SOLAR POWERING OF HIGH EFFICIENCY ABSORPTION CHILLER

Final Report

Randy C. Gee

SOLAR COOLING, LLC
1378 Charleston Drive
P.O. Drawer 10
Sanford, NC 27331-0010

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ABSTRACT

This is the Final Report for two solar cooling projects under this Cooperative Agreement. The first solar cooling project is a roof-integrated solar cooling and heating system, called the Power Roof^{TM}, which began operation in Raleigh, North Carolina in late July 2002. This system provides 176 kW (50 ton) of solar-driven space cooling using a unique nonimaging concentrating solar collector. The measured performance of the system during its first months of operation is reported here, along with a description of the design and operation of this system. The second solar cooling system, with a 20-ton capacity, is being retrofit to a commercial office building in Charleston, South Carolina but has not yet been completed.

PROJECT #1

The Power Roof^{TM} system is a new building-integrated solar energy system. The Power Roof^{TM} uses solar energy concentrators to provide space cooling, heating, and domestic hot water - plus it also serves as an insulated roof, a radiant barrier and a daylighting system. The operating Power Roof^{TM} is shown in Figure 1.

Fig 1: Power Roof^{TM} Installed in Raleigh, NC

The Power Roof^{TM} reflectors are simple curved sections (not parabolic) and are stationary. The fixed reflectors concentrate sunlight onto a linear thermal receiver, incorporating a secondary reflector, which moves during the day as the sun's position changes. As illustrated in Figure 2, the use of a cylindrical concentrator results in large optical aberrations, creating a caustic, or envelope, pattern to which the reflected rays are tangent. The nonimaging secondary is designed to restore some of the concentration lost to aberrations of the circular primary.

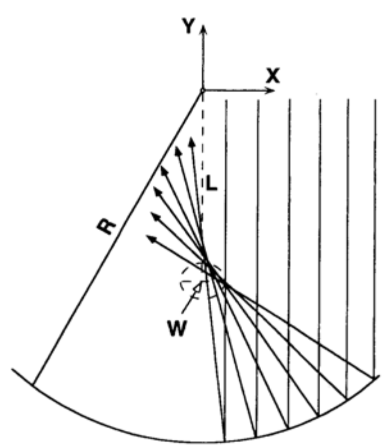

Fig 2: Rays Reflected Off a Circular Arc

The receiver, shown in Figure 3, has an evacuated annulus between the 42 mm stainless steel absorber tube and the surrounding 150 mm diameter glass cylinder. The evacuated space also contains the silver-coated secondary reflector. The derivation of the shape of the secondary reflector is described in Jenkins and Winston (1). The evacuated glass cylinder has an anti-reflection coating on its surfaces to improve light transmission. The absorber tube has a Cermet selective coating that provides high solar absorptance (>0.96) and very low emittance (<0.10). This is the same advanced technology that is used on the UVAC receivers (2) developed by Solel for parabolic trough collectors.

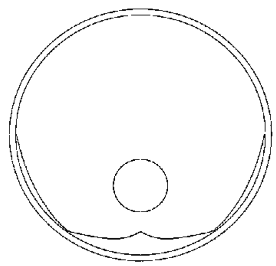

Fig. 3: Power Roof^{TM} Receiver with Secondary

The basic design of the Power Roof^{TM} is illustrated in Figure 4. Not all of the reflected light is intercepted by the receiver; a portion passes through translucent vertical glazings (not yet installed in Fig.1) onto the backside of the curved concentrator panel just to its south, which boosts the daylighting level in the building space below. The secondary reflector has an acceptance angle of 55 degrees, which limits the reflector area viewed by the secondary to less than its full width. The full aperture width of the primary reflector is 4.0 m (13.1 ft), but the maximum aperture width that can be viewed by the secondary reflector is 3.6 m (11.8 ft). The concentration ratio is therefore 86:1 (3.6 meter/0. 042 meter).

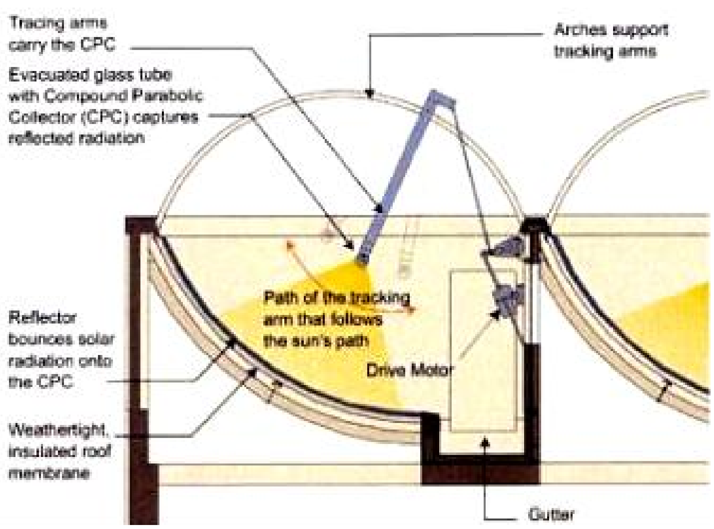

Fig 4: Illustration of Power Roof^{TM}

A primary function of the Power Roof^{TM} is to provide space cooling and heating for the building. Space cooling is provided using a solar-driven absorption chiller as shown in Figure 5. The Power Roof provides thermal energy at temperatures high enough to efficiently operate double-effect (two-stage) absorption chillers. Since double-effect chillers operate with COPs (Coefficient of Performance) almost twice as high as single-effect chillers, the solar energy that is collected can be used much more effectively. Although higher temperatures (about 330^{o}F or 166^{o}C) are required to operate double-effect chillers, the Power Roof^{TM} achieves these temperatures with minimal loss in efficiency.

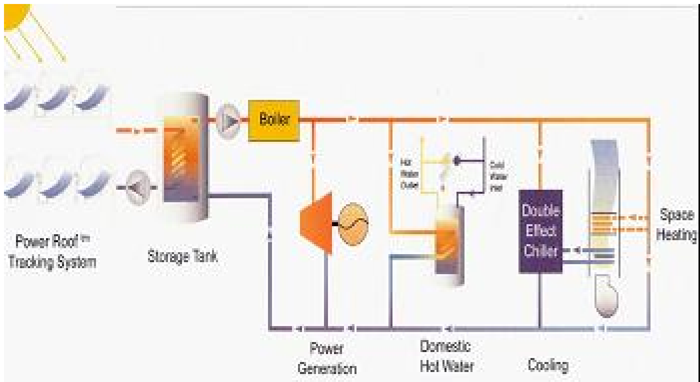

Fig. 5: Power Roof^{TM} System Schematic

Since the Power Roof^{TM} uses an evacuated receiver and has a high concentration ratio, the collector system has the capability to operate at high temperatures (up to 350^{o}C), and can be used to generate electric power as indicated in Figure 5. However, power production is not part of the first system installed in Raleigh, reported on here. Rather, this system provides space cooling in the summer and space heating in the winter.

This first commercial-scale Power Roof^{TM} system is installed in Raleigh, NC adjacent to a large commercial office building called the Parker-Lincoln building. For this first installation, the major objectives were to demonstrate the Power Roof^{TM} concept in full scale, and verify that the collection system could produce the design point energy collection rate of 176 kW (600,000 Btu/hr). The expected peak collection rate was established at 176 kW based on small-scale prototype tests (3) and efficiency measurements at Sandia National Laboratories (4). Demonstrating and measuring the daylighting features of the Power Roof^{TM} was not an objective of this first full-scale system, so the Power Roof^{TM} collection system was built by itself, not as an integral part of the roof of a building as would normally be done. Figure 6 shows the installed solar energy collection system constructed adjacent to the Parker-Lincoln building. The axis of the Power Roof^{TM} concentrators is 32 degrees east of south because this orientation allowed the structure to line up with the existing building, but this off-axis orientation does reduce overall energy collection.

Fig 6: Power Roof^{TM} Energy Collection System

The system is designed to provide 176 kW (50 tons) of cooling in the summer, using a double-effect absorption chiller. The chiller has a COP of 1.23 at the design point conditions, requiring 142 kW (484,000 Btu/hr) of thermal input to produce 176 kW of cooling. The installed chiller is shown in Figure 7.

Fig 7: 50-ton Double-Effect Absorption Chiller

Two high-temperature circulation pumps are used in the system. One pump is used to circulate water to/from the solar collector field, and the other is used to deliver the high temperature water to the absorption chiller. These pumps have a design that requires no seal cooling, which improves overall system performance and simplifies operation. The photo below (Figure 8) shows the two pumps, and the insulated 7,500-liter (2,000-gallon) storage tank can be seen in the background. The storage tank was sized to act as a thermal buffer between the solar field and the absorption chiller, and provides less than an hour of storage at the design point thermal requirement of the chiller.

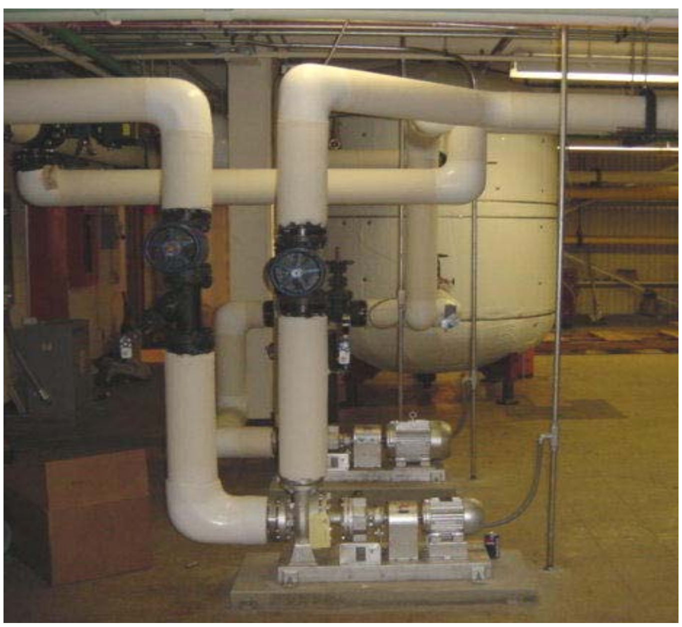

Fig 8: Circulation Pumps and Storage Tank

Figure 9 is a photo of one of the three Power Roof™ rows. Each row of collectors is 50 m (144 ft) long, comprised of twelve 3.66 m (12 ft) long receivers. The reflectors extend about 1.2 m (4 ft) beyond the receivers on each end and total 46 m (152 ft) in length. The reflectors are aluminum-based (a PVD-applied oxide layer on aluminum) and are installed as sheets that are 4.27 m x 1.20 m (14 ft x 4 ft) in size. A manufacturing problem with the custom-ordered sheet thickness (0.032 inch or 1.26 mm) reduced the specular solar-weighted reflectance of these sheets to less than 85%. Although this lower reflectance reduced the performance of this first commercial-scale Power Roof™ system, future systems will have higher operating efficiencies when deployed with improved reflectors.

Fig 9: Power Roof™ with Tracking Receivers

Figure 9 also shows the receivers that track the sun during the day, and the pivoting receiver arms that position the receivers in the proper location. The receiver arms are attached to the curved arches shown in the photo and pivot from these points. All the receiver arms are linked together to a rotating torque tube that ensures that all the receiver arms move in unison. The torque tube rotates in response to a motorized linear actuator that positions the receiver arms to the proper pre-calculated tracking angle. The torque tube and linear actuator are more easily seen in the Figure 10 photo.

Fig 10: Power Roof™ Receiver Positioning System

The performance and efficiency of the Power Roof™ solar collection system is calculated through measurements of temperature, flow rate, and beam irradiance instrumentation. The system has three rows, as shown in Figure 11. Only the solar cooling system is shown in this figure.

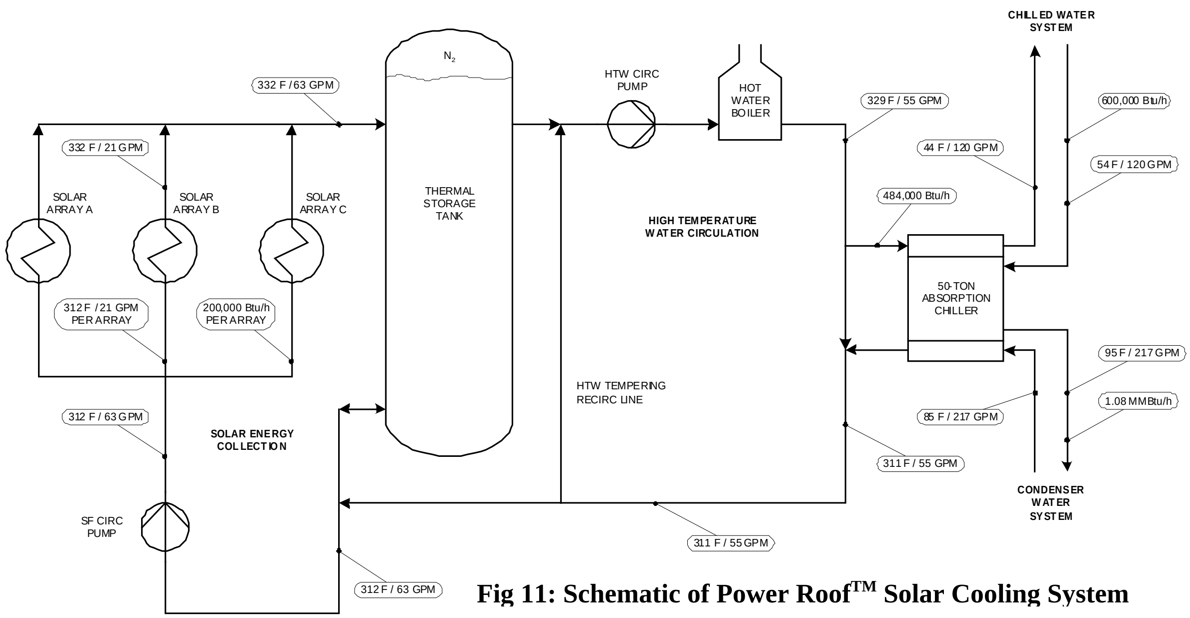

Fig 11: Schematic of Power Roof™ Solar Cooling System

Each of the three rows is separately instrumented. Inlet and outlet temperatures are measured using thermistors, and flow rates are measured using turbine meters. Direct normal irradiance is measured using a Rotating Shadow Band. The Power Roof™ energy collection rate is calculated by multiplying the temperature rise across the solar field by the mass flow rate and the specific heat of the heated fluid (water in this case). All data are recorded every 60 seconds.

The flow rate through each of the three Power Roof™ rows is nominally 80 liters/min (21 gpm), and the design point temperature rise is 11°C (20°F).

The measured energy collection of the Power Roof™ system is shown in Figure 12 for a clear sunny day in August. All data shown in this figure is based on 10-minute averages. Direct normal irradiance is shown to peak at just over 930 W/m^2. Available Beam Irradiance is beam insolation in the plane of the collector and corrects for the cosine loss of the incoming solar radiation.

Peak energy collection on this day was 790,000 Btu/hr, and occurred around 11:10 am. Peak energy collection occurs before noon for this system because the collector aperture faces the morning sun (the collector faces 31 degrees east of south). Note that this off-south orientation results in a shortened length of operation in the afternoon; the system shut down about 3 pm in the afternoon.

Note also the fluctuations in energy collection prior to 10 am. These fluctuations occurred because of the startup of the chiller, which introduced a volume of cold water into the storage tank. This volume of cold water temporarily influenced the collector field inlet (and then outlet)

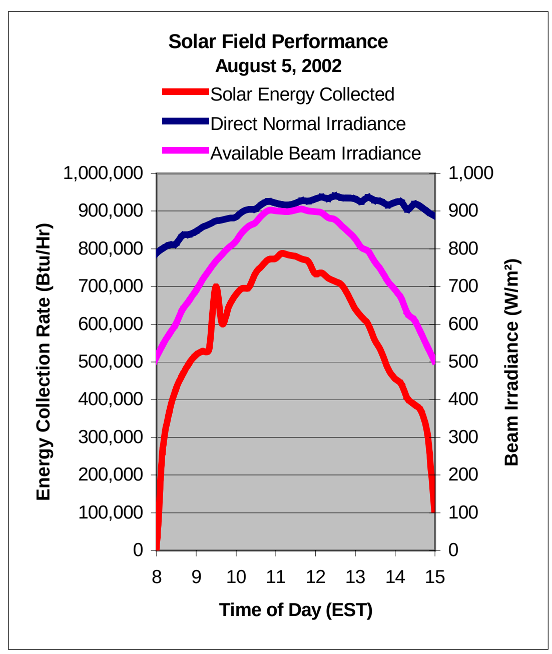

Fig 12: Clear Day Performance of Power Roof

temperatures and caused the observed energy collection fluctuations.

Finally, we note that the energy collection rate exceeded the 176 kW (600,000 Btu/hr) design point for almost four hours. The peak solar field outlet temperature on this day was 162°C (324°F) and the temperature rise across the field was 14°C (25°F) at a solar field flow rate of 253 liters/min (66 gpm).

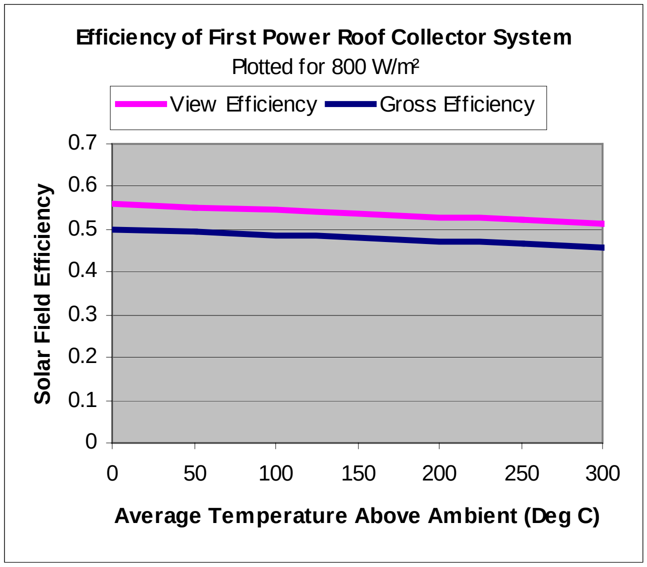

Fig 13: Measured Efficiency of Power Roof

The solar field thermal efficiency is plotted in Figure 13 for August 5th. Efficiency is calculated as the fraction of available beam insolation (insolation in the aperture plane) that is collected by the solar field. Two different measures of efficiency are plotted: Gross Efficiency and View Efficiency. "Gross Efficiency" is based on the gross aperture area of the solar collectors, which is 176 m^2 (1894 ft^2) per row. The "View Efficiency" is based on the maximum aperture area of the reflectors that can be viewed by the receiver. As described earlier, the receiver has an acceptance angle of 55 degrees, so a portion of primary reflectors cannot be utilized. The maximum viewed reflective area is limited to 157 m^2 (1692 ft^2) per row, so the efficiency based on viewed area is therefore higher, reaching a maximum of 54%.

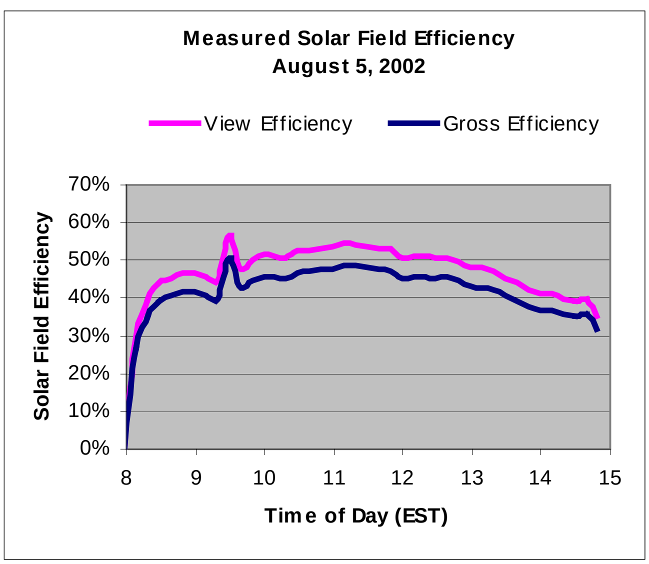

Fig 14: Power Roof Efficiency at Normal Incidence

Solar collector efficiencies are generally expressed in terms of an optical efficiency and a heat loss coefficient multiplied by the term $\Delta T/I$, where ΔT is the collector temperature above ambient, and I is solar irradiance. Based on the measured performance presented above, and using the measured heat loss coefficient determined at Sandia National Laboratories for the Power Roof™ (4), the normal incidence Power Roof™ efficiency equations are:

$$\eta_{gross} = .501 - 0.116\ \Delta T/I$$
$$\eta_{view} = .561 - 0.130\ \Delta T/I$$

where ΔT is in degrees Celsius, and
I is irradiance in the aperture plane in W/m^2

Based on these measured efficiencies, we have projected normal incidence collector efficiencies for the next installed Power Roof™, assuming that the specular reflectance of the primary circular reflectors can be increased to 93%. These projections are shown in Figure 15.

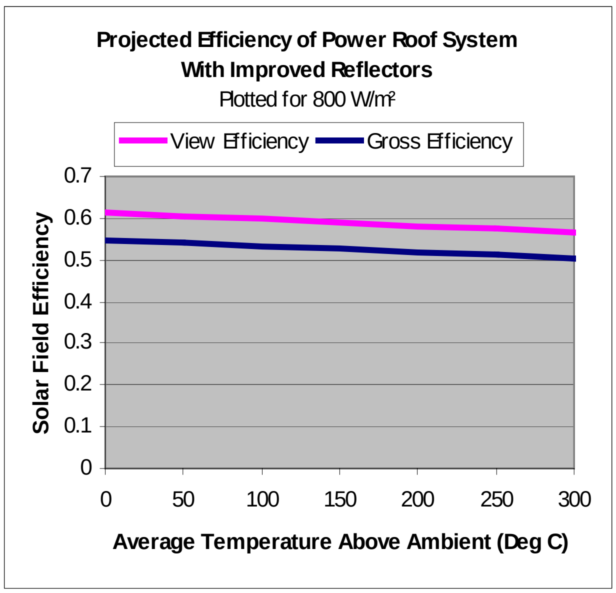

Fig 15: Projected Power Roof™ Efficiencies

Note that neither Figures 14 and 15 include incidence angle modifiers, that is, the efficiency data is given for normal incidence. Once additional operational data has been gathered, further analysis will be carried out to evaluate performance-related factors such as incidence angle modifiers and shading losses. Future work will also include the development of a system performance model that includes these performance factors, allowing accurate Power Roof™ performance estimation for other sites, system sizes, and roof orientations.

PROJECT #2

The second solar cooling system is being installed on the Cambar Software Inc. building in Charleston, South Carolina. This building is already constructed, as shown in the photos below. The single-story building is 34,000 square feet in size, incorporates daylighting features to reduce lighting loads. This project will provide for an advanced solar cooling system for space conditioning.

Figure 16: Cambar Software Building, Site of Project #2

The daylighting system is installed as a series of north-facing glazings that also provide an ideal mounting location for the solar energy collectors that will be used to operate the solar cooling system.

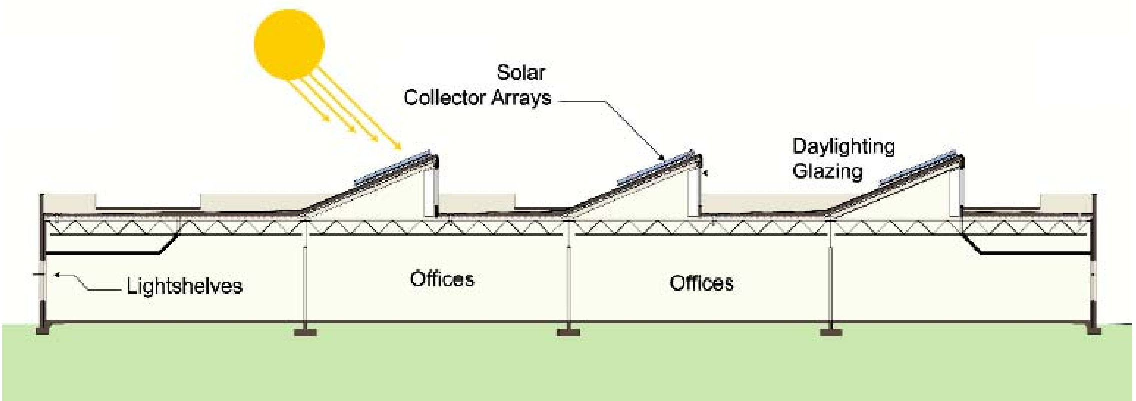

Figure 17: Cross Section of Rooftop Solar

A total of 132 solar collectors are being installed onto the rooftop area of the Cambar Software building, using an advanced linear concentrating CPC collector. A cross section of the CPC collector is shown in Figure 18. This collector uses nonimaging optics to concentrate sunlight onto the absorber tubes.

Figure 18: Cross Section of CPC Collector

Figure 19: CPC Collectors on Rooftop

These collectors will power a 20-ton chiller, shown in the Figure 20 below, being provided by AIL Research Labs of Princeton Junction, NJ. We refer to this unit as the LDAC (liquid desiccant air conditioner). This unit is being custom built and is presently being leak tested.

Figure 20: Liquid Desiccant Air Conditioner

The LDC unit is being mounted on the roof right over the mechanical equipment room, and will integrate with the two heat pumps that satisfy the large core center of the building, as outside air comes in a single duct that branch between the heat pumps air handlers. All of the outside air will go through the LDAC and then to the branch point. The LDAC has a gas-fired hot water heater on the skid for backup, and we will be able to use it as backup for winter heating. The CPC collectors will charge a 5,600 gallon storage tank, which will extend operating hours of the solar cooling system as well as provide for operating stability.

ACKNOWLEDGMENTS

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