Building Integrated Photovoltaic Test Facility

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The widespread use of building integrated photovoltaics appears likely as a result of the continuing decline in photovoltaic manufacturing costs, the relative ease in which photovoltaics can be incorporated within the building envelope, and the fact that buildings account for over 40% of the U.S. energy consumption. However, designers, architects, installers, and consumers need more information and analysis tools in order to judge the merits of building-integrated solar photovoltaic products. In an effort to add to the knowledge base, the National Institute of Standards and Technology (NIST) has undertaken a multiple-year project to collect high quality experimental performance data. The data will be used to validate computer models for building integrated photovoltaics and, where necessary, to develop algorithms that may be incorporated within these models. This paper describes the facilities that have been constructed to assist in this effort. The facilities include a mobile tracking photovoltaic test facility, a building integrated photovoltaic test bed, an outdoor aging rack, and a meteorological station.
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Introduction

The photovoltaic (PV) power generation market is currently experiencing rapid growth. Worldwide PV module shipments increased 38% in 1997 and 29% in 1998, as shown in Fig. 1. This rapid growth is expected to continue. The international photovoltaic industry is projected to grow at a rate of around 20 to 25% per year over the next 15 years. It is anticipated that by the year 2010 annual PV shipments could reach 1,600 MW [1].

Industry analysts estimate that solar power is a $1.5 billion business today. The vast majority of present photovoltaic sales are for applications such as navigational signals, call boxes, telecommunication centers, consumer products, and off-grid electrification projects. More recently, small grid-interactive rooftop installations have started contributing to the demand for PV products. Building-integrated photovoltaic installations will be aided if more information and better design and analysis tools are made available to the building industry and the buying public.

Several factors support the growing interest in building integrated photovoltaic systems. Increased concerns over global warming, President Clinton's *Million Solar Roofs* program, legislation that requires utilities to buy excess energy generated by on-site, distributed power sources, and the fact that 40% of U.S. energy consumption is attributed to buildings are all providing incentives to incorporate photovoltaics into buildings.

Figure 2 [2] provides two examples of building integrated photovoltaic products. Residential roofing products are commercially available that incorporate amorphous and crystalline cell technologies. Crystalline cells can be incorporated into fenestration elements, and photovoltaic spandrel panels are available for use in curtain wall applications.

A survey of 900 building professionals in the United Kingdom found that 88% would consider the use of integrated photovoltaic building products if there was greater evidence of the performance and reliability of these products [3]. Forty-nine percent of the survey respondents noted that they would only consider building integrated products after they had seen them utilized in demonstration sites. Although a similar survey has not been conducted within the U.S., it is anticipated that the results would be comparable.

The Building and Fire Research Laboratory at NIST hopes to accelerate the deployment of building photovoltaics by providing high quality experimental data for the development, validation, and improvement of computer simulation tools. These computer simulation tools will be used to predict the electrical and, in some cases, thermal performance of building integrated photovoltaics. The combination of experimental data and validated computer simulation tools will play a crucial role in economic decisions concerning the future use of photovoltaics in buildings.

Approach

Although there are several computer tools for predicting the electrical performance of photovoltaic products, there is a lack of experimental data that can be used to determine how close the predicted results agree with measured performance. Data, if available, are generally limited to a measurement of the total energy delivered by the photovoltaic system. The lack of measured meteorological data and electrical performance data during various meteorological conditions, incident angles, and panel temperatures limits the ability to compare predicted to measured results. As a result of conversations with researchers at Sandia National Laboratory, the National Renewable Energy Laboratory, the Florida Solar Energy Center, and the University of Wisconsin, it became apparent that providing performance data would fill a void without replicating any current or planned activities. NIST confirmed the need for building integrated photovoltaic performance data by subsequent conversations with manufacturers of photovoltaic cells and of building integrated photovoltaic panels. In addition to supplying the needed data, NIST's building integrated *test bed* will provide the first opportunity to compare the performance of building integrated photovoltaic panels using various cell technologies under identical operating conditions.

One of the existing computer simulation tools used to predict the performance of photovoltaic modules and/or building integrated photovoltaics is PVSIM, an electrical simulation model for photovoltaic cells, modules, and arrays, developed by King et al. [4] at Sandia National Laboratory. The University of Wisconsin Solar Energy Laboratory has developed PHANTASM (PHotovoltaic ANalysis and TrAnsient Simulation Method) [5] to study the potential benefits of building integrated photovoltaics. The model uses photovoltaic performance data typically supplied by the

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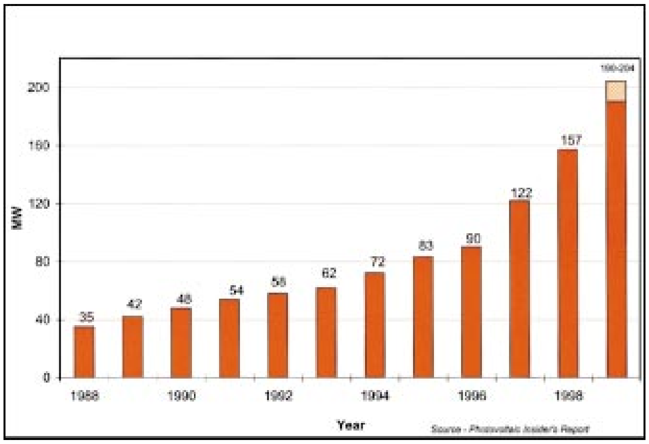

Fig. 1 Annual worldwide PV module shipments

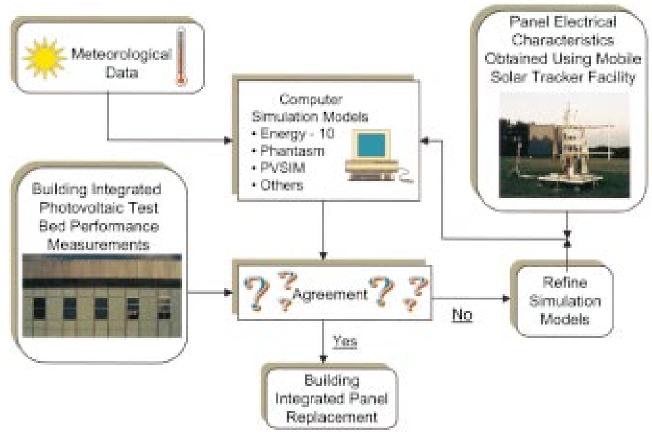

Fig. 3 NIST's Building Integrated Photovoltaic Program

manufacturer. ENERGY-10 [6] computes the annual energy consumption of a user defined building based on hour-by-hour calculations. The program is especially helpful in comparing various design options such as additional insulation, energy efficient lights, daylighting, and passive solar energy. Future versions of ENERGY-10 will include building integrated photovoltaics as a design option. Ultimately these and other models will be used to predict the annual performance and economics of building integrated photovoltaics.

The overall approach being taken at NIST to validate and refine these models is shown in Fig. 3. The approach includes short-term characterization of building integrated photovoltaic panels, long-term performance measurements, validation and refinement of the computer simulation models, and studies to document the performance changes that amorphous silicon exhibits as a result of exposure.

In order to accurately predict the electrical output of building integrated photovoltaic products, computer simulation models require a number of input parameters. These parameters will be obtained from short-term tests using a mobile solar tracking facility. For example, the model advocated by King [7] requires the following parameters:

- Influence of solar angle-of-incidence
- Influence of solar spectrum
- Temperature coefficients for the open circuit voltage and maximum power voltage
- Temperature coefficients for the short circuit current and the maximum power current
- Module operating temperature as a function of ambient temperature, wind velocity, and solar radiation

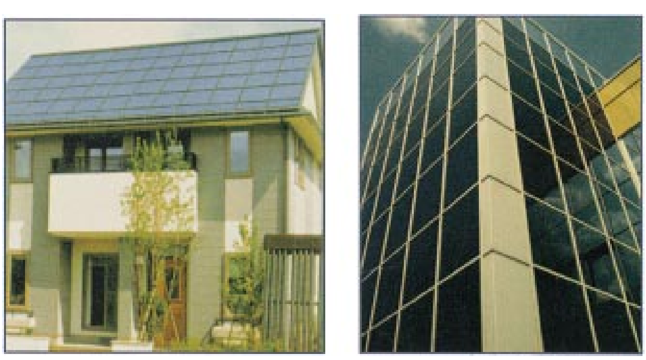

Fig. 2 Building integrated photovoltaic examples (Source, Paul Maycock)

The long-term performance of building integrated photovoltaic panels will be measured *in-situ* using a *test bed* that is located within the south wall of a building located on the NIST campus in Gaithersburg, MD. The facility will provide comparisons between different building integrated photovoltaic panels when exposed to identical meteorological conditions. Comparisons based on energy production, operating temperature, heat flux, and characteristic current versus voltage (IV) curve traces will be available. This *test bed* initially consists of crystalline, polycrystalline, amorphous, and silicon film building integrated photovoltaic products. Two identical panels of each photovoltaic cell technology, one insulated and one un-insulated, are installed.

Using the short-term characterization results, obtained from the solar tracker facility, and the measured long-term performance of the *in-situ* building integrated photovoltaic products, NIST researchers will exercise the currently available simulation models and compare predicted to measured results. The meteorological data will be provided by the combination of a rooftop meteorological station and a south wall meteorological station. NIST researchers will work closely with the models' authors to improve and refine them in order to obtain acceptable agreement with measured results.

An additional challenge in the validation of predictive models for amorphous silicon building integrated photovoltaic products are changes in electrical performances attributed to outdoor exposure. In order to explore the magnitude of the performance change over time, an aging facility has been constructed. The amorphous panels installed at this facility will be initially characterized using the mobile solar tracking facility prior to exposure on the aging facility. The panels will be installed on the aging facility and removed on a periodic basis for additional testing on the mobile tracking facility. The resulting information will be used to determine the radiation and/or temperature exposure required before steady-state performance is achieved.

Experimental Facilities

Mobile Solar Tracking Facility. The mobile solar tracking facility is used to characterize the electrical performance of building integrated photovoltaic panels (Fig. 4). Software has been developed for the mobile solar tracker that allows the user to select from the following tracking modes:

- Azimuth and Elevation Tracking
- Azimuth Tracking
- Elevation Tracking
- Azimuth Tracking with User Selected Offset
- Elevation Tracking with User Selected Offset
- User Selected Incident Angle Tracking

Table 1 NIST mobile solar tracker facility specifications

Azimuth range	+/-135° from center
Elevation range	90° from horizontal
Pointing accuracy	+/-0.1° in wind up to 11 m/s
Maximum backlash	0.05°
Slew rate	2° to 10° per second, user defined
Survival wind speed	18 m/s
Maximum collector weight	140 kg
Platform tilt adjustment	Leveling jacks, 0.1° resolution
Weight (unloaded)	900 kg
Tracking communications	RS-232 interface

In addition to the various tracking modes, the software is used to move the tracker to a fixed position, facilitate aligning the tracker with regard to true south, and setting limits on the tracker movement to preclude damage to the tracker and/or building integrated photovoltaic panels. Stepping motors in combination with spool drive systems permit movements as small as 0.1° and 0.2° in azimuth and elevation, respectively. A servo-controller interfaces the stepping motors to a personal computer.

Deployment begins by positioning the tracker in the direction of true south and then manually leveling it. The tracker is then aligned to magnetic south using a digital magnetic compass. Once magnetic south is established true south is established using the magnetic declination. Experience has shown that this technique results in misalignments of 1° or less. Final alignment is achieved by using the diopter incorporated within a pyrheliometer. The azimuth and elevation angles of the sun are computed on a real time basis using equations set forth by Duffie and Beckman [8]. Design specifications for the tracking facility are given in Table 1.

The mobile solar tracking facility incorporates meteorological instruments, a solar spectroradiometer, a data acquisition system, and a single-channel photovoltaic curve tracer. Precision spectral pyranometers are used to measure total (beam plus diffuse) solar radiation. The pyranometer's detectors, optically black thermopile sensors, are independent of radiation wavelength over the solar energy spectrum. Two instruments are used to provide redundant measurements. A pyrheliometer is used to measure the beam component of solar radiation. The detector, a multi-junction thermopile, coated optically black, is positioned at the end of a collimating tube. The aperture angle of the instrument, 5.7°, receives radiation from the sun and an area of the circumsolar sky two orders of magnitude larger than that of the sun. Long-wave radiation greater than 3 μm is measured using a precision infrared radiometer.

A three-cup anemometer assembly is used to measure wind speed. The wind sensor has a speed threshold of 0.2 m/s and has a maximum speed of 55 m/s. The wind direction sensor consists of a counter-balanced, lightweight vane and a precision, low torque, potentiometer yielding a voltage output proportional to wind direction. The ambient temperature is measured using a perforated tip, type-T thermocouple sensor enclosed in a naturally ventilated multi-plate radiation shield.

The output signals of the meteorological instruments and thermocouples attached to the building integrated photovoltaic panels are measured using a data acquisition system. The data acquisition system incorporates a 6 $\frac{1}{2}$-digit multi-meter, IEEE 488 and RS 232 interfaces, and multiplexing relay cards that can accommodate up to 60 transducers. It can be used to measure voltage, resistance, current, and frequency. Although the multiplexer cards have built-in thermocouple reference junctions, improved accuracy is obtained through the use of an electronic ice point reference. The reference temperature is established by the physical equilibrium of ice and water within a sealed vessel.

Spectral radiation data from 300 nm to 1100 nm is obtained using a spectroradiometer with selectable scan intervals of 1 nm, 2 nm, 5 nm, or 10 nm. The optical receptor has a 180° field of view. A filter wheel is used to filter out light that is not in the same region of the spectrum as that being measured. Operation of the filter wheel is controlled by an internal microprocessor. The polychromatic radiation transmitted through the filter wheel is dispersed into narrow wavebands by a monochromator. After emerging from the monochromator, the radiant power is received by a silicon photodiode detector that produces a current proportional to the amount of radiation. The current signal is amplified, converted to a voltage, and passed through an analog-to-digital converter.

The solar tracker's photovoltaic array tester measures and records the current versus voltage (IV) characteristics of photovoltaic panels. The tester is capable of measuring panels or groups of panels with power outputs ranging from 10 W to 36 kW. Irradiance from a reference cell and a thermocouple attached to the panel are recorded and used to normalize the data to a user-selected irradiance and temperature. In addition to sweeping the panel IV curve and storing the measured values, the curve tracer calculates the values of maximum output power, open circuit voltage, short circuit current, and fill factor.

Building Integrated Photovoltaic Test Bed. The building integrated photovoltaic test bed was created by removing five adjacent windows from the south wall of a building located on NIST's Gaithersburg, MD campus. All five windows are part of a high-bay laboratory and exposed to identical indoor environmental conditions. The original window framing system was modified to facilitate the installation and removal of building integrated photovoltaic test specimens. The front of each panel is recessed 8 mm from the frame's outer surface. An exterior view of the *test bed* and the eight building integrated photovoltaic panels chosen for the initial evaluation are shown in Fig. 5. A horizontal aluminum shelf was added to partition each window into two test cells. One lower test cell was further divided by adding a vertical aluminum partition. The end product is a south wall test bed composed of 11 test cells.

Building integrated photovoltaic panels selected for the *test bed* include custom-made panels using crystalline, polycrystalline, and silicon film cells as well as commercially available amorphous silicon modules. Specifications for the building integrated photovoltaic panels are given in Table 2. Three of the five window openings have the horizontal shelf positioned at the vertical midpoint of the opening. Two identical panels, utilizing crystalline, polycrystalline, or silicon film cells, are installed, one above the other, in the resulting six openings. The upper panels are not insulated. The lower panels are insulated with 10.2 cm of extruded polystyrene. Each of these six panels are 1.38 m by 1.18 m. For the remaining two windows, the horizontal shelf is positioned below the vertical midpoint. Tandem, commercially available, amorphous silicon PV modules, having overall measurements of 1.37 m by 1.48 m, are installed in the upper test cells of both windows. The east amorphous silicon panel is insulated with 10.2 cm of extruded polystyrene insulation. The west amorphous silicon panel is un-insulated.

Two of the three remaining test cells are allocated to instrumentation. A black, 1.38 m$\times$0.87 m plexiglass panel accommodates up to three precision spectral pyranometers, one precision infrared radiometer, and two radiatively shielded type-T thermocouples. An ultrasonic wind sensor, used to measure the magnitude and direction of air movement in a vertical plane is mounted in the second test cell.

The final test cell contains a scaled-down version of the single crystalline building integrated photovoltaic panel specified in Table 2. The backside of this panel is not insulated.

In an effort to investigate the thermal performance of building integrated PV panels, heat flux transducers were attached to the four panels having backside insulation and to the scaled-down, un-insulated PV panel. Heat flux transducers were not added to the un-insulated, paired panels because of concerns that the transducer may alter each panel's electrical performance due to changes induced in the panel's temperature profile. Finite element calculations revealed that the addition of the heat flux transducer to the un-insulated panels would alter the temperature of adjacent

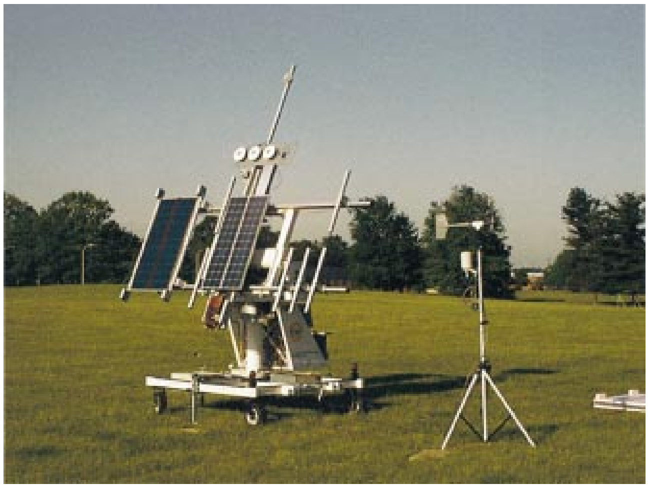

Fig. 4 NIST's mobile solar tracking facility

Fig. 5 Building Integrated Photovoltaic *Test Bed*

cells by as much as 1°C. Similar analysis for the insulated panels showed virtually no impact on cell-to-cell temperature variation. As a hedge, the scaled-down PV panel was added and instrumented with a heat flux transducer to provide some data on the thermal performance of un-insulated PV panels.

Heat flux transducers having active areas of 250 mm ×250 mm and 305 mm×305 mm are being used. These transducers, which have total areas twice their active areas, were selected because they completely cover an integer number of photovoltaic cells. In addition to the noted installations on PV panels, a heat flux transducer was also mounted on the curtain wall that separates each of the test cells. The heat flux transducers were calibrated using the NIST 1-meter guarded hot plate prior to installation [9].

As summarized in Table 3, multiple temperature sensors are installed on each PV panel. Sensor locations include the rear of each panel and, where applicable, the rear face of the heat flux transducer and the rear face of the attached insulation. Figure 6 depicts the setup used on the insulated panels. The panels utilizing crystalline, polycrystalline, and silicon film cells, in addition, were fabricated with two sensors embedded within each panel to measure actual cell temperature. All of the noted temperature sensors are foil-type, type-T thermocouples. Each temperature sensor was individually calibrated prior to installation.

Two instrumentation systems are used to monitor the building integrated photovoltaic *test bed*. The test bed data acquisition system, identical to one used on the mobile solar tracking facility, is used to measure the output signals of the outdoor meteorological instruments (with the exception of one precision spectral pyranometer and an outdoor ambient temperature sensor), the heat flux transducers, the panel temperature sensors (Table 3), and two radiatively shielded indoor ambient temperature sensors. This data acquisition system scans the sensors and records the data every five minutes. The second data acquisition system is a custom built photovoltaic measurement system and is referred to as a multi-tracer.

The multi-tracer simultaneously loads and collects electrical performance data on multiple PV panels. The multi-tracer can operate with a maximum of 14 panels connected while dissipating up to 2400 W. User selectable load options include: (1) peak power tracking, (2) fixed voltage operation, (3) user specified voltage profile, and (4) unloaded or open circuited. For NIST's initial long-term studies, peak power tracking is being used. When operated in this mode, the multi-tracer maintains the power output of each PV panel within 0.2% of the maximum power output by making continuous load setting adjustments [10].

The multi-tracer samples panel temperature, current, and voltage every 15 seconds and then integrates the readings, along with

Table 2 Building integrated photovoltaic panel specifications

Cell efficiency (%)	13	8.7	12	6.9
Cell technology	Single crystalline	Silcon film	Polycrystalline	Tri junction amorphous
Cell dimensions (mm)	125×125	150×150	125×125	120×350
Number of cells	72	56	72	44
Total cost	$1324	$995	$1123	$578
Price per watt	$8.71	$10.70	$8.44	$4.52
Rated power output (W)	152	93	133	128
Glazing covered by PV cells (%)	72	82	72	92

Table 3 Location of panel temperature sensor

Temperature sensor location	Custom-built PV panel	Commercial PV panel
Embedded behind PV cell: connected	X	
Embedded behind PV cell: disconnected (spare)	X	
Indoor-side of test panel: connected to test bed DAS	X	X
Indoor-side of test panel: connected to multi-tracer	X	X
Rear face of heat flux transducer	X[1]	X[1]
Rear face of backside insulation	X[2]	X[2]

[1]For PV panels where a heat flux transducer is installed.
[2]For PV panels installed with backside insulation

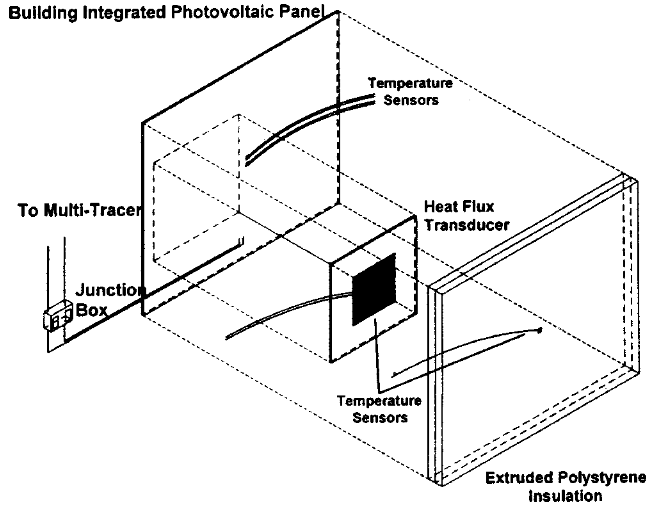

Fig. 6 Instrumentation schematic

instantaneous power, over time before recording mean values of each parameter to disk. A user-specified averaging interval of 5 minutes is used for the eight paired *test bed* PV panels. In a follow-up data reduction step, the mean power quantities are used to determine daily energy production. A digital power analyzer, connected between the multi-tracer and a PV panel, provides a redundant measurement for the 5-minute-interval and daily energy produced by one test panel.

The multi-tracer also collects current versus voltage (IV) traces. Presently, the multi-tracer is configured to record an IV trace for each PV panel every five minutes if the measured irradiance exceeds a threshold value of 5 W/m^2. The multi-tracer typically requires less than 45 s to complete the eight IV traces of the paired panels. The IV data associated with each panel is saved to a unique data file. The file contains up to 257 IV data pairs along with irradiance, panel temperature, and outdoor ambient temperature measurements recorded before and after collecting the IV data. Also included in each file is the short circuit current, open circuit voltage, peak power, current at peak power, voltage at peak power, fill factor, system efficiency, aperture efficiency, a time stamp, and several other parameters that contribute to providing a stand-alone summary of the panels instantaneous electrical performance. Overall, the test bed provides extensive electrical and thermal data for characterizing the performance of building integrated photovoltaic panels.

Meteorological Station. The computer simulation tools require meteorological data in order to predict the electrical performance of building integrated photovoltaic panels. This data is being provided by two meteorological stations, a complete rooftop station and the *test bed* meteorological station previously described.

The roof top meteorological station, Fig. 7, incorporates an automated solar tracker and instruments to measure solar radiation, ambient temperature, and wind conditions. Two pyrheliometers are mounted on an automated solar tracker and are used to measure the solar radiation's beam component. The automated solar tracker is a two-axis azimuth/elevation device programmed to align the solar radiation instruments with the normal incidence of the sun. The tracking is achieved using a computer program that calculates the solar position for the time and location and subsequently transmits pulses to electronic drives, which operate two stepping motors. In addition to the pyrheliometers, a precision spectral pyranometer and shading disk are also mounted on the automated solar tracker. The shading disk is positioned such that the precision spectral pyranometer on the tracker is continuously shaded, providing a measurement of the of solar radiation's diffuse component.

A pair of redundant precision spectral pyranometers, mounted on a horizontal surface near the automated solar tracker, is used to measure global solar radiation. Long-wave radiation, beyond 3 μm, is measured using a precision infrared radiometer. Wind speed and direction are measured using a three-cup anemometer and wind direction sensor. A sheathed type-T thermocouple sensor, enclosed in a naturally ventilated multi-plate radiation shield, is used to measure ambient temperature. The output signals from the meteorological station's instruments are measured using a data acquisition system identical to the one used on the solar tracking facility. A personal computer interfaced to the data acquisition system permits viewing of real time and historical weather data by means of a local area network.

Aging Facility. A series of indoor and outdoor stability studies, Hof et al. [11]; Klotz et al. [12]; von Roedern and Kroposki [13]; have shown that the electrical performance of amorphous silicon degrades with solar and/or temperature exposure. This shift in performance presents an additional challenge in attempting to predict the annual energy production of building integrated photovoltaic panels that utilize amorphous silicon. Parameters obtained from the initial short-term tests to characterize the panels may not be appropriate for long-term performance predictions.

In order to assess the magnitude of performance changes as a result of exposure, data are being gathered on three amorphous silicon panels mounted on an outdoor exposure rack, Fig. 8. The exposure rack faces true south and has a tilt angle of 40°, which is the rack's incremental setting that is closest to the site's latitude, 39°. The three amorphous silicon panels exposed on the rack are identical to those being evaluated within the building integrated photovoltaic test bed. Each panel and its associated backside insulation, if used, is supported by a 6.4 mm thick piece of aluminum plate that extends 100 mm beyond the panel's perimeter. In order to subject the panels to three different temperatures during outdoor exposure, one panel is attached directly to the aluminum plate, whereas extruded insulation having nominal thicknesses of 25 mm and 102 mm is placed between the second and third panels, and the aluminum plates, respectively.

A calibrated type-T thermocouple is attached to the center of each panel's rear surface. A precision spectral pyranometer is used to measure the incident radiation on the aging rack. An ultraviolet radiometer is used to measure radiation present between 295 μm and 385 μm. Located in close proximity to the aging rack are a radiation-shielded thermocouple and a wind station to measure ambient temperature and wind conditions. The output signals from the thermocouples and meteorological instruments are measured using a data acquisition system and electronic ice point reference cell identical to those previously described for the mobile solar tracking facility.

The electrical performance of the three panels was initially measured using the mobile solar tracking facility. At periodic intervals, the panels will be removed and re-characterized on the tracking facility to determine the magnitude, if any, of performance changes due to exposure.

The computer used with this facility, as well as the computers used in all of the other building-integrated photovoltaic test facilities are automatically time synchronized with the NIST atomic clock.

Summary

The widespread use of building integrated photovoltaics appears likely as a result of the rapid growth that photovoltaics is experiencing, the relative ease in which photovoltaics can be incorporated within a building, and the fact that buildings account for over 40% of the United States' energy consumption. Obstacles to the proliferation of building integrated photovoltaics include the lack of validated computer simulations to predict the electrical

Fig. 7 Rooftop meteorological station

performance of building integrated photovoltaics and an insufficient database on how well these products perform. Economic decisions regarding the use of building integrated photovoltaics are dependent upon the availability of accurate simulation tools and the availability of product performance data, especially under representative field installation conditions. NIST's Building and Fire Research Laboratory hopes to accelerate the deployment of building integrated photovoltaics by providing high quality experimental data for the development, validation, and improvement of computer simulation tools.

A mobile photovoltaic solar tracking facility, a building integrated photovoltaic *test bed*, an outdoor aging rack, and meteorological stations have been constructed to assist in this effort. The mobile solar tracking test facility is used to capture the effects of specific parameters, such as incident angle, panel temperature, and solar spectrum, on the panel's electrical performance. The building integrated photovoltaic *test bed* is used to conduct side-by-side comparisons of building integrated wall panels. The outdoor aging rack is used, in conjunction with the mobile tracking facility, to investigate the magnitude of electrical performance changes in amorphous silicon panels as a result of exposure to outdoor conditions. The meteorological stations are equipped to measure solar radiation, wind, and temperature conditions during the performance monitoring of the building integrated photovoltaic panels.

Building integrated photovoltaic panel characteristics obtained using the mobile solar tracking facility and the measured meteorological data will be used in conjunction with simulation tools to predict the electrical performance of building photovoltaics installed in the test bed. The predicted performance will be compared to measured data from the building integrated photovoltaic test bed in order to evaluate the prediction capabilities of the simulation tools.

Fig. 8 Aging facility

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