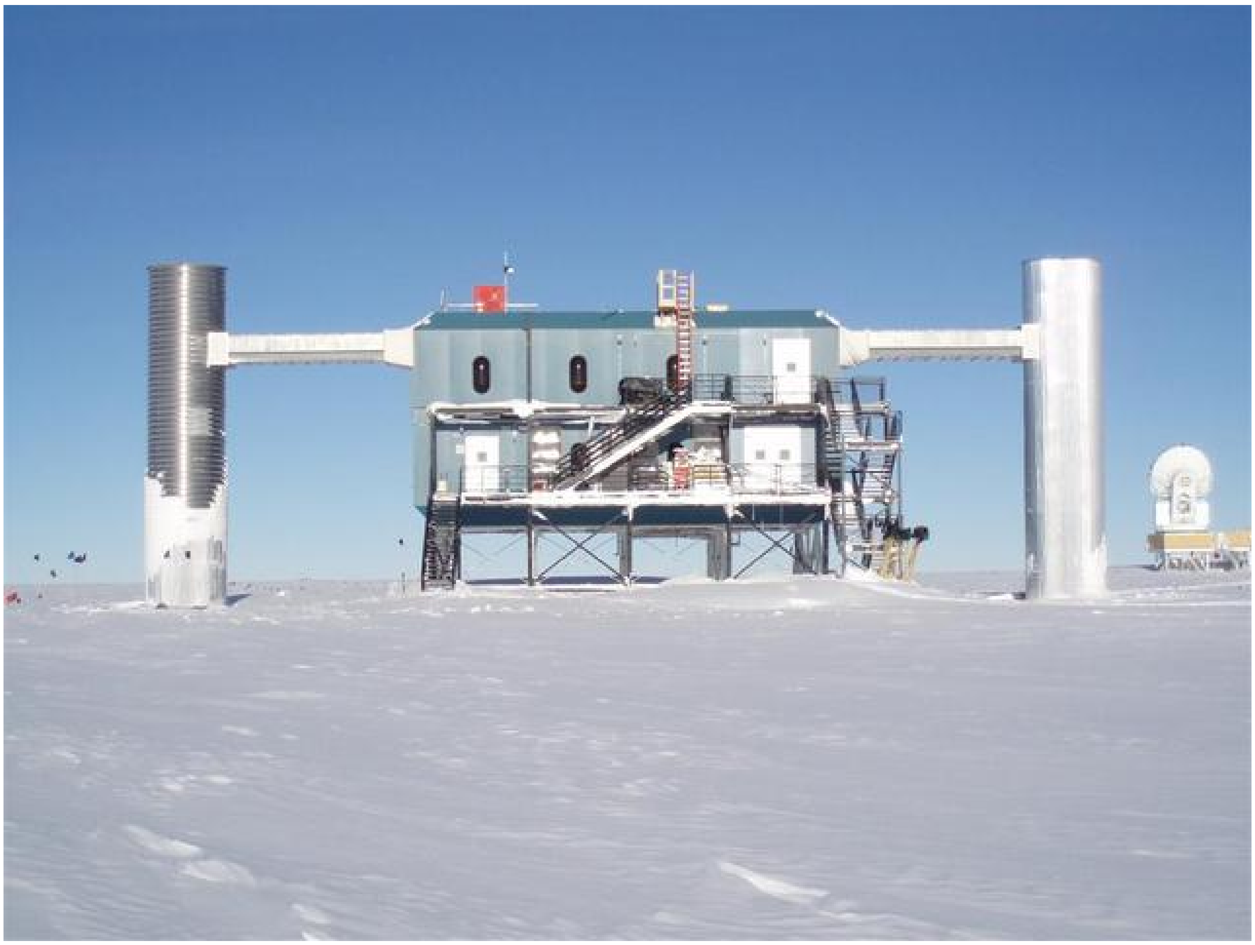
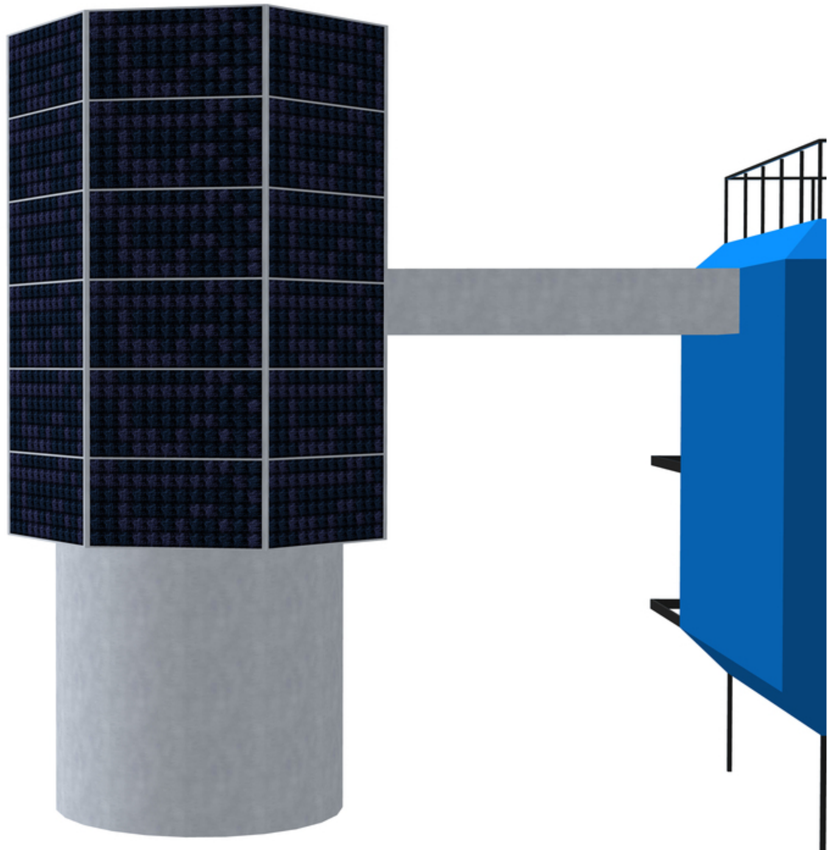
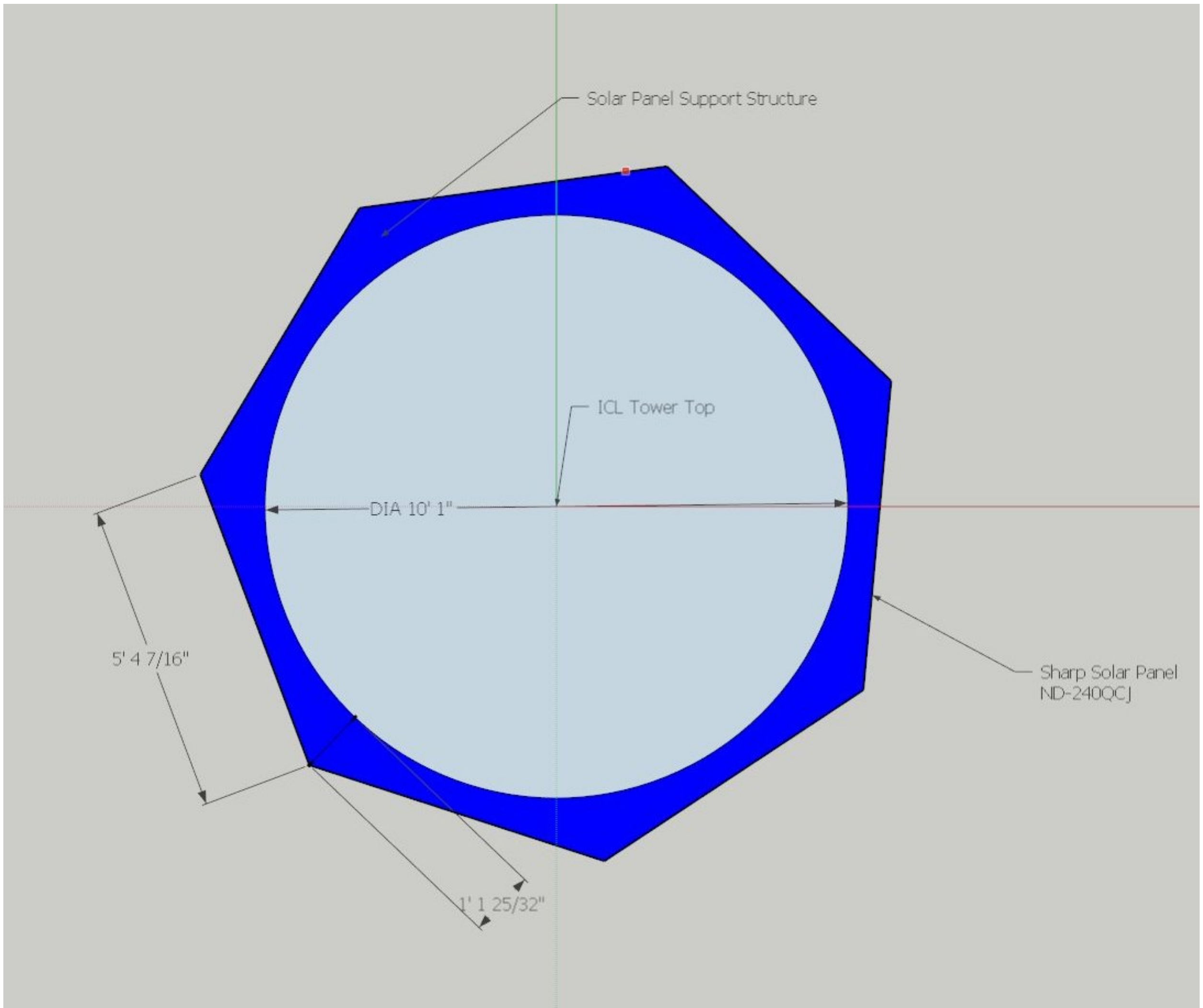
Project:

The IceCube neutrino telescope is located at the South Pole. At the direction of the National Science Foundation we are attempting to help reduce the logistical cost of running the detector. Power costs recently reached $1.61 per kw hour. A proposal was circulated to panel the towers of our observatory building with solar panels.

The IceCube Laboratory:

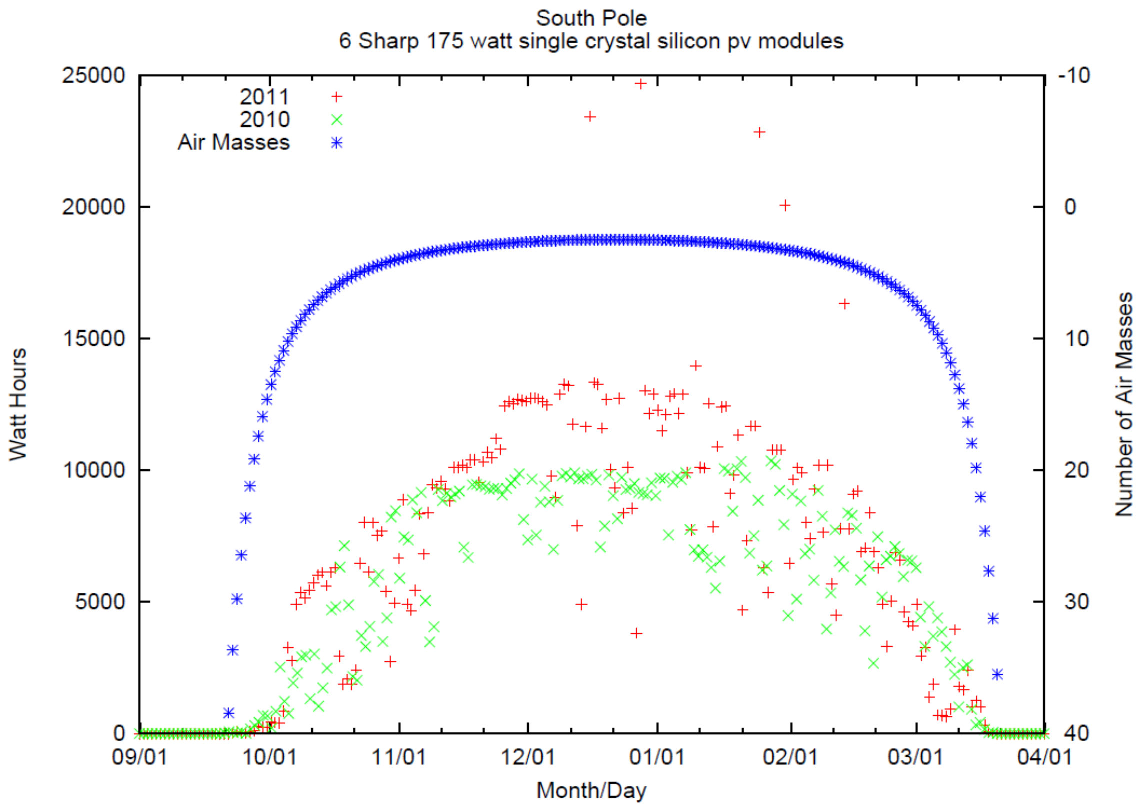






A feasibility study of using solar panels at the South Pole was done by the Cold Regions Research and Engineering Lab of the Army Core of Engineers (CRREL). The true value of this report is that they proved that solar panels could survive a winter at the South Pole. There are some technical issues with the report however. The output of different panels was measured with identical with an identical load (no attempt was made to perform maximum power point tracking), making the relative comparisons questionable. They also state that the output power of a given panel is related to the sun angle. While true to a point, a parameter with a better fit is the number of air masses though which the sunlight must travel. A valuable photo was included on page eleven of the report showing snow accumulation on the panels (the Antarctic equivalent of shading).

A six panel test was installed in Summer Camp consisting of six mono-crystalline NT-R5E3E 175 W Sharp panels with each panel having a Enphase M175 microinverter. The write up also questions why panels oriented in different directions produce different amounts of power. The answer is fairly obvious given the photo available in the report. The panels with the highest output are located closest to the edge of the roof allowing light reflected from the snow to illuminate the panel. The panels producing lower amounts of power are shielded by a the roof of the building where they are mounted. The design we presented above avoids the shielding issue and allows panels to be wired in to a string inverter located inside the ICL Additionally the enphase inverters do not start harvesting power until the voltage reaches 25 volts leaving some energy energy uncollected. Below is a graph showing the daily power production of the test setup as described against a plot of the number of air masses sunlight at pole travels through.



Configuring the ICL array with a string inverter will allow us to harvest energy at a lower voltage per panel. This should allow increased energy generation during the months with a lower sun angle. It is suggested that we use a power-one PVI-3.6-OUTD-US inverter.

The power one inverter has a maximum input voltage of 600 VDC which must be derated for altitude. The derate curve for the power one inverter is located here. The derated maximum input voltage is 528 VDC.

The sharp panels used in the test setup are no longer available and similar panels from sharp are becoming harder to obtain given that sharp is exiting the solar buisness.

The extreme environment at the South Pole required a search for the most rugged and reliable panel we could find. An attractive option presented itself in Sunpreme with their innovative glass on glass construction. In addition to the rugged construction, these panels do not require the array to be grounded which is a definite bonus in an environment where there not an easily accessible ground (the telescope is situated on top of a glacial ice over 2500 meters in thickness). Additionally the maximum power point voltage was higher than the alternatives leading to lower cabling loss and reaching the MPPT turn on voltage earlier. Finally the lack of a frame will hopefully help alleviate the snow accumulation shown in the CRREL report.

Sunpreme kindly provided us with four G60-02-190 watt panels with the following specifications:

Peak Power Pmax: 190 watts
Voltage At Pmax: 29.7 volts
Current at PMax: 6.4 amps
Open Circuit Voltage (V): 37.1 volts
Short Circuit Current: 7.1 amps
Standard test temperature 25 degrees C

The panels supplied to us where non-standard in that the junction boxes were replaced with tyco junction boxes. They also included sufficient clamps to mount their panels for testing.

Goals of tests:

1) Test cold survivability of the panels. The record low temperature at the South Pole is -82 C. The record low temperature during the summer months is -79C. This extreme low temperature presents a danger to connectors, cabling, any semiconductors, adhesives, mounting hardware etc. We will examine the following components during this test:

a) Connectors
b) Cabling
c) Barrier Diodes
d) Junction box
e) Split / cracked cell from extreme temperatures
f) mounting hardware

2) Test linearity of the open circuit voltage temperature coefficient. Due to the high altitude of the South Pole (reducing the insulating properties of air) the maximum input voltage of any inverter must be derated. For example a power-one PVI-3.6, at sea level has a maximum input voltage of 600 VDC, while at 9,301 ft above msl that must be derated to 528 VDC.

Combining this reduction with the extreme low temperatures which increase the open circuit voltage testing the linearity of the supplied open circuit voltage is important to design the array.

Test Environment:

The tests where performed in Stoughton Wisconsin at the Physical Sciences Laboritory (http://www.psl.wisc.edu/). The panels are large enough that they would only fit in our walk in freezers. Two panels mounted on a temporary 2x4 structure and placed inside walk in freezer #2. See the attached picture

Iteration 1:
For the first iteration of the tests we cooled two test panels to -60C. After cold soaking for four days and while cold we measured the open circuit voltage at the ambient freezer light and at the

‘high and low’ setting of a 500 watt halogen lamp. Light hammer strikes on the junction box, cabling, and connectors resulted in no shattering or broken materials. However the rubber in the mounting clamps fractured into multiple pieces when tapped with a hammer.

The panels were warmed up to ambient and the tests repeated. In order to rule out any damage from cold exposure the open open circuit voltage was measured in both panels outside facing the sun. For comparison’s sake a reference, unfrozen panel was removed from storage and had it’s open circuit voltage measured at the same time.

Cold tests:
Freezer started on the 10th of June

Cold measurements taken on the 14th of June.

Cold Tests	Ambient Light	Low Setting	High Setting	Average Temperature
Panel A	9.2 v	15.6 v	19.2 v	-59.25C
Panel B	11.7 v	18.5 v	23.3 v	-59.25C

June 18th:
Ambient Temperature:

During the ambient tests the inside of the freezer was at 20 deg C, and the outside temperature was 19 deg C. The panels had a little condensation on them which was wiped off with a chem wipe before proceeding. the outside measurements were taken between 11:10 and 11:15 on the 18th of June. The panels were left in their test stands (mounted vertically so not perfectly oriented to the noon-day sun with respect to elevation).

A visual inspection of the front and back of both panels showed no visible defects. No cracked cells and no solder trace issues anywhere to be seen.   The cables have returned to original pliability and were easy to wrap around a six inch pipe.

Ambient Tests Jul 18, 2013	Freezer Ambient	Freezer Low Setting	Freezer High Setting	Outside Direct Sunlight
Panel A	7.14	11.9	16.9	36.4
Panel B	8.9	14.1	19.2	35.5

Reference Panel Unfrozen				35.6

Conclusion? These panels spent almost four days below -60C. Other than the rubber in the mounting brackets I don't see any single component that failed obviously.

Iteration 2:
Repeat iteration one, but increase the test duration, and obtain some method of measuring the irradiance on the panel.

The test panels were placed in the freezer on the 28th of June and retested on the 10th of July. The total duration of the test was twelve days at approximately -60C. On July 10th the open circuit voltage tests where repeated with the same light sources as used in iteration one but a digital light meter was added (a Dr. Meter LX-1330B). The placement of the lights and panels was the same as the previous tests (to a pencil mark on the racks in the freezer).

	Panel A	Panel B	Lux
Ambient	10.4	12.12	50
Low Setting	16.8	17.8	150
High Setting	21.73	22.7	550

Before the test the freezer temperature sensors read -60C and -59C. After the tests they read -58C, -53C.

I believe the ambient voltage readings are slightly higher as the outside humidity is lower today than it was during the original tests (less snow generated when opening the freezer door).

A general inspection of the panels revealed no defects.
The cable passed a very gentle bend test.
Light hammer impacts on the cable and junction boxes revealed no cracking.

Note: Communication of this result with engineers at Sunpreme revealed that where where not using light sources of sufficient intensity and this iteration was cut short in order to repeat the tests with more lights.

Iteration 3:
Repeat previous test but add additional lights and add an extra test position moving the panel closer to the light source.

Light Sources:
4x 500 watt halogen lamps
1x 750 watt halogen lamps

Position 1 - Average lux = 2465 lux
Position 2 - Average lux = 3517.5 lux

Ambient	Position 1	Position 2	Average Temperature
Panel A	28.92 Vdc	31.36 Vdc	22 deg C
Panel B	28.25 Vdc	31.38 Vdc	22 deg C

Cold	Position 1	Position 2	Average Temperature
Panel A	35.3 Vdc	38.7 Vdc	-54.5 deg C
Panel B	32.3 Vdc	36.7 Vdc	-52.25 deg C

STC: 25 deg C

As the light source was held constant between the ambient and cold test data above we can calculate the VoC Temperature Coefficient. This was considered important to check as the panels will be exposed to extreme temperatures and if the VoC temperature coefficient was not linear it could lead to damaging voltages at the inverter.

	Position 1	Position 2
Panel A	-0.287 %/deg C	-0.305 %/deg C
Panel B	-0.193 %/deg C	-0.228 %/deg C

Note that the tester was inside the freezer with the panels during the test. After testing panel A, despite the extreme cold weather gear the tester left the freezer to warm up for a few minutes. As the relative humidity was high leaving the freezer caused a small but significant quantity of snow to blow into the freezer and stick to panel B. Despite attempting to wipe the snow off the panel with a chem-wipe there was a persistent coating of frost that defied cleaning (A realistic problem in the field). This coating would explain the out of specification VoC temperature coefficient measured for panel B.

Conclusion:

The Sunpreme solar panels where cold soaked to -60C for long periods of time and showed no evidence of failure. The cabling, junction box, and wiring showed no catastrophic failures. The one minor failure noted was the rubber in the mounting clamps shattered when tapped with a hammer at -60C. Any extreme cold installations should use different mounting hardware. A possible replacement material for the clamps would be delrin (a non-marring resin used with great success in many antarctic applications).

The open circuit voltage temperature coefficient proved to be linear at extremely low temperatures and any low temperature array design should be able to use this specification with confidence.

String Sizing:

Conservatively assuming full sunlight at -60C, the open circuit voltage of the sunpreme panels would be calculated as follows:
37.1 + (85 * .003 * 37.1) = 51.46 VDC.

This limits the string size to a maximum of ten panels wired in series to stay below the altitude derated max input voltage for the power one inverter. Additionally it means that to reach the turn on voltage of 120VDC each panel must produce a minimum of 12VDC (a full ten volts lower than the enphase inverter).

Wiring configuration:

Note that with the proper design of the support structure the towers can have faces that align. This will allow a string on tower A to be wired in series with a string on tower B.

The astute observer will note that the power-one inverter has two MPPT tracker inputs and that two strings of ten panels each could easily exceed the rated 3.6KW. To get around this problem a single inverter should be wired to two different strings that face opposite directions.
A series of photos of the ICL with dimensions added is available here.

Modeling Output:

There are two methods for modeling the output of a solar array.

The first combines the following equations with solar radiation data from SSEC and weather data from MET to calculate the power produced by a given solar array.

$$T_{cell} = T_{ambient} + G\left(\frac{NOCT - 20degC}{0.8KW * m^{-2}}\right)$$

$$P_{max} = P_{stc}\left[1 - \gamma\left(T_{cell} - 25degC\right)\right]$$

A calculator spreadsheet is available here.

When checked against the RPSC solar proof of concept array it estimates low (off by 10-15%). As stated in the document accompanying the SSEC data, they do not measure radiation from reflections, soirradiance levels probably higher. With more time and power data from ASC's array we could recreate the actual irradiance numbers. Also the estimator does not account for the movement of the sun.

The second method is to simply scale the output of the ASC array by the size and number of panels.

Future work:

In both the second and third iteration of cold testing it was noted that when warm moist air from outside the freezer hit the panel it sometimes formed a frost that would not wipe off. On occasion snow accumulation is an issue at the South Pole, see page 11 of the 2001 CRREL test http://www.crrel.usace.army.mil/library/technicalreports/TR00-4.pdf. A major advantage of the sunpreme technology is that it does not have a frame and thus less of a surface for snow to accumulate. It would be interesting to investigate some nano-tech super hydrophobic coatings from companies such as lotus leaf, acculon, nanosonic to see if coatings would further improve the properties of the sunpreme panel.

After testing the sunpreme panels to -60C in the freezer here in Madison WI it is believed that they are rugged enough to justify shipping to Antarctica for further testing. While we have tested them to extreme temperatures, we cannot exactly replicate the conditions to which they would be exposed in the Antarctic (40 knot winds, -80C ambient temperatures, UV radiation with the ozone hole). It is proposed that they be shipped to Antarctica and setup for one year to test. The goals for this experiment would be to test survivability, maximum measured open circuit voltage, and generate data to improve the power output model (and thus have a better idea of a ROI for the funding agency).