Energy Performance Monitoring For Passive Solar Residences

Methods used to determine and locate specific data measurement points and specification of data acquisition equipment directly affect the emphasis of a monitoring effort for passive solar residences. Careful selection should be made with full consideration of monitoring objectives and analytical techniques.

THOMAS M. GIFFIN
Associate Member ASHRAE

THE purpose of this article is to describe the methods and considerations employed in the development of a detailed monitoring and evaluation program for passive solar residences. Discussions herein outline the major concerns in selecting equipment and the monitoring of key building components.

Project description

In Upstate New York several hundred passive solar homes have been designed and constructed by Adirondack Alternate Energy. These homes have exhibited extremely low energy requirements for heating and are simple to construct and operate. Key features of the homes are a super insulated envelope, glazing oriented to south, and a unique sand mass storage system.

Under sponsorship by Niagara Mohawk Power Corporation, a monitoring program was initiated by Adirondack Alternate Energy with W.S. Fleming and Associates, Inc. acting as independent evaluators. A single home was monitored to gather sixty-five key temperature and electrical data for a one-year period. Twelve other homes were monitored to collect data for one-to two-month intervals to provide a large profile data base.

The principal objectives of the study were to: 1) provide specific measurement of the overall energy performance for each house; 2) develop an accurate data base to isolate energy performance of building components; and 3) comparatively analyze key component contributions to overall building energy performance.

Data acquisition procedure

At the onset of a monitoring project, it is critical to define specifically the equipment and procedures to be used. Capabilities of the equipment and the data gathering technique should be specified to coordinate directly with program objectives.

Available techniques span a wide range in terms of capability and cost. For example, a basic energy performance evaluation of a passive, or any building, can be performed by simply monitoring the inside and outside air temperatures manually. This technique would require only simple temperature measurement devices and labor. A short-term profile of the building performance could be developed, and this may then be extrapolated to apply to long-term analysis by utilizing standard energy estimating methods (heating degree days, bin temperatures, etc.) which can be modified as required.

Specific procedures for performing this analysis are not typically available, and the engineer would be required to apply considerable professional judgment. Such techniques would be relatively inexpensive, but would provide only an estimate of the long term performance; little would be known of particular component performances.

On the other extreme, more detailed monitoring techniques may be employed. Data logging systems are available which can produce output from strip charts to automatic data averaging and magnetic media storage. Some may also be directly linked to a computer to perform automatic analysis of the data. The equipment available and the cost ranges are quite extensive. Simple strip chart recorders and microprocessor based data ac-

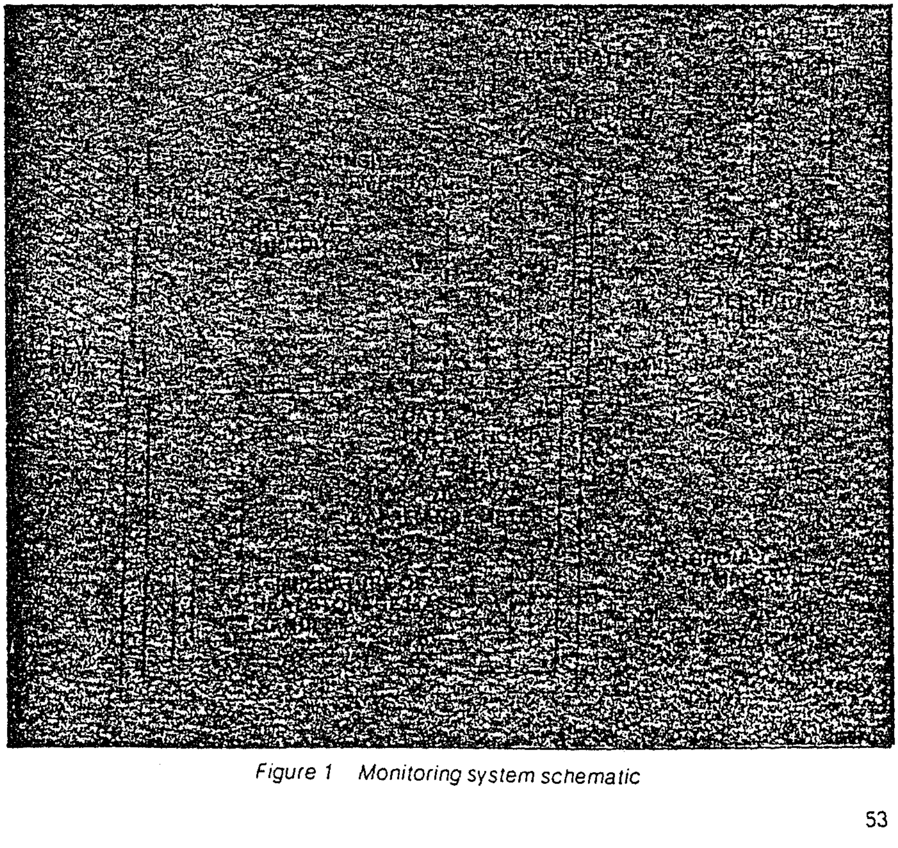

Figure 1 Monitoring system schematic

Thomas M. Giffin is a senior associate with W.S. Fleming & Associates, Inc.

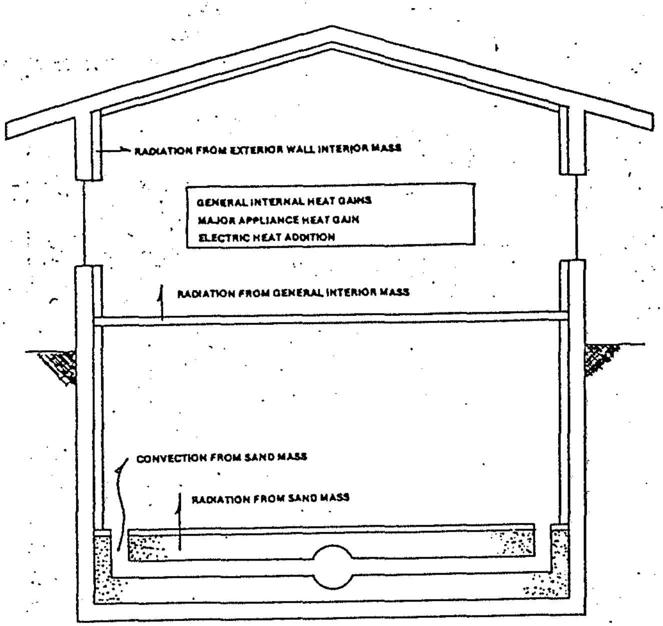

Figure 2 Interior heat transfer components

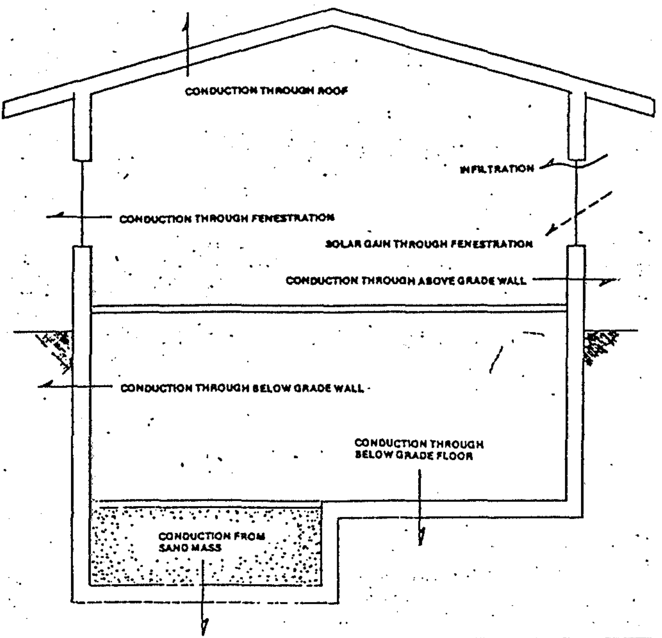

Figure 3 Exterior heat transfer components

quisition systems can be purchased for as little as $1000 to $2000 for application to as many as 20 data points. Systems capable of literally thousands of data points with large computer capacity range from $40,000 and up.

For this particular project, an onsite microprocessor based data acquisition system (DAS) was selected which can monitor up to 100 data points. Fig. 1 illustrates the monitoring system concepts. The cost for the site DAS equipment was $12,000. For analysis and control of the data, a 1200 baud transmission network utilizing common telephone lines was developed to deliver data on a daily basis. This was necessary due to the remote location of the monitored house. To allow for unattended operation of up to twelve days, a dual cassette tape recording unit was interfaced to the DAS. For the homes monitored on a one-to two-month basis, data is stored on cassette tapes to be mailed upon completion. Data reduction and analysis is performed using a 64K microcomputer coupled with a 20 megabyte hard disk. Typical monitoring projects of this scale could not be done expeditiously with a microcomputer without the hard disk or other large storage media due to the sheer amount of data. However, for small efforts a stand-alone microcomputer may be considered. Additionally, a plotter is also interfaced. This latter is practically a necessity when dealing with large amounts of data. The cost of this equipment in total was approximately $13,000.

Data is read by the DAS every five minutes; hourly averages are stored on cassette tape and printed at the site for hard copy back-up. Upon transmission, the data is reduced and checked for accuracy and indication of possible site problems. The DAS has the ability to show alarms in the data. From here, the analysis is performed using software developed exclusively for this project. Commercial software has not been found which can take measured building data and execute an energy performance analysis. However, software packages which allow the microcomputer to act as a terminal, data base management systems and plotting software can be of great value.

Data analysis

The overall goals of the data analysis are: 1) define total building energy requirements—peak, annual, monthly; and 2) isolate building component contributions.

Data analysis is performed by determining the hourly heat transfer of all critical energy transfer components. The heat transfer is calculated on an hourly basis directly from monitored data for each component. Total building heat balance over the long term is then determined by summing the results of each individual component's hourly heat transfer. Illustrations of the heat balance components considered are contained in Figs. 2 and 3.

The heat balance logic of data analysis for the entire building and external effects considers the following general rule: "what goes in must go out and/or must increase internal heat"; or Heat gains + Heat losses + change of state = 0.

Overall, the major analysis logic is to combine monitored data and the laws of heat transfer together to provide an hour-by-hour analysis of building and component performance.

Monitoring strategies for specific components which are critical to passive solar residences' energy performance are detailed next.

Solar gain through fenestration

This is perhaps the most important parameter to be monitored for a passive solar residence, and can be one of the most difficult to analyze. The key result desired is the amount of insolation entering the space on a net basis. Consideration must be given to solar incident angle, glass reflectance and transmittance properties, and interior and exterior shading.

Local horizontal plane insolation data are widely available and are commonly used in many monitoring efforts. However, to use this data to determine the amount of insolation entering the space, particular calculation of solar incident angle and glass properties must be applied. There are software routines developed for these procedures, but many times they are subcomponents of a larger package.

A simplified approach may be used which inherently considers these concerns: placing the solar measurement device on the interior of the glass. In this project, pyranometers are located directly inside glazing on the east, south, and west exposures, mounted parallel to the glazing surface. This sensor placement allows for fenestration transmission characteristics and associated solar incident angle modifications to be included in the sensor's measurement. Also, total sit horizontal insolation is measured t provide a tie to commonly availabl data. If large amounts of glazing on th north exposure are present, or a dif

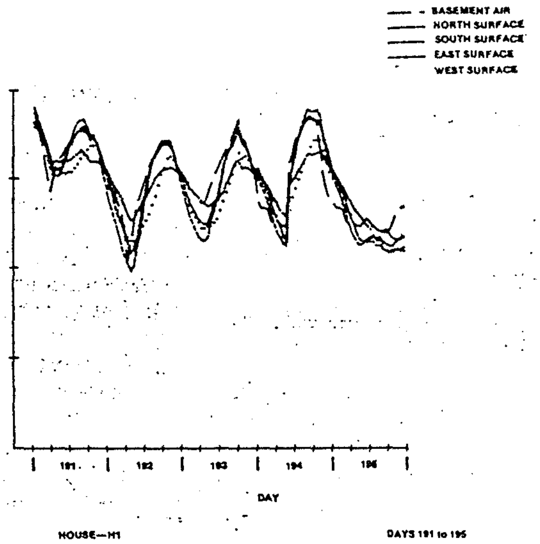

Figure 4 Interior surface vs. space air temperatures

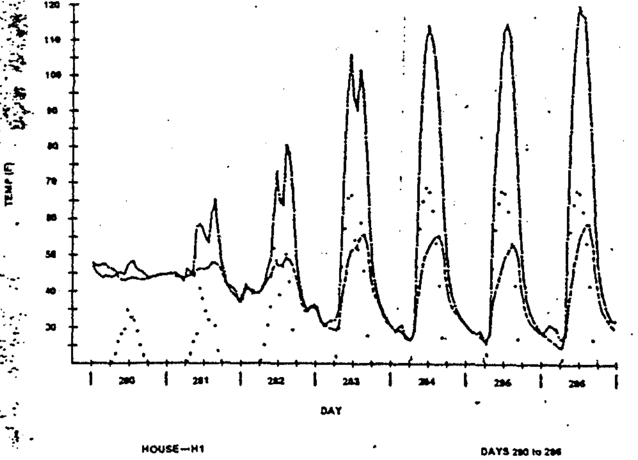

Figure 5 South wall exterior surface vs. outside air temperatures

fuse insolation measurement is required for shaded areas, it is recommended that a pyranometer be located on the north exposure. Otherwise this measurement may be omitted.

If shading due to external devices is a consideration, the solar altitude and azimuth angles must be applied to calculate the shaded area. A true shading determination procedure is a very complicated and lengthy calculation, even with computer assistance. A more common and simple technique is to assume infinite length overhangs and to calculate shading area based on the altitude angle only. For most applications this provides an acceptable level of accuracy.

For interior shading devices, the ASHRAE shading coefficients may be used in a modified form. Since these include the properties of the glazing and the sensor is located behind the glass, this must be adjusted. A simple test to adjust these coefficients for specific shading devices would be to measure the incident solar radiation before and after the shading device. The ratio of before and after insolation is then the applicable shading coefficient. Additionally, the schedule for shading device use should be clearly specified by building occupants. Alternatively, the sensor may be placed behind the shading device. This would allow the shading coefficient and usage schedule to be included directly in the measurements.

Finally, with respect to shading, care should be taken not to locate sensors near the side of the window where indentation may create shadows. Also, external obstructions such as trees and snow should be considered.

Above grade envelope conduction

For simple building analysis, it may be sufficient to determine envelope conduction simply by using inside versus outside air temperature difference. However, this method ignores the effect of insolation and the thermal storage characteristics of the envelope mass. A more exact technique is to measure the inside and outside surface temperatures.

For this project, data points were located on the insulation surface beneath the interior and exterior finishes. Sensitivity studies have shown that the interior wall surface temperatures closely track the space air temperature (Fig. 4), indicating that accurate performance analysis of the envelope can be maintained even if the interior space air temperature is used. However, actual interior surface temperatures are superior. For the outside temperature parameter, observations show that significant variations occur between the south exterior wall surface temperature and the outdoor air temperature. Sample data are presented in Fig. 5. Considering this, it is imperative that the south and roof sections have exterior surface temperatures measured. Measurement of east and west surfaces may be critical depending on the requirements of the monitoring program. The north exposure could in most cases be measured using air temperatures exclusively, since no direct insolation is received on the surface. For conduction through glazing, the inside and outside air temperatures are usually sufficient.

Another factor to consider is the adjustment of the outside surface air film coefficient to the wind speed. However, if the envelope components have a high R-value, the effect of this will be minimal.

Below grade envelope conduction

It is recognized that much discussion has occurred concerning accuracy of the standard ASHRAE conduction methods when applied to below grade surfaces. However, considering the extremely low conductance of the below grade construction and the relatively small temperature differentials, the total building to ground heat transfer is a very small component of the total building heat transfer, so any inaccuracies with the ASHRAE method may be considered negligible. For monitoring programs where below-grade components are critical (*i.e.* earth sheltered buildings) a more detailed analysis method may be required.

For this project, data points were installed at four feet below grade at the mid-point of the basement wall and below the basement floor (below sand mass). (Depending on the particular building being monitored additional points may be required.) It was found that the four-foot temperature varied quite rapidly with the outside air conditions (*i.e.* 3-5 days), while the below-floor temperature remained relatively constant throughout the year. Therefore, if the below grade envelope conduction was a major heat transfer component, more points would be required.

The inside wall and floor surface temperatures were used as the interior parameter, but inside space air temperature would be acceptable as previously discussed.

Internal heat gains

Next to solar gain, internal heat gains are typically the largest heat transfer component in a passive solar home. Measurement of these can be accomplished at a basic level by recording manually periodic kWh meter readings. Higher level automatic monitoring can be done by installing individual kWh meters with pulse output for major appliances, or by monitoring operation time using relays or clocks. Operation time monitoring alone is not recommended because it cannot measure the variable loads present in many household appliances. Lighting and miscellaneous loads may be determined by subtracting the individually-monitored appliances from main meter readings.

Once these data are determined, the analysis should consider the effectiveness of heat transfer to the space of each appliance (percent of electrical energy which is released to the space as heat). The effectiveness of total heat gain to the space can be determined hourly based on a weighted average of all appliances, or can be applied to individual appliances as follows:*

Appliance	Effectiveness
Hot water tank	30%
Dryer	50%
Washer	100%
Stove	100%
Refrigerator and Freezer	90%
Supply Fan	90%
Lighting and Misc. Appliances	95%

Weighting the above ratings by typical annual appliance energy consumptions and comparing these results gave a closure within 3 percent. An average total home effectiveness rating for all appliances (including electric heat) was found to be 68 percent.

Another consideration in determining internal heat gain is the occupancy of the home (including pets). The exact schedule of occupancy is difficult to determine for a long term monitoring program, and is extremely difficult if not impossible to monitor directly. The most practical method is to develop an average profile of occupancy and apply this uniformly over the monitoring period. Although this may introduce some short term inaccuracies in the analysis, they are relatively small compared to other components and will equalize over the long term.

Auxiliary heat

Measurement of auxiliary heat requirements is critical because independently it is the most common scale to compare passive solar homes to other residences.

The measurement technique can be as simple as periodic manual meter readings. However, more extensive techniques are dependent on the type of auxiliary heat. Direct automatic measurement can be made for electric resistance heat by monitoring pulses from kWh meters. Since the system is 100 percent efficient, no efficiency factor needs to be applied. For gas or oil heat, direct measurement of a fuel flow device or system on time is required and a system efficiency must be applied. This efficiency should consider the gross difference between burner and delivered output under actual operating conditions. For wood or coal heat, direct measurement is more difficult, less reliable, and not readily adaptable to automatic monitoring. The weight and quality of fuel burned and the time of fire can be manually logged. Efficiency factors must also be applied.

Direct monitoring techniques can be supplemented by indirect techniques. For solid fuel heat this may be used as a primary method to automatically record data. This would consist of monitoring the inlet and discharge air or fluid temperatures of the heating device. If a variable speed fan, pump, or a gravity system is being monitored, flow rates should also be measured.

Mass storage

For most passive solar buildings, heat storage is typically achieved by two media: 1) general building mass, and 2) specific storage system (sand mass, rock bed, concrete slab, etc.).

The analysis logic for heat storage in masses is to monitor the change in temperature over a specific time period. Most efforts consider a one-hour period within an acceptable accuracy.

The general building mass consists of all materials and furnishings which are located inside of the insulation envelope. Key data necessary to determine the heat transfer of this media are the average mass temperatures of the materials. If the interior surface temperatures are used to evaluate above or below grade envelope conduction, these may also be used to measure the heat storage of the mass on the interior of the envelope. Complete interior masses should also be monitored. The particular location of points should be chosen to correspond with the temperature distribution of the space air temperatures. For a simplified program, the space air temperature can be used in lieu of specific mass temperatures. Although there are time lags between space air and general building mass temperatures, they track very closely. Additionally, over the long term the average general building mass temperatures approximate the space air temperatures, and the net heat transfer of the building mass approximates zero.

The monitoring of a specific storage mass system in a passive solar residence is far more critical than in other buildings. Such systems are designed to provide an inertia to the building to temper the space air temperature swings. Their performance in discharging and charging cycles in reference to the space air temperatures and corresponding insolation levels provides a clear profile of the mass heat transfer characteristics.

To measure specific reactions within the mass, temperatures should be measured on a grid network which corresponds to the design of the mass system, so the stratification between different volumes or layers of mass can be isolated. Additionally, measurements should be taken at several locations over the mass system to determine the relative effectiveness of remote versus close areas in terms of nearness to the heat source, *i.e.*, inlet air temperature. For applications where points are difficult to install (such as with existing buildings) the remote measurements may consist of single points at key locations which correspond to a section of mass with detailed grid layout measurements. The section of mass which contains the detailed grid layout should be in a location that exhibits average heat transfer characteristics.

Heat transfer from the enclosure of the storage mass system, *i.e.*, the top of a rock bed, should be considered. Also, the transfer fluid (if applicable) should be isolated for inlet and outlet temperatures. This can serve as a direct check on the results derived from points located directly in the mass.

When considering the installation of storage system monitoring points, in an existing building, the desires of owners and/or occupants should be carefully considered; often the storage mass is sealed permanently and installing data points requires disassembly or even destruction of parts of the building or its components. These concerns can be foregone if it is possible to install monitoring points during construction.

Testing of the specific storage mass material may also be required if an exact analysis is needed. Tests may include determining specific heat, density, or percent solids.

For this project, a sand mass with buried ductwork comprises the storage system. Measurement points were installed after the building was constructed by drilling a concrete slab and driving sensors into the sand mass. A section of the sand mass considered as average was monitored with a grid

---

**Effectiveness ratings are based on data supplied by the Singer Corp., Lawrence Berkeley Laboratory, and various other sources.*

layout; specific point locations are shown in Fig. 6. A percent solids test was used to determine the compactness of the sand.

For the sand mass analysis, the basic assumption was made that the properties of the monitored sand area are true of the entire sand mass. The volume of contoured sand mass was determined for a one-foot segment of the monitored duct/sand section, then multiplied by the total duct length to find total volume. Volume contours were defined by individual data points so that actual temperature readings could be applied to each. For data points which were relatively far apart and with relatively large temperature differences, intermediate temperatures were averaged between measured data points and applied to the volume segments. The heat transfer of the sand was isolated for each volume segment using these procedures. Heat transferred through the sand mass interior and exterior surfaces has been considered by monitoring inside and outside temperatures relative to the sand mass.

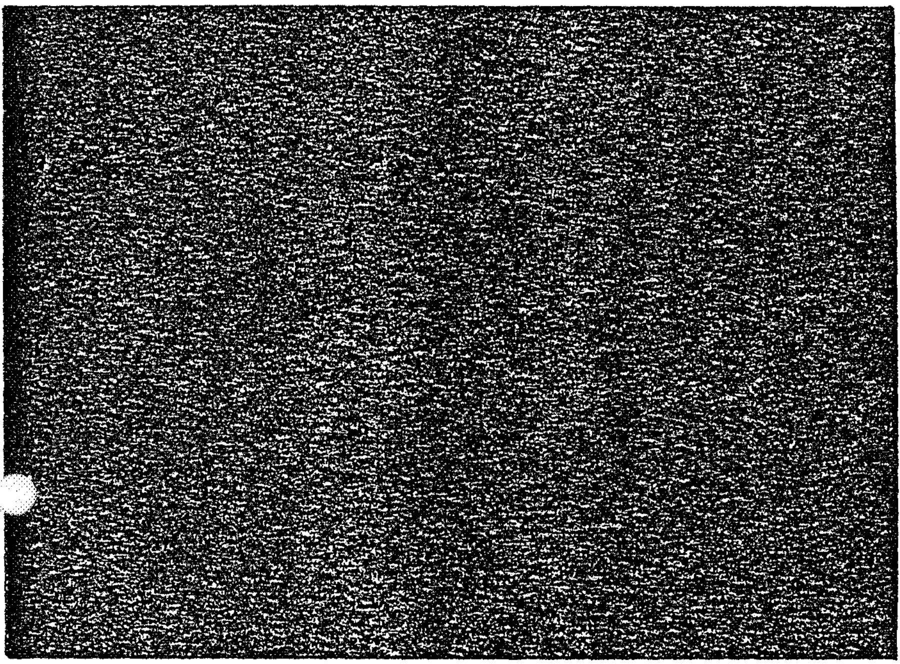

Figure 6 Sand mass thermocouple and segment locations

Infiltration

In comparison to the other components of passive solar building energy performance, the monitoring of infiltration is relatively difficult. At the ultimate level, techniques should consider several parameters: wind speed, wind direction, inside air temperature, outside air temperature, humidity, window and door openings, and building tightness. However, measuring all such parameters continually may be very costly and time-consuming.

One particular concern is the monitoring of window and door openings. Not only are the time and number of openings required, but also the amount of opening. Monitoring this data can be done with relays and/or strip sensor networks, but the reliability, expense, and true need for the equipment must be carefully considered. This level of detail is not necessary for most infiltration analyses. Many times the occupants can simply log the required data with less cost and effort.

For simple analysis of heat transfer due to infiltration, a common practice is to sum all measured component heat transfers and assign the remaining difference from absolute balance (zero) to infiltration. This method may be acceptable if infiltration is not a key parameter in the final analysis. However, even in very tight and well insulated buildings, infiltration can comprise up to one-third of the long term building losses, so this method is advised only for very rough cut analyses.

A blower door test may also be used to determine the effective leakage of a building. This result can then be applied to calculation techniques which incorporate monitored wind speed, and inside to outside air temperature differentials. Methods should provide consideration of infiltration due to direct wind effects and building stack effects. The methods of measurement are relatively inexpensive and have been widely applied. However, it should be noted that this technique is an indirect measurement of infiltration and that assumptions must be applied to adjust general techniques to specific buildings.

A more direct method is using tracer gas techniques. Two methods are available: 1) integrated monitoring, and 2) continuous monitoring.

The integrated monitoring technique can be performed by passive monitoring equipment. This equipment releases a continuous amount of tracer gas and measures the total or integrated tracer gas concentration over a time period, giving data to determine total amount of infiltration. This technique is relatively inexpensive and provides a very direct measurement of infiltration. It is applicable to simple, short term energy monitoring efforts.

Continuous monitoring of infiltration can be accomplished by continuous tracer gas measurement equipment. This equipment releases a continuous amount of tracer gas to maintain a constant concentration and periodically measures and records amount of the gas released. Results can be used to determine infiltration rates for each measurement concentration and provide a direct profile over time. This method is the most extensive of infiltration monitoring techniques and provides results which can be used for long or short term analysis. However, the costs are very high and must be weighed against the goals of the monitoring effort.

For the subject project, the blower door measurement technique was applied. Window openings were considered to be critical, so measurements were taken at several building envelope opening levels. These were then used in conjunction with a schedule of window openings as defined by the house occupants. When performing a total building energy balance, results proved to be quite accurate during periods when the windows were closed. However, the blower door could not measure large effective leakage areas such as when many windows were open, requiring the extrapolation of blower door data, and did not provide accurate results for periods of large window openings.

Conclusions

The methods used to determine and locate specific data measurement points and specification of data acquisition equipment directly affect the emphasis of a monitoring effort. Careful selection should be made with full consideration of monitoring objectives and analytical techniques to be applied. Short term and one-time tests can be extremely useful in determining specific characteristics of building components. The components should be evaluated in relation to the total building at the onset, and integrated throughout the monitoring program. □□