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Calorimetric Test Facility for Field Measuring Thermal Performance of Passive/Hybrid Solar Components

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ABSTRACT

Studies of the thermal performance of passive solar buildings have indicated a need for precise field measurement of solar heat gain and thermal heat loss or gain for modular passive/hybrid solar components. A description of the conceptual design and the major assemblies and subsystems for a new calorimetric test facility is presented in this paper. The facility is designed for field testing of passive solar components at the National Bureau of Standards in Gaithersburg, MD. It is anticipated that the test facility will provide a substantial improvement in the field measuring techniques for passive and hybrid solar components over the test cells currently in use and thereby provide a firm technical basis from which laboratory test procedures can be evaluated.

Computer studies of the thermal performance of the metering chamber assembly made with a 65-node finite-difference thermal model are described. The model was used to compute the heat balance for the solar absorber panel and the air-conditioning units, located in the metering chamber. Design days in both summer and winter were studied for a worst-case test article, which consisted of a single sheet of window glass. A description of the passive/hybrid solar components proposed for testing in the calorimeter during the winter season of 1982-1983 is also provided.

INTRODUCTION

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed a design procedure for predicting the instantaneous rate of solar and thermal energy transfer through fenestration systems having no significant thermal storage capability.[1-3] The ASHRAE procedure, while orginally intended for use in determining summertime design-day heat gains through fenestration systems to permit sizing of cooling systems, is currently being used to characterize the thermal performance of non-energy storing systems in passive solar heating applications. Design procedures are available for estimating long-term, i.e., monthly, thermal performance of energy storage systems used in conjunction with fenestration systems, however, no general accepted design procedure is available for dynamic analysis of these systems.

In chapter 27 of the ASHRAE Handbook -- 1981 Fundamentals, the results of a heat-transfer analysis for a double-glazed window are presented.[4] That analysis is based on energy balance relationships for convective and radiative heat transfer and predicts the instantaneous rate of heat transfer between the ambient and interior environments through a solar irradiated window. The ASHRAE analysis, while quite general, does not include the effects of additional heat transfer by conduction through the sash or other structural members of the fenestration, or by mass transfer caused by pressure and moisture differences across the window. These other heat transfer considerations are usually determined by testing full-size specimens in environmental chambers.

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The ASHRAE analysis for the instantaneous rate of heat transfer through a solar irradiated window shows that the net heat gain of the room consists of the following three:

1. Transmitted solar irradiation,

2. Solar irradiation that is absorbed in each layer of glazing and transferred to the room by convection and radiation at the inner surface,

3. Heat transfer due to outdoor-to-indoor temperature difference.

The first two heat transfer terms are usually combined into a parameter called the shading coefficient (SC),* and the third heat-transfer term is a parameter called the overall coefficient of heat transfer (U-factor), which is also known as the overall thermal transmittance or the overall thermal conductance.

The simplified design procedure has led to the development of a thermal test methodology for fenestration systems in which shading coefficient is determined independently of U-factor. Shading coefficient is measured in the absence of temperature difference and U-factor is measured in the absence of solar irradiation. The methodology assumes that the net heat-transfer rate per unit area of fenestration can be determined by adding the contribution due to solar irradiance (shading coefficient x solar heat gain factor)** to the contribution due to temperature difference ($U \times \Delta T$).

This methodology appears to provide reasonably accurate results for simple fenestration systems, with low solar absorbing components such as single- or double-glazed clear windows; however, its application for characterizing the more complex fenestrations proposed for use in passive solar applications is unknown.[5] Multiglazed fenestrations with spectrally selective low emittance coatings that reduce radiative heat loss without substantially reducing solar gain are now commercially available. New optical switching materials that modulate solar gain in response to temperature or solar intensity are also being developed. The development of these new, high-performance fenestration systems suggests that the existing test methodology and building fenestration characterization should be carefully reviewed to determine their adequacy for passive solar applications.

Test methods for passive solar systems and components have evolved differently from the test methods for building fenestration systems. Most often, testing was performed on passive solar systems installed in small outdoor test rooms or cells, with naturally occurring climatic conditions and with widely varying test room air and surface temperatures.[6] Although the results of those passive solar testing programs have yielded significant information on the operating principles and the relative thermal efficiencies of various passive solar systems and components, the use of such test rooms with uncontrolled air and surface temperatures is not recommended for standard testing of modular passive and hybrid components.[7] In the uncontrolled test rooms, room temperature is sensitive to such test room characteristics as insulation thickness, surface area, thermal mass, and infiltration. Uncontrolled air and surface temperatures in test rooms tend to modify temperature-dependent heat-transfer mechanisms, such as free convection and infrared radiative transfer. This results in measured thermal performance that is strongly facility-dependent, a highly undesirable characteristic for a standard test procedure.

It appears that a more appropriate thermal boundary condition for standard testing of passive solar components is to establish fixed conditions of indoor air temperature and room surface temperature and to measure accurately the rate of heat transfer occurring between the outdoors and indoors through the passive solar component. This paper discusses the conceptual design and the major assemblies and subsystems for a calorimetric test facility designed for field testing of passive and hybrid solar components. Additional details of construction and performance specifications are given in Ref 8.

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* Shading coefficient of a material is the ratio of solar heat gain for that material to the solar heat gain for a single sheet of double-strength glass at the same solar intensity and solar incidence angle.

** Tabulated values of solar heat gain through a single sheet of double-strength clear window glass.[4]

A computer model prediction of thermal performance of the test facility is presented for winter and summer design days for a worst-case test article consisting of a vertical, south-facing, single sheet of window glass. The test article has neither wintertime night insulation nor summertime shading since these would reduce the magnitude of the heat gains and losses. It is assumed that a test facility designed to provide a controlled internal thermal environment under these extreme conditions would readily be able to maintain a controlled thermal environment with more realistic test articles and more moderate climatic conditions. It is anticipated that the test facility will provide a substantial improvement in the field measurement techniques for passive and hybrid solar components over the test rooms currently in use and thereby provide a firm technical basis from which laboratory test procedures can be evaluated.

DESCRIPTION OF PASSIVE SOLAR CALORIMETER TEST FACILITY

The passive solar calorimeter has been installed in one of the test rooms in the NBS/DOE Passive Solar Test Building, which is located at the NBS Annex immediately south of the main NBS campus in Gaithersburg, MD. A photograph of the exterior of the test building, which was completed in 1981 to obtain thermal performance data for full-scale passive solar systems integrated into buildings, is shown in Fig. 1. A floor plan of the building showing the interior layout of the building experiments and the calorimeter is provided in Fig. 2. Additional details on the passive solar features and instrumentation installed in the Passive Solar Test Building are provided in Ref 9.

An advantage to locating the solar calorimeter in the Passive Solar Test Building is the opportunity for the simultaneous thermal testing of two identical passive solar components: one in the idealized room environment provided by the calorimeter and the other in the more realistic, full-scale room environment provided by one of the test cells. This will allow qualitative assessment of the effect of the calorimeter environment on component thermal performance.

The passive solar calorimeter test facility consists of the following major assemblies and subsystems, each of which is described in the following sections:

1. metering chamber assembly,

2. fluid conditioning subsystems,

3. building-test article interface,

4. data acquisition system.

Metering Chamber Assembly

The metering chamber assembly, shown schematically in Fig. 3, includes a five-sided metering chamber constructed of rigid polyurethane foam insulation 6 in. (150 mm) thick, which completely encloses the interior of the passive solar test article and which can be mounted either vertically against the south wall or horizontally against the ceiling of the calorimeter room. The metering chamber is sealed against the building interface with a clamp and gasket arrangement to minimize infiltration air exchange with the test room. A small charge of dessicant is placed in a pan near the return duct to dehumidify the metering chamber air. The dessicant is replaced at the completion of each test in order to prevent condensation on cold surfaces of the test article. The metering chamber surface temperature and air temperature are controlled by the solar absorber panel and the air-conditioning unit, respectively.

A uniform surface temperature is maintained in the calorimeter by forced circulation of water through the solar absorber panel. The panel shown in Fig. 4, is constructed of a soldered assembly of copper sheets and tubes painted with a black paint having measured solar absorptance of 0.95 and normal emittance of 0.88. The solar absorber panel fits within the metering chamber and is positioned sufficiently close to the test article to absorb almost all the solar energy transmitted by the test article and to provide a temperature controlled, nearly isothermal, radiative heat sink (or heat source) for the test article. Temperature control is achieved by sensing the average surface temperature of the panel with a grid of six thermocouples in parallel. The averaging thermopile is connected to a temperature controller that regulates the duty cycle of the water heater located at the absorber panel inlet.

A uniform air temperature is maintained in the calorimeter by forced circulation of air at a velocity less than 100 fpm (0.5 m/s) between the test article interior surface and the absorber panel. Temperature control is achieved in the air conditioning unit by first removing heat and then adding heat to the circulating air using the water-cooled heat exchanger and electric heater, respectively. The cooling water flow rate and inlet temperature to the heat exchanger are manually set to provide a constant rate of energy removal from the airstream based on anticipated ambient conditions. The electric heaters have a manually set range switch and Variac power supply to permit operation over power dissipation ranges of either 0 to 200 W or 0 to 1000 W. The average air temperature in the metering chamber is sensed by a grid of six thermocouples in parallel. The thermopile controls the duty cycle of the air heater by means of a solid-state temperature controller. Control of air velocity and direction in the metering chamber is provided by a solid-state motor controller, which controls the speed and direction of a belt-driven, axial-flow fan. The fan circulates the airflow over the test article in the downward direction in the winter and upward direction in the summer in accordance with the motion that would result from free convection flow patterns.

Fluid Conditioning Subsystems

Distilled water is used for the heat transfer medium in both fluid conditioning subsystems. Fig. 5 shows a schematic drawing of the solar absorber panel's cooling water circuit, which contains the primary coolant circulating pump, emergency pump, heat rejection pump, 52 gal. (195 ℓ) storage tank, 2500-W immersion heater, solid-state temperature controller, and an air-cooled water chiller. Thermal energy from the absorber panel is transferred to the storage tank from which it is rejected to ambient air by the 9000 Btu/hr (2.6 kW) water chiller. Emergency coolant circulation is provided by a battery-operated, low capacity pump to prevent freezing of the absorber panel due to a loss of power to the primary circulation pump. The thermal energy contained in the storage tank will maintain the temperature of the absorber panel above freezing for at least 24 h. The emergency coolant pump storage battery is kept on a trickle charge using a small photovoltaic array.

The air conditioning unit cooling water circuit (not shown) is similar to that shown in Fig. 5 and consists of a circulating pump, a 30 gal. (114 ℓ) storage tank, a 500 W immersion heater, and a 2500 Btu/h (0.7 kW) water chiller. The thermal energy absorbed in the water/air heat exchanger in the metering chamber is rejected to the calorimeter room through the water chiller.

Building-Test Article Interface

The passive or hybrid solar component to be tested is assembled in a suitable test frame and installed in either the vertical south-facing aperture, or the horizontal aperture of the NBS Passive Solar Test Building. The purpose of the building interface is to provide structural support for the test article and thermal isolation from the building. Flanking loss, the undesired heat flow between the metering chamber and outdoors through the building interface, is minimized by carefully sealing joints to prevent air leakage and by reducing heat conduction with a substantial thickness of rigid insulation.

Fig. 6 shows the details of the vertical aperture of the building interface. Modular passive solar components provided with a self-contained glazing system are accommodated by removing the double-glazed window provided for nonglazed components. Automatically controlled electric strip heaters are installed on the four building interface surfaces facing the vertical test article. The strip heaters perform the function of thermal guards to minimize undesired heat transfer between the test article and the building interface.

Test articles substantially smaller in size than the nominal 49 1/2 by 82 1/2 in. (1.26 by 2.09 m) test article can be accommodated in the test facility by installing blanking heater panels in the unused portion of the aperture. The electric strip heaters in the blanking panels are automatically controlled to maintain nearly adiabatic boundary conditions at their interior surfaces.

Fig. 7 shows the installation of a skylight/shutter test article in the horizontal aperture of the building interface. In this case, the nominal 48 by 72 in. (1.22 by 1.54 m) horizontal aperture is fitted with a special, insulated test fixture to accommodate the 30 1/4 by 30 1/4 in. (0.79 by 0.79 m) skylight. Flanking loss is minimized in this configuration with seals and additional thick layers of rigid insulation, so that guard heaters are not necessary.

Data Acquisition System

The data acquisition system consists of the various measurement sensors, signal conditioning circuits, display meters, and data scanning and storage devices shown schematically in Fig 8. Measured variables include temperature (absolute and differential), solar irradiance (total and direct normal), flow rate, velocity, and electric power. The primary measurement sensors used in the test facility are thermocouples, differential thermopiles, pyranometers, a pyrheliometer, turbine flow meters, two types of air velocity sensors, and watt transducers.

Temperature is measured with premium-quality 30 gauge, type-T (copper-constantan) thermocouples. Sixteen surface-mounted thermocouples attached to the absorber panel and eight thermocouples installed in the air space between the absorber panel and the test article monitor the operation of the metering chamber and the temperature control systems. Thermocouples also measure the temperature at various locations on the metering chamber walls, on the test article in the two fluid conditioning subsystems, and of the outdoor and room environments.

The temperature change of each water conditioning subsystem in the metering chamber is measured with an averaging differential thermopile. Each thermopile consists of thirty, type T thermocouple junctions located in the metering chamber inlet pipe and outlet pipe. The thermocouple junctions are connected in series to provide a voltage signal that is proportional to the average temperature change between the inlet and outlet streams.

Turbine flowmeters are used in each of the water conditioning subsystems to measure flow rate. These sensors develop a pulsed millivolt signal that is proportional to the volume of fluid flow. A digital to analog converter makes this signal compatible with the data logger.

A normal incidence pyrheliometer (NIP) and two precision spectral pyranometers (PSPS) are used to measure beam and total solar irradiance, respectively. The NIP is installed in a sun tracking mount and measures direct normal solar irradiance. One of the pyranometers is installed horizontally at the roof aperture and the other is installed vertically at the vertical aperture. The pyranometers measure the total amount of solar irradiation including both beam and diffusely reflected radiation from the sky, ground, and building.

The electrical power and energy supplied to the metering chamber are measured with watt transducers and an integrating module, respectively. The watt transducers consist of Hall Effect devices that provide an output analog signal of instantaneous power. The analog power signal is integrated to provide an analog signal proportional to the number of watt-hours of energy. These transducers measure all the electrical power and energy input to the metering chamber, including the air heaters, the fan motor and speed control, and the test article (if it requires operating energy).

The velocity of the air circulated in the metering chamber between the absorber panel and the test article is sensed with a hot-wire anemometer. The signal from the anemometer is processed in a signal conditioning unit, which produces a digital readout of velocity and an analog voltage output proportional to velocity. The outside wind velocity and direction are sensed with three mutually perpendicular, wind driven propellers. Each propeller produces a voltage signal that is proportional to the component of wind velocity in the direction in which the propeller is facing.

The data acquisition system uses an analog data logger to scan and print the temperature and millivolt sensor readings and a nine track tape recorder to store data on magnetic tape. The data logger has the capability of reading 40 type-T thermocouple channels for temperature measurement and 20 channels for other analog voltage measurements, including solar radiation, outdoor wind velocity, metering chamber air velocity, water flow rate, and electric power and energy. Voltage dividing networks are required for several of the sensors which produce voltages that exceed the 400 mV maximum input to the data logger.

Visual display of up to 30 channels of temperature data is available with a digital panel meter having a resolution of 0.2°F (0.1°C). Selected voltage signals are also available for display on a digital voltmeter having a resolution 0.1 mV. Other analog sensor displays such as pressure, temperature, and flowrate, are available using pressure gauges, liquid-in-glass thermometers, and rotameters, respectively. These sensors are primarily used to monitor operation of the test facility.

PERFORMANCE EVALUATION

Due to the large quantity of data collected, system performance is evaluated using off-line computing facilities available at NBS. Automated performance evaluation procedures are shown schematically in Fig. 9. Sensor data, scanned by the data logger, are recorded on magnetic tape and printed on paper tape. Approximately two minutes are required to scan the 60 data channels. The scan rate may be varied between 12 and 30 scans per hour. A data file containing the raw scan data is created in the off-line computer from the data stored on the magnetic tape. A listing is made of this file to allow a visual comparison with data on the paper tape to verify proper data transfer. The scan data are converted to engineering units using measured calibration constants, which are stored in a separate data file. The scan data in engineering units are then used to perform a heat balance calculation, and a listing is made of all computed and measured energy flows. The scan data heat balance information is then integrated to provide hourly average values, which are archived. Further evaluation of the hourly test results is performed using statistical analysis programs and graphics plotting routines.

The net rate of thermal and solar energy transfer from the test article into the metering chamber, Q_{NET} is determined by applying an energy balance to a control volume surface located within the metering chamber, as shown in Fig. 10. The various energy flows shown on the right side of Fig. 10 are measured quantities. It is assumed that all electrical energy supplied to the heating coils and for operating the fan and test articles (not shown) is converted into thermal energy. Q_{LOSS} is the heat transfer rate between the metering chamber and the surrounding room due to conduction through the chamber walls and piping and convection through the instrumentation wiring openings. Q_{LOSS} is measured during the calibration tests, during which the test article is replaced by an adiabatic guard heater panel.

The planned operating condition for the metering chamber is to have the absorber panel temperature, T_{ABS}, and the air temperature, T_{AIR}, set at constant values. This implies that $Q_{STORED} = 0$ and allows Q_{NET} to be calculated as shown in Fig. 10.

Thermal analysis of the heat balance equation for the absorber panel suggests that if the mean temperatures of both the absorber panel and the adjacent airstream are equal, so that there is no net convective heat exchange, then the absorber panel heat gain is due entirely to radiative heat transfer from the test article. This allows the test article's net heat-transfer rate, Q_{NET}, to be resolved into its convective and radiative components. Data of this type are believed to be of value to the research community in understanding the thermal behavior of passive solar components and the interaction of the building space in which they might be installed.

THERMAL ANALYSIS OF METERING CHAMBER ASSEMBLY

To aid in the design of the test facility, a thermal network model of the metering chamber assembly was developed for use with the general purpose thermal analyzer program SINDA.[10] In this model, a 65-node resistance-capacitance thermal network is used to represent the metering chamber, the absorber panel and cooling water tubes, the air in the metering chamber, the design-case test article, and the room and ambient air. A transient thermal analysis of the design case thermal network was performed using an explicit, forward--differencing method in the SINDA computer program to solve the heat transfer equations. A typical computer run covers a 24-hour period with results printed at hourly intervals.

The computer model results were used to determine maximum thermal loads for the calorimeter facility under simulated, worst-case environmental conditions during winter and summer operation. The lower curves in Figs. 11 and 12 show the assumed ambient temperature and solar irradiance conditions used for the facility design study. The middle curves in Figs. 11 and 12 show the predicted rate of solar heat gain of the solar absorber panel during the winter and summer design conditions respectively, for the operating extremes of calorimeter temperature and test room temperature. The upper curves in Figs. 11 and 12 show the predicted rate of net heat loss to the air conditioning unit for the same design conditions. Components in both of the fluid conditioning subsystems are sized to accomodate the peak instantaneous loads at these design conditions.

The solid lines in Figs. 11 and 12 are based on design case wind conditions of 15 mph (6.7 m/s) and 7.5 mph (3.4 m/s), respectively, for winter and summer conditions. The dashed lines are the calorimeter heat balances with zero windspeed. Figs. 11 and 12 shows a small increase in absorber panel duty with no wind during winter and a negligible decrease during summer. They also show a substantial decrease in the air conditioning unit heat transfer requirements between the winter-design and the zero windspeed conditions. The significance of these results is that the temperature controller for the airconditioning unit should be able to react to a step change in the net heat load of the magnitude displayed by Fig. 11 due to wind gusts on the order of 15 mph (6.7 m/s).

Although the air-conditioning unit net heat load displayed in Figs. 11 and 12 is always positive (i.e., heat is added) during the winter design day and always negative (i.e., heat must be removed) during the summer design day, it is apparent that some days would require both heat removal and addition. This is accomplished by operating the cooling water circuit at a constant heat removal rate to cool the air entering by approximately 2°F (1°C) and then by modulating the output of the electric heater to maintain the desired air temperature.

TEST FACILITY STATUS AND FUTURE ACTIVITY

Construction of the test facility was completed in June 1982, and shakedown testing was planned for the summer of 1982, using the skylight/shutter test article shown in Fig 7. However, problems resulting from late delivery of test equipment, minor equipment malfunctions, and major changes in the instrumentation for measuring electrical power resulted in a delay in the checkout phase, which is now planned for early fall of 1982. Calibration of the metering chamber is planned for late fall and a winter test program is planned, which includes the retesting of two direct gain fenestration (DGF) test articles that were previously tested in commercial testing laboratories and the testing of two new DGF test articles and four new collector-storage wall (CSW) test articles. Two of the CSW test articles will be water storage modules and the other two will be salt hydrate phase change material storage modules. In addition, it is planned to test simultaneously a DGF test article in the calorimeter and in the direct gain cell of the Passive Solar Test Building.

The initial evaluation of the DGF component test results will focus on developing statistical correlations between U-factor and Shading Coefficient for the climatic conditions of ambient temperature, solar irradiance, and wind speed. Since thermal characterization of CSW modules has not yet been developed, several different concepts for performance evaluation of energy storage systems will be investigated. These would include performance characteristics such as "dynamic U-factors" and "solar response factors."[11] Both of these concepts will be investigated using the test data from the four CSW test articles to determine the potential utility of each concept.

CONCLUSIONS

Field testing of passive and hybrid solar components in a calorimetric test facility provides the opportunity for measuring the net rate of thermal and solar energy transfer under actual climatic conditions and controlled indoor conditions. The ability of the test facility to resolve the net thermal gain into radiative and convective components will enhance understanding of the basic heat transfer mechanisms and will also permit more detailed study of thermal interaction between passive and hybrid solar components and the building spaces in which they are installed. Thermal performance data measured in the test facility under field conditions can be compared with test data measured in laboratory conditions involving simulated outdoor conditions of air temperature, wind and solar irradiation. These comparisons can provide the technical basis for the field validation of proposed laboratory test procedures.

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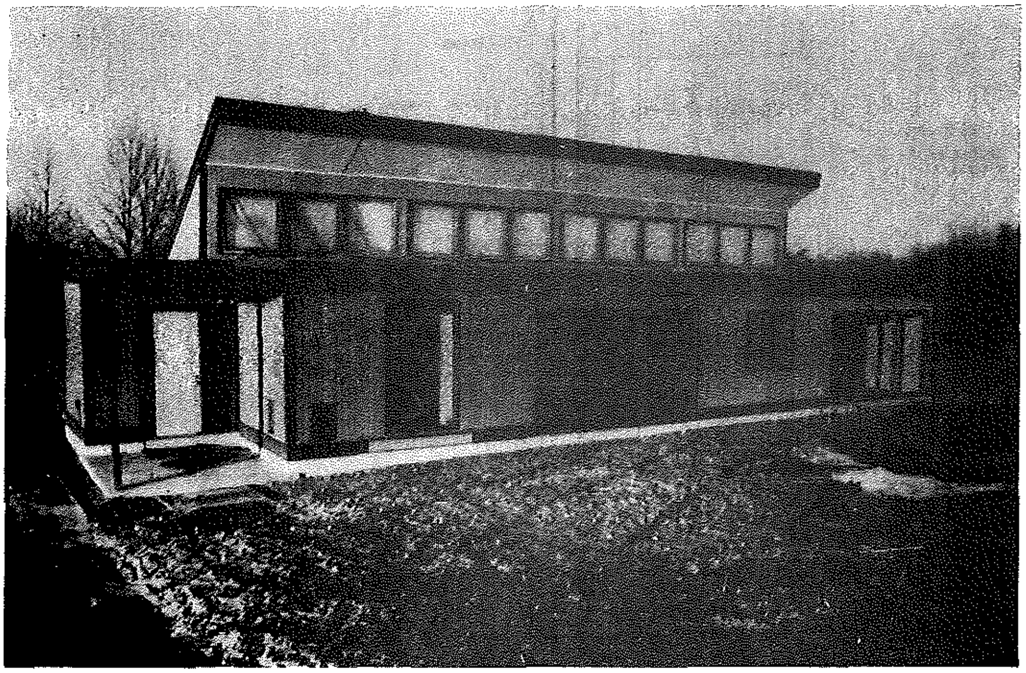


Figure 1. *Photograph of NBS/DoE Passive Solar Test Building*

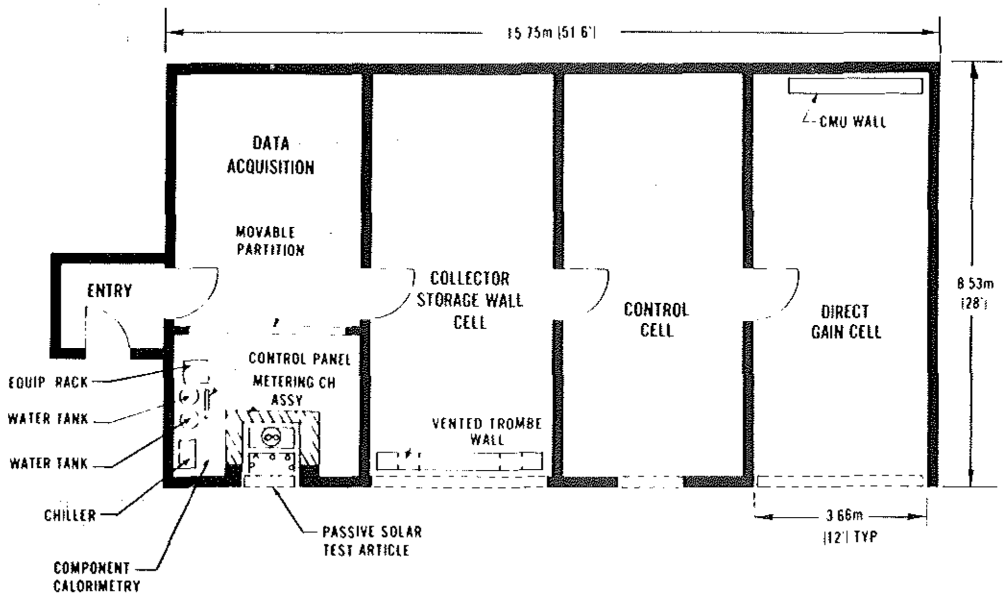


Figure 2. *Floor Plan of Passive Solar Test Building*

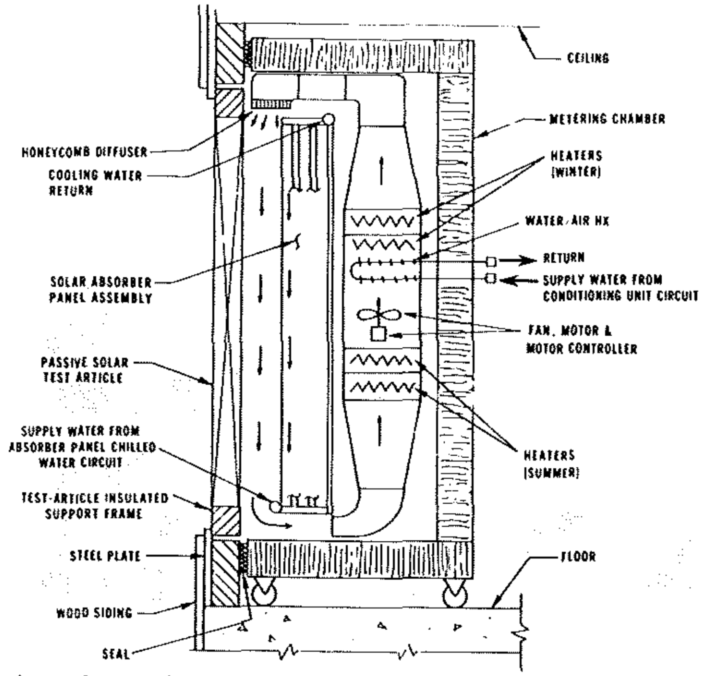
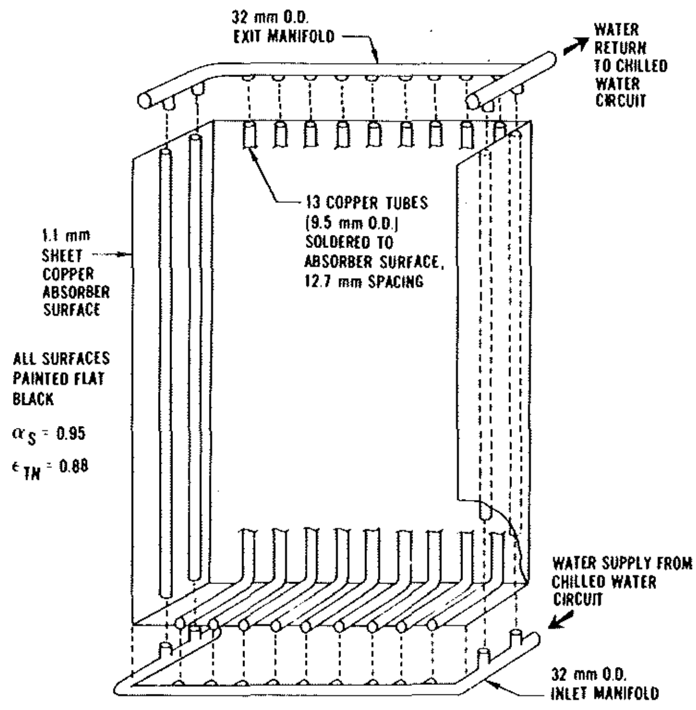


Figure 3. Schematic Drawing of Metering Chamber Assembly

Figure 4. Solar Absorber Panel Assembly



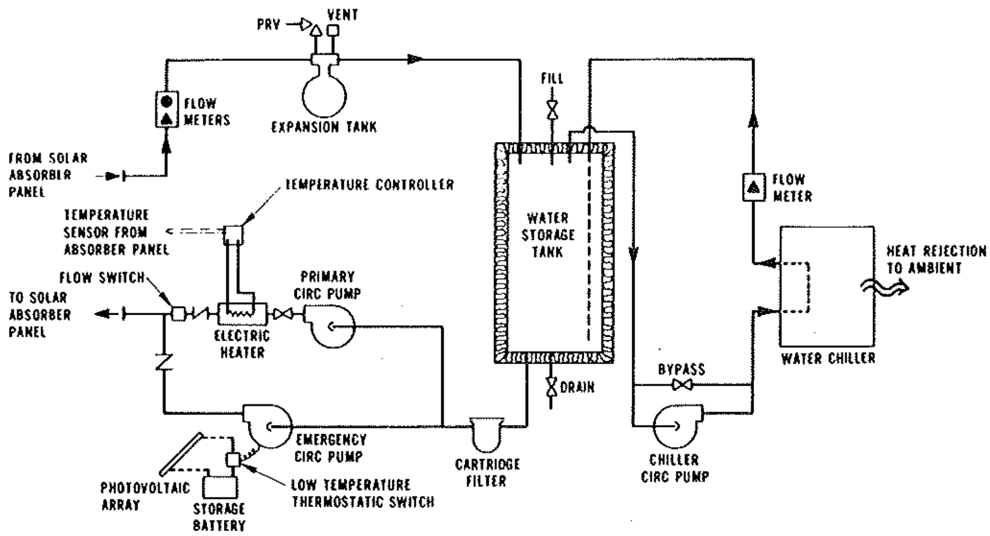


Figure 5. Solar Absorber Panel Cooling Water Circuit

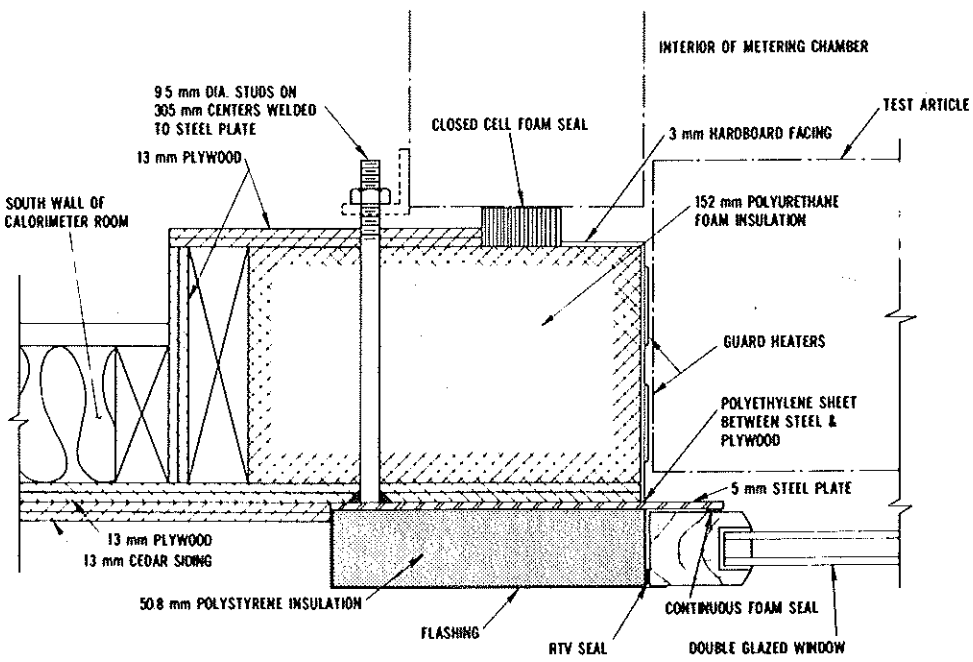


Figure 6. Test Article - Vertical Aperture Interface

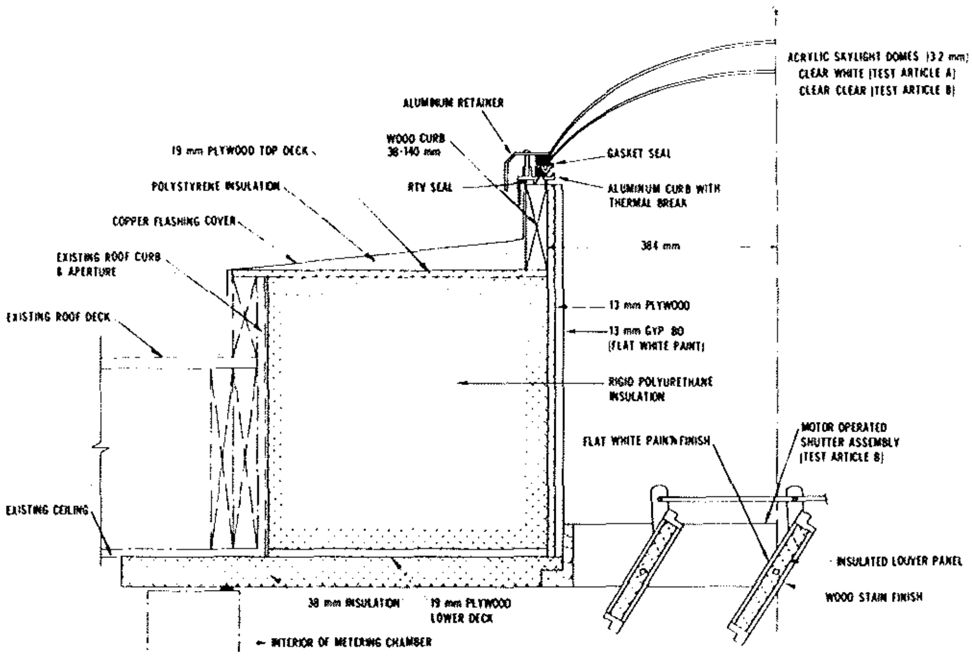


Figure 7. Skylight/Shutter Test Article - Horizontal Aperture Interface

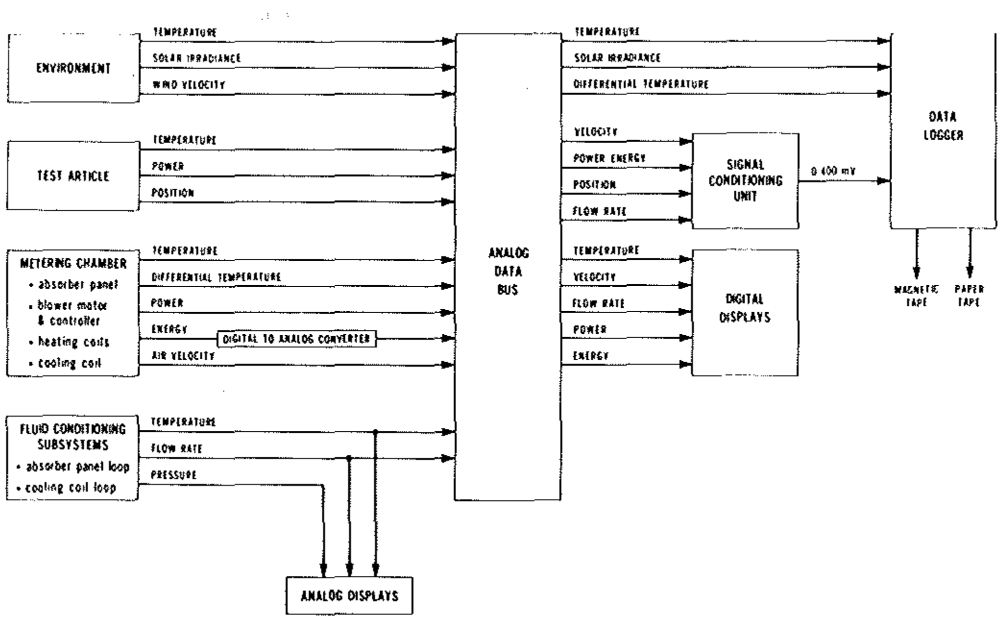


Figure 8. Schematic Drawing of Data Acquisition System

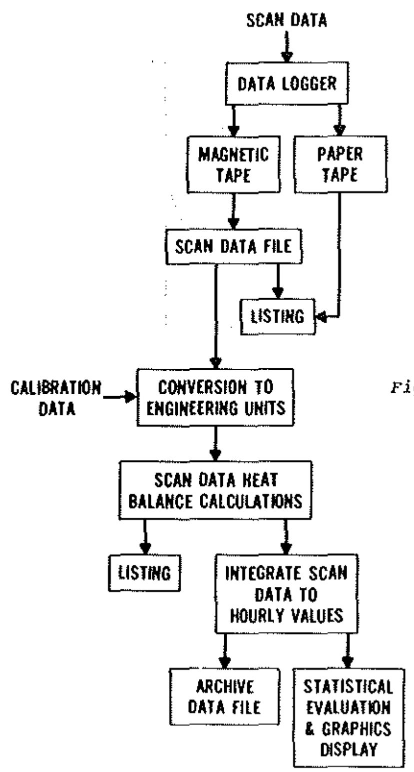


Figure 9. Schematic Drawing of Performance Evaluation

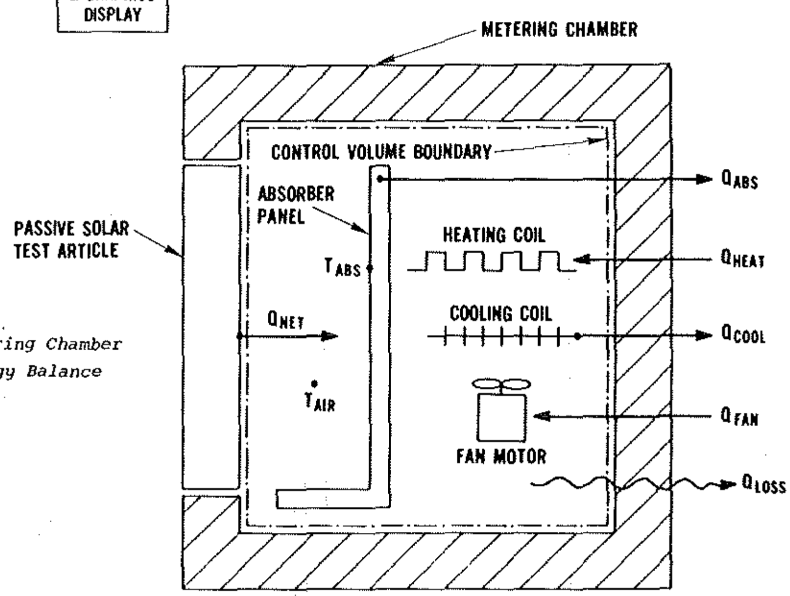


Figure 10. Metering Chamber Energy Balance

$Q_{IN} = Q_{OUT} + Q_{STORED}$

FOR T_{ABS} AND T_{AIR} = CONSTANT, $Q_{STORED} = 0$

$Q_{NET} = Q_{ABS} + Q_{COOL} + Q_{LOSS} - Q_{HEAT} - Q_{FAN}$

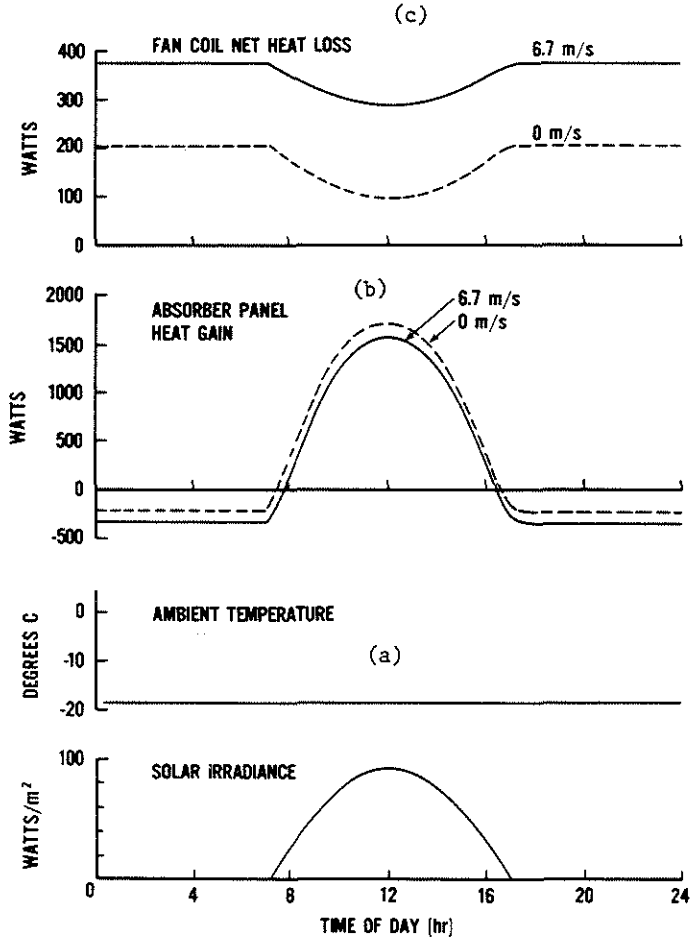


Figure 11. Predicted Energy Balance - Winter Design Case

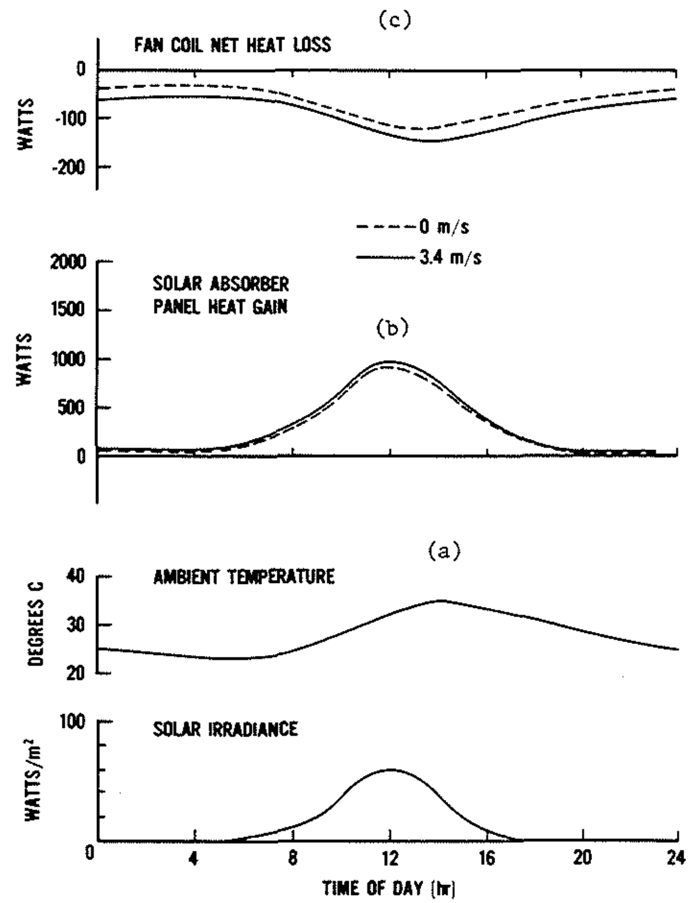


Figure 12. Predicted Energy Balance - Summer Design Case