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Bauman, F.

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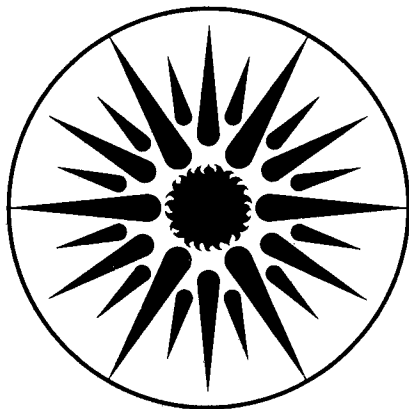
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F. Bauman, W. Place, J. Thornton, and T.C. Howard

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FOR BEAM DAYLIGHTING MEASUREMENTS
IN SCALE-MODEL BUILDINGS

by

Fred Bauman, Wayne Place, John Thornton, and Thomas C. Howard
Building Systems Analysis Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

SOLAR BUILDINGS RESEARCH AND DEVELOPMENT PROGRAM
CONTEXT STATEMENT
November 21, 1985

In keeping with the national energy policy goal of fostering an adequate supply of energy at a reasonable cost, the United States Department of Energy (DOE) supports a variety of programs to promote a balanced and mixed energy resource system. The mission of the DOE Solar Buildings Research and Development Program is to support this goal, by providing for the development of solar technology alternatives for the buildings sector. It is the goal of the program to establish a proven technology base to allow industry to develop solar products and designs for buildings which are economically competitive and can contribute significantly to building energy supplies nationally. Toward this end, the program sponsors research activities related to increasing the efficiency, reducing the cost, and improving the long-term durability of passive and active solar systems for building water and space heating, cooling, and daylighting applications. These activities are conducted in four major areas: Advanced Passive Solar Materials Research, Collector Technology Research, Cooling Systems Research, and Systems Analysis and Applications Research.

Advanced Passive Solar Materials Research. This activity area includes work on new aperture materials for controlling solar heat gains, and for enhancing the use of daylight for building interior lighting purposes. It also encompasses work on low-cost thermal storage materials that have high thermal storage capacity and can be integrated with conventional building elements, and work on materials and methods to transport thermal energy efficiently between any building exterior surface and the building interior by nonmechanical means.

Collector Technology Research. This activity area encompasses work on advanced low-to-medium temperature (up to 180° F useful operating temperature) flat plate collectors for water and space heating applications, and medium-to-high temperature (up to 400° F useful operating temperature) evacuated tube/concentrating collectors for space heating and cooling applications. The focus is on design innovations using new materials and fabrication techniques.

Cooling Systems Research. This activity area involves research on high performance dehumidifiers and chillers that can operate efficiently with the variable thermal outputs and delivery temperatures associated with solar collectors. It also includes work on advanced passive cooling techniques.

Systems Analysis and Applications Research. This activity area encompasses experimental testing, analysis, and evaluation of solar heating, cooling, and daylighting systems for residential and nonresidential buildings. This involves system integration studies, the development of design and analysis tools, and the establishment of overall cost, performance, and durability targets for various technology or system options.

This report is an account of research conducted in the systems analysis and applications research area concerning the evaluation of daylighting systems in residential and non-residential buildings.

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FOR BEAM DAYLIGHTING MEASUREMENTS
IN SCALE-MODEL BUILDINGS*

Fred Bauman, Wayne Place, John Thornton, and Thomas C. Howard[†]
Building Systems Analysis Group
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

An experimental device has been developed to measure the total amount of solar radiation transmitted through glazed apertures in scale-model buildings. The device, an integrating window pyranometer (IWP), has two distinguishing characteristics: (1) it provides a measure of transmitted solar radiation integrated over a representative portion of the model glazing, accounting for nonuniform radiation distributions; and (2) it is spectrally independent. In applications to scale-model daylighting experiments, the IWP, together with photometric sensors mounted in the model, allows the direct measurement of the fraction of transmitted solar gains reaching the work plane as useful illumination, a convenient measure of the daylighting system performance. The IWP has been developed as part of an outdoor experimental facility to perform beam daylighting measurements in scale-model buildings. In this paper, the integrating window pyranometer is described; the results of calibration tests are presented and evaluated; the advantages and limitations of the device are discussed.

INTRODUCTION

The potential for reducing energy consumption in commercial and industrial buildings through the use of daylighting design strategies has become increasingly well recognized during recent years. An accurate assessment of the net beneficial impact of a particular daylighting design on the energy performance of a building can be made only when reliable information is available on the illumination levels within the building, as well as on any significant thermal effects associated with the introduction of the daylighting aperture. During a building's design phase, illumination data can be obtained through three methods: (1) scale-model measurements, (2) detailed calculations, and (3) graphic

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[†]Present addresses of authors: Fred Bauman, Department of Architecture, University of California, Berkeley, CA 94720; Wayne Place, Architecture Department, North Carolina State University, Raleigh, NC 27605; Thomas C. Howard, Synergetics, Inc., P.O. Box 33422, Method Station, Raleigh, NC 27606.

techniques. This information is then typically used in building energy analysis computer programs such as BLAST* and DOE-2 to predict reductions in lighting electricity and the impacts on energy consumption for heating and cooling the building.

Of the three methods mentioned above, measurements in scale-model buildings are the most reliable source of illumination data due to the fact that such data collected in a carefully constructed model can accurately represent the combined effects of a large number of building and environmental parameters. Experimental scale models have the additional advantage over other techniques of providing an opportunity for qualitative evaluation through visual observation and photography. When scale model experiments are performed in the outdoor environment, however, natural variations in the external solar conditions will occur. An important consideration, therefore, is the method used to account for the functional relationship between the collected interior illumination data and external solar conditions. This is briefly discussed below.

Traditionally, scale-model illumination data have been reported in terms of the "daylight factor," the ratio of interior illumination on the work plane to the external horizontal illumination. The daylight factor is, however, limited to overcast sky conditions, making it inappropriate in daylighting applications involving beam sunlight. To overcome this limitation several researchers have defined and measured various beam sunlight ratios involving the ratio of interior illumination to external beam illumination on the vertical window plane [1], on a plane directly normal to the sun [2], and on the horizontal [3]. There are still, however, two major difficulties in the application of any such daylight factors to real buildings. First, although recent efforts at Lawrence Berkeley Laboratory (LBL) [4] and Solar Energy Research Institute (SERI) [5] are improving the situation, reliable daylight and sunlight availability data exist for only a few locations in the U.S. and for only relatively limited periods of time. Secondly, as demonstrated by McCluney and Goebel [6], the use of the daylight factor approach to daylighting design is complicated whenever direct sunlight is incident on the work plane as well as when significant variations in the outside illuminance distribution occur.

In contrast to exterior illumination data, hourly solar radiation data have been measured and/or predicted for many years and are presently available for over 200 U.S. locations as part of the "SOLMET" data base [7]. Not surprisingly, researchers have used solar radiation data as a basis for predicting exterior daylight availability information [5,8]. In addition, as an alternative to the daylight factor approach, building researchers have used scale-model measurements to establish an empirical relationship between interior illumination and exterior solar radiation for various daylighting configurations [9-11]. An $(\text{interior illumination})/(\text{exterior solar radiation})$ ratio of this kind can then be fairly easily incorporated into a building energy analysis computer program in order to study the net energy impact of a particular daylighting design [11].

The measurement of transmitted solar radiation at the interior surface of the daylighting aperture concurrently with interior illumination levels in scale-model buildings provides a

*BLAST (Building Loads Analysis and System Thermodynamics) is copyrighted by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

convenient characterization of the daylighting system performance and has several advantages over the above described methodologies.

- The ratio of useful daylight on the work plane (in lumens) to the total power emanating from the interior surface of the daylighting glazing (in watts), which has been previously defined as the Solar System Luminous Efficacy (SSLE) [12], is analogous to the Electric System Luminous Efficacy (ESLE), the ratio of useful electric light on the work plane to the total power introduced to the building by the electric lighting system. The ESLE can be calculated from information found in the IES Handbook [13]. Determination of the SSLE for a particular daylighting design permits an easy comparison to the ESLE for the building in order to calculate the amount of electric lighting which can be usefully replaced by daylighting. This, in fact, is the methodology used in BLAST to perform simulations of daylit buildings [11,12,14,15].
- The SSLE represents the performance of the building-portion of the daylighting system. By comparing the SSLEs for different daylighting configurations under identical beam sunlight incidence angles (clear sky conditions), the relative performance of alternate designs can be quickly evaluated without having to account for other external solar conditions.
- Measurement of SSLEs in scale-model buildings reduces the variability of daylighting data associated with changes in the luminous distribution of the natural sky.
- For daylighting systems involving the use of beam sunlight, the transmitted solar radiation is an important parameter in assessing the total energy performance of the building. Building energy analysis computer programs have the capability of calculating this quantity, but for more complicated daylighting apertures these codes are somewhat limited in their accuracy without the aid of experimentally measured values.

For the reasons described above an experimental device (integrating window pyranometer [IWP]) has been developed by the Building Systems Analysis Group at LBL as part of an outdoor experimental facility to measure the transmitted solar radiation at the interior glazed surface of daylighting apertures in scale models. In this paper the integrating window pyranometer is described, and the results of calibration tests are presented and discussed. In a separate paper [16] the outdoor experimental facility is described in detail, and the application of the integrating window pyranometer to scale-model measurements is demonstrated through the presentation of experimental results for a linear roof aperture daylighting system.

DESCRIPTION OF INTEGRATING WINDOW PYRANOMETER

The major design criteria used in developing a device to measure the transmitted solar radiation at the interior surface of daylighting apertures in scale-model buildings were as follows: (1) the device should provide a measure of the total transmitted solar radiation integrated over the entire glazing surface area (i.e., the device should be able to handle

highly non-uniform radiation distributions associated with partially shaded windows or geometrically complex daylighting apertures); (2) measurements made by the device should be independent of the spectral characteristics of the incident solar radiation (i.e., it should be a thermal device); and (3) the device should be relatively inexpensive and easy to fabricate. All off-the-shelf pyranometers were unacceptable because their sensing surface was too small, they were nonthermal devices, or they could not be properly mounted behind glazing surfaces in scale models.

A schematic cross-sectional diagram of the integrating window pyranometer (IWP) is shown in Figure 1. The key element of the IWP is a four-inch (102 mm) square by 0.055-inch (1.4 mm) thick thermal flux meter of the variety commonly used to measure conductive and convective heat fluxes in buildings. The flux meter is based upon the principle that the one-dimensional heat flux through a layer of material of known thermal resistance may be determined from the temperature difference across that layer. The temperature difference across the flux meter plate is measured by means of a multi-junctioned thermopile having alternate junctions (more than 100 junctions per side) distributed across each side of the sensor plate. The layer of conducting material in the flux meter is made of a polyimide-glass.

As indicated, the flux meter is contained in a wood housing and is mounted behind the interior surface of the glazing in the scale model. The wood housing can be modified to exactly match the exposed outward-facing surface of the flux meter to the height of the glazing in the scale model. Incoming solar radiation is absorbed by the exposed surface of the flux meter, which is coated with a high absorptivity flat black paint (manufacturer's specified absorptivity of 0.96). A five-inch (110 cfm) muffin fan blows air directly on the back-side of the flux meter in order to increase the heat removal rate along that surface. The air is then exhausted through a flow channel having a cross-sectional area of 0.5 inches (12.5 mm) by 4.0 inches (102 mm). With this design, a large percentage of the transmitted thermal radiation is absorbed by the flux meter, conducted through it, and lost out the back side to the turbulent airflow. In operation, the millivolt signal from the thermopile in the heat flux sensor is recorded to obtain the conductive heat flux through the sensor. The following steps were taken to reduce the loss of heat from the absorbing surface out through the scale-model glazing and therefore to maximize the heat transfer through the flux meter. All glazing configurations tested were at least double glazed. A 2-mm air gap, tightly sealed against outside air leakage, separated the flux meter and the model glazing. Excessive heat gain through the wood housing to the flux meter due to incident solar radiation was minimized by covering exposed surfaces with aluminum foil.* In this way, unwanted conductive heat gains and losses through the edges of the flux meter plate were maintained at relatively insignificant levels. The presence of the flux meter directly behind the model glazing obviously affects airflow along the inside glazing surface. The large radiant fluxes associated with beam sunlight were so dominant for the measurements reported here that any variation in the convective heat flux along the glazing could be neglected.

*Separate tests indicated that without the aluminum foil in place, the IWP consistently overpredicted the incident solar radiation by more than 10%.

CALIBRATION RESULTS

A test version of the IWP was fabricated and calibrated by side-by-side comparisons with a spectral pyranometer (PSP). As shown in Figure 2, both instruments were placed in a 17-inch (43 cm) by 22-inch (56 cm) black box covered with a panel of double-pane clear ordinary glass. The IWP wood housing was protected with a layer of aluminum foil placed on the outside glazing surface, as indicated. The hemispherical dome over the PSP required that its sensing surface be displaced from the inside glazing surface. The black color of the test box prevented multiple reflections from the interior glazed surface onto the PSP. Clear glazing was chosen instead of diffusing glazing to reduce additional errors associated with the positioning of the PSP. In addition to the muffin fan attached to the IWP, a second muffin fan was mounted, as indicated, in the floor of the box. This second fan kept the air in the box well mixed and prevented overheating. The mounting configuration shown in Figure 2 permitted a 180 degree field of view for the IWP, but only a 160 degree field of view for the PSP. This was not considered to be a serious limitation in the calibration procedure for two reasons: (1) The accuracy and sensitivity of the PSP drops off substantially for angles of incidence greater than 80 degrees, and (2) For beam sunlight incidence angles less than 80 degrees, the fraction of total radiation contributed by the ring of diffuse sky in the 80 to 90 degree incidence angle range is extremely small (under worst conditions less than 8% of the total diffuse blue sky radiation; when beam sunlight is present this fraction will be significantly reduced). For beam sunlight incidence angles greater than 80 degrees, the above methodology is inappropriate. The limitations of the IWP at large beam sunlight incidence angles are discussed more later.

During initial tests, significant (up to 10% of full scale) and rapid (up to one cycle per second) variations in the output signal of the IWP were observed and were attributed to turbulence effects on the back side of the flux meter plate. To improve this situation, the IWP signal amplifier was modified to provide an integrated output, with an integration period of a few seconds. The temperature of the flux meter plate was monitored during these tests and found to consistently fall in the range of 64 to 68° F (18 to 20° C), which was 3 to 5° F above the ambient air temperature. Therefore, no temperature compensation factor (recommended by the flux meter manufacturer for large temperature variations) was required during the calibration.

Using the modification to the amplifier circuitry described above, several long-term calibration tests were made with the IWP and PSP. During these tests, only 43% of the flux meter surface area (1.77 in [45 mm] by 3.86 in [98 mm]) was exposed to incoming radiation. This particular area was chosen to match the size of a representative glazing element from the scale-model building being prepared for daylighting experiments. The results of these subsequent scale-model experiments are described in a separate paper [16]. Comparisons were made between the IWP and the PSP for seven beam sunlight incidence angles, ranging between 7 and 60 degrees. It was discovered that when a significant change in the magnitude of the transmitted solar radiation occurred (large change in beam sunlight incidence angle) the IWP signal had a relatively slow response time (taking up to one minute to level off at the new measured value). The thermal mass effects of the unexposed portion of the flux meter and the wood housing were responsible for this problem, which was overcome by simply waiting the required length

of time for the signal to stabilize before resuming data collection. The collected data from the IWP were fitted to the PSP data by means of a least squares program. The results are shown in Figure 3, in which the solid 45 degree line represents the line of perfect agreement between the PSP and IWP measurements. The seven clumps of data points are the result of the seven distinct beam sunlight incidence angles for which measurements were made. The root-mean-square (rms) difference was only 22.0 W/m^2 between the two sensors for 140 data points spanning the range of 300 to 800 W/m^2 .

In Figure 4 a series of IWP calibration lines (in terms of W/m^2 per measured millivolt) are presented to demonstrate the capability of the device in handling partially shaded glazing configurations. The 100% line ($21.6 \text{ W/m}^2 \cdot \text{mV}$) represents the measured result of a recalibration performed on the flux meter by an independent laboratory.* The two additional dark lines represent the measured calibration results for two different exposed areas of the flux meter surface. The 43% dark line is the calibration line discussed in Figure 3. Note that this best fit line possesses a slightly negative intercept, further indicating that the IWP (at this relatively small exposed surface area) may not be suitable for applications involving low incident radiation levels. The other dark line is the result of a separate calibration performed with 78% of the sensor surface area exposed using the same methodology described above. In both of the partially shaded calibration tests, the IWP wood housing was modified to cover the unused portion of the flux meter surface. The two lighter lines in the figure represent the predicted calibration lines obtained by using a simple area correction factor to adjust the original calibration line (for 100% exposed surface area). The adjusted calibration constants are $27.7 \text{ W/m}^2 \cdot \text{mV}$ and $50.2 \text{ W/m}^2 \cdot \text{mV}$ for the 78% and 43% exposed surface areas, respectively. This calculation assumes that only the exposed area participates in the heat transfer through the flux meter. The unexposed area remains inactive. The good agreement between the measured and predicted calibration lines (within 10% over the range of interest -- 300 to 800 W/m^2) is evidence that the IWP can properly integrate over its sensing surface, even when a large portion of the surface is shaded, to obtain an accurate measure of the total transmitted solar radiation.

CONCLUSIONS

The integrating window pyranometer (IWP) described in this paper provides a direct measurement of the total amount of solar radiation transmitted through glazed apertures in scale-model buildings. In its present form, the IWP is applicable to scale-model studies in which transmitted beam sunlight is an important quantity to be measured. The IWP, together with photometric sensors mounted in the work plane of a scale model, allows the measurement of the Solar System Luminous Efficacy (SSLE), the fraction of thermal radiation entering the space through the daylighting glazing that reaches the work plane as useful illumination. The advantages of the integrating window pyranometer described in this paper are listed below.

*The flux meter was recalibrated at the Department of Mechanical Engineering, Massachusetts Institute of Technology, and found to agree to within 4% of the manufacturer's calibration constant.

- The IWP sensor surface is large enough to cover a representative portion of the daylighting aperture in the model. In this way the IWP accounts for not only the transmissivity of the glazing material, but also any geometric effects produced by the construction details of the daylighting aperture.
- Due to the thermopile construction of the flux meter, the IWP is capable of properly integrating over its entire sensor surface to provide an accurate measure (even under the partially shaded conditions of the current tests) of the total amount of solar radiation entering the model through the glazing. This is a distinct advantage over smaller sensors, which are unable to accurately account for highly nonuniform incident radiation distributions created by partially shaded apertures.
- In contrast to photodetectors, which have a limited spectral response, the IWP is a thermal device, responding equally over a broad spectral range. In its present application to the measurement of transmitted solar radiation behind glazed surfaces, this is an extremely desirable characteristic due to the spectral variations that will occur for different glazing materials. This is also an important advantage when performing experiments in the outdoor environment, where natural variations in the spectral distribution of the incoming thermal radiation will occur.
- The accuracy of the IWP is adequate for scale-model beam daylighting measurements. Based on the calibration tests reported here, the measurement error of the IWP was estimated to be no greater than 10% for radiation levels of 300 W/m^2 or higher.

At its present stage of development, the integrating window pyranometer does have some limitations, which are outlined below.

- The IWP displays reduced accuracy at incident thermal radiation levels below about 250 W/m^2 . In its current design, therefore, the IWP is not suitable for the measurement of transmitted solar radiation when beam sunlight is not a significant fraction of the incoming radiation. During the present experiments, the IWP could not accurately measure transmitted radiation (1) at very large beam sunlight incidence angles (greater than 70°), (2) under completely shaded (no beam sunlight) conditions, and (3) under cloudy sky conditions.
- One limitation of any thermal device is its longer response time. The IWP required a waiting period of at least one minute between measurements at different model orientations.
- Variability in the IWP output signal, produced by turbulence effects by the muffin fan on the back side of the flux meter plate, contributed to the inaccuracy of the device at lower radiation levels.

Developmental work on the integrating window pyranometer is continuing. This work will address the limitations described above.

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The flux meter used in the integrating window pyranometer was International Thermal Instrument Co. Thermal Flux Meter, Model A.

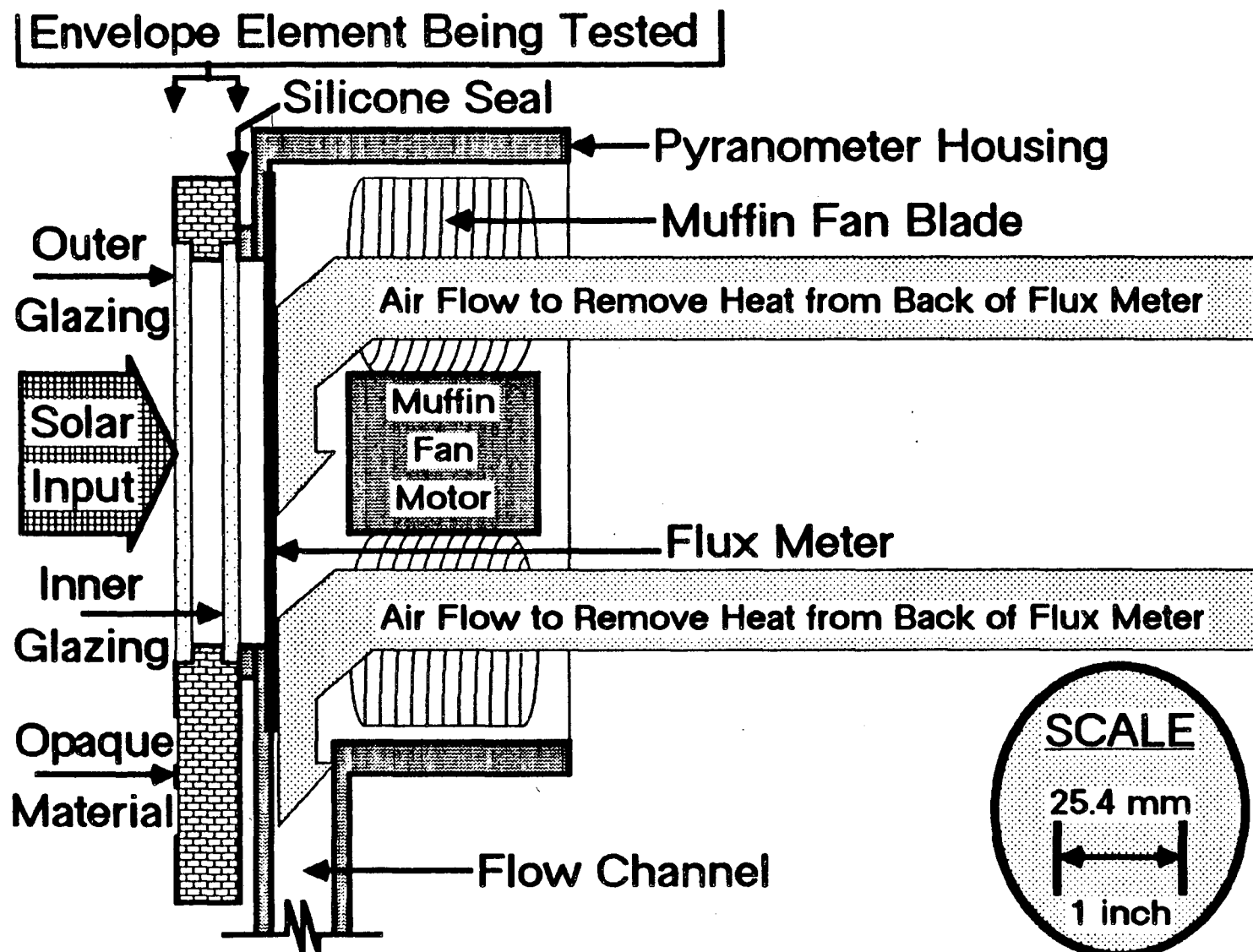


FIGURE 1: INTEGRATING WINDOW PYRANOMETER

FIGURE 2: CALIBRATION TEST BOX

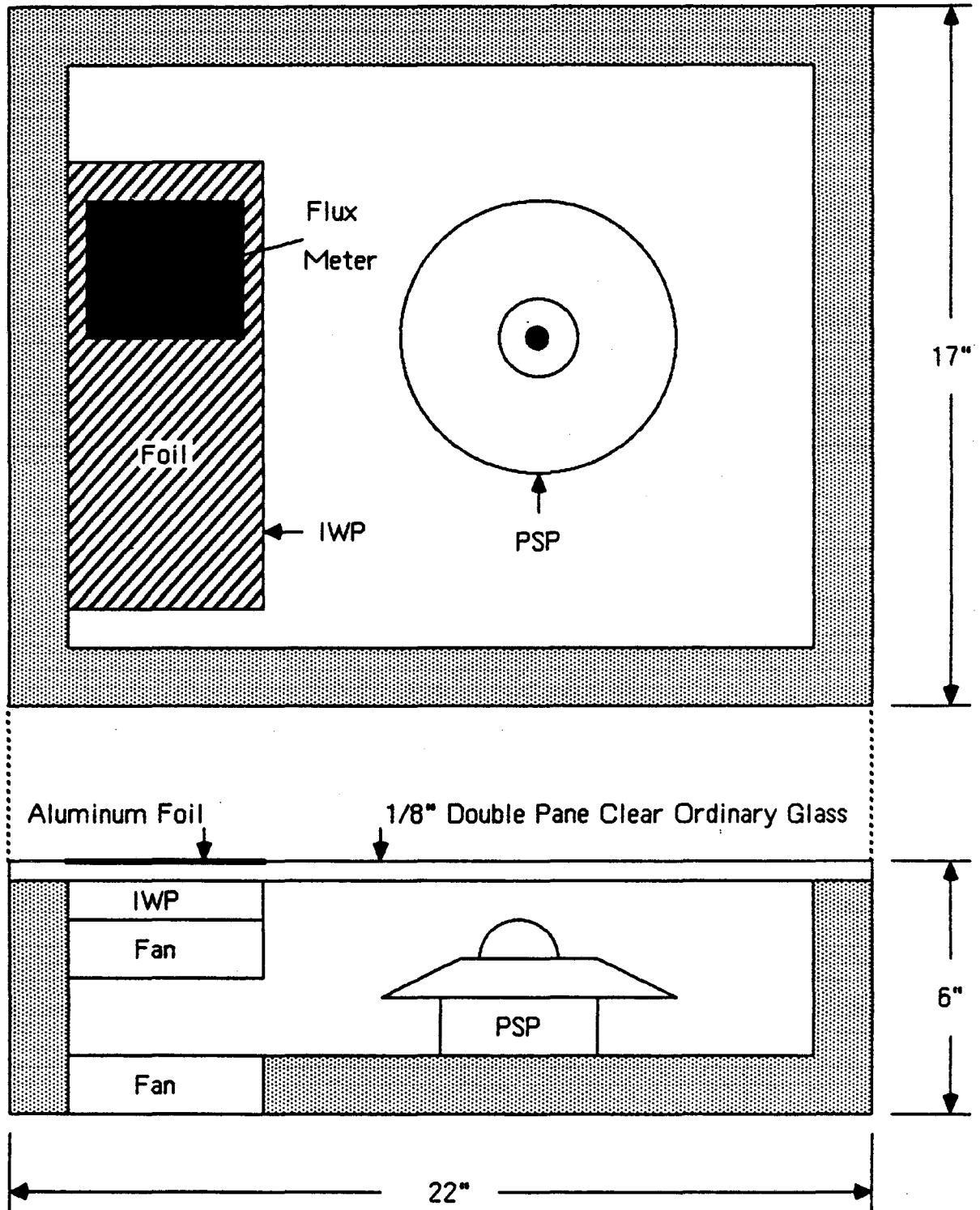
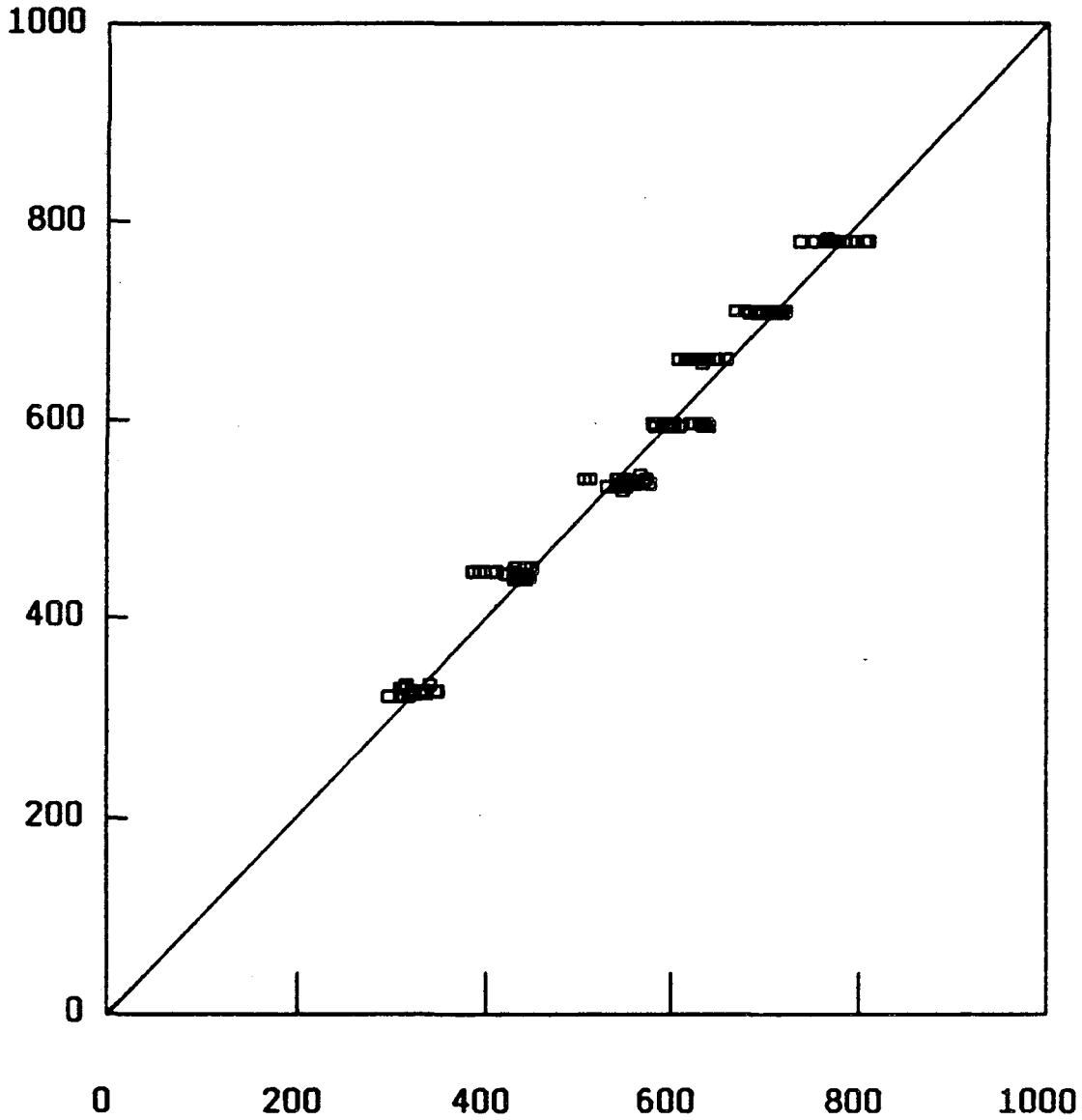


FIGURE 3

INTEGRATING WINDOW PYRANOMETER CALIBRATION RESULTS

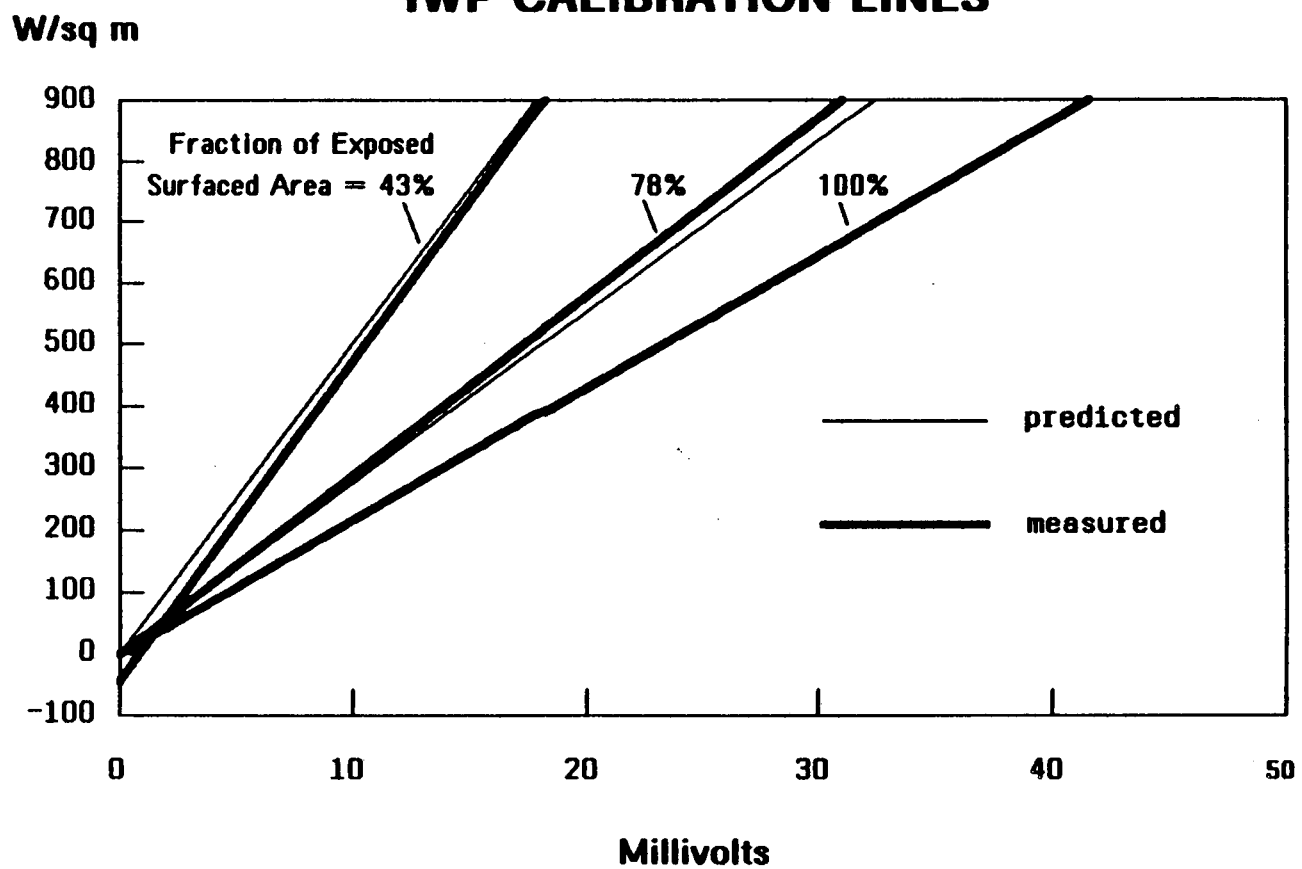
PSP (W/sq m)



IWP (W/sq m)

FIGURE 4

**COMPARISON OF MEASURED AND PREDICTED
IWP CALIBRATION LINES**



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