THE STOCKHOLM PROJECT: PROGRAM FOR MEASURING AND ANALYZING NEW ENERGY-EFFICIENT APARTMENT BUILDINGS

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ABSTRACT

The program for measuring, evaluating, and analyzing the energy use in six new energy-efficient apartment buildings in Stockholm -- the Stockholm project -- is discussed. The aim is to analyze these buildings´ energy consumption in a strictly comparable way, although there are very different energy conservation methods used in the six different buildings.

The measurement program is connected to the analysis of the total energy balance for each building. On the basis of measured parameters we are better able to calculate parts in the energy balance that are not being measured directly. In addition, the computer techniques used for collecting data and for preanalysis are described, with emphasis on the ease and speed of data analysis that a large data-collecting system provides. A preanalysis program produces automatic monthly data on the main parts in the energy balance for each building. These data are used in maintaining monthly control of the energy balance. For further analysis of different parts of the energy system, hourly data are used.

Measurements will continue at least two years, the first of which is used to make the building and the energy system run in an efficient way, as well as to make the measuring equipment work. Examples of results from the first year of the evaluation period are presented.

INTRODUCTION

The Stockholm project consists of six new energy-efficient multifamily buildings. All the houses are built using well-known construction methods. However, in each of these buildings one or more innovative methods to reduce the consumption of purchased energy (i.e., electricity and district heating) is being tested. The goal is to reduce the quantity of purchased energy to 50% of that consumed by an otherwise identical building constructed according to current building standards. The means of achieving this goal is either through the improvement of well-tried existing techniques or the use of advanced new techniques. These techniques can concern either the building shell or the HVAC system. For details of the individual buildings, see Elmroth and Jägbeck (1985). The evaluation of the Stockholm project is being carried out by the Energy Conservation in Buildings Group at the Royal Institute of Technology, Stockholm, Sweden.

The goals of the energy evaluation section of the Stockholm project are (1) to map out the total energy balance for each of the buildings and divide the total energy flow into its components; and (2) to evaluate the specific experimental techniques used in each building, with regard to how they reduce the total energy demand how they affect the operation of the rest of the building.

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To achieve these goals, an overall measurement program was set up and then customized to suit each individual building. The program established what could and what should be measured, and what would have to be calculated. Calculated values would come either indirectly from measured values, or from one of the two independent simulations (made with the computer programs DEROB and BRIS) of the energy use of the buildings.

A very important part of the evaluation is the monitoring system. The Monitoring Center for Energy Research (MCE) at the Royal Institute of Technology has supplied and operated the monitoring system in this study. A unique data handling system has been developed to simplify computations with large amounts of time series data. It allows the user to carry out all the necessary operations, including plotting of results, with comparative ease.

The timetable for the project allows a one-year period after the completion of the buildings for the debugging of both the monitoring systems and the HVAC systems. Previous experience has shown that such a shakedown period is needed, not only to get all the hardware working, but also to check out the software needed for real-time analysis of the performance of the buildings.

THE MEASUREMENT PROGRAM

The following is an overview of the organization of the measurement program for the whole project. The building Konsolen is used as an example to illustrate how the program is employed for more detailed evaluation.

General

A general model of the energy balance in a building is the basis for the program. The values of the input parameters are known to various degrees of assurance since they come from several different sources, including (1) direct measurements, e.g., energy, temperature, water flow; (2) calculations based on spot measurements or indirect measurements, e.g., heat flow meters, tracer gas decay; and (3) estimations based on handbook values and the DEROB or BRIS simulations, e.g., metabolic heat.

The model used as a framework for the energy balance - including the assurance level of the input parameters - is as follows. Note that the Level A measurements occur mostly on the input side of the energy balance.

Energy Inputs

1. District heating or electric resistance heat, Level 1, can be measured directly as the total energy supplied. It may also be submetered. Examples: heat to radiators or domestic hot water.

2. Electricity, Level 1, can be measured directly as the total energy supplied, or it may be submetered. Examples: domestic electric use, electric use for common areas.

3. Passive solar gain, Level 2, can be calculated indirectly from the measured horizontal solar radiation. Examples: gain through windows or glazed atria (glazed courtyards).

4. Metabolic heat, Level 3, can be estimated on the basis of the number of occupants.

5. Active solar gain, Level 1, can be measured directly as delivered energy from the solar collector.

6. Recovered heat, Level 1, can be measured directly as delivered heat on the secondary side of a heat exchanger. Examples: heat recovered from ventilation air by a heat pump or air-to-air heat exchanger.

7. Cold water heat content. Level 1, can be measured directly from the cold water temperature and flow rate. The measurement is needed for the estimation of grey water losses. (Hot water flow and temperature are of course submetered.)

Energy Outputs (Losses)

1. Transmission, Level 2, can be calculated with the help of spot measurements (e.g., with a guarded hot box or heat flow meters) and continuous measurements of outside and inside temperature.

2. Ventilation losses, Level 1, can be measured directly from the temperature and flow rate of the exhaust air (after the heat recovery devices, if any).

3. Air leakage, Level 2 or 3, can be calculated/estimated with the help of spot measurements (tracer gas or pressurization tests).

4. Grey water losses, Level 2, can be estimated from the measured total cold water usage and the difference between the temperature of the incoming cold water and the temperature of the outgoing grey water.

5. Electricity losses (summer operation only), Level 2, can be estimated on the basis of theoretical calculations to determine the length of "summer", i.e., the period during which space heating is not required.

Example: Konsolen

In the Konsolen building (for construction details see Elmroth and Jägbeck, 1985) space heating is provided by hot-water radiators. Energy is supplied to both the radiators and the domestic hot water from two sources, district heating and an exhaust air heat pump. The building has concrete facade units, which act as solar collectors, containing vertical air channels in which the feed air to the building is preheated.

All the necessary parameters for the characterization of the energy use of the building are being measured. For each energy flow at least two temperatures and one mass flow (air or water) measurement are needed. To calculate transmission flows a large number of dry-bulb air temperatures in and around the building are measured. Outdoor sensors measure wind speed, outdoor temperature at two points, and solar radiation on two vertical surfaces. Airflow is measured by pressure difference between two points, and water flow is measured with turbine flow meters. The measurement program contains the calibration curves and temperature corrections for all sensors. In all, almost 200 sensors are installed at this site. Along with the raw data, a number of simple derived values -- such as water flow times water density times heat capacity (both corrected for temperature) times temperature difference across a radiator loop -- are stored. Measurements are taken every five minutes, and hourly average values are stored on cassette tape every hour.

An analytical structure such as the one outlined aboveis essential in making comprehensible the mass of incoming data. For each component of the balance that can be evaluated at Level 1, a subprogram has been written. The output of each subprogram is a diagram that shows how the particular energy flow varied with time. A barchart summarizing the total energy flow is also given. These outputs are available within a few days of the end of the month and give a quick overview of how well the building is performing. The input energy is broken down as follows.

District Heating is measured as the total energy supplied by the utility. It is submetered into space heating, domestic hot water, and pumped loop losses, all shown in the same diagram (Figure 1). The monthly sum gives an immediate check of instrument function, since the sum of the submeters must equal the reading from the main utility meter (Figure 2).

Electrical Energy used for various purposes is summed in a different diagram (see Figure 3).

Heat Recovered from ventilation air by a heat pump is shown in a third diagram.

Active Solar Gain from the solar wall is only measured as the temperature increases across it. (See Elmroth and Jägbeck for further details of this system.) Spot measurements of the air flow rate through one section of the solar wall are being made. These measurements will be used for the analysis of efficiency and output.

Other energy inputs, such as passive solar gain, cannot be calculated easily with a subprogram. The following energy losses in Konsolen are measured at assurance level 1.

Ventilation Losses are measured before any recovery. To avoid double counting, recovered heat is considered a heat input from the recovery system.

Grey Water Losses are calculated from the measured total cold water usage and the difference between the temperature of incoming cold water and the temperature of the outgoing grey water. We assume that all water entering the building leaves as grey water. The heat used for domestic hot water (DHW)is shown in the same diagram as the grey water (Figure 4). The ratio between the grey water losses and the DHW heat input is used to estimate the grey water losses in the other five buildings.

COMMISSIONING - EXPERIENCE AND ANALYSIS

Measurements will be made at all the buildings in the project for a period of two years. The first year will be used to ensure that both the building's HVAC system and the monitoring equipment function as designed. It is of great importance that a complete year's worth of data be collected, so interruptions caused by HVAC or monitoring equipment malfunctions are to be avoided. Problems arise when old, well-tested techniques interface with techniques that are being employed for the first time. The new energy techniques being tested put new demands on the conventional HVAC system and the house in general and also set new operational requirements on the system.

It should be pointed out that many of the system errors that were discovered would have gone unnoticed were it not for the system, of monitoring and analysis. In this context it is interesting to note that Swedish buildings have an international reputation for being well constructed with regard to structure and equipment. Since these new buildings are at least as well constructed as any conventional building, it should be expected that careful monitoring would reveal a large number of system operational problems in conventional buildings. Analysis during this one-year commissioning period will provide useful feedback to the building industry. Below are some examples of system errors detected at two of the buildings during the commissioning period.

Example 1: Konsolen

During January and February 1985, the measurements showed that the exhaust air heat pump always operated less than 50% of the time. During the winter it should be possible for the heat pump to operate continuously, delivering energy to either the radiators or to the DHW system. It stopped every night at the same time, producing the same result as a deliberate night setback. The only timeclock installed on the site was supposed to turn off a circulation pump for one circuit of the DHW pumped loop at night. A pump for the second circuit was supposed to be left on, so that night losses from the loop could be measured as the difference between the two circuits. It was found that the clock not only turned off both circulation pumps, but it turned off the circulation pumps for the radiators as well. Thus the heat pump could not deliver any heat to these loops, and it stopped. Heat might still have been stored in the water storage tanks were it not for a clause in the district heating supply contract. The clause stipulated that when the outdoor temperature was less than 5 xC, the heat pump was to be used only for the radiator loop and not for storage. This was so that the return water was at an optimal temperature for the district heating company. The net effect was that on cold nights the heat pump did not work at all.

This example shows the interactions that can occur when welltested technology is coupled with experimental technology. In principle, the system is quite simple: a standard pumped loop is heated by district heating. However, in practice a number of quite unexpected interactions between the heat pump, the district heating, and the heat storage tanks (combined with a trivial error in the wiring of a time clock) reduced the on-time of the heat pump by 50%, thus significantly reducing the savings it provided.

Example 2: Kejsaren

During nonheating (summer) operation, the heat collected by air circulation through the solar collectors is used to heat the DHW via an air-to-water heat exchanger. Because the system does not recirculate air through the collectors, the air is then dumped outside. Ventilation air for the apartments is taken from outside. Airflow is controlled by a three-way damper. This damper has an unavoidable leakage of air, allowing unneeded hot air to flow down to the apartments. The results are three-fold:

1. The apartments get too hot in summer.

2. If the measurements are taken at face value, the solar collector efficiency appears better than it really is, because heat that should be dumped is included with useful output.

3. The building thermal integrity appears worse than it really is because extra heat is apparently being used.

This example shows that the readings taken from sensors cannot always be taken at face value. Unless the system is working as designed, meaningless output can come from sensors that are functioning perfectly. Similar effects occur with water flow taking unusual paths, resulting in unexpected energy use.

DISCUSSION

The buildings of the Stockholm project use different techniques such as active solar heating, seasonal storage of heat in bedrock, extra-thick insulation, and extremely heavy construction to minimize energy consumption. With such different buildings, it is important to set up the method of analysis so that the components of the energy balance can be compared between buildings. For example, the length of the heating season can be very different for the different buildings. As a result, the allocation of household electricity (is it wasted or useful for heating?) becomes an important aspect of the balance. Similarly, some buildings have heated garages - one building even has a large area of rented office space! - and the energy required for these purposes must be separately metered and excluded from the balance if a fair comparison is to be made.

In semiexperimental buildings, such as those of the Stockholm project, extensive submetering is required if the performance of all the individual systems is to be determined accurately. The Stockholm project buildings have rather complicated systems involving heat pumps, heat exchangers, solar collectors, borehole storage, solar walls, heat recovery, and heat transfer from an office to a residence. As an example of the type of system used in the buildings, Figure 5 shows the heating system for space heat and DHW in Konsolen.

The results from all this submetering, from all the gathering of data (approximately 10 million data values will be produced by one year of monitoring), must be easy to understand. For this reason, a clear and simple conceptual outline is essential. For exactly the same reason, the analytical program must be in working order before the second year of data is collected. Otherwise, the amount of data will be extremely difficult to handle.

CONCLUSION

Since the Stockholm project buildings are so advanced -- they are designed to use half the purchased energy of a new Swedish apartment building -- it is certain that they will have their teething troubles, even in the second year of operation. Hopefully, that the monitoring program described above will aid in reducing such problems. Other important uses of the program include its use in commissioning the building and ensuring that all the equipment is functioning as designed. The program should also give a clear indication of the relative cost-effectiveness of the innovative techniques employed in these buildings. Special features of the program are its speedy analysis of data and regular monthly outputs. Other programs will of course be written to analyze the effectiveness of building components, such as the solar collector in Kejsaren and the exhaust air heat pump in Konsolen.

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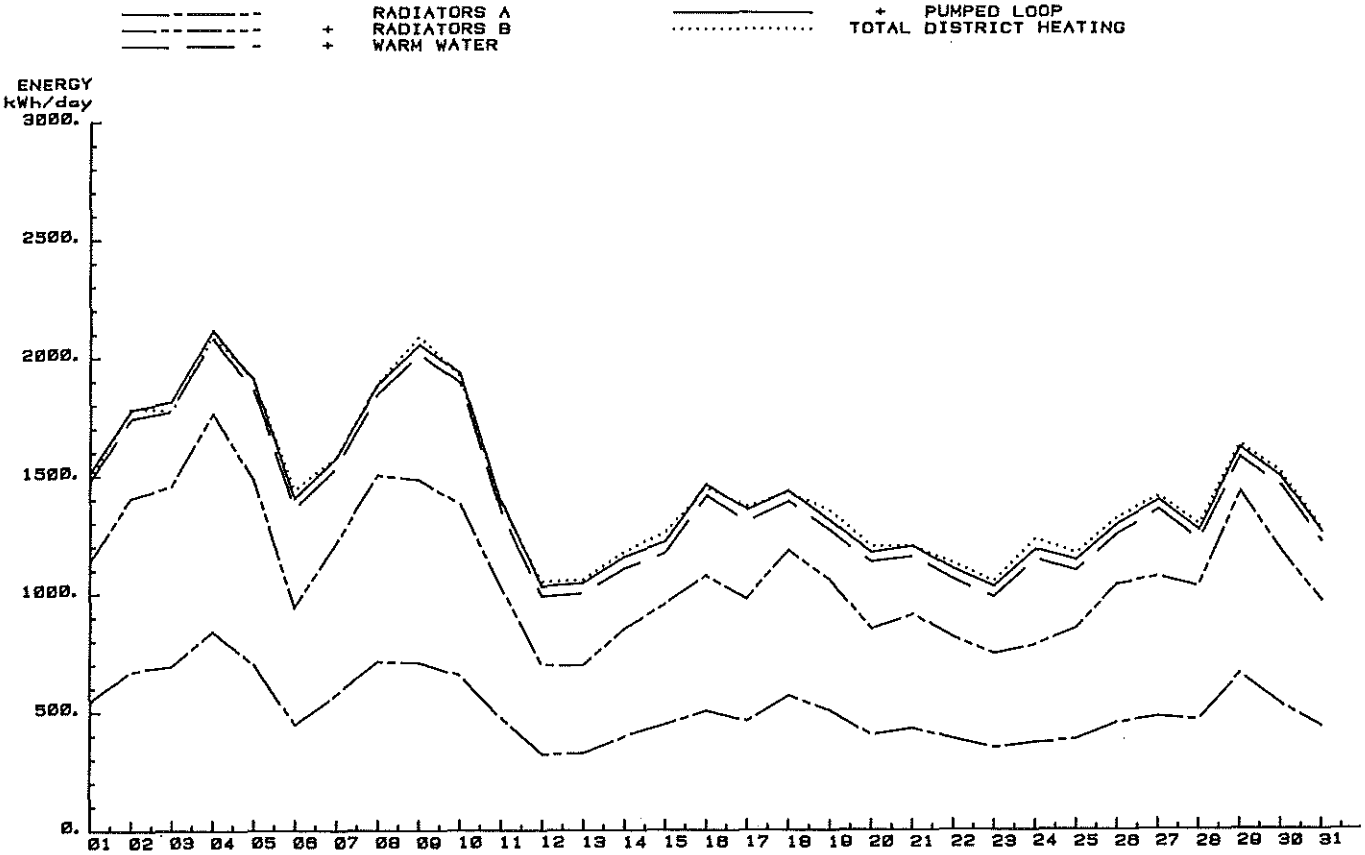

Figure 1. Time variation of district heating in Konsolen building, March 1-31, 1985, broken down by end use

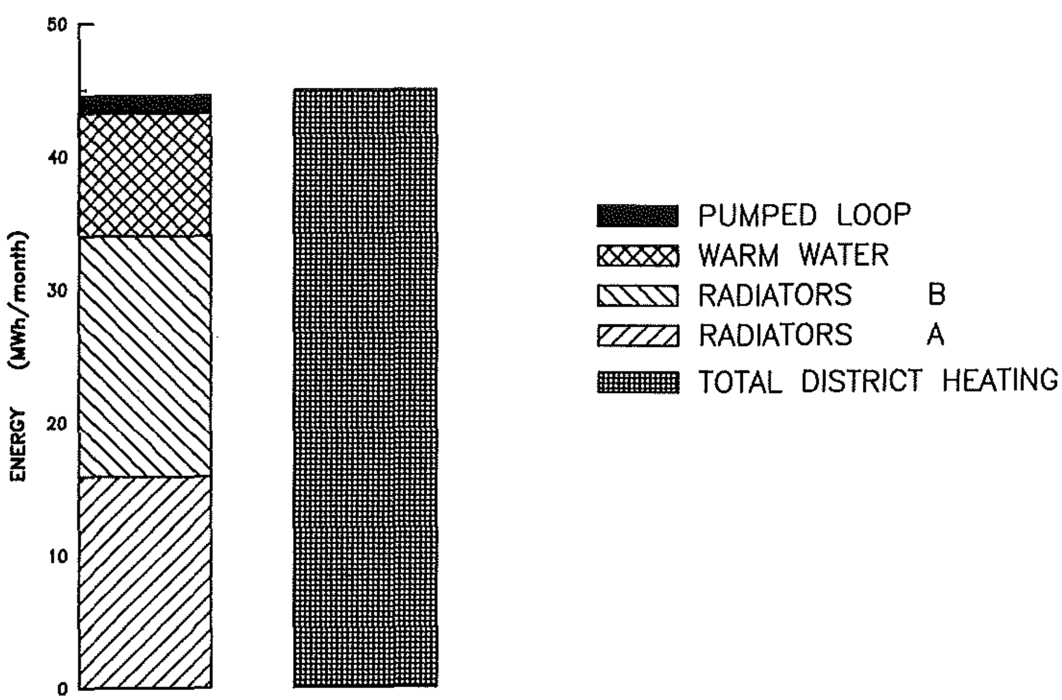

Figure 2. Total district heating in Konsolen building, March 1-31, 1985, broken down by end use

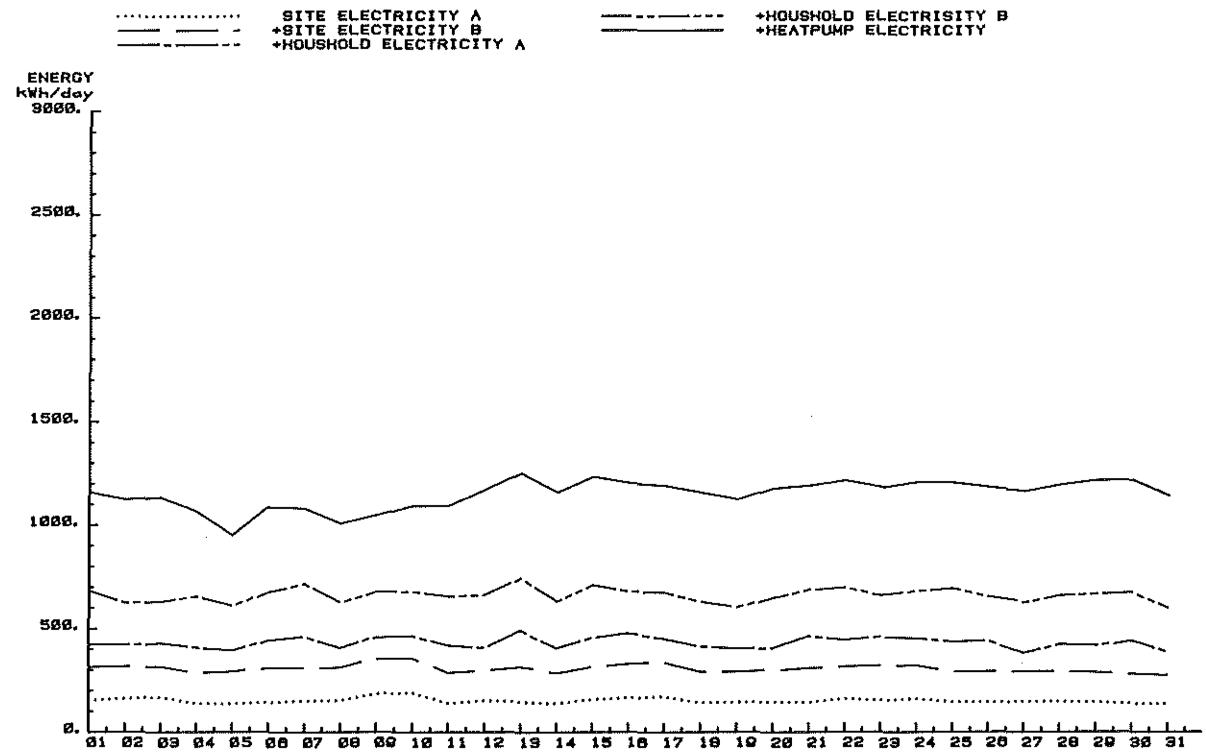

Figure 3. Time variation of electricity use in Konsolen building, March 1-31, 1985, broken down by end use

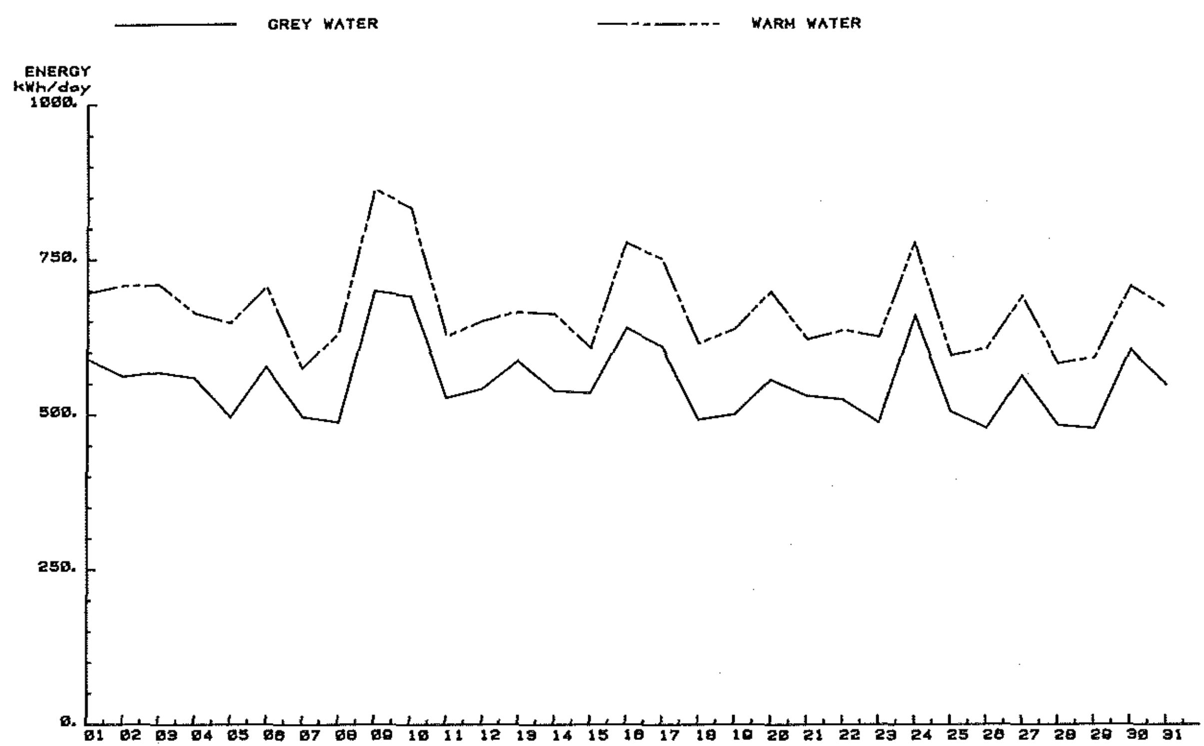

Figure 4. Time variation of grey water losses and domestic hot water use in Konsolen building, March 1-31, 1985

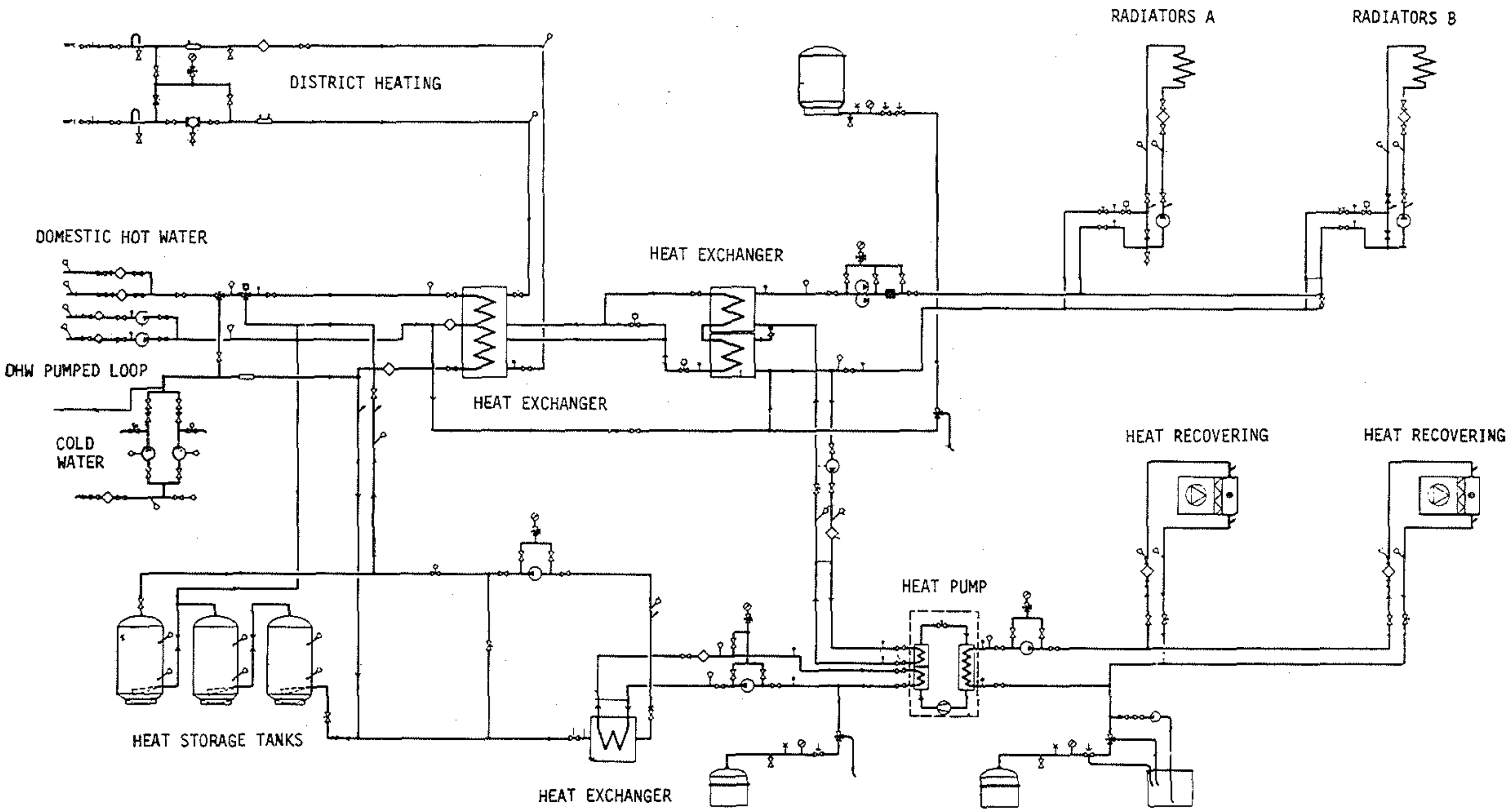

Figure 5. Space heating and domestic hot water systems in Konsolen building

WINDOW U-VALUES: RESEARCH NEEDS AND PLANS

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ABSTRACT

Recently, there has been significant interest in developing a standard test procedure for determining the thermal transmittance (U-value) and thermal conductance (C-value) of window and window treatment products. Currently, several test methods are used to measure these quantities, and the proponents of these methods do not agree on a standard procedure for measurement. As a result, it is difficult to compare the U-values and overall thermal performance of different windows and window treatment products. This paper discusses the specific research needed to address the above problem, as well as a detailed two-phase program to perform that research.

INTRODUCTION

There is no universal laboratory or field method for measuring U-value (overall thermal transmittance) for fenestration products such as windows, glass patio-doors and skylights. Manufacturers have usually tested their products by one of the following laboratory techniques; a) the AAMA test method (AAMA 1980), b) the ASTM C236 Guarded Hot Box method (ASTM 1985a), or c) the ASTM C976 Calibrated Hot Box method (ASTM 1985b). The differences and the similarities between each of these test methods have been described by Goss (1985).

Because of numerous testing methods, the window U-values obtained from different test methods and quoted in manufacturers' product literature are not necessarily consistant, making the information provided to the consumer unreliable. McCabe et al (1986) compared U-value test data for the same window unit from two laboratories; one following the AAMA test method which uses a perpendicular wind direction to simulate wind effects and the other following the ASTM C236 test method which uses a parallel wind direction. The results were in general agreement for test conditions with essentially zero wind speed on the environmental (cold) side of the window units, but there was a large difference in the results at the ASHRAE winter design wind speed of 15 mph (6.7 m/s).

In subsequent testing of the same window unit in a field calorimeter (McCabe et al. (1984), it was observed that measured wind velocities were almost always below 5 mph (3 m/s) and that variable climatic conditions resulted in considerable scatter in the measured night-time U-values, therefore it was concluded that laboratory testing was the preferred method for measuring U-value of window systems. Based on these field and laboratory test results, a test procedure for measuring U-value of fenestration systems was proposed (McCabe 1984). The test procedure requires the laboratory measurement of both the U-value and the surface heat transfer coefficients for a sealed glazing unit over a range of simulated outdoor conditions of wind speed and air temperature. In addition, the test procedure requires measurement of U-value for a window unit consisting of the sealed glazing unit installed in a sash and frame assembly at a single outdoor condition.

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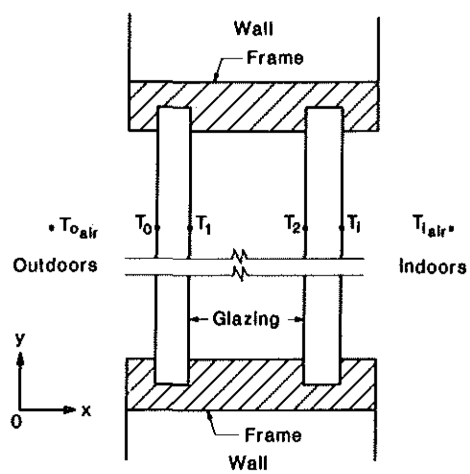
ASTM Committees C16 (Thermal Insulation) and E6 (Performance of Building Constructions) formed a joint task group to modify the laboratory test method of measuring window U-values into a consensus-based standard. That task group is currently preparing a standard practice for measuring the thermal performance of windows (ASTM Committee C16.30 1985). The draft describes the use of both ASTM hot box test methods (C236 and C976) for measurement of window thermal performance. In addition to developing this standard practice, the ASTM C16/E6 joint task group has identified a number of research activities that will determine the adequacy of the proposed standard practice. The purpose of this paper is to describe several of the provisions of the proposed test method and to outline a two-phase research program to assist in development of the standard practice.

REVIEW OF HEAT TRANSFER THEORY APPLIED TO GLAZING UNITS

If the effects of air leakage and solar irradiance are not considered, the rate that energy is transferred through the idealized double-glazed window depicted in Figure 1 is proportional to the inside-to-outside air temperature difference. This is a heat transfer process involving the combined effects of radiation, conduction and convection. Consider the winter time condition at night in which heat from the room air $T_{i,air}$ is transferred to the interior window surface at temperature T_i by radiation and convection. This heat is then conducted through the interior glazing layer to the outer surface at temperature T_2 where it is transferred by radiation and natural convection across the air space to the outer glazing surface at T_1. For a triple or quadruple glazed window, this process continues until the exterior glazing surface at temperature T_o is reached where it is radiated and convected to the outdoor air at $T_{o,air}$. It should be noted that in an actual window system, there are usually additional heat conduction paths through the sealed edges of the glazing unit (not shown) and also through the window sash and/or frame members that support the glazing unit. Thus, the radiative/convective/conductive heat transfer process described above applies only to the center portion of the glazing unit and in determining the overall performance of a window unit, additional consideration must be given to heat transfer via the the frame and edges.



Heat transfer theory relates the steady rate of heat flow through a fenestration system by the following, deceptively simple equation:

$$Q = U\,A\,(T_{i,air} - T_{o,air}) \tag{1}$$

<u>where</u> Q = glazing unit heat transfer rate Btu/h (W),

U = overall thermal transmittance or U-value $Btu/hft^2F (W/m^2{\cdot}C)$,

A = glazing unit heat flow area ft^2 (m^2),

$T_{i,air}$ = indoor average air temperature ^oF (^oC)

$T_{o,air}$ = outdoor average air temperature ^oF (^oC).

The expression for overall thermal transmittance can be separated into the surface heat transfer coefficients and the glazing unit surface-to-surface thermal conductance by the following equation:

$$U = \frac{1}{\frac{1}{h_C} + \frac{1}{C} + \frac{1}{h_H}} \tag{2}$$

where h_C = cold side surface heat transfer coefficient (combined radiation and convection) Btu/hft^2F $(W/m^2 \cdot C)$,

C = glazing unit thermal conductance Btu/hft^2F $(W/m^2 \cdot C)$,

h_H = hot side surface heat transfer coefficient (combined radiation and convection) Btu/hft^2F $(W/m^2 \cdot C)$.

For most glazing systems, the temperature difference across any individual glazing layer is quite small, therefore the thermal conductance can be defined by the following expression:

$$Q = C\, A\, (T_i - T_O) \tag{3}$$

where T_i = glazing unit average indoor surface temperature ^oF (^oC),

T_O = glazing unit average outdoor surface temperature ^oF (^oC).

To adequately measure the glazing unit U-value, accurate measurements must be made of the heat transfer rate, the glazing surface area and air-to-air temperature difference. Since the glazing unit is usually mounted in a wall that separates the hot and cold chamber in most hot boxes, the heat transfer rate through this wall (called a mask wall) must be known since it is subtracted from the total measured heat transfer rate to obtain the glazing unit heat transfer rate:

$$Q = Q_T - Q_{MW} \tag{4}$$

where Q_T = total heat transfer rate through glazing unit and mask wall Btu/h (W),

Q_{MW} = mask wall heat transfer rate Btu/h (W).

Ideally, the mask wall heat transfer rate should be small fraction (<10%) of the glazing unit heat transfer rate and its thermal conductance should be well characterized. This usually requires that the mask wall be constructed of a relatively thick, homogeneous insulating material to minimize the mask wall heat transfer rate, and that its thermal conductivity be measured over a range of temperatures in an accurate instrument such as a Guarded Hot Plate (ASTM C177). The mask wall conductance and its surface-to-surface average temperature difference enable approximate calculation of the mask wall heat transfer rate from a one-dimensional conductive heat transfer analysis, or if more accuracy is desired, from a multi-dimensional conductive heat transfer analysis.

The mask wall heat transfer rate should also be experimentally measured by performing a calibration test so the multi-dimensional heat conduction paths that normally exist at the glazing unit/mask wall interface are determined. The method of calibration of the mask wall can be done in several ways. One method is to place different thickness insulation boards having known thermal conductivity in the window opening in the mask wall. This allows the window flanking heat transfer rate (the three-dimensional heat transfer effects in the window mounting opening area) to be measured. A second method is to use heat flux transducer that has the same general dimensions as the window test specimen. The heat flux transducer is calibrated independently and is then used to calibrate the mask wall. It can also be used to determine the surface heat transfer coefficients for different environmental wind speeds and directions. It is anticipated however, that surface heat transfer coefficients determined for the heat flux transducer and similarly dimensioned insulating glass units (IGUS) may not necessarily represent surface coefficients for other size IGUS or for actual window units.

Temperature measurement is another important factor necessary in accurately measuring window U-value. Typical temperature sensors used in hot boxes are thermocouples which are often constructed from relatively large diameter wire (24-gauge). However, for measuring the surface temperature of window glazings, smaller diameter wire (30 or even 36-gauge) is often used in European laboratories to minimize the effect that the wire might have on the surface convection heat transfer coefficients. As an alternative, NRC/Canada researchers have recommended that the average temperatures of the glazing surfaces be calculated by performing an energy balance on the enclosures on both sides of the test window. This requires that the surface temperatures and emittances of all test chamber surfaces capable of radiant exchange with the test window be accurately measured.

As a final point on temperature measurement, thermocouples are reasonably accurate when used to measure temperature differences. For situations where the absolute temperature rather that temperature difference is desired, thermocouples are less accurate. This can be improved by accurately calibrating the thermocouple/data acquisition system or by substituting more accurate RTD temperature sensors.

RESEARCH PROGRAM FOR DEVELOPING WINDOW TESTING STANDARDS

The first phase of a two-phase program specifically designed to address the above cited research needs for developing window testing standards is currently underway at the thermal measurements laboratory at the University of Massachusetts at Amherst using the calibrated hot box (hereafter called the Research Calibrated Hot Box - RCHB). This phase focuses on measuring the U-values of IGUS for a range of environmental conditions. The following sections present some primary features of Phase 1 research.

Phase 1 Research

Test Facility Modifications. The RCHB will be modified so that both parallel and perpendicular wind directions can be simulated. By using variable speed fans, wind speeds varying between low velocities typical of natural convection up to the ASHRAE winter design conditions of 15 mph (6.7 m/s) will be simulated. With a single test facility providing both parallel and perpendicular wind directions, a direct comparison can be made of the effect of wind direction on the window U-value.

The mask wall used for supporting the test window and for separating the hot and cold chambers is constructed of 6 in (152 mm) extruded polystyrene and covered with 1/4 in (6 mm) plywood faces. The mask wall has a centered opening where the IGUS will be mounted flush with the environmental side surface.

Heat Flux Transducer. The 40 x 40 in (1016 x 1016 mm) heat flux transducer (HFT) used for the Phase 1 research program will be similar in design to the HFT used by NRC/Canada. It consists of a 1/2 in (13 mm) layer of expanded polystyrene and two sheets of glass. Type T thermocouple wire in a thermopile configuration is installed between the glass sheets and the polystyrene. The thermal conductivity of the polystyrene is accurately measured using the ASTM C177 Guarded Hot Plate method. This value, along with the measured temperature difference, is used to determine the heat flux through the HFT. A second heat flux transducer will also be designed and fabricated. This HFT will be more sophisticated in design than the first and will be capable of obtaining heat flux distributions.

Temperature Measurements. Small diameter (30-gauge) calibrated thermocouples will be used to measure the IGU surface temperatures and the air temperature near the IGU surfaces. In addition, the RCHB baffle wall temperatures will be measured so that the IGU surface temperatures can be determined by calculation. Results of this research will provide a technical data base for thermal performance standards for windows, including both calculation and measurement procedures for determination of U-value for a variety of applications. In addition, the IGU will be well characterized and should be quite valuable in the subsequent Phase 2 research program.

Test Specimens. During the Phase 1 program, testing will be performed on the following 40 x 40 in (1016 x 1016 mm) insulated glazing units (IGUS).

1. Standard double glazed unit:

   1/4 in (6 mm) glass - 1/2 in (13 mm) airspace - 1/4 in (6 mm) uncoated glass.

2. Low emittance double glazed unit:

   1/4 in (6 mm) glass - 1/2 in (13 mm) air space - 1/4 in (6 mm) glass with low emittance coating on inner surface.

3. Triple glazed spectrally selective unit:

   1/4 in (6 mm) glass - 1/2 in (13 mm) airspace - spectrally selective, low emittance plastic film - 1/2 in (13 mm) airspace - 1/4 in (6 mm) glass.

<u>Test Conditions</u>. The following matrix of test condition was selected to obtain data relating the sensitivity of IGU test specimens to the environmental conditions:

1. Temperature outside/inside F (^{o}C)

winter:	18/68	(-8/20)
summer:	95/75	(35/24)
fall/spring:	38/68	(3/20)

2. Wind speeds mph (m/s)

free convection	0	(0)
summer design	7.5	(3.4)
winter design	15.	(6.8)

3. Wind direction

   parallel
   perpendicular

4. Position of outside of test specimen (relative to environment side of mask wall)

   flush
   recessed

Phase 2 Research

Specific details for the Phase 2 research program will depend on the outcome of the Phase 1 research program. A broad-based testing and analysis program is envisioned for Phase 2, including continuation of the RCHB testing initiated in Phase 1 and extension of the testing program to include both commercial hot box testing in laboratories and field testing in outdoor facilities.

<u>Research Laboratory Testing and Analysis</u>. The insulating glazing units tested in the RCHB facility in Phase 1 will be further tested in order to enlarge the technical data base from which the thermal performance standards will be developed. In Phase 2, several of the standard 40 x 40 in (1016 x 1016 mm) IGUS will be fabricated into windows by adding sash and frame members composed of wood, aluminum, and PVC plastic. These windows will be tested in the RCHB according to the draft standard practice (ASTM Committee C16.30 1985). Heat transfer models will also be prepared for each window, and analytical predictions will be made for thermal performance. The model predictions and the test results for the IGUS and IGUS with sashes will be compared, and empirical frame adjustment factors established for the different frame materials. This research will assist in development of standard calculation procedures for estimating frame and sash adjustment factors from IGU test results.

The effect of both test specimen size and of slope angle (deviation from vertical) on the U-value will also be determined. Several IGUS differing in size but having the same generic configuration as those tested in Phase 1 will be tested. The IGUs will have nominal dimensions of 24 x 24 in (610 x 610 mm) and 48 x 80 in (1219 x 2032 mm), corresponding to a small window and a large patio door respectively. This testing, which includes window specimens with and without edge framing, will establish 1) sizing effects of the IGU, and 2) sizing effects of the IGUS plus frame on the U-value. In addition, several 40 x 40 in (1016 x 1016 mm) standard glazing units from Phase 1 will be tested at various orientation angles between vertical and horizontal, with heat flow in both the up and down directions. Determination of size and slope adjustment factors are essential in establishing whether or not testing is required for each unique window size and whether or not nonvertical glazing systems, such as those used in artria and sunspace applications, require special testing.

In addition to measurement of window U-Value in an RCHB facility, a certain level of wind tunnel testing appears to be appropriate in order to determine exterior surface convective heat transfer coefficients. Scale model testing will be performed in a wind tunnel for several window/building configurations to determine the distribution of surface heat transfer coefficients with wind speed and wind direction for windows that are either flush mounted or are set back from adjacent building walls. Flow visualization techniques and methods for measuring convective heat transfer coefficients are available for small scale wind tunnel experiments; however, they need modification for full-scale window geometry and typical wind speeds used in hot box testing.

Commercial Laboratory Hot Box Testing. A coordinated research effort, aimed at obtaining operating experience for the new window testing standards in commercial laboratories, is desired for measuring the consistancy between differing test facilities. Previous research (McCabe 1986) indicates that for different laboratory test methods there are substantial discrepancies in U-value measurement for windows. These discrepancies are attributed to different methods of simulating wind and are possibly due to air leakage. To avoid ambiguities in window testing, steps must be taken by the window-testing laboratories to reduce possible air leakage and to verify that the residual levels of leakage are within a tolerable range. In addition, a standard method for calibration of the mask wall and a technique for measurement of surface heat transfer coefficients must be developed. These are considered key elements in the draft standard practice for testing windows and doors. A number of commercial testing laboratories will participate in a round-robin evaluation of the new testing standard for windows, using the IGU specimens from Phase 1. At least two testing laboratories for each type of hot box testing facility will participate, including facilities designed according to the ASTM C236, ASTM C976, and the AAMA test methods.

Field Testing. Several field testing facilities have been constructed, each having different capabilities to measure the thermal performance of full-sized fenestration systems. Performance is measured under carefully controlled indoor conditions with prevailing outdoor conditions of air temperature, wind velocity and solar radiation. The performance data produced by this method of testing are more realistic than those produced by simulating outdoor environments in laboratory facilities. However, outdoor testing inherently results in limited productivity, since relatively long test periods are often required for each test specimen to obtain sufficient test data and time when testing is possible is limited by local climatic conditions. Extrapolation of the test results to other times of year, weather patterns or to other climatic regions is also required.

The IGU test specimens from Phase 1 will be installed in the participating outdoor testing laboratories and tested during both winter-time and summer-time testing seasons. The field test results will be compared with the laboratory test results and the simulation models. Due to complexities in characterizing the exterior thermal boundary conditions in field testing, it is apparent that additional air temperature, air flow and radiant heat flux measurements will be required, which may require new sensors and measuring techniques.

CONCLUSION AND RECOMMENDATIONS

The research plans described in this paper should provide many answers to some of the research needed to provide a basis for window U-value measurements. Once there is a standard method for accurately measuring the thermal performance of window and door systems with no air leakage and solar effects, then several possible uses of the data provided are possible. One use is for comparing the performance of different window and door products for consumer use. A second use is to have well characterized window and door systems for validation of analytical models of fenestration systems. These may be single window models or the window portion of large building energy analysis computer programs.

Once this research is completed and a standard practice is approved, the results should be combined with those studies concerning air leakage and solar transmission. This might be carried out analytically, or it may result in an overall window thermal performance test method and rating system similar to what has been developed for solar collector systems.

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