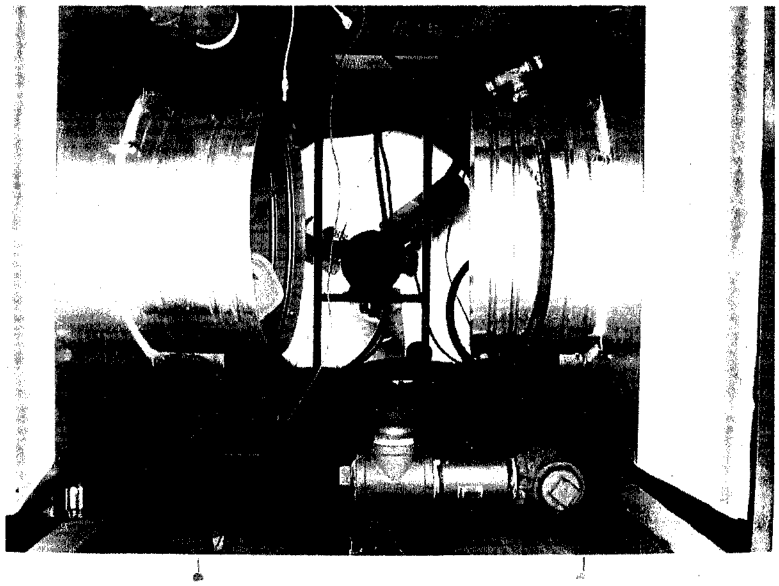


Figure 20 Supplemental fans

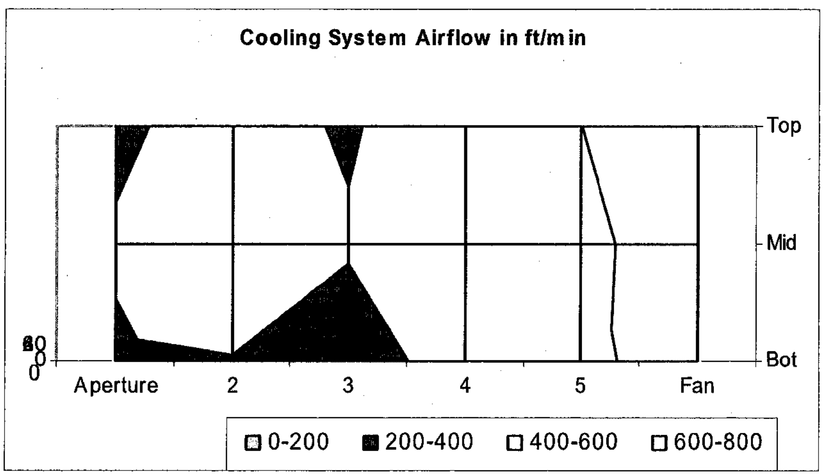


Figure 21 Supplemental fan data

Figure 21 shows a plot of the airflow in ft/min as a function of position on the side of the heat rejection radiators with the supplemental fans installed. Because the fans are positioned very close to the radiator surface, they actually restrict airflow in the corners and accelerated flow in the center.

With the cooling system abilities measured and engineered by UNLV, module design could begin at NREL. It was decided that the receiver would be reduced to 1/6th of the original size, four modules. A smaller array ensured that the heat rejection system would definitely be able to handle the cooling load. It was also decided that the array would be plumbed in parallel with flow meters measuring the individual module conditions. Sealing the modules mechanically rather than by soldering the cavity closed was also to be considered.

After numerous meetings where design characteristics were considered, a SolidWorks model (Figure 22) was completed. When all agreed on the basic design shown in SolidWorks, a FLUENT model (Figure 23) of the module concept was developed by NREL. The FLUENT model was used to generate performance expectations and refine tolerances and the overall look.

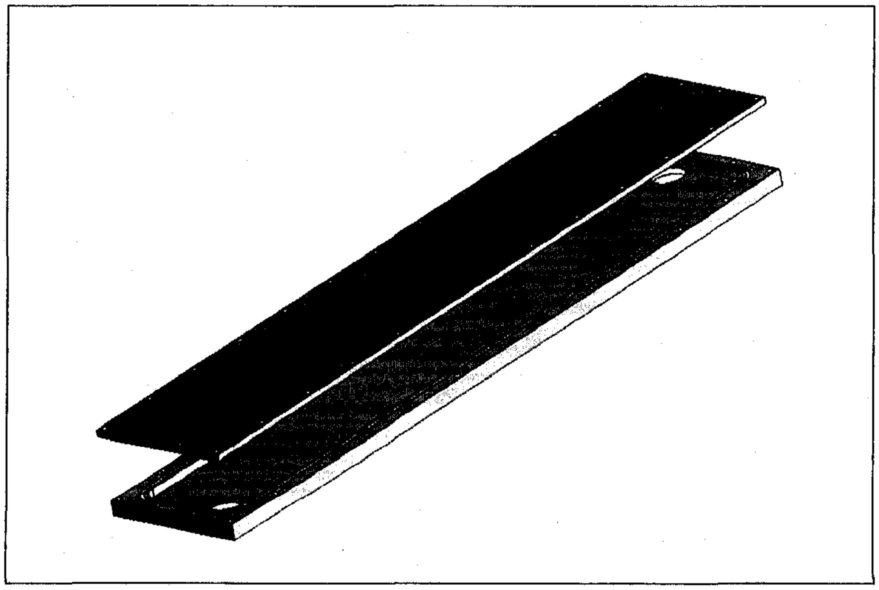


Figure 22 SolidWorks model screenshot

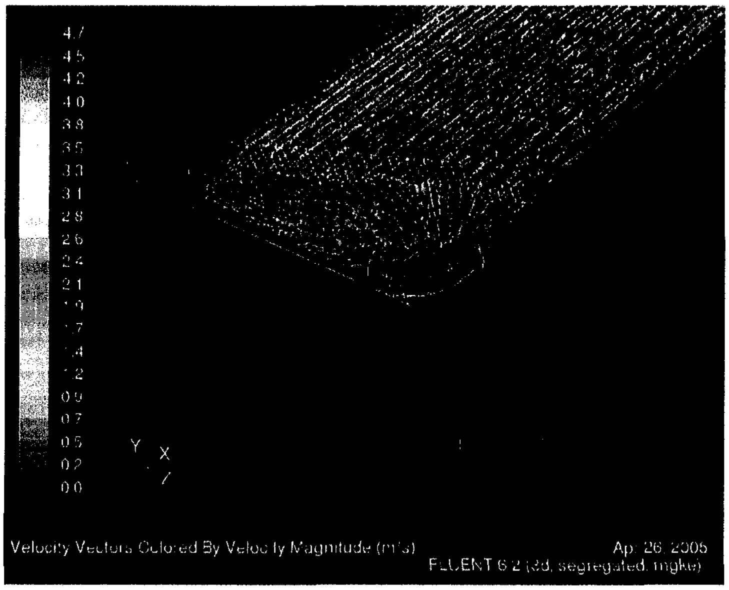


Figure 23 FLUENT model screenshot

The most significant modification to the phase one design was the use of mechanical fasteners to seal the modules. The phase two design used 30 evenly spaced stainless steel cap screws to seal the receiver plate and cooling housing by compressing a gasket material. This was accomplished by making the phase two modules 1cm wider and longer than their phase one counterparts. Preliminary tests showed that the new configuration is capable of holding pressures well above the required 103kPag (15psig).

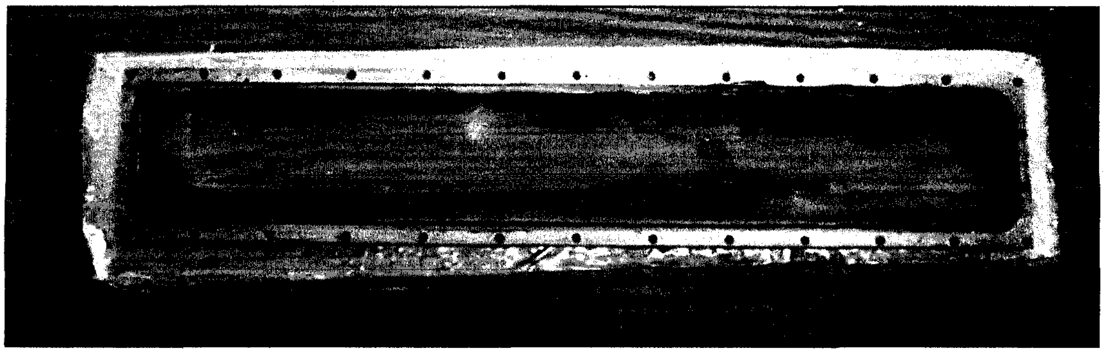


Figure 24 Phase two cooling housing with O-ring channel and screw holes

Another significant modification to the module design was the relocation of cooling fins. The phase one modules used 15 fins machined into the cooling housing whereas the phase two module relocated the fins to the back of the receiver plates and increased the number to 21 fins.

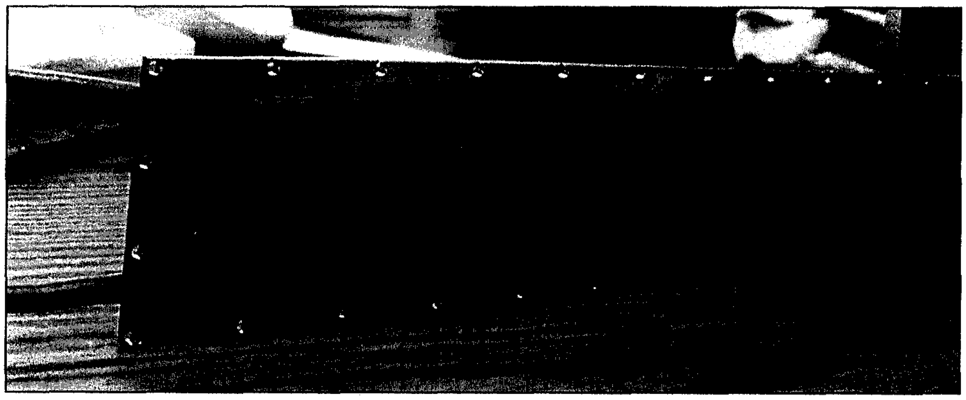


Figure 25 Fins on the back of a receiver plate

The new module designed was laboratory tested at NREL with UNLV. To test the modules, a thermal loop was plumbed to a module and the water temperature was manipulated in 5 degree increments from 40C to 60C. The surface of the module was coated with thermal paste, and an electric heater was placed in contact with the module. The module and heater were then insulated and clamped to concentrate on the liquid heat rejection capabilities of the module. The lab tested design was capable of keeping the module surface temperature around 80C with 60C cooling water circulating under 2kW of heat.

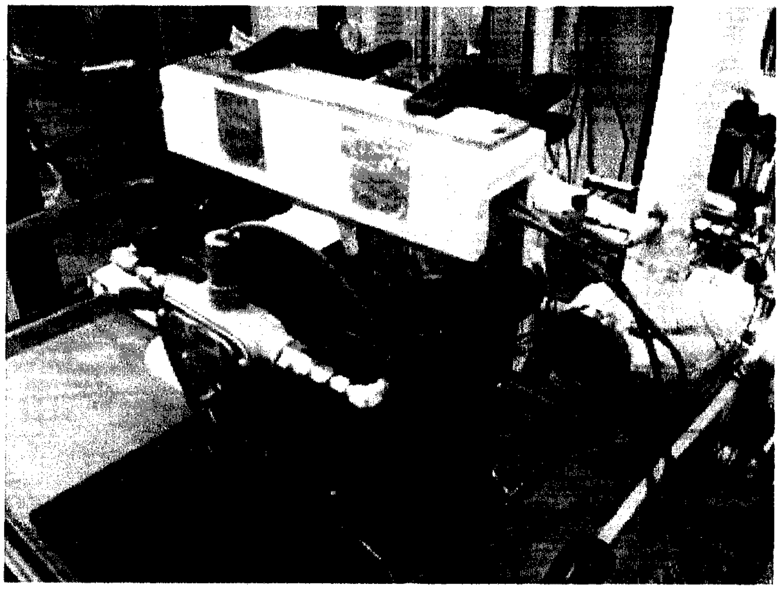


Figure 26 Module laboratory thermal test rig

Figure 27 Module laboratory thermal test rig from another view

After the lab test validated the FLUENT model, it was time to test the design on the SAIC concentrator. A four module dummy receiver was fabricated. The receiver used a single 50cm (20in) by 30cm (12in) copper plate that was machined to form four modules with excess copper. The dummy receiver was mounted on the concentrator and plumbed into the heat rejection system.

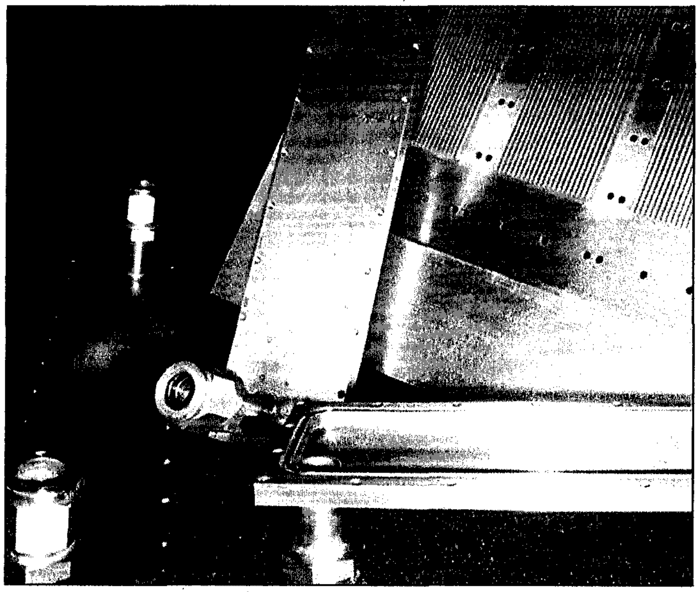


Figure 28 Dummy receiver and cooling housings

The heat rejection system collected into 5cm (2in) diameter galvanized pipe which then went to a 5cm (2in) square tube manifold. As seen in Figure 29, four 2.5cm (1in) diameter pipes went to flow meters just visible at the top of the picture, and then to the individual cooling housings. The inlets and outlets of the cooling housings were plumbed with brass tees where Omega type K thermocouples were installed.

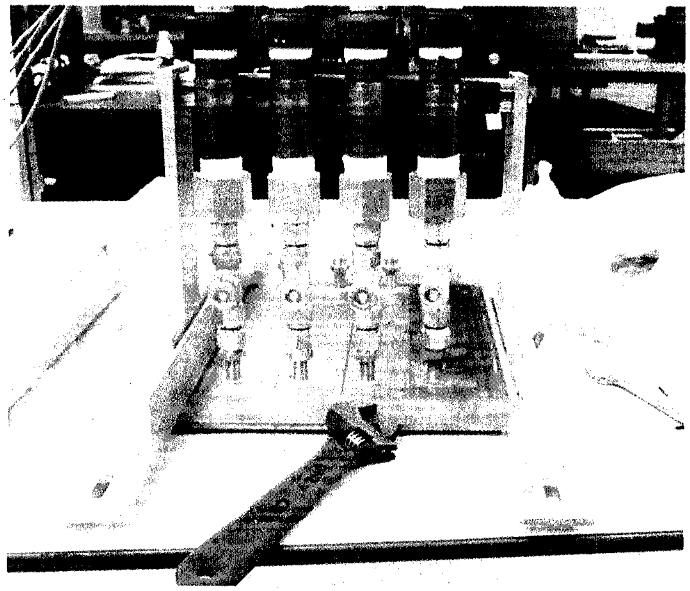


Figure 29 Dummy receiver during bench assembly at UNLV

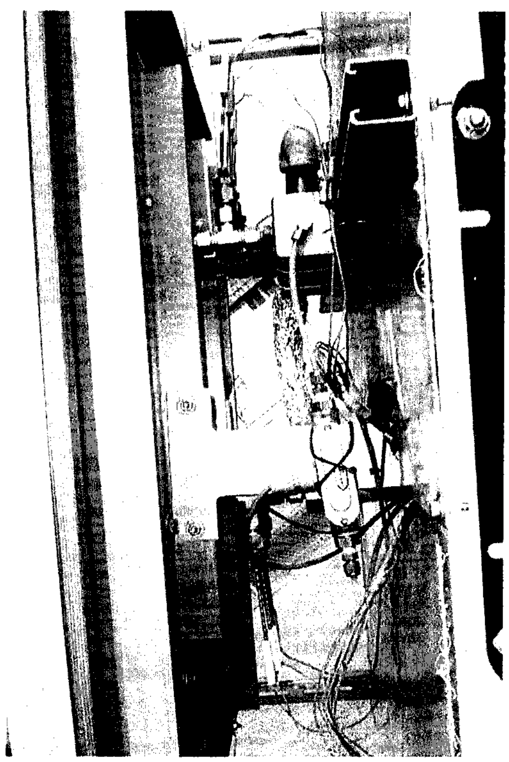


Figure 30 A side view of the module inlet and outlet instrumentation

In Figure 30, the pipes partially visible at in the middle behind the tee bracket are the inlet water flows from the flow meters, and the upper brass tee pipes are the outlets from the receiver modules, connected to a manifold. The outlet thermocouples are seen mounted in the tees at the top; the inlet thermocouples are pointed down in the middle of the picture. There are also seven strategically placed thermocouples measuring surface temperature and a pressure transducer used to measure the pressure differential between the inlet and outlet manifolds.

To measure the flow meters, NREL built an analog-to-digital circuit board specifically for the flow meters used. The circuit, pictured in Figure 31, used 12VDC to convert analog signal generated by the flow meters and converted it to a corresponding voltage.

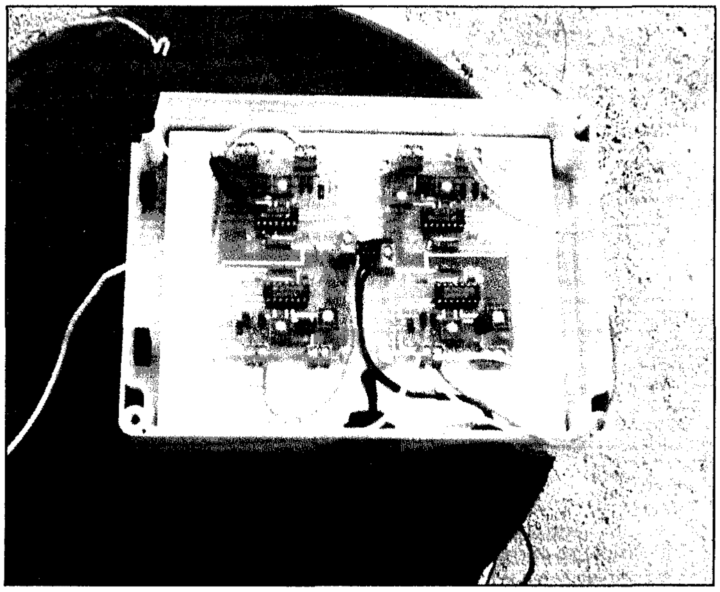


Figure 31 Flow meter circuit

The flow meters, thermocouples, and pressure transducer were connected to an Agilent HP 34970A Data Acquisition System (DAS) that was located underneath the heat rejection system at the end of the receiver support arm. The DAS unit was connected to a laptop computer for real-time monitoring of the measurements during on-sun operation. Figure 32 shows the receiver system with the data acquisition system and monitoring computer as they were set up for testing of the receiver system. The data logger is located in the triangular space below the heat rejection system.

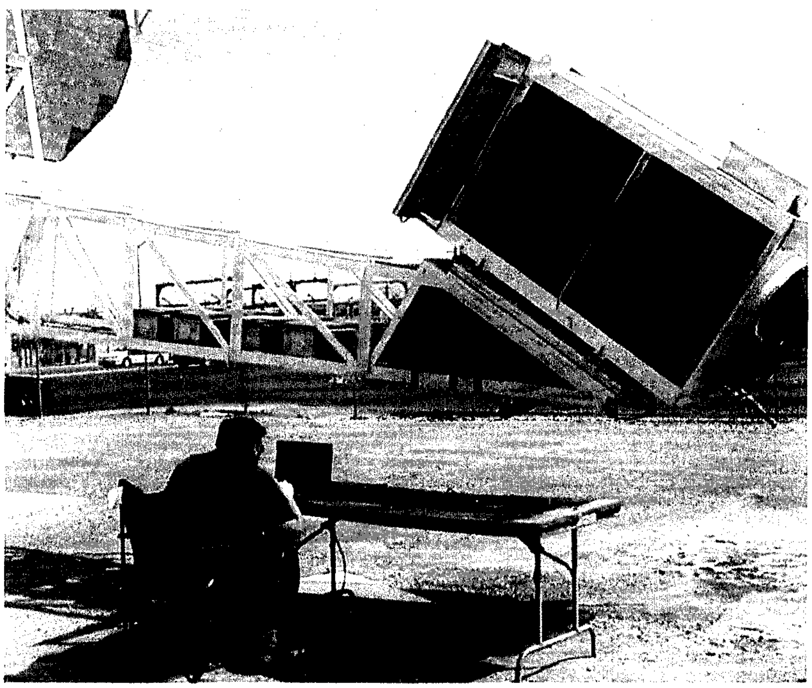


Figure 32 DAS monitoring process

The system was taken on sun to perform a real world version of the lab test that occurred at NREL. The receiver plate performed the same as the test module had in the laboratory test rig and was ready for population.

Once pre-testing was completed with the dummy receiver, the plate used for testing as well as a second plate were sent to Amonix for population with cells. In order to attach the PV cells, it was necessary to cut the receivers apart into eight separate modules. Part of the mounting procedure was the development of a soldering procedure. The procedure development used three modules. The completed and the final populated receiver modules, five total, were sent to UNLV in early 2007. Figure 33 shows one of the modules as it was received at UNLV. The modules included wires with polarized connectors suitable for connection to a Daystar I-V tracer.

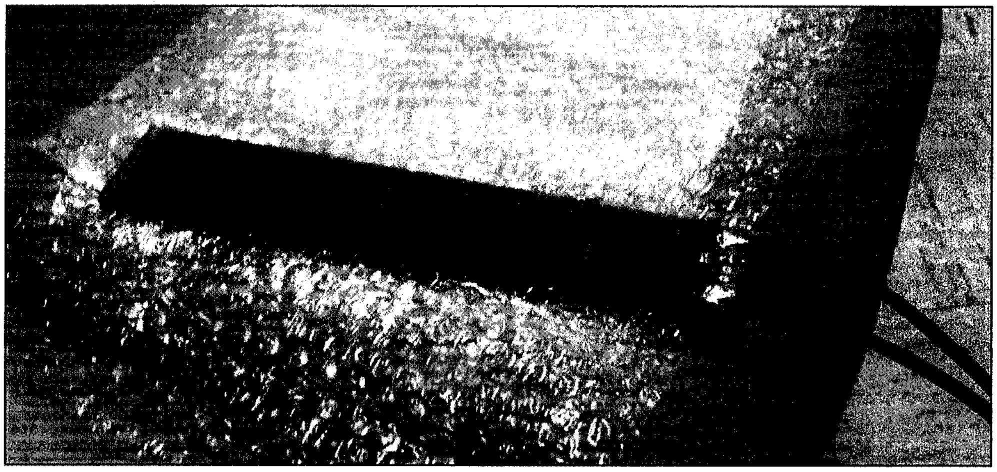


Figure 33 Populated PV module

The modules were assembled into an array of four, and then mounted on the front of the heat rejection system on an aluminum frame structure.

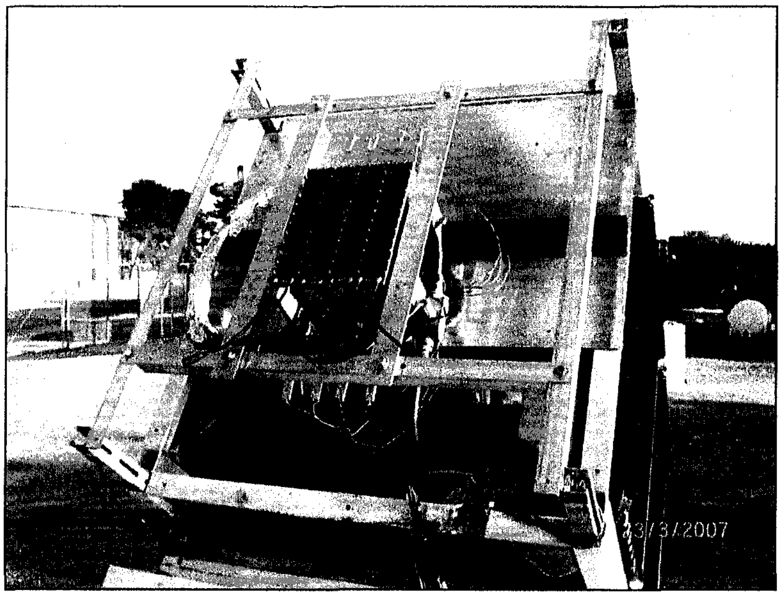


Figure 34 PV receiver mounted on heat rejection system

A sheet of Fiberfrax high-temperature insulation was placed immediately in front of the receiver modules and a cut-out was made for the modules. The insulation was installed on the receiver to account for the receiver size reduction. Figure 35 shows the insulation sheet installed on the system.

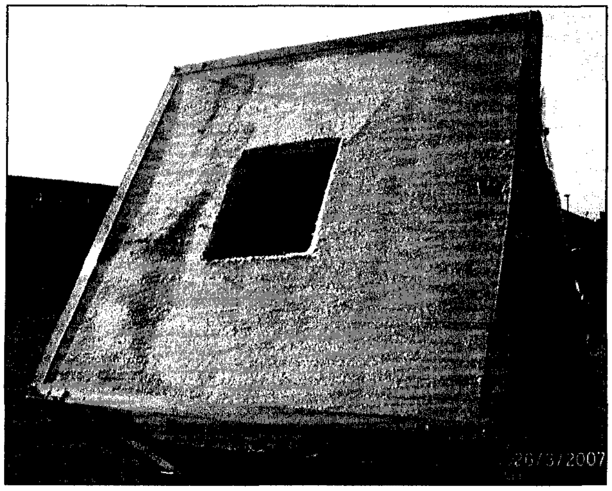


Figure 35 Fiberfrax insulation

The receiver was installed on the system in late March 2007, and initial operational tests of the system were performed, including I-V measurements of the array. Then, the system entered a 50-hour initial test phase. During this test, the receiver modules were connected to an inverter and the output of the inverter was monitored. The cooling system was instrumented to measure temperatures, flows, and other parameters. Figure 36 shows the phase two system on sun and operating.

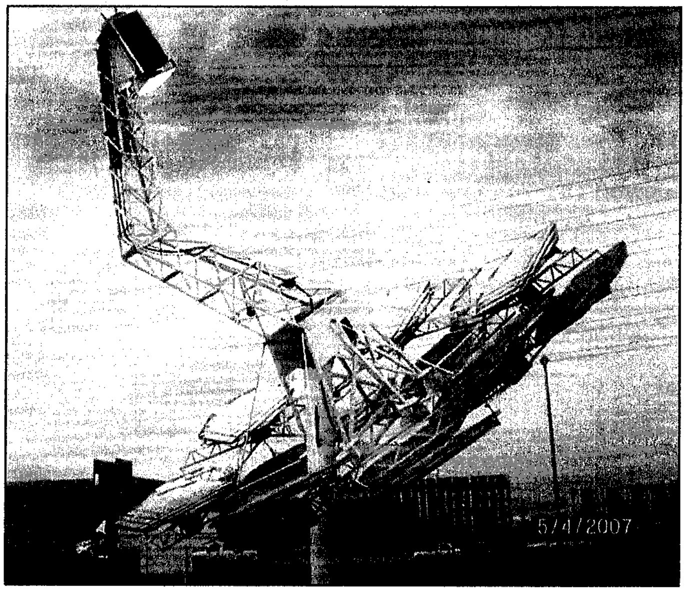


Figure 36 Phase two receiver on sun

CHAPTER 3

RESULTS

The DAS used during the on-sun phase two 50 hour testing was first configured for the dummy receiver. The DAS is comprised of four flow meters, one pressure transducer, and 15 strategically placed thermocouples. The flow meters were configured such that there was one meter in line with a single module, giving an individual flow throw each module. The pressure transducer measured the pressure change between the inlet manifold and the outlet manifold of the entire array. The thermocouples were configured to measure the individual inlet and outlet temperatures of the modules, as well as different surface temperatures during operation.

All data measurements were made using an Agilent HP34970a data logger, with a 20 channel digital multiplexer. Data was recorded using Agilent Benchlink data logging software and compiled using Microsoft Excel.

During the 50-hour operation period, the cooling system functioned well and kept the receiver plates well cooled. The following graphs were generated using data recorded during dawn-to-dusk operation. Figure 37 shows a plot of the temperature change of all the module outlet temperatures above ambient temperature over the course of a day. The figure shows that the cooling system kept the outlet water temperature 10 degrees or less above the ambient temperature throughout the day.

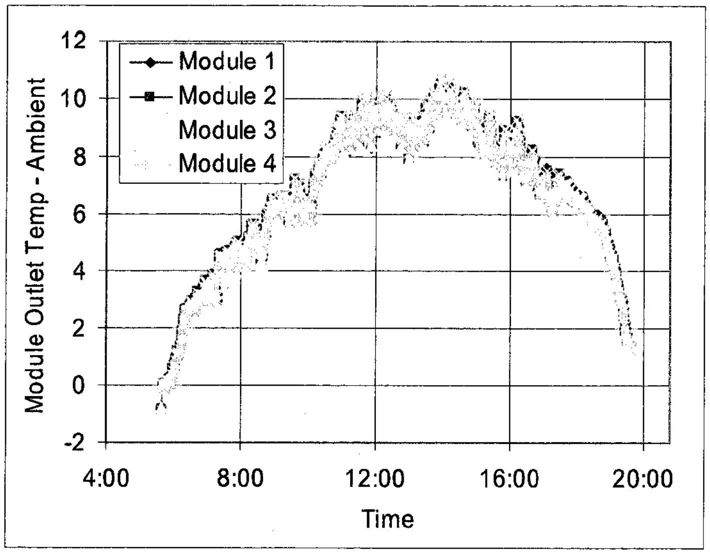


Figure 37 Module outlet temperatures minus ambient temperature vs. time

The plot shows the uniformity of the temperature across all four modules. The irregular dip in the plot at 1300 is most likely explained by high wind gusts at that time as there was not any cloud cover.

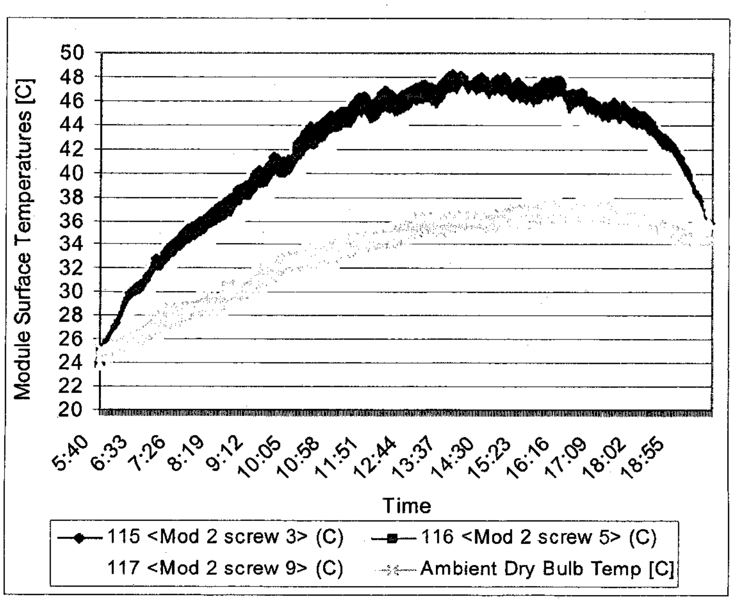


Figure 38 Module surface temperatures vs. time

Figure 38 is a plot of surface temperatures measured on the modules as a function of time over the course of the day. Also shown is the ambient temperature. The cooling system kept the surfaces below 50C at all times through the day.

Figure 39 shows the temperature increase in the cooling water through one of the receiver modules as a function of time. The temperature rise is only 1.5-2 degrees during the peak part of the day. Comparison of this plot with Figure 40 shows that the temperature rise is nearly linear with the direct normal insolation (DNI), which is what would be expected since the solar insolation is the system heat source.

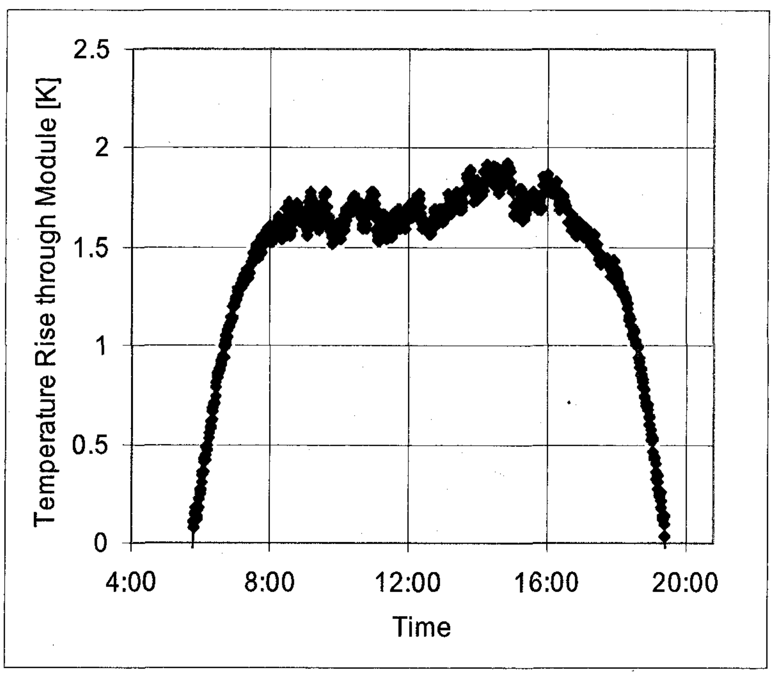


Figure 39 Cooling water temperature rise through module vs. time

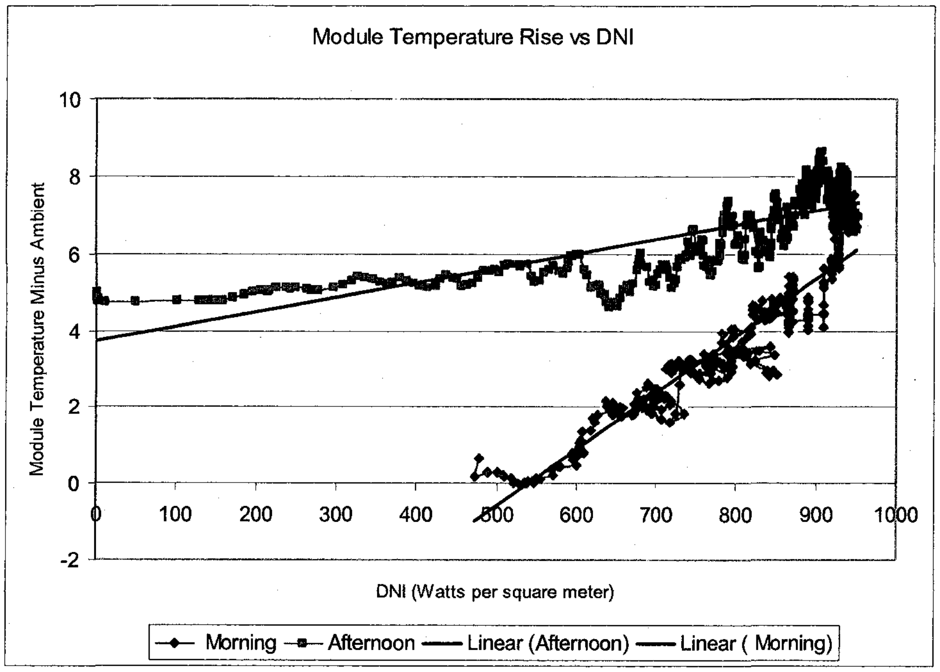


Figure 40 Cooling water temperature rise vs. DNI

The data were split into two different sections, morning and afternoon. The transition occurred at solar noon and was done because a typical temperature curve is offset from the DNI. Not only is the temperature rise nearly linear, but as seen in Figure 41, the corresponding power output at a given insolation is also almost linear.

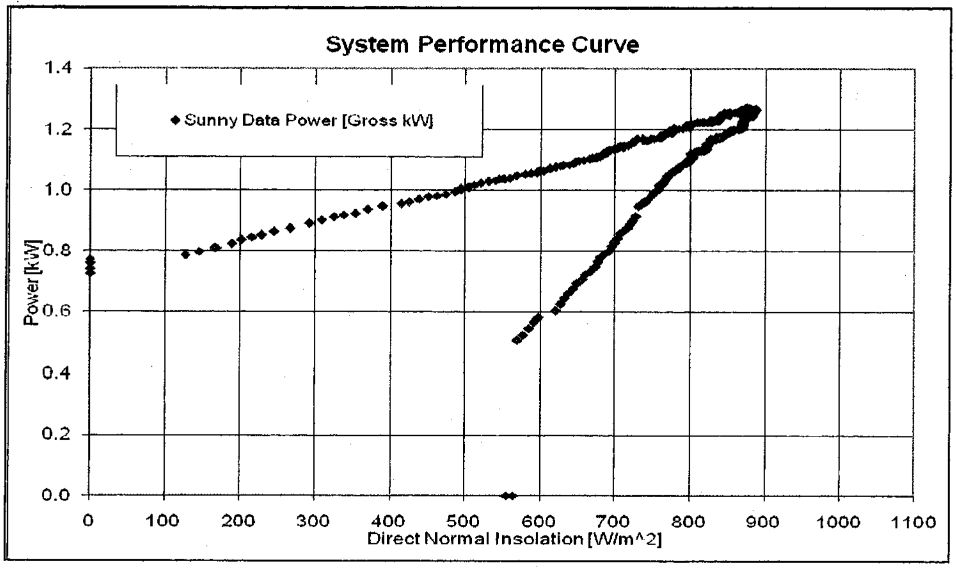


Figure 41 Power output vs. DNI

Using the data recorded during the experiment, an overall array efficiency, η, can be calculated using the following equation

$$\eta = \frac{power\ output}{sun\ input} = \frac{\lambda}{\phi \cdot \gamma \cdot A}$$

Where

$$\lambda = Measured\ Power\ Output\ (W)$$

$$\phi = Measured\ Direct\ Normal\ Insulation\ \left(\frac{W}{m^2}\right)$$

$$\gamma = Concentration\ Ratio$$

$$A = Array\ Area\ (m^2)$$

The above equation is used to calculate the efficiency at any given time during the experiment, resulting in Figure 42. A key assumption required for this equation to be valid is a constant concentration ratio of 250 suns on the array, which was validated through flux mapping [1].

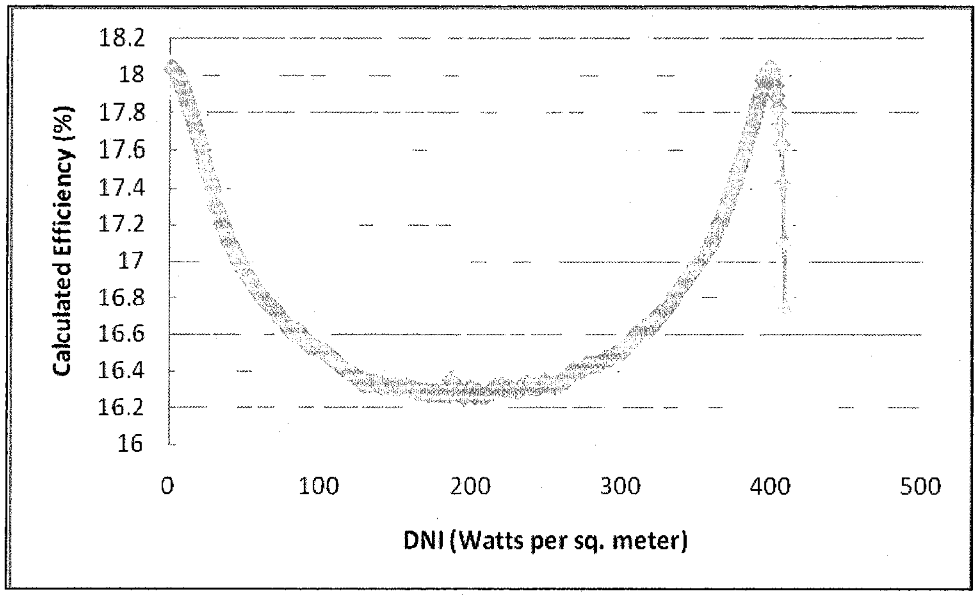


Figure 42 Calculated efficiency vs. measured DNI

Averaging the calculated efficiency in Figure 42 results in a value of 16.25%. Using this value, the array output can be computed for any reasonable insolation value, Figure 43.

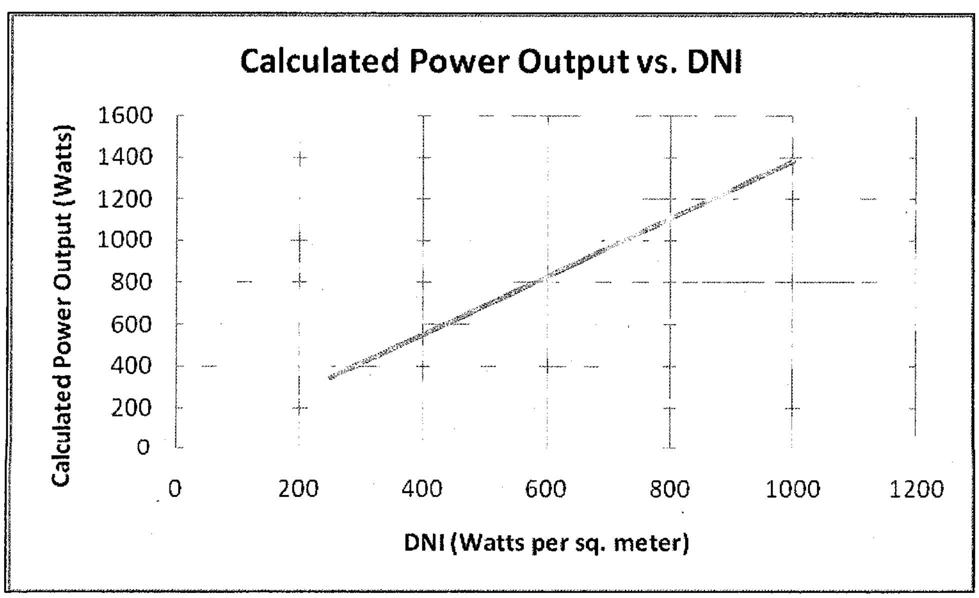


Figure 43 Calculated power output vs. DNI

Because the above efficiency calculation and Figure 43 do not account for efficiency variations due to temperature fluctuations, an error analysis is required. The combination of calculated power output and a percent error analysis would provide the best tool for power generation estimation. The following equation is used to find the percent error.

$$\%error = \frac{\lambda_{measured} - \lambda_{calculated}}{\lambda_{measured}} \cdot 100\%$$

By applying the above equation to the data calculated and computed, Figure 44 is generated. The figure shows that using an average efficiency becomes less erroneous as sun intensity peaks.

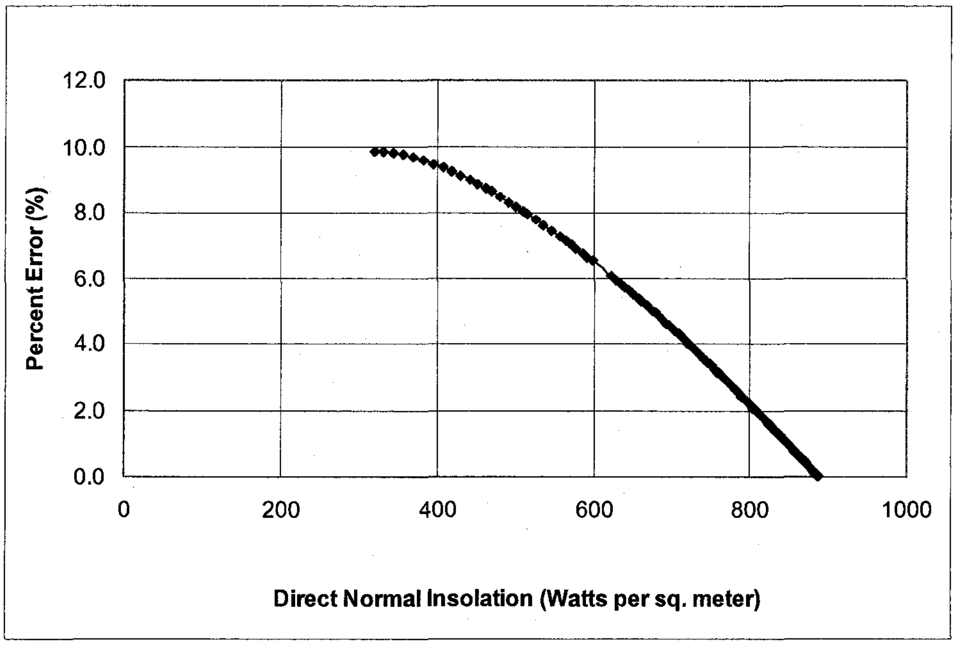


Figure 44 Percent error vs. DNI

CHAPTER 4

CONCLUSIONS

The SAIC PV concentrator did not have immediate success. Between a combination of the poor flux distribution and inadequate cooling, the design failed. As a result, NREL, UNLV, and SAIC decided to push forward with an advanced receiver design. Points considered included the revision of the cooling cavity seal, the flux distribution, and the validity of the cooling systems heat load capacity.

By changing the module design to use mechanical fasteners as a sealing method as apposed to the original brazing technique, all leaking problems were eliminated. The design also allowed for easier installation and removal of individual modules.

A reduction in the receiver size not only ensured that even flux covered the receiver; it also reduced the cooling load by one-sixth. The addition of high temperature insulation surrounding the receiver aided in flux reflection.

Several different testing methods were used to validate the heat rejection systems abilities. Through the combination of air and water flow manipulation, the whole heat rejection system was refined to perform at an optimum state.

This method of solar electric generation proved to eventually be successful. Although the use of concentrated solar to illuminate photovoltaic cells is not new, and has been used successfully by a few different companies, the use of a dish style concentrator has been explored in relatively few areas. A few advantages of this method include a centralized cooling system and the ability to use a stand alone receiver/heat rejection package. Some disadvantages include the difficulties of cooling a dense photovoltaic array and questionable flux uniformity of a dish concentrator when compared to a Fresnel lens.

APPENDIX A

OPERATING MANUAL

SAIC/UNLV Two Axis Concentrator and Dense Photovoltaic Receiver with Active Cooling Operating Manual

October 2007

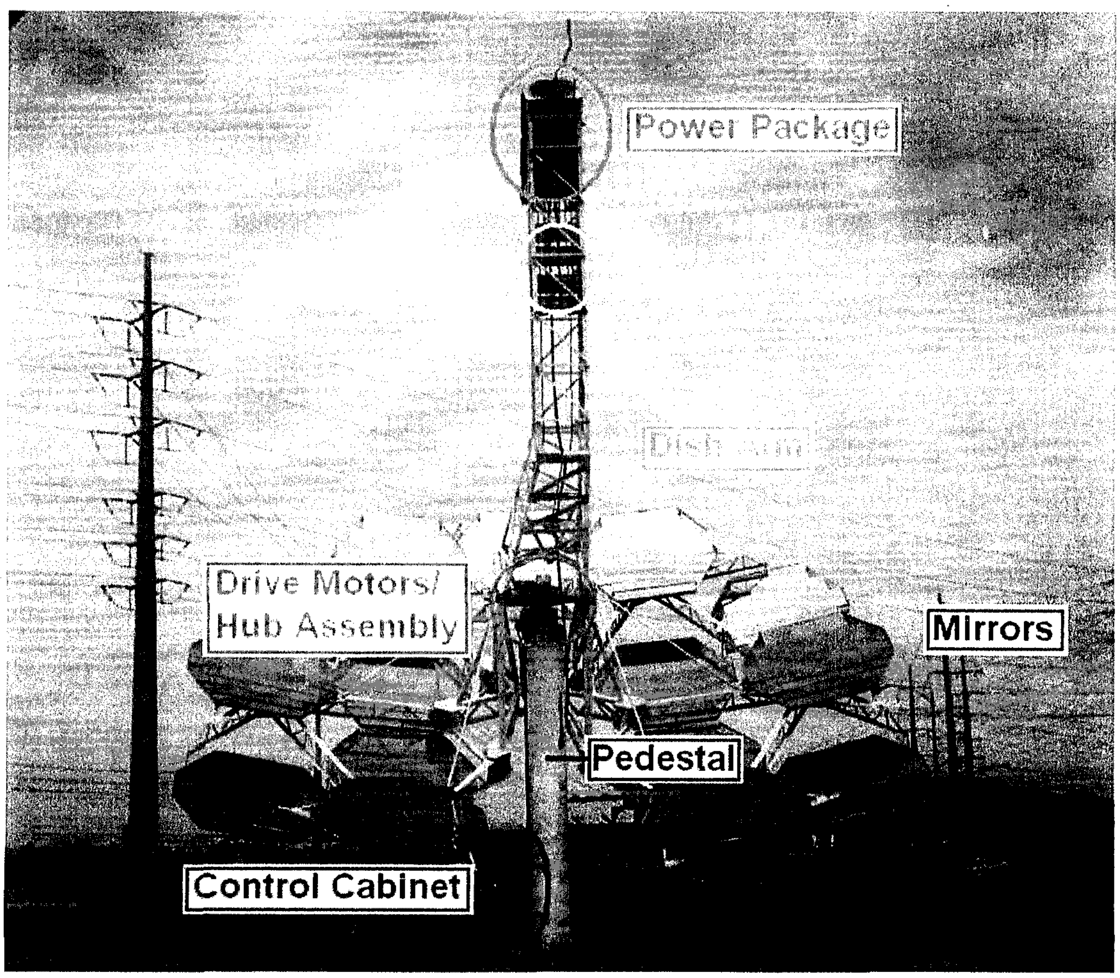
Section 1
General Information

1.1 Introduction

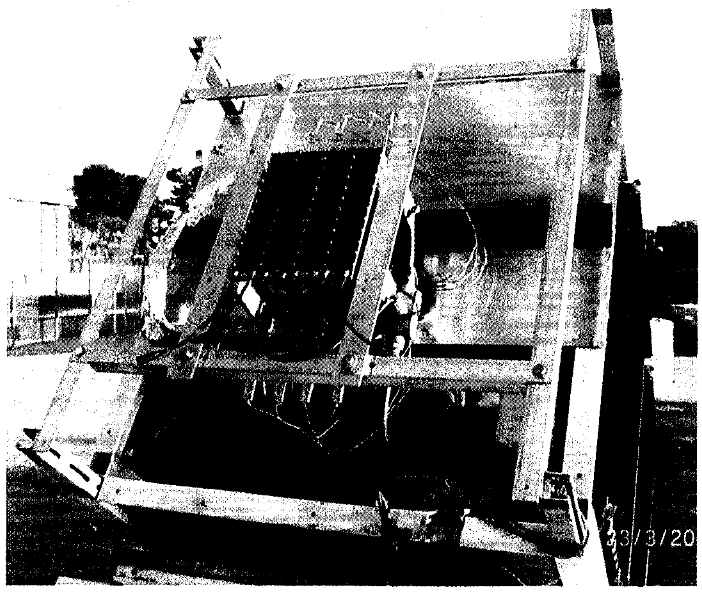
Congratulations! You have been given the opportunity and responsibility of operating the Science Applications International Corporation (SAIC) two axis concentrator equipped with a dense photovoltaic array and active cooling. As an operator, it is your responsibility to monitor the position of the dish in relation to the sun, the electrical output of the receiver, and the condition of the heat rejection system. To do this effectively, we will first cover the basic support systems and their functions.

1.2 System Overview

The following figure has several key components labeled. These component names will be important to know while operating or diagnosing the system.



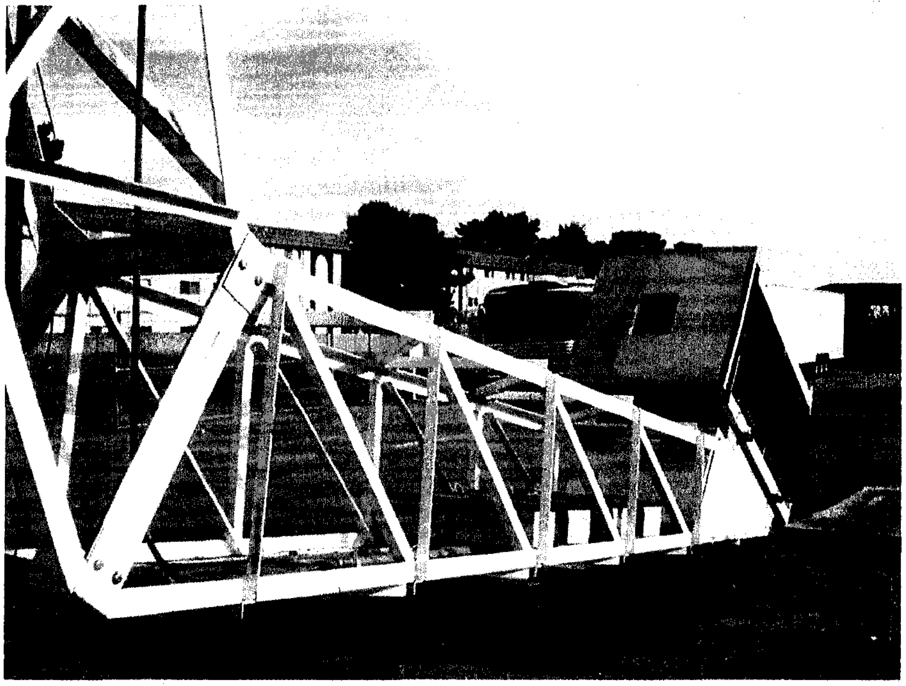
Power Package
The power package is the place where the solar radiation is converted to electrical energy and excess heat from the process is discarded. On the front of the package is a photovoltaic array comprised of four modules, each module having 88 solar cells. The modules are made of copper and plumbed into the heat rejection system. The heat rejection system (HRS) uses four automotive radiators and a centrifugal pump to circulate deionized water. There are a total of three fans moving air through the radiators to remove heat.



Inverter Bank
Below the power package, on the concentrator arm, there is a bank of eight power inverters. The inverters are connected to the electrical portion of the modules. The array is capable of roughly 220VDC and 1500W at ideal condition. One inverter utilizes four modules to generate an electrical output; therefore, there are seven inverters that are not active.

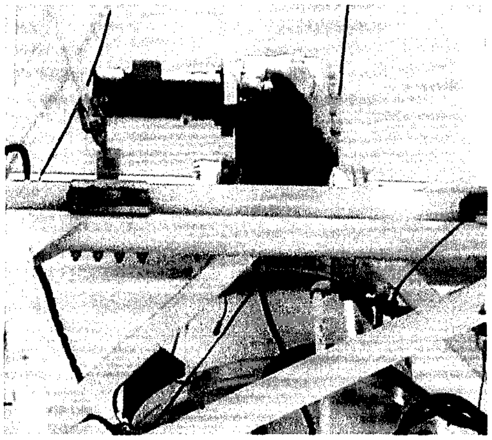
Dish Arm

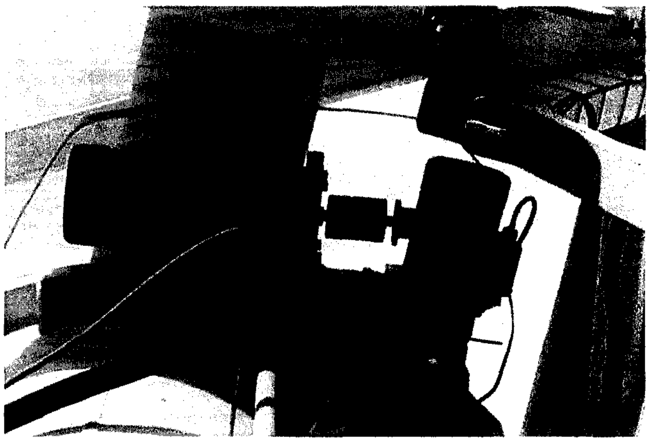
The arm is what supports the power package and keeps it at the focal point of the concentrator. The inverters also use the arm as a mounting point.



Drive Motors/ Hub Assembly

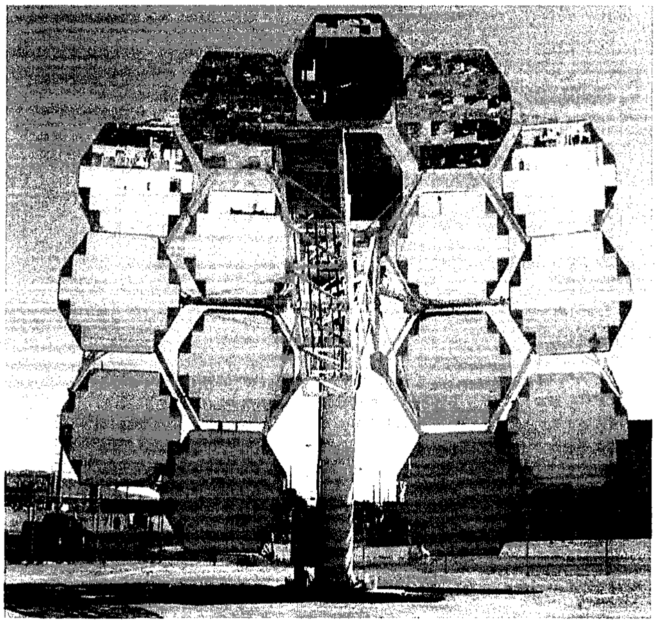
This portion of the dish is responsible for all of the movement that takes place throughout operation. There are two motors located here, azimuth (east-west movement) and elevation (up-down movement). The hub is coupled with the elevation motor to make the elevation drive.





Mirrors

The mirrors are fixed to 16 aluminum-honeycomb fixtures via fixed angle pucks. The mirrors are oriented such that when the concentrator follows the sun, the mirrors concentrate the suns image to the receiver on the power package.

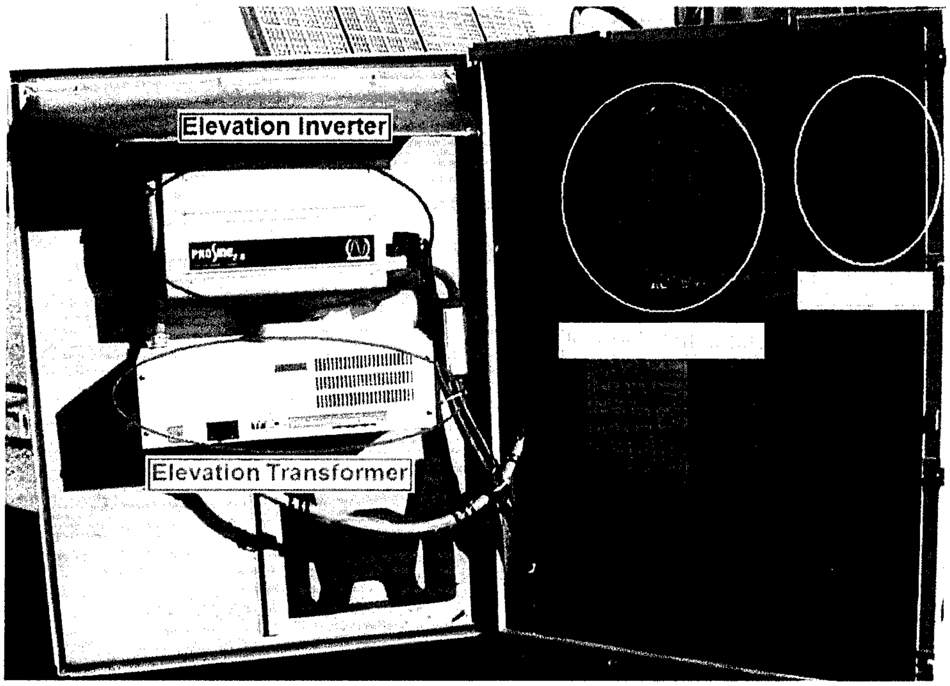


Pedestal

The pedestal is a long (approximately 30ft) tube anchored to the ground on which the dish rests. The pedestal does not move at all, the dish moves on top of it.

Control Cabinet

The majority of the controller components are housed in the cabinet at the base of the pedestal. The control system is comprised of the tracking controller board, the azimuth and elevation drive motor controllers, the elevation drive inverter and transformer. The purpose of the tracking controller board is to calculate the sun position via an algorithm and coordinate the relative dish position. To do so, the controller sends various signals to the azimuth and elevation drive controllers to change the dish position.



Section 2
Operating Checklist

2.1 Morning Startup

At dish

- ❑ Check ground for debris and liquid
- ❑ Uncover and examine the receiver
- ❑ Electrical breakers on
- ❑ Remove system enable
- ❑ Connect manual controller
    - o Turn on cooling system
    - o System pressure at or above **10psi**
    - o Turn off cooling system
- ❑ Disconnect manual controller
- ❑ Plug in system enable
- ❑ Disable **SCRAM** button

In control room

- ❑ Concentrator controller software running
- ❑ Operation log open
- ❑ Synchronize clocks
- ❑ Inverter software running
- ❑ Change wind stow position to 180
- ❑ When the system is at face-up stow (85 elevation), enable **Solar**

Section 2 continued
Operating Checklist

2.2 Operation

Dish

- ❑ Watch the image move **down** onto the receiver
- ❑ Monitor image location on the receiver throughout day (centered on receiver)
- ❑ Verify cooling system operation **visually** (tails) and **aurally**

In control room

- ❑ Record inverter total kWh delivered
- ❑ Watch for any system faults
- ❑ Log power output throughout the day

2.3 Evening Shutdown

In control room

- ❑ Record inverter total kWh delivered
- ❑ Disable **Solar**

Dish

- ❑ Watch the image move up off the receiver
- ❑ At face-up stow, send the system to face-down (-87 elevation)
- ❑ At stow, Enable **SCRAM** button
- ❑ Inspect and cover the receiver

Section 3
Operating Procedures

3.1 Morning Startup

1. Check for any leakage of water around the system or for any other problems with the receiver or heat rejection system.
2. Remove the tarp covering the receiver and fold it up neatly. Inspect the array and insulation surrounding it for any damage.
3. Ensure the electrical breakers on the outside of the control cabinet are on. If they are off, contact SAIC to verify the dish operating status.
4. Remove the system enable plug by pulling it straight out.
5. Plug in the manual control box and turn on the PV cooling system to verify the fan and pump come on and that the pressure inside the package reaches at least 10psi.
6. Unplug the manual control and plug in the system enable connector.
7. Disable the red SCRAM button on the right side of the control cabinet.
8. Make sure the control computer is on and running in the control room.
9. Check the concentrator controller software for errors.
10. Open the UNLV site log on the desktop and input the status of the system
11. Check the clocks on the control computer, PCS computer, network controller, and dish controller. Note in the log if the dish time is more than 10 seconds off and synchronize the times.
12. Switch between computers using the KVM switch and run the Sunny Data inverter software program
13. Change the wind stow position of the dish to 180 to move the dish to face-up stow.
14. When the dish reaches face-up stow, **Enable solar** – the dish should track in azimuth to the sun's position, then down onto the sun.

3.2 Operation

1. When the system starts moving down, verify the fan comes on by observing the tails on the fan.
2. When the dish stops, verify the image is centered on the receiver by going outside and looking through the tinted glass.
3. Back in the control room, the Sunny Data software should have detected the inverter activity and display the total kWh delivered. Note this number in the log as it will be used to keep track of the total power generated.
4. After 5 minutes on sun, the inverter should enter "Waiting" mode, followed by "MPP-Search" and then "MPP". After the inverter enters "MPP" mode, record the

instantaneous voltage output as well as instantaneous power output and total kWh in the UNLV site log.

5. Throughout the day, monitor the concentrator control for errors. If a fault should occur, the system will automatically detrack. It is your responsibility to note any activity in the UNLV site log.
6. While the dish operates throughout the day, it is important to keep track of the system power generation. Record the instantaneous voltage output as well as instantaneous power output and total kWh in the UNLV site log at regular intervals while operating.

3.3 Evening Shutdown

1. At the end of the operating period, record the total kWh delivered by the inverter.
2. **Disable solar** – this will cause the system to move to face-up stow
3. Watch the image move up off the receiver towards face-up stow
4. At the face-up stow position, change the wind stow position to -85 to cause the dish to rotate down to face-down stow position.
5. When the dish reaches the stow position, enable the SCRAM button.
6. Inspect the receiver for any damage. Cover the receiver with the tarp you folded at the beginning of the day.

Section 4
Procedure Details

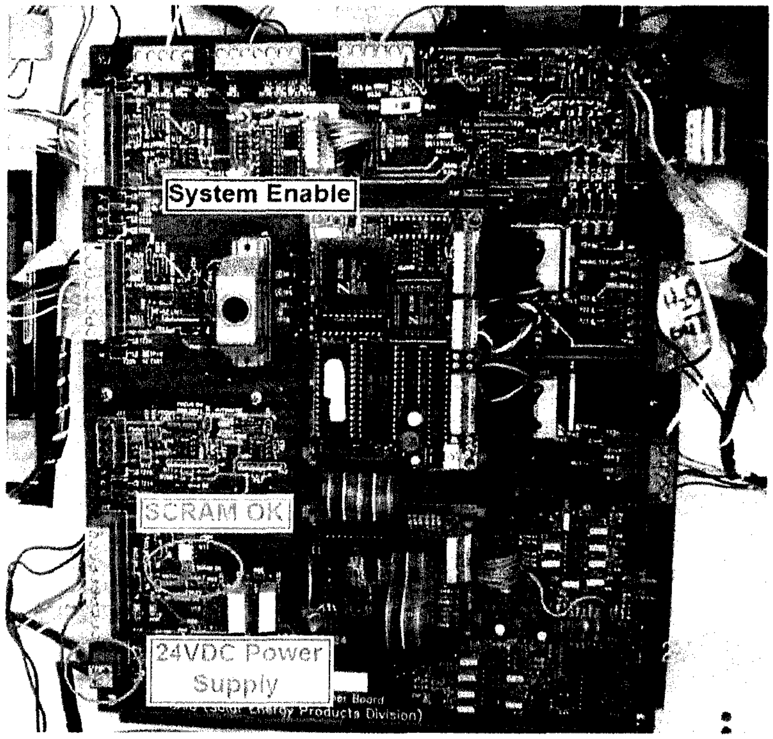
4.1 Morning Startup

A key part of the startup procedure is to check for any liquid or glass on the ground. If either of these is found, it is a good indication that the system is not in an operational mode due to a cooling system fail, or in the case of glass, something has damaged the mirrors.

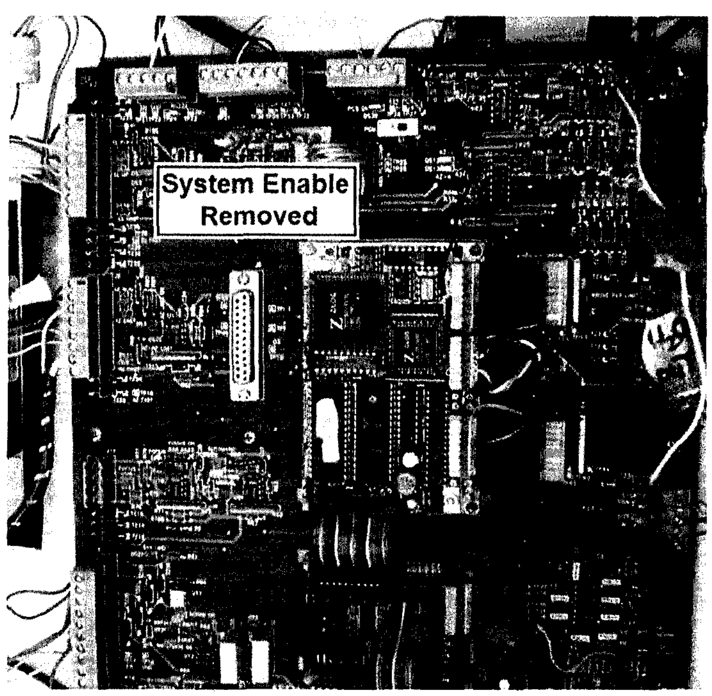
Remove the tarp covering the receiver and fold it up neatly. Check the array and insulation for any damage. If there is there is something on the receiver not noted in the daily log, contact SAIC before attempting to operate.

The next step is to make sure that the electrical breakers at the base of the pedestal are on. If any of the breakers are off or have lock out tags on them, there is most likely a reason and SAIC should be contacted.

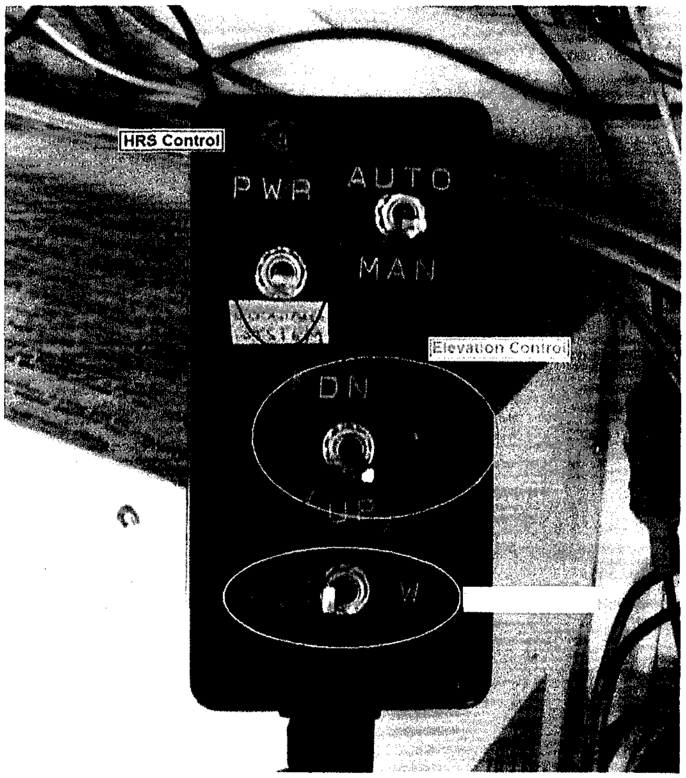
When it comes time to connect the manual control box to the controller board, you will need to unplug the system enable from the controller board.



The manual control box is located inside of the control cabinet at the base of the pedestal next to the hinge. On the end of the long cable attached to the manual control box is a DB25 connector (the type of connector used for printers before USB).



Once the control box is plugged in, flip the cooling system switch to on. A green LED should come on indicating power is activated. You will also hear the fans turn on. Set the manual controller down and go over to the power package.

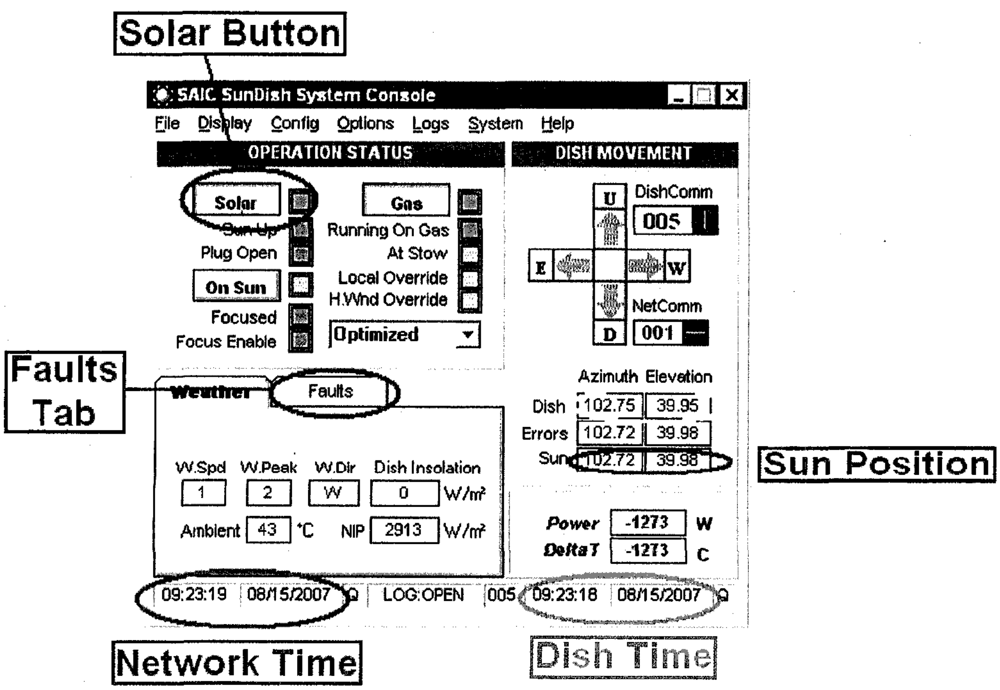


By looking through the fan at the rear of the system you will be able to see a pressure gauge to the lower left of the package. The gauge should read at least 10psi indicating the pump is working and there is an adequate amount of water in the system.

If the pressure can be verified, go back to the control cabinet and turn off the cooling system switch. When the system powers down, disconnect the manual control box from the controller board and reinsert the system enable plug.

Close up the cabinet and disable the SCRAM button. It is very important to disable the SCRAM button otherwise the system will not move. It is also important to check that the system enable plug is inserted into the control board, otherwise you will not be able to command the system to go move.

Moving into the control room, you need to make sure that the concentrator controller software is running. The concentrator controller software is what you will use throughout the day to operate the dish.



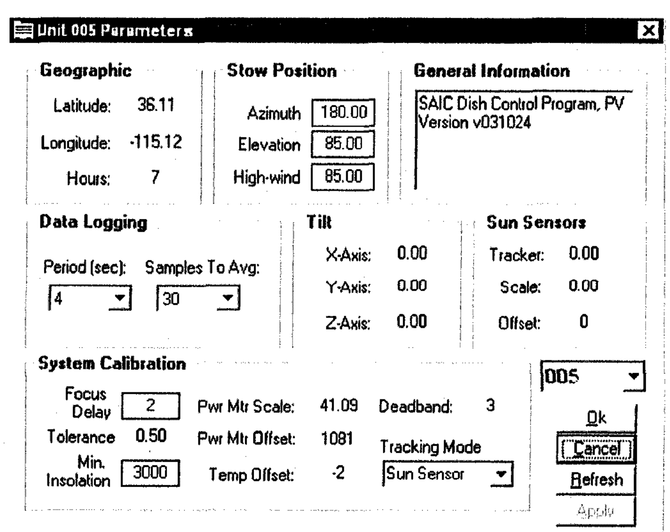
Open the UNLV site log and record the date and system status. Leave the log open as you will be using it to record data throughout the day.

Before you begin operating, make sure the clocks are synchronized to Greenwich Mean Time (GMT) via the atomic clock in the building or the clock synchronization software on the computer. The dish time and network time are located on the bottom of the concentrator controller console software. To synchronize the clocks, change the computer time to the correct minutes and seconds. Then, on the console, click System>Synchronize Clocks. Two windows will pop up, one saying the network was synchronized and one saying the dish was synchronized.

It is also important to make sure the Sunny Boy inverter software is running so you can monitor the electrical output of the array. To do this, use the KVM switch next to the desk to connect to the Gateway computer. Open the Sunny Data program.

Now you need to move the system to face-up stow. It is important that this step be done either before or after solar-noon; otherwise the dish may be damaged by solar concentration. A good rule to follow is to keep the dish azimuth 90 degrees away from the sun position at the time you transition from face-down to face-up. Due to the way the system is physically designed, the dish cannot and will not rotate in azimuth at any elevation below 0 degrees. So, a suggested strategy is to command the dish to move to 0 degrees elevation, then add 90 degrees azimuth to the sun's current position, finally, move the dish to 85 degrees elevation and 180 degrees azimuth.

To move the system, click Config>Dish Parameters on the concentrator controller software. This will cause the performance parameters to pop up in a separate window. To change the dish position in Elevation, you will need to click on the box for the Elevation position in the "Stow Position" section. The numbers in this section correspond to the degrees on a compass, thus, 0 degrees is north, 180 degrees is south, etc. The face-up stow position is 180 degrees azimuth and 85 degrees elevation, face-down is 180 degrees azimuth and -87 degrees elevation.



When the system reaches face-up stow and you are ready to go on sun, enable Solar. The dish will rotate in azimuth to the sun's position, and then down in elevation.

4.2 Operation

As the system begins to track the sun, watch the receiver and monitor the direction the image moves on the receiver. The fan should come on and you can observe the tails moving. The image should move downward from the top of the receiver. You should be able to see this through the window in front of the control computer.

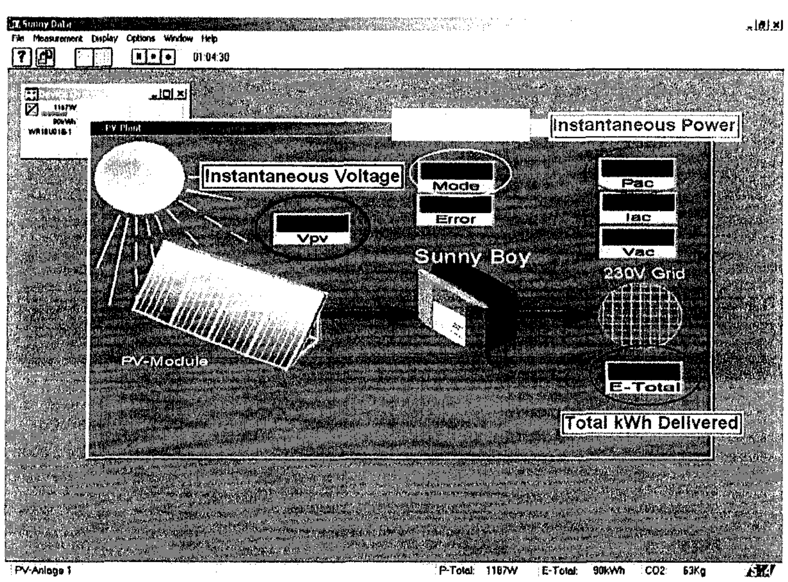
It is important to make sure the image is centered on the receiver. A centered image provides uniform flux on the receiver and will maximize the electrical output of the array. To do this use the tinted glass by the door to look at the receiver.

Shortly after the system goes On-Sun, the inverter will "wake up". At that time, it is good to record the total kWh delivered. This number will be used to determine how much power you made for the day.

After 5 minutes on sun, the inverter should enter "Waiting" mode, followed by "MPP-Search" and then "MPP". After the inverter enters "MPP" mode, record the instantaneous voltage output as well as instantaneous power output and total kWh in the UNLV site log.

Throughout the day, you must periodically check the status of the dish on the concentrator controller, the image location on the receiver, as well as the inverter status and output.

While the dish operates, it is important to keep track of the system power generation. Record the instantaneous voltage output as well as instantaneous power output and total kWh in the UNLV site log at regular intervals while operating.



4.3 Evening Shutdown

At the end of the day, you will need to tell the system to go to stow by disabling solar. At that time, you should record the total kWh delivered on the inverter software.

By subtracting the total kWh recorded at the beginning of the day from the total recorded at the end of the day, you can calculate how much power the array produced during operation.
As the system moves off sun, it is a good idea to watch the image move up off of the receiver. The dish will move up in elevation to the face-up stow position, and then rotate in azimuth to complete its transition.

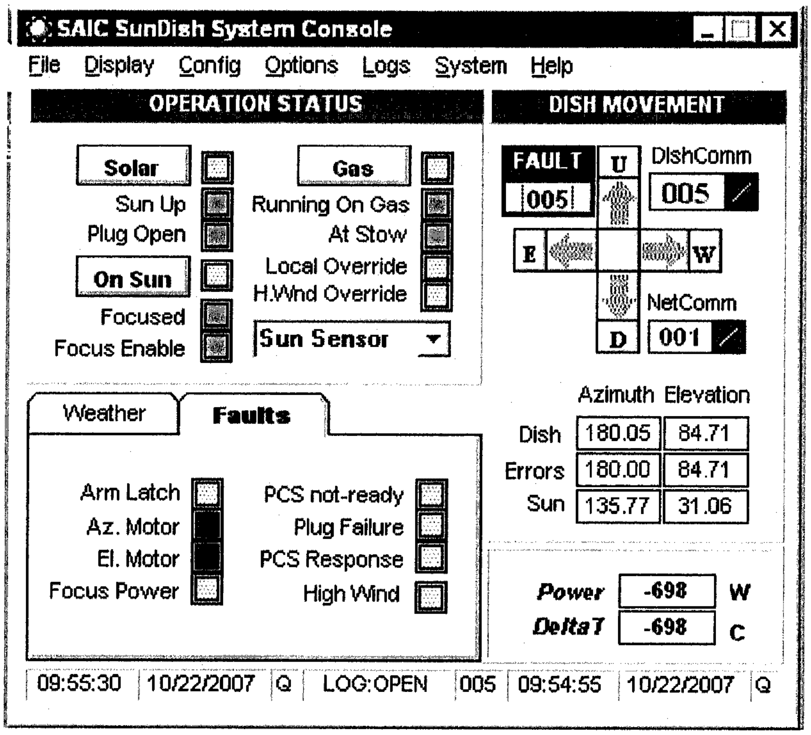
When the system reaches face-up stow, change the wind stow position to -87. This will maneuver the system to face-down stow. After the system stows, you should enable the SCRAM button to secure the concentrator in stow position until the next time it will be operated.

Inspect the receiver for any damage. If damage is found, note it in the UNLV site log and contact SAIC. Cover the receiver with the tarp from earlier in the day to protect it.

Section 5
Troubleshooting

5.1 How to clear a fault

If a fault should occur on the concentrator controller software, you will hear an audible alert and the software will have a flashing red error displayed. As soon as this happens disable Solar. This will ensure the dish will not try to go back on sun before you have properly diagnosed the problem.



To stop the audible alert, click the flashing "FAULT 005" alert. Next, click the "Fault" tab on control console software. The fault that has occurred will have a red block illuminated next to it. Note the fault name in the UNLV site log and the time it occurred.

To decide whether or not the error will require maintenance, consult the quick reference sections below. If the fault does not require SAIC support you may clear it and resume operation.

To clear a fault, you must enable, and then quickly disable Solar. The block next to the Solar button will illuminate green then go back to grey, and the fault block will turn from red to grey.

When you are ready to go back on sun, you will now only need to enable Solar.

5.2 Concentrator / Controller Software quick reference

Fault	Causes	Solutions
Arm Latch	Software Error	Call SAIC for support
Az Motor Fault	1. SCRAM Enabled 2. SCRAM Stuck 3. Stuck Relay	1. Disable SCRAM 2. Repeatedly enable and disable SCRAM until OK LED illuminates 3. Call SAIC for support / see below
El Motor Fault	1. SCRAM Enabled 2. El Inverter/Charger Error 3. Drive Fluid Low	1. Disable SCRAM 2. Restart El Inverter/Charger 3. Call SAIC for support
PCS not-ready	Controller jumper wire malfunction	Call SAIC for support
Plug Failure	Software Error	Call SAIC for support
PCS response	Controller error	Call SAIC for support
High Wind	Wind speed above 25 mph	Wait until average wind speed decreases
CCS communications lost after clock synchronization	Control board malfunction	Disconnect and reconnect 24VDC from control board
HRS pressure below 10psi	HRS is low on water	Fill the HRS with water from the deionizer

5.3 Sunny Data Software quick reference

Fault	Causes	Solutions
Software freezes	1. Inverter has turned off 2 .Software Crashed	Restart software
EarthCurMax	Array is damaged	1. Stow system and check for damage 2. Call SAIC for support
GFDI	Inverter fuse is defective	1. Stow system and check inverter fuse 2. Call SAIC for support
Offset	Grid voltage check failed	Restart software

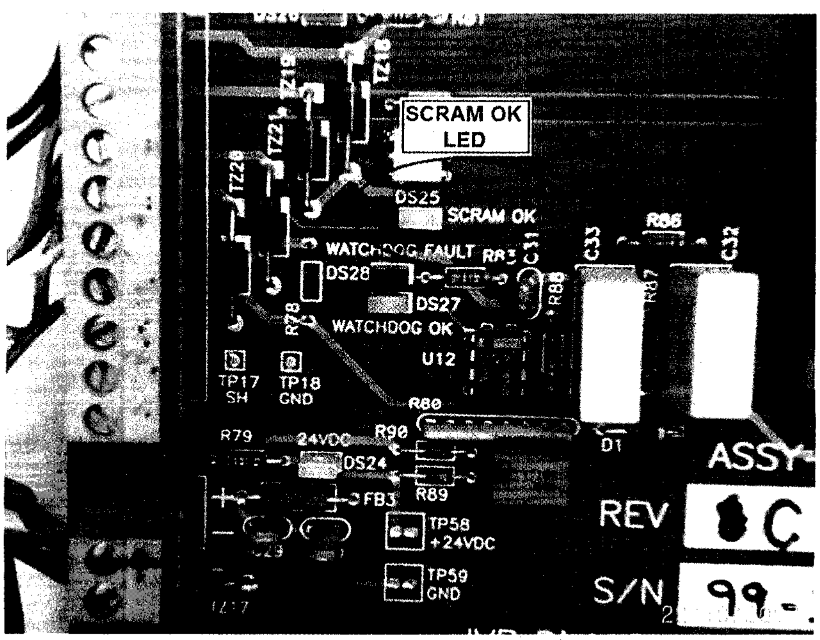
5.4 Fault resolutions explained

<u>Arm Latch</u>

This error is the result in an anomaly in the concentrator controller software. It is a left over error from the dish's original Stirling engine system. If this error should occur, you should contact SAIC for support.

<u>Az Motor Fault</u>

This error is the result of either the SCRAM being enabled or the motor relay being stuck. The SCRAM button is disabled by twisting it clock wise 90 degrees. However, as of late, the SCRAM button has not been fully disengaging. To check if the SCRAM has been disengaged, check the LED at the bottom left of the control board labeled "SCRAM OK".



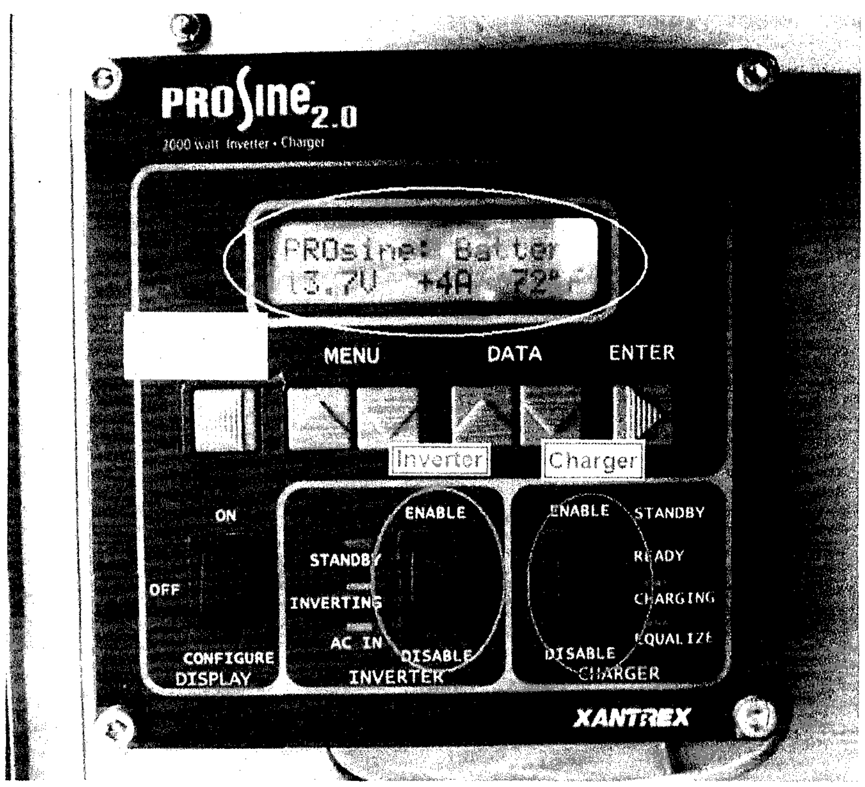
If the SCRAM is not the cause of the fault, the relay is most likely stuck. You should contact SAIC for support.

To test the relay, remove the system enable and plug in the manual control box. If you press the red button label Az motor, you should hear the relay click and the motor should turn the system. If you do not hear the relay click, it is stuck. There is a blue button on the side of each relay. Press in the blue button on all relays. The one that is stuck will likely click when you press it. You can now try the manual control box again. If the dish rotates, reinstall the system enable and resume operations, otherwise call SAIC.

El Motor Fault

This error is the result of either the SCRAM being enabled, an elevation inverter error, or the elevation drive is low on fluid. The SCRAM button is disabled by twisting it clock wise 90 degrees. If the SCRAM is not the cause of the fault check the inverter for errors.

If there is an error with the elevation inverter, turn off the inverter and charger via the display on the door of the pedestal cabinet, then the switch on the side of the inverter and then the breaker on the elevation transformer. Wait 30 seconds, and then turn transformer. Wait 30 more seconds and turn on the inverter via the switch on its side. Wait 30 more seconds and turn on the inverter switch on the display on the cabinet door. Wait an additional 30 seconds and turn on the charger. Watch the display for any errors. If there are no errors, you can resume operations.



If the dish is getting stuck at low elevation angles, there is a good change the elevation drive has leaked out most of its gear oil. If there is oil running down the side of the pedestal, it is a good indicator of elevation drive's fluid level. Call SAIC for support.

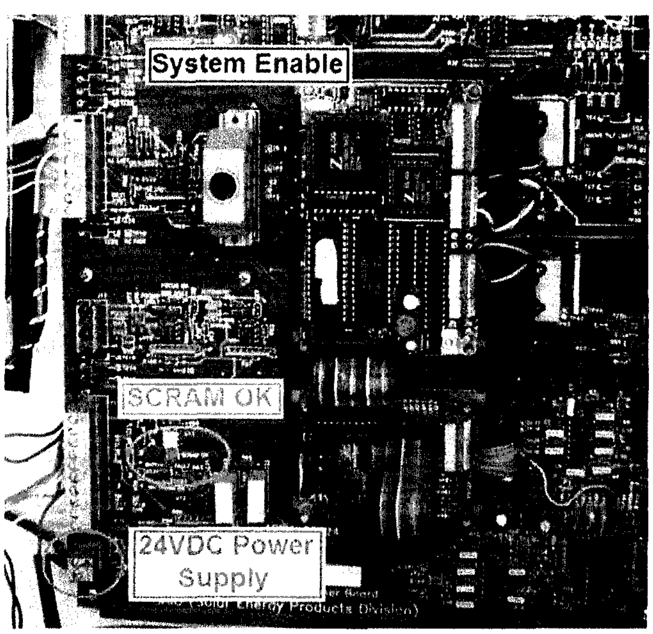
PCS not-ready
This error is the result of a lack of a ready signal by sent through the control logic. It is currently a simple jumper wire providing 24VDC. If this error should occur, you should contact SAIC for support.

Plug Failure
This error is the result in an anomaly in the concentrator controller software. It is a left over error from the dish's original Stirling engine system. If this error should occur, you should contact SAIC for support.

PCS response
This error is the result in an anomaly in the concentrator controller software. It is a left over error from the dish's original Stirling engine system. If this error should occur, you should contact SAIC for support.

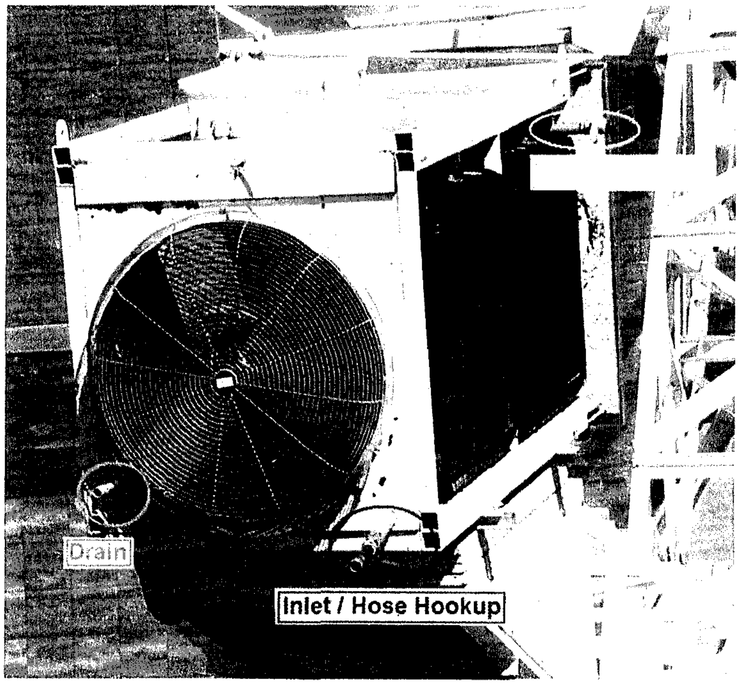
High Wind
This fault results when the wind speed reaches an average above 25 mph. The fault will cause the system to move to face-up stow in elevation, but continue to track the sun in azimuth. You cannot clear this fault until the wind speed subsides.

CCS communications lost after clock synchronization
This error usually happens when you command the clocks to synchronize. After the synchronization, the dish time and position will go blank and you cannot command it. This is due to an error in the control board logic. To regain communications, unplug the 24VDC connector (bottom left on the control board) for 30 seconds, then plug it back in.



HRS pressure below 10psi

This means the HRS is low on water. To fill it back up, hook up the hose from the deionizer to the inlet on the package. Turn on the water and open the inlet valve at the package. Watch the pressure gauge and when it reaches 5psi shut the inlet valve. Turn off the water. Cycle the cooling system switch on the manual control box and verify the pressure is at or above 10psi.



Sunny Data Software freezes

The Sunny Data software is not a very stable program. It has a tendency to freeze or crash. If this happens, simply restart the software. If it happens continuously, restart the computer and then restart the software. Some ways to combat this is to limit your other activities on the Gateway PC to only Sunny Data and restarting the software every two hours regardless of anomaly.

EarthCurMax

This error results from the inverter detecting a ground in the array other than the negative terminal. This error usually means there is significant damage done to the PV array and the system should be detracked immediately. You should stow the system face-down and record any damage found. You should also contact SAIC if this happens.

GFDI

This error is the result of the ground fault fuse in the inverter blowing. If this happens, it is a good indicator that a more serious problem with the PV array is on its way. You should detrack the system immediately and stow it face-down. Check the inverter fuse to confirm it is blown by measuring its resistance, and contact SAIC for support.

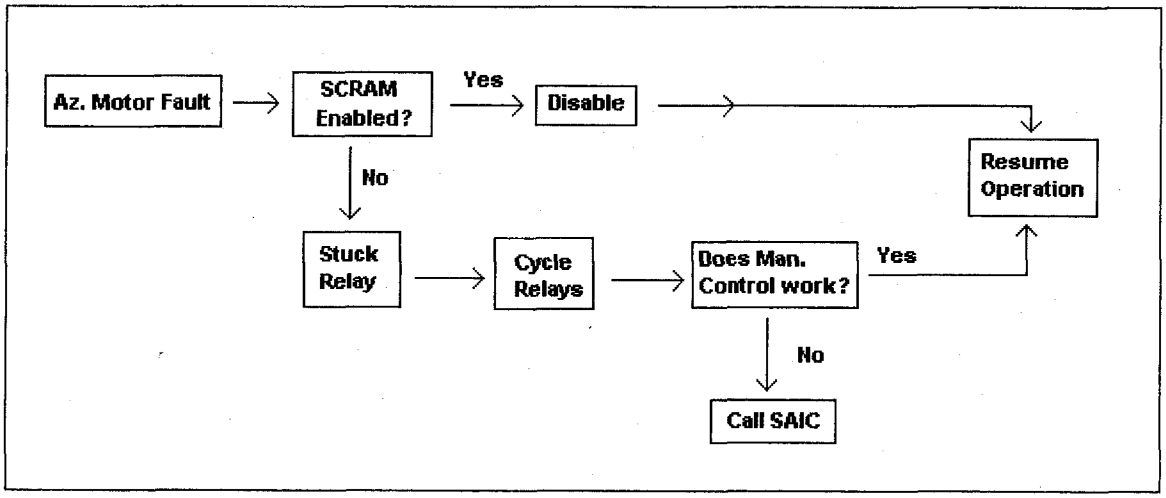
Offset

This error is defined as the result of the inverters inability to connect to the grid. However, the actual conditions that cause this fault are sporadic as are the results of its occurrence. If you notice the Sunny Data displaying a mode of "Offset", wait a few minutes for the inverter to come back online. If nothing happens, restart the Sunny Data program. If the inverter continues to remain in "Offset" mode, disable Solar, wait 15 minutes, then enable Solar. This will usually clear up the situation. This is one of the most common errors with the Sunny Data program.

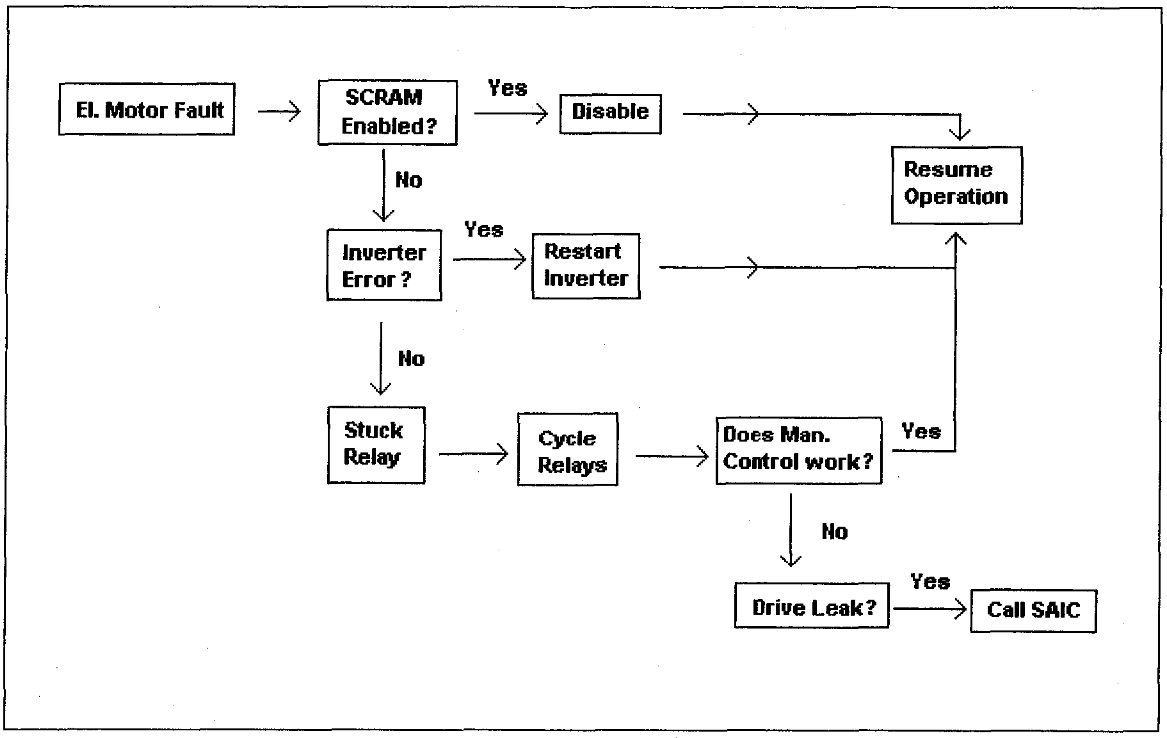
5.5 Common fault troubleshooting flowcharts

The following flowcharts describe solutions to the most common faults that occur while operating:

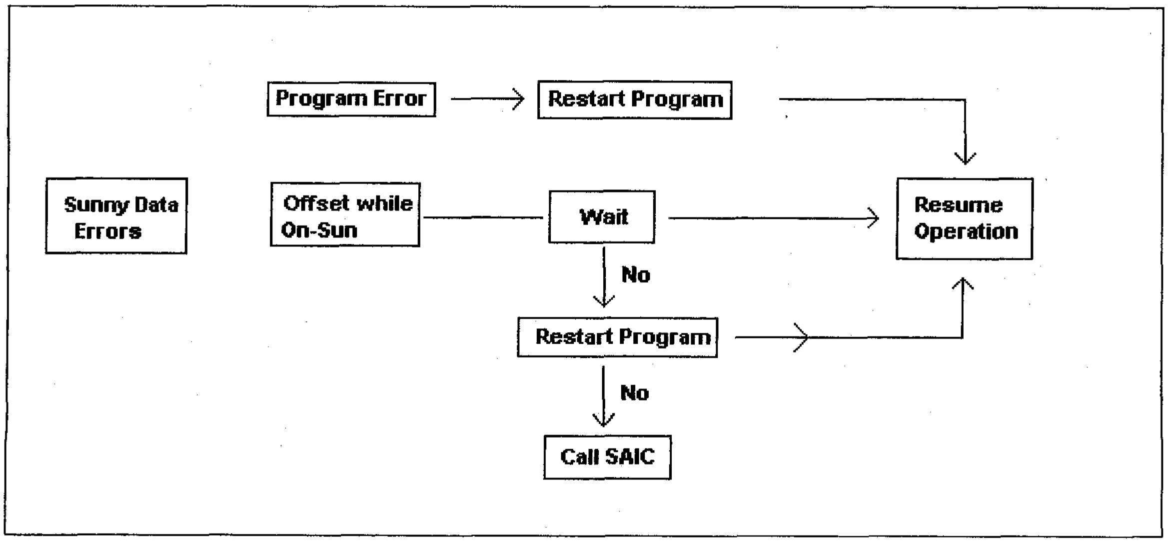
Azimuth faults



Elevation faults



Sunny Data faults



Section 6
Glossary

azimuth	The angular position along the horizon, clockwise from due north
CCS	Concentrator Controller Software
concentrator	A device that uses lenses and/or mirrors to focus and enhance the sun's rays onto a central surface
detrack	The term used when a fault occurs and the system moves off sun
elevation	The angular distance above the horizon
face-down	When the system is positioned with the mirrors facing down, -87 degrees elevation
face-up	When the system is positioned with the mirrors facing up, 85 degrees elevation
fault	The term used when an error or anomaly occurs during operation
HRS	Heat Rejection System, the cooling system attached to the PV receiver
image	This term refers to the concentrator focal point
inverter	An electronic device that produces alternating current (AC) from direct current (DC)
kWh	A unit of measure equal to 1 kilowatt or 1,000 watts of power per one hour
manual controller	A small black box that allows an operator to move the dish as well as power the cooling system
MPP	Max Positive Power
MPP-Search	Max Positive Power Search
on sun	Term used to describe when the dish is pointed directly at the sun
photovoltaic	The process of converting light into electricity
SCRAM	A red button at the base of the dish pedestal that stops concentrator movement, derived from nuclear reactor emergency procedures
system enable	A plug that, when inserted in the control board, allows the concentrator controller software move the dish
wind stow	The position the dish moves to in the event that winds exceed the set maximum speed

Section 7
Contact List

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