

# Building Performance Monitoring— The Thermal Envelope Perspective—Past, Present, and Future

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## ABSTRACT

Monitored performance results and methodologies from energy-efficient buildings are reviewed in the perspective of determining building thermal envelope effectiveness. The reader is provided with an historical perspective, and current state-of-the art progress is described. Results are reported from exemplary studies that revealed thermal envelope defects were a chief factor inhibiting the performance of many early prototype passive solar buildings. Current work in developing low-cost, short-term measurement methods compatible with both new and rehab residential construction is progressing in both the public and private sectors. Short-term methods like the measured performance rating (MPR) of residential buildings are discussed.

## BACKGROUND AND SIGNIFICANCE

The oil embargo "shock" of 1973 had a significant impact on the pace of research and development (R&D) in the area of energy-efficient buildings, along with many other energy using sectors of the U.S. economy. Prior to the early 1970s efforts had been made to upgrade the insulation levels in residential construction, but the energy crisis quickened the pace greatly. The determination of the effectiveness of insulation, vapor retarders, fenestration, and mechanical systems had, until then, largely been a matter of engineering calculations made to determine whether there would be ample heat available to maintain comfort under design conditions. From the mid-1960s on, mechanical air-conditioning systems began increasing their market share of residential buildings. These systems were designed using methods philosophically similar to the sizing of heating systems, since electricity prices were largely thought of as "affordable."

With the advent of rapid doubling and tripling of fuel prices for residential space conditioning, very pessimistic projections for future energy prices led to the formation of a federal Energy Research and Development Administration (ERDA), which was later given cabinet-level status by the Carter Administration as the U.S. Department of Energy (DOE). The formulation of energy R&D plans by the DOE included significant programs in the area of performance evaluation by both sophisticated computer simulation techniques, and by the instrumentation and monitoring of exemplary buildings and systems designed to save fuels and/or utilize energy from the sun. Many of the building energy monitoring procedures used today sprang from the early investigation of solar heating and buildings technology.

This paper will concentrate on the methods used to evaluate building performance, particularly residential thermal envelope assessment in the whole building perspective.

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## HEATING EFFECTIVENESS MONITORING

Early monitoring efforts to determine the effectiveness of conservation and passive solar designs usually began with detailed calculations of the installed building envelope and solar design features. These calculations were later checked using iterative methods embedded in data analysis software (Weston 1977). The computerized energy balance model based on building plans and site visit information was driven by data on temperatures, auxiliary consumption, status of fenestration and doors, internal gains, solar radiation, and weather. These calculations were derived from ASHRAE methods (ASHRAE 1985) and embedded in analysis software at the hourly calculation level, using hourly site-acquired digital data that had been converted to engineering units. This energy balance approach was used by the National Solar Data Network (NSDN) from 1977 through 1984 (DOE 1980).

By late 1979, studies had shown that a preferred method included a building "co-heating" test to determine its overall envelope load value (Sonderegger et al. 1980) combined with a direct test of the building air leakage rate using a blower door or equivalent test (Sherman and Grimsrud 1980). The results from these two relatively easy to apply tests enhanced the accuracy of monitored load values and reduced the cost of monitoring programs (Palmiter et al, 1979). Another advantage was the ability to drive the software model with fewer field-measured data points. Envelope performance was more accurately analyzed in this manner. The cost of the instrumentation was reduced compared to the earlier NSDN efforts, where as many as 94 sensors were required to obtain a passive solar building's energy balance. The extensive software data manipulation required to "back into" an overall building energy balance between gains and losses was reduced, along with the potential for errors.

The Class B method was developed (Palmiter et al. 1979; Swisher et al. 1982) with the goal of quantifying thermal and solar system performance in a new generation of passive solar homes. These passive homes numbered more than 70 by 1984, and were built in several regions of the U.S. Unfortunately, just as it was getting into full swing, a decision was made to reduce the funding for all solar building programs. A decision was made in 1984 causing the transfer of the Class B program from the Solar Energy Research Institute (SERI) to the home building industry via the NAHB National Research Center.

A disadvantage of the simplified "Class B" monitoring method developed after the NSDN was that it was suited more for light buildings with little intentional thermal storage, such as water tubes, concrete, rock, masonry brick, and/or block mass (Swisher et al. 1982). At NSDN sites that used thermal storage, as many as one-third of the temperature probes were devoted to tracking the heat balances of storage materials. However, as the passive solar design discipline advanced, architects and engineers soon discovered that better insulation, combined with reducing air leakage and somewhat smaller glass areas, resulted in a more balanced overall building system, reducing the size of thermal storage mass needed to dampen temperature swings.

The new industry-based effort, the "Residential Building Thermal Performance Evaluation Program" (Bishop 1984), suffered from more funding cutbacks and a premature expectation that the building industry was ready to pay for private sector monitoring services using methods developed by federal researchers. This was not the case. The NAHB effort was successful, however, in refining and demonstrating enhanced short-term methods, discussed later in this paper, and in developing targeted reports using many SERI results. These builder-oriented reports covered various areas of concern to designers but were never widely distributed.

The "Class A" program, using even more elaborate methods and instrumentation than the NSDN, was developed in a joint effort by SERI, the National Institute for Standards and Technology (then NBS), and a national laboratory with the goal of providing data for validation of computer simulation programs capable of accurately estimating passive solar building performance (Hunn et al. 1982). As a result of monitoring an unoccupied single-family "laboratory" home in Golden, CO, a higher level of detailed data was produced. The data were used to verify the ability of four computer simulation programs--SUNCAT2.4, DOE2.1, BLAST3.0, and DEROB-4--to predict passive solar performance (Judkoff et al. 1983). A detailed validation approach was described, and conclusions showed faulty input assumptions could introduce as much as 60% prediction error into simulation results. Also, researchers found accurate measured temperature data do not "guarantee" accurate load values. Prediction errors were in the range of 10% to 17% even when measured thermal parameters (rather than "handbook" data) were used. Results also showed "microclimates" existed in and around the home, confirming earlier observations from NSDN sites. Key areas for further Class A monitoring research were: corroboration of results with in situ measurements of component thermal conductance, determination of techniques to more accurately estimate solar radiation absorbed by the building and sensitivity of results to sky-model assumptions.

Monitoring efforts were not confined to homes located in the field like NSDN, or to highly instrumented "lab-houses" like SERI's Class A house. A university developed a reconfigurable building, appropriately called the "REPEAT" facility, in late 1981 (Wynn 1983). This facility was used extensively to test envelope design options, window systems, indoor convection, and other factors affecting building energy use.

The Los Alamos National Laboratory was also involved in monitoring efforts. Its investigations began with the construction and instrumentation of seven two-bay test cells, with a fixed "control" bay, capable of running 13 separate experiments under actual weather conditions (Balcomb et al. 1977). These test cells were monitored nearly continuously from 1976 through late 1983 for a variety of federal solar energy and private industry research, development, and product demonstration purposes. The data from these test cells were used as the basis for the development of the "solar load ratio" (SLR) method, now used in an ASHRAE publication (Jones 1986). The data were also used to confirm the performance of such developments as selective surfaces, phase change storage, and advanced glazings.

Individual efforts by state energy offices to document the performance of passive solar buildings occurred in California (Mahajan et al. 1983) and in Minnesota (Huchinson et al. 1982). The California study included 11 homes that were fully monitored at the Class B level and an additional 52 that were analyzed using Class C methods. Class C analysis is best described as a very detailed envelope energy audit combined with careful performance estimates and the recording of detailed occupant information.

A review of the California findings by others indicated that passive solar designers must be careful not to compromise envelope conservation features (i.e., good insulation and air tightening), window thermal controls need to be operated carefully, thermal storage systems showed no long-term effect beyond one-day (diurnal) heat stored and released, and "optimal" conservation - glass - storage relationships varied by climate region (Duffy and Saras 1981).

In Minnesota, results showed passive solar homes tended to have higher rates of stack effect and wind-driven envelope air leakage than "typical" energy-efficient homes. The measured performance levels of energy use were frequently higher than predictions indicated they should be. Some of the passive solar homes actually exceeded performance targets for energy use, gauged by a "thermal integrity factor" (TIF), which was the Btu/ft<sup>2</sup>/°F value for the homes. This TIF value averaged 2.66 Btu/ft<sup>2</sup>/°F compared to typical homes having looser 6 to 8 TIFs. The TIF values were correlated with the area of south glazing, but not with design-estimated values for TIF. The authors also observed little correlation of occupant influences with performance results (Huchinson et al. 1982).

## UTILITY MONITORING PROGRAMS

Utilities also became interested in passive solar and energy-efficient house performance monitoring. Three of many studies stand out notably for the purposes of this paper.

A project was funded by a national utility research institute at a state university (Peck et al. 1982) to monitor three homes with similar floor plans--one control and two with passive design features--to evaluate the heating and cooling performance of the various strategies.

All three homes have some concrete masonry (C/M) walls, but the solar homes used full masonry walls with exterior insulation and filled core voids, while the control home has foam-filled C/M core walls with interior gypsum wall board, and wood frame R-11 walls on only one-third of the exterior. The research institute was keenly interested in the off-peak power implications of the passive design approach, particularly the effects of the thermal storage mass. Winter performance of the passive mass-wall homes was good, and they used less than half the peak total service demand of the control home. However, even though the passive homes (high mass envelope) could be partially cooled by off-peak evaporative means, the mass's cool storage alone was not sufficient to completely offset the following day's entire thermal cooling load. Some additional on-peak operation of the evaporative cooler was needed for comfort. The researchers concluded that thermally massive, off-peak-cooled residences could be beneficial in less humid summer peaking areas if they offset mechanical refrigeration. The envelope's high-mass design had a beneficial impact upon both the summer and winter loads.

Two utility companies joined to build and monitor eight small test homes as a "passive solar test facility" 50 miles outside of San Diego, CA (Clinton 1983). The test buildings were located on a common site, instead of being geographically scattered like other monitoring projects. Interior floor areas were small, at 250 to 270 ft<sup>2</sup> (approx 24 m<sup>2</sup>). Seven of the buildings used typical passive designs, and one was a more conventional control. The buildings were monitored both summer and winter over a three-year period.

In the southern California climate, the insulated buildings with higher mass seemed to be advantageous. The authors recommended the use of movable shutters or shades on the windows to control overheating in the fall on buildings with enlarged glass areas. The utilities are summer peaking, between 1:00 p.m. and 4:00 p.m. local time; thus building designs that reduce demand during this time frame are advantageous. Winter loads peak about 6:00 p.m. to 8:00 p.m. local time, so buildings that can also lower furnace operation until after 8:00 p.m. would be advantageous. The utilities indicated more research is needed, but that a combination of good thermal protection systems and mass and proper fenestration design optimized for the climate could provide significant benefits.

A Colorado utility company studied 21 passive solar homes in the Denver area, and compared their energy performance statistically with three other home samples totaling nearly 500 homes (Corn and Wilson 1983). The net heating use (indexed by a TIF value like that in [Huchison et al.]) of the passive homes was quite low, below that of "well-insulated" homes, at a 1.31 Btu/ft<sup>2</sup>/HDD mean (range 0.19 to 3.22) versus a 3.46 mean (range 0.77 to 6.40) for the well-insulated homes. The envelope R-values for the passive solar and well-insulated homes were quite similar, except the passive solar home roofs had lower average R-values, their floors were better insulated, and walls were nearly identical. In comparison, conventional homes averaged 4.43 TIF and ranged up to 13.20 Btu/ft<sup>2</sup>/°F. The passive homes saved \$315/yr (1983) vs. the "average" utility customer's home. The best performing passive solar homes were also those that were well insulated, a consistent finding throughout all the studies reviewed.

#### PASSIVE SOLAR STUDIES--DATA COMPARISON

A data base was developed which now contains analysis results from more than 100 passive solar monitored homes, including those specifically cited in this paper. This information was first reported in a paper (Howard 1983) that came about as the result of a conference panel discussion on the "super-insulation vs. passive solar" issue. Criteria for inclusion (there are more than 400 "monitored" passive houses that we know of) included some measured auxiliary energy use and an attempt had to be made to calculate an "energy balance" on the building to determine errors. The author has added to the data base from 1981 to the present time, with a goal of 200 homes upon which statistical analysis may be performed.

Analysis of the data indicates that a balanced mix of envelope conservation, passive solar design, and appropriate mechanical sizing and distribution produces the best results. In comparing passive solar and super-insulated homes, if one considers only the purchased specific heating energy, both approaches can provide similar numerical results, that is, low fuel consumption. If the measure is confined to steady-state envelope thermal integrity, not including the solar energy net gains, then the passive home looks less efficient. There is evidence that floor-area-based internal loads from lighting in super-insulated homes are greater. However, if envelope loss rates are very low, this heat may meet the heating load. Using the data base results from 72 residential examples of the 100 buildings, relationships of measured parameters to one another were plotted, following unsuccessful attempts at curve fitting. In no case for the 72-home population are any correlations significant at the 95% interval. However, this finding itself may be indicative of the general nature of most of the passive solar homes reviewed--they are all unique designs.

Figure 1 shows the measured seasonal heating loads vs. heating degree days base 65°F (18.3°C). A descending "cap" on the thermal integrity factor as a function of degree days is observed. No homes are observed to have a value of greater than 8.0 Btu/ft<sup>2</sup>/HDD beyond 6500 HDD base 65°F. In milder climates below 3500 HDD base 65°F, a wide range of integrity values seemed to have been "acceptable" to designers. Bear in mind that a home designed to the 1989 CABO-Model Energy Code (CABO 1989) should have a building thermal integrity value of about 3.75 to 4.5 Btu/ft<sup>2</sup>/°F, depending on climate location.

A comparison of the solar heating fraction (SHF%) based on monitored energy balance results was made with the measured auxiliary consumption (Figure 2). The SHF here is the portion of the total building thermal load supplied by solar gains to the building, not solar gain compared to just the mechanical load or to the load of the non-solar portion of the envelope. Auxiliary consumption (load), in this case, is defined as the efficiency-corrected intentional purchased energy for heating. Homes with high auxiliary loads always had lower solar fractions above about 3.0 Btu/ft<sup>2</sup>/HDD. As auxiliary loads diminished, the range of solar heating fractions widened and the average shifted up slightly. The home with the lowest solar fraction had a higher than average auxiliary use, but the highest auxiliary user had a fair 30% solar heating fraction. These results indicate that designers of some homes missed obtaining a balanced relationship between envelope thermal integrity and passive solar heating during the planning phase. The buildings in this data base were all designed and built between 1976 and 1985. One might expect a different pattern to emerge in a sample screened for homes designed more recently (since the advent of PC-based design aids and industry-based "builder guidelines").

To save energy and ensure comfort using both good insulation and effective passive solar design in some roughly optimal and climate-responsive combination, the relationship between auxiliary heat required and the building thermal integrity might be a linear one. The sample data indicate most, if not all, of the buildings save one had a sizable solar contribution (Figure 3). However, below 5.0 Btu/ft<sup>2</sup>/HDD building load factor, the auxiliary energy requirement quickly drops off. In the buildings with greater envelope losses, the auxiliary loads are higher and very widely scattered. Some buildings with poor thermal integrity (greater than 7.0 to 8.0 Btu/ft<sup>2</sup>/HDD) indeed had reduced auxiliary loads due to solar, but were also those that tended to have wider thermal swings and potential summer cooling problems, according to the data.

These early efforts were instructive on the relative merits of various design theories in passive solar homes. However, much remains to be done to improve both energy-efficient buildings and methods we use to understand their performance. The latest efforts to enhance building monitoring will now be reviewed.

## **MONITORING PROTOCOLS FOR BUILDING THERMAL PERFORMANCE**

New data specification protocols were developed through DOE sponsorship to identify the critical parameters needed to evaluate the retrofit performance of single-family and multifamily buildings (Ternes 1987; Szydlowski and Diamond 1989). The data specification guidelines offer superior standardization, which may facilitate data exchange within the research community. An interest in obtaining sufficient data in a short test period for the prediction of long-term building thermal performance led to the development of short-term test methods.

### **SHORT-TERM TEST METHODS**

Short-term methods using test periods on the order of one night to three days to obtain empirical information for predicting the thermal performance of a building are a recent development. Short-term test methods are derived from two general approaches--predictive computer simulation models and long-term performance monitoring. Predictive simulation models used to provide heating and cooling efficiency estimates ranged from relatively simple methods, such as the Solar Load Ratio (SLR) (Balcomb et al. 1977; Jones 1986) method, to detailed computer simulation models such as DOE 2 (Los Alamos National Laboratory 1980) and SERI-RES (Palmiter and Wheeling 1980).

In concept, short-term test methods utilize the advantages of both approaches, i.e., the speed and low cost of the predictive simulation methods and the accuracy of long-term performance monitoring. The general idea of a short-term test method is to perform a series of tests on a building, extract the appropriate thermal parameters from the data, and use the thermal parameters in a simulation tool for prediction of thermal performance. The result is a quick, relatively inexpensive, and reasonably accurate set of building performance data.

Today, many short-term test protocols utilize an electric coheating test. This technique was developed as a diagnostic tool and was first utilized to determine the in situ thermal response of a building (Sonderegger et al.

1980). In early 1980, the Class B program performed electric coheating tests on all its homes. The coheating tests were used to define the building load coefficient (Btu/°F), a vital thermal parameter in determining the thermal behavior of a building. The building load was then computed during the monitored period by multiplying the coheat test result by the monitored indoor-outdoor temperature difference ( $\Delta T$ ). In addition, the Class B monitoring program measured instantaneous air leakage by the blower door test. Infiltration was also estimated by tracer gas analysis.

Various methods to obtain a short-term empirical measure of a building's thermal mass were devised soon after the demise of the Class B program, which did not monitor thermal storage effects. A "cool-down test" was one technique that was developed during this period. The cool-down test is performed immediately after the coheating test following a time period when the indoor air and thermal mass are in equilibrium (Kelley et al. 1984). In the absence of solar and internal gains, and with reasonably stable ambient temperature and wind, the indoor temperature decay is characteristic of the building capacitance, and its time constant may be calculated. The cool-down test is the simplest method to empirically measure the thermal capacitance.

The building capacitance has also been measured using Fourier analysis (Subbarao et al. 1985). This technique requires a slightly longer test period of several days. Results have indicated that the thermal capacitance could be well determined by varying a known sinusoidal heat input into the building.

## **CURRENT SHORT-TERM TEST METHODS**

Work in building performance monitoring led to the development of a series of short-term tests that could be implemented to obtain empirical measures of building parameters. Empirical information about a building, such as the load coefficient, air leakage and infiltration characteristics, and effective thermal capacitance, are obtained by the dynamic analysis of measured performance data for a building. Given the measured performance data, and what can be learned about the physical characteristics of the building envelope and its energy systems, a model is developed and refined using the monitored data. This is generally known as the inverse problem, in contrast to the forward problem, where the building description is known and a designer subsequently obtains energy information to enhance the description and to project longer-term effectiveness.

Currently, a number of building performance monitoring techniques exist and have been demonstrated to yield reasonably good results. The available methods include thermal networks, differential equations, Fourier analysis, autoregressive moving average (ARMA) models, modal analysis, and detailed computer simulations. A recent overview of the different methods for parameter estimation in buildings showed that although the methods basically are equivalent to the problem of identifying the coefficients of a differential equation, there are many ways of implementing the identification process (Rabl 1987). Similarly, short-term test methods also are basically equivalent in problem identification but differ in implementation of the identification process.

### **The BTR Meter Development**

A transient analysis procedure can be used to measure the overall building thermal resistance (BTR) (Janssen and Rasmussen 1985, 1988) or the inverse of its loss rate. In this procedure a furnace-off period of 90 minutes followed by a furnace-on period of 90 minutes was sufficient to separate the envelope heat storage effects from the heat conduction through the building shell. An instrument called a BTR meter was developed to control the procedure and calculate the results automatically. The BTR meter is intended to measure the insulation in existing buildings and to measure the effectiveness of energy conservation measures. Measurements on three homes agreed with ASHRAE method (ASHRAE 1985) heat loss calculations within -6% and +9%.

### **PSTAR (STEM)**

A test protocol for short-term energy monitoring (STEM) based on an energy balance equation called PSTAR (primary and secondary terms analysis and renormalization) has been successfully used to determine energy

performance of both typical light frame and high-mass passive solar homes (Subbarao et al. 1988; Subbarao 1988). PSTAR estimates parameters of a relatively complex building model from measured data obtained over a short period. The protocol calls for a detailed audit description of a building's walls, glazings, mechanical systems, and other key parameters. Using a computer simulation code, heat flows are calculated based on the audit description under the driving functions measured during the tests. Primary heat flows are adjusted (renormalized) with the measured parameters to obtain a least squares fit for the energy balance.

The PSTAR test protocol requires a brief (approximately three-day) period that is "relatively" sunny along with one night of coheating and one night of cool-down to provide data necessary for the parameter estimates. In addition, one night of heating system operation may be needed to determine the heating system efficiency. A one-time blower door test is performed and the LBL model (Sherman and Grimsrud 1980) is used to estimate infiltration. Long-term extrapolation of building energy efficiency is performed using long-term weather data.

In 1987-1988, this test method was performed on three homes. Measured PSTAR (STEM) results differed from the audit results, as might be expected, due to a number of factors such as uncertainties in the building audit description, audit R-values, and infiltration. In general, the PSTAR (STEM) approach appears to be a useful tool. Future research plans are to investigate the sensitivity and repeatability of the methods and to extend it to provide cooling season performance estimates.

### **BEMA (Building Energy Performance Monitoring and Analysis)**

From 1984 to the present, a prototype procedure for evaluating the space-conditioning efficiency of existing buildings has been developed by an industry-based thermal performance evaluation program and tested in three homes (Duffy and Puri 1985; Spears 1985; Duffy and Saunders 1987). A simplified thermal network model of two resistors and one capacitor was used to model a simple building. The protocol involved only one night of monitoring for a light frame one-zone home. The tests included a coheating test to estimate the heat loss coefficient in conjunction with a tracer gas infiltration test to identify the infiltration component of the heat loss coefficient.

Unlike Class B methods, the building heat balance was more accurately predicted by measuring thermal mass surface temperatures and accounting for charging and discharging from the mass. A blower door test was performed and the LBL's model (Sherman and Grimsrud 1980) was used to predict infiltration rates. The infiltration model was later refined with the tracer gas test results. A useful thermal capacitance value was measured by a cool-down test. The gains and losses of the solar aperture and effects of fixed shading devices were considered. The estimated building parameters from the tests were used with long-term weather data to predict the heating load of the home and to estimate a normalized building performance index (Btu/ft<sup>2</sup>/HDD).

The results were relatively accurate and the method appeared useful (Duffy and Saunders 1987). Table 1 shows the predicted space-heating load of the three homes calculated by the ASHRAE degree-day method (ASHRAE 1985) based on actual measured weather data, actual interior setpoint of the home and the thermal parameters estimated by ASHRAE methods, and the short-term test method compared to the measured space-heating load for the same heating season (1985-1986). Specific information on the homes is contained in Duffy and Saunders (1987). From Table 1 it is apparent that use of the thermal parameters determined by BEMA lead to closer correspondence in estimated space-heating energy to measured space-heating energy in two of the three homes. For the three test homes, the predicted building performance index differed from the measured heating season average value by no more than 4%. Although the sample of three homes is small, the results suggest that the BEMA procedure may be useful.

A more recent study, developed to evaluate the accuracy and repeatability of short-term test methods, compared PSTAR and BEMA (Palmiter et al. 1988). A detailed simulation model simulated the results of the short-term test methods. In summary, the PSTAR annual heating load predictions showed relatively high accuracy with a standard deviation of no more than 3% for three prototype homes. The BEMA annual heating load predictions produced satisfactory results for the typical light frame prototype (standard deviation was less than 2%) and for the super-insulated prototype (standard deviation was less than 3%); however, the results for the high-mass, solar-driven prototype had a high standard deviation of 12.7%. Since BEMA was developed to test typical light frame construction, these results are not altogether surprising.

Given all of the available short-term test methods, one might ask which method will provide the best results? The answer to this question is not yet known. However, a short-term test method may be suitable for a given application. The preference in choosing a short-term test method may be determined by the length of time one is able to test, the cost, and the application the user wishes to address.

## **FUTURE RESEARCH AND BENEFITS**

### **MPR--Measured Performance Rating**

Currently, testing is under way on a short-term test method called MPR (measured performance rating), an extension and refinement of BEMA, for evaluating the effectiveness of weatherization retrofits and determining the measured energy performance rating of new homes. Ten new homes and eight newly weatherized homes will be tested over the 1989-1990 heating season. Repeatability tests will be conducted at two control homes that will be continuously monitored. The results of the MPR project will be a system consisting of a semi-automated hardware/software package that provides a measured performance rating of the building envelope and its heating system, and an uncertainty analysis of the data produced. The system is designed to provide both analytical output and direct digital control of the monitoring process in a self-contained, user-friendly package. The intended users of the system are primarily state weatherization professionals. In addition, builders, realtors, designers, buyers, appraisers, policy makers, etc., may also benefit from use of such a system in lieu of calculations to verify the energy efficiency of homes, such as those intended to be eligible for "energy-efficient mortgage programs." In addition to the MPR analysis, further plans are to perform PSTAR on the project's control homes. The results of the PSTAR and MPR analyses will be compared to the continuously monitored data and to each other.

## **CONCLUSIONS**

### **Benefits to Building Envelope Systems Analyses**

Short-term test methods have a number of applications in the assessment of building envelope performance. In summary, short-term test methods:

- Appear useful in predicting long-term performance of new and retrofit construction;
- May evaluate the effect of building envelope conservation measures if the tests are performed before and after weatherization;
- Are a first step toward an overall measured energy rating for building thermal envelopes;
- Can perform diagnostics of HVAC systems;
- Can be relatively low-cost and easy to implement; and
- Can be conducted in one night for simple buildings.

The limitations of short-term test methods may be summarized as follows:

- They currently do not adequately address the prediction of long-term cooling performance;
- They are not performed during actual periods of occupied use; and
- For simpler short-term methods, they do not account for solar and internal gains without some type of simulation or statistical model.

### **Historical Monitored Results**

Several conclusions about thermal envelope design in residential buildings can be reached using information from monitoring programs. Enhanced envelope thermal protection should take first priority in the design phase. Today, good methods exist for taking a balanced approach to envelope and passive solar design criteria, such as the ASHRAE publication on the topic (Jones 1986), so neither solar or building loads need be accentuated.

Total thermal storage requirements tend to diminish at higher building thermal integrity levels. The intrinsic mass in exterior construction materials and the heat capacity of building contents should be taken into account. The designer may find they are a more cost-effective source of heat capacity than specific purchased interior "thermal storage" units.

Solar building orientation can be quite important, particularly if it has a higher envelope load and larger solar fraction. One of the worst performing homes in the data base (Howard 1983) had an orientation 42° off equatorial bearing and rather large glazing areas. However, on building lots where views or other matters take precedence, getting to within about  $\pm 30^\circ$  of equatorial bearing is thought to be adequate.

Well-insulated walls deserve glazings of superior thermal resistance. There tended to be an emphasis on quantity rather than quality of glazings in earlier passive solar buildings. Today, glazings of up to R-6 to R-7 are available or may be fabricated at low cost to complement thermally "tight" construction. Such fenestration may provide significant net gains throughout the heating season in temperate climates, and can resist unwanted cooling loads.

Lastly, the internal gains from appliances, lights, and persons were shown to add 12% to 37% of the total building load. These gains become an appreciable portion of the cooling load in summer. Consideration of energy-efficient appliances and light fixtures can reduce this portion of the overall load significantly. Designers should not become so consumed by the building as a "heat engine" that fundamentals of comfort and aesthetics are lost.

### Future Programs and Needs

Short-term test methods and programs under development are undergoing further testing and validation. Additional short-term tests of the MPR approach during periods of occupancy will be completed in the near future. Further comparisons of short-term test methods need to be conducted. Accurate short-term test methods should be transferred to weatherization practitioners, utilities, state energy offices, and other interested users. In the next few years, as more technology transfer occurs, we expect to see more practitioners using short-term test methods.

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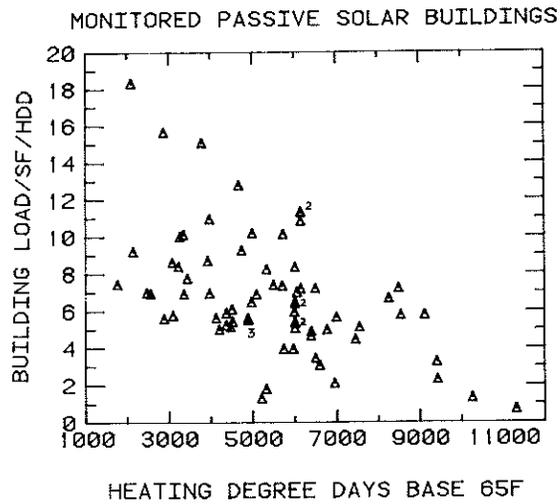
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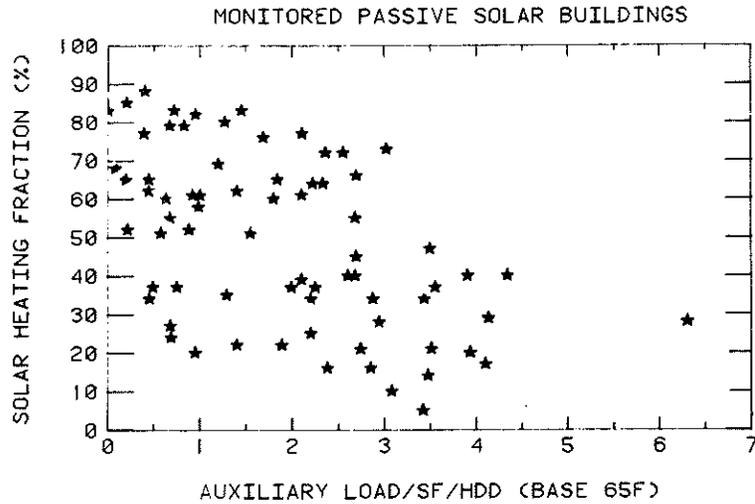
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**TABLE 1**  
**Predicted Results Compared to Monitored Results**  
**(Duffy and Saunders 1987)**

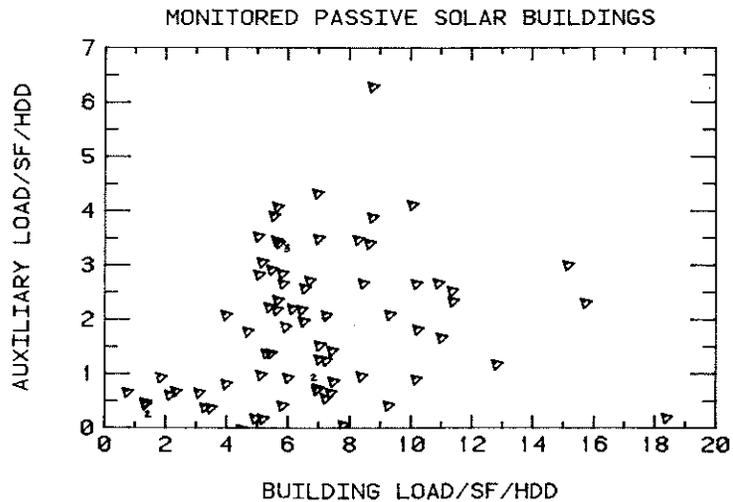
<u>Predicted Results</u>	HOME 1		HOME 2		HOME 3	
	ASHRAE Parameters	Experimental Parameters	ASHRAE Parameters	Experimental Parameters	ASHRAE Parameters	Experimental Parameters
<u>ASHRAE Design Method</u>						
Space Heating Energy (MMBtu)	53.4	50.3	71.8	80.5	145.5	103.8
BPI (Btu/ft <sup>2</sup> .HDD)	53	50	73	70	90	64
<u>Monitored Results</u>						
Space Heating (MMBtu)	HOME 1		HOME 2		HOME 3	
	52.5		79.4		99.1	
BPI (Btu/ft <sup>2</sup> .HDD)	5.2		6.0		6.2	



*Figure 1. Building envelope load index versus heating degree days*



*Figure 2. Solar heat fraction versus measured auxiliary use index*



*Figure 3. Measured auxiliary use index versus building envelope load*