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PSTAR — Primary and Secondary Terms Analysis and Renormalization

A Unified Approach to Building and Energy Simulations and Short-Term Testing

A Summary

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PREFACE

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

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

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

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

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

The research described in this report was supported by the Office of Solar Heat Technologies. It was performed as part of the Short-Term Energy Monitoring (STEM) project. The goal of the project is to develop, field test, and transfer to industry a technique for assessing the energy performance of a residential building through short-term tests. Extensions to nonresidential buildings, especially for control and diagnostics of heating, ventilation, and air-conditioning systems are planned for the future.

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ABSTRACT

This report summarizes a longer report entitled PSTAR - Primary and Secondary Terms Analysis and Renormalization: A Unified Approach to Building Energy Simulations and Short-term Monitoring, SERI/TR-254-3175. These reports highlight short-term testing for predicting long-term performance of residential buildings. Our efforts resulted in developing a test procedure and analytic tools.

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1.0 GENERAL SUMMARY

Testing and monitoring the energy performance of buildings has several important applications, among them: extrapolation to long-term performance, refinement of design tools through feedback from comparing design versus actual parameters, building-as-a-calorimeter for HVAC diagnostics, and predictive load control. The primary emphasis of this report is on short-term testing for predicting long-term performance of residential buildings. A test procedure and analytic tools were developed.

A dilemma arises when analyzing building energy. The thermal response of a building is complex and, therefore, requires complex models; however, the parameters obtained from fitting to performance data were, so far, generally based on gross oversimplifications. If more realistic models are attempted, the parameters are so poorly determined that they make the entire parameter estimation process suspect. This dilemma is resolved by the analytical tool developed here, called the Primary and Secondary Terms Analysis and Renormalization (PSTAR). PSTAR ensures a meaningful estimation of parameters of a realistically complex building model from few data channels over a short period (a few days). This is accomplished by starting with an "audit" description of the building--nominal description of walls, glazings, etc. Heat flows are calculated for this audit building under the driving functions measured during the tests. Because the audit description is, in general, different from the "as-built" description, the aforementioned heat flow terms will not satisfy the energy balance equation. The primary heat flow terms are renormalized so that the renormalized energy balance equation is best satisfied in the least squares sense. Hence, the name PSTAR. (PSTAR is derived from an earlier method--Building Energy Vector Analysis, BEVA. Significant modifications were made over the years.)

From a user's perspective, the PSTAR process can be envisioned to consist of entering a quick audit description of the building into a microcomputer. The output consists of a test protocol that comprises the electric heater power needed, the profile of indoor temperature and heat input, the expected duration of the test, etc. A one-time infiltration test is performed, and the sensors and data acquisition system are set up. This can be accomplished in less than half a person day. Testing of the building (preferably unoccupied) continues as the computer acquires data and performs on-line analysis, uncertainties, etc. The testing ends when the results are deemed satisfactory.

Figure 1-1 schematically shows the software for the above process. The first version of the software is scheduled for distribution in the near future. Reports on application to real buildings are available.

The PSTAR process is very flexible. For example, sinusoidal heat input tests are not necessary unless accurate values of certain parameters are needed to compare the design versus the actual performance. In nonresidential buildings, such tests are generally not feasible.

By combining realistic building models, simple test procedures, and analysis involving linear equations, PSTAR provides a powerful tool for analyzing building energy as well as testing and monitoring. It forms the basis for the Short-Term Energy Monitoring (STEM) project at SERI.

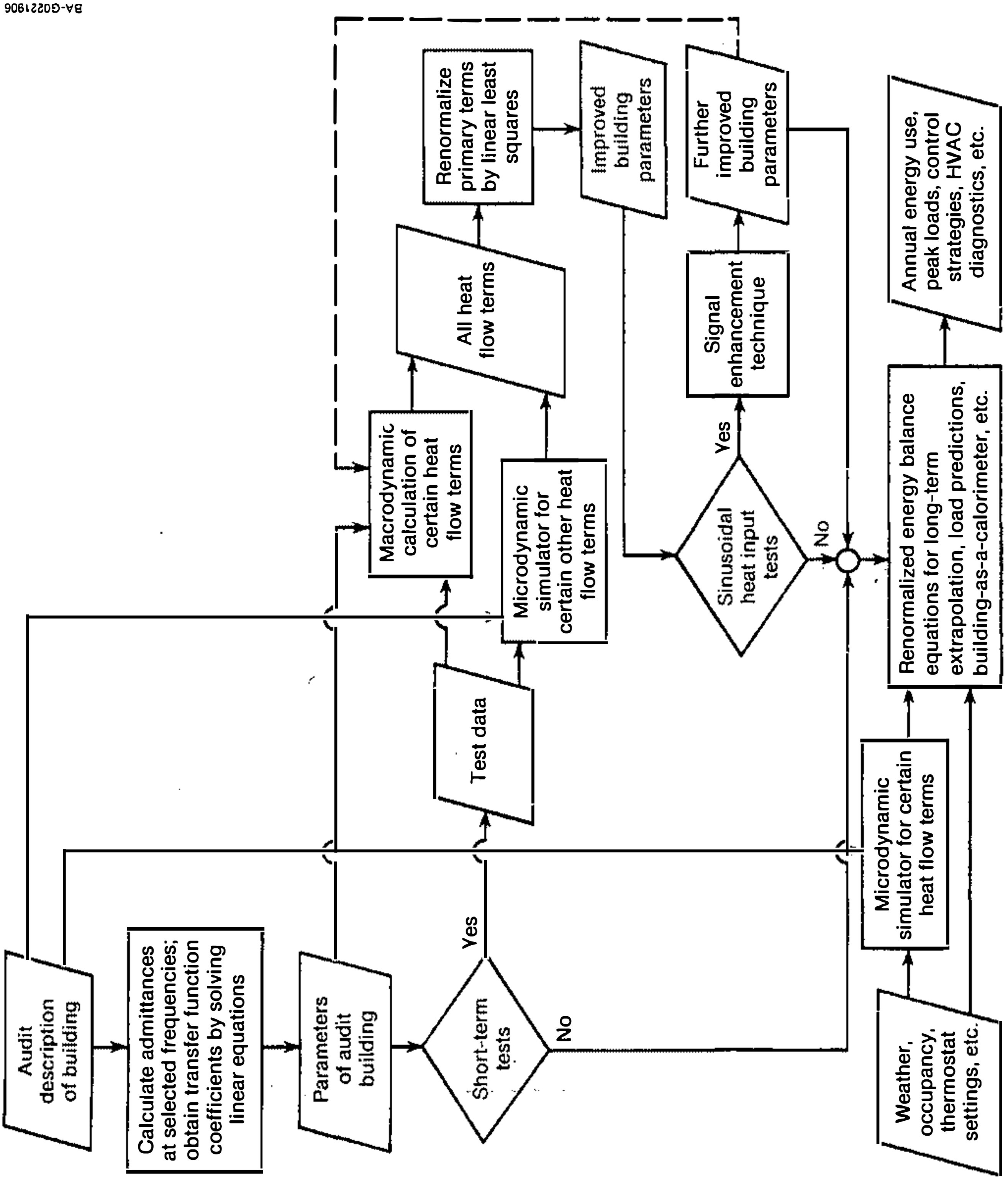

Figure 1-1. Flowchart for PSTAR Software

2.0 TECHNICAL SUMMARY

The PSTAR process is based on relatively simple ideas; however, putting these simple ideas into practice is quite complex. The software for a variety of applications was developed.

Our primary emphasis is in analyzing performance data even though PSTAR, being an hourly simulation, is applicable to design problems. Although a graph of the various terms in the energy balance equation (Eq. 2-1) helps us understand how the different forces influence building performance even in the design stages, we will discuss the application to performance evaluation. More specifically, we will focus on short-term tests on a building to evaluate its parameters for long-term performance extrapolation, building-as-a-calorimeter, peak-load determination, etc.

Instead of treating the building as a "black box," we begin with a quick audit description of the building. The building is thus treated as a "gray box." The quick audit description allows us to prepare the inputs rapidly for an hourly simulation such as SERIRES (detailed in the longer report entitled PSTAR-Primary and Secondary Terms Analysis and Renormalization: A Unified Approach to Building Energy Simulations and Short-Term Monitoring). Although the audit description is imperfect (that is the reason for testing the building), it provides two important pieces of information: (1) solar geometry for gains from multiple orientations and shading, and (2) relative distribution of qualitatively different types of masses (for example, mass in concrete walls and in frame walls). The qualitative aspects of this distribution are insensitive to details, thereby allowing a realistically complex model of the building without too many parameters to be determined from performance data. The mathematical formulation of this idea is through transfer function renormalization and is detailed in the longer report. This technical summary presents the basic ideas in general terms by using two example buildings.

2.1 First Example Building

Consider a one-zone building with a slab-on-grade floor. This can be a residential or a nonresidential building. (Multizone buildings are incorporated into the PSTAR framework, but we will not discuss them in the examples here.) The energy balance for the building can be written, under certain mild assumptions, in the following form (we used the heating season terminology; modifications for cooling season are straightforward):

$$Q_{int}(t) = L[T_{in}(t) - T_{out}(t)] + Q_{storage}^{in}(t) + Q_{storage}^{out}(t) - Q_{sun}(t) + Q_{vent}(t) - Q_{aux}(t) + Q_{ground}(t) + Q_{sky}(t)\,, \qquad (2\text{-}1)$$

where

Q_{int} = internal gains

L = skin loss coefficient; so the first term denotes the heat loss in the absence of storage effects, T_{in} represents the inside temperature, and T_{out} the ambient temperature

$Q_{storage}^{in}$ = net heat that goes to charging (or, if the term is negative, discharging) the masses caused by inside temperature variations only

$Q_{storage}^{out}$ = net heat that goes to charging (or, if the term is negative, discharging) the masses caused by outside temperature variations only

Q_{sun} = net heat gain by the indoor air node caused by the combined action of sun and solar-radiation-coupled capacitances

Q_{vent} = heat loss caused by infiltration and ventilation

Q_{aux} = heat supplied by the heating system

Q_{ground} = heat flow to the ground

Q_{sky} = heat loss caused by sky temperature depression.

This decomposition of heat flows is extremely useful. Physically, a heat flux meter mounted on a wall would measure the net effect of all the driving functions (T_{in}, T_{out}, sun, etc.) on that particular wall.

Let us consider each one of the terms. Q_{int}, the internal gains, are treated as known; during short-term testing (in an unoccupied building) it consists of electrical heat introduced through computer-controlled heaters to follow a specific profile (constant temperature, sinusoidal heat input, etc.). In nonresidential buildings, where introduction of electrical heat may be impractical, the Q_{int} term may consist of known heat input through the HVAC system.

The term L (T_{in} - T_{out}) is the steady-state loss to outside air.

The term $Q_{storage}^{in}$ is obtained by (1) fitting the admittance (with respect to inside temperature) at selected frequencies and (2) combining the result with the present and past values of the inside temperature.

The term $Q_{storage}^{out}$ is obtained in the same manner as $Q_{storage}^{in}$ with the replacement of T_{in} by T_{out}. This term is typically much smaller than $Q_{storage}^{in}$.

The term $Q_{sun}(t)$ is obtained as follows: perform a simulation with $T_{in} = T_{out}$ = constant (and no internal gains, etc.); the resulting cooling load gives $Q_{sun}(t)$.

The term Q_{vent} is obtained as follows: through a one-time test involving blower door or tracer gas in combination with a suitable model giving the dependence on T_{in} - T_{out} and wind velocity, determine this heat flow. A simpler option is to write this term as an unknown constant times a known function of T_{in} - T_{out} and wind speed (and obtain the unknown constant along with many others from a fit to performance data). An even simpler option is to assume a constant infiltration, in which case this term can be absorbed in the loss coefficient. In nonresidential buildings, this term is obtained either through measuring airflow or by performing tests under conditions of relatively small infiltration. (Once the building parameters are evaluated, the building-as-a-calorimeter technique can be used to study this term.)

The term Q_{ground} consists of a constant term (during short-term tests) plus a fast response term; the latter can be absorbed in $Q^{in}_{storage}$.

The Q_{sky} term represents the heat flow caused by sky temperature depression. This heat flow is generally small but if, during the short-term tests, the sky is unusually clear or cloudy the effect on long-term extrapolation may be significant. This term is obtained much like $Q^{in}_{storage}$ or $Q^{out}_{storage}$ except that the driving function is sky temperature depression.

Typically, the terms $L(T_{in} - T_{out})$, $Q^{in}_{storage}$, and Q_{sun} are primary terms. The terms $Q^{out}_{storage}$, Q_{sky}, and Q_{ground} are secondary. The terms Q_{int} and Q_{vent} are measured terms. For simplicity, we will assume in this summary that $Q_{aux} = 0$; this term is discussed in greater detail in the longer report.

Because we expect the actual building to differ from the audit one, Eq. 2-1 will not be satisfied by the various terms previously obtained. We will introduce renormalization parameters for the primary terms and estimate them from a linear least squares fit:

$$Q_{int}(t) = p_o\, L\, [T_{in}(t) - T_{out}(t)] + p_{in}\, Q^{in}_{storage}(t) + Q^{out}_{storage}(t)$$

$$- p_{sun}\, Q_{sun}(t) + Q_{vent}(t) + Q_{ground}(t) + Q_{sky}(t) \ . \qquad (2\text{-}2)$$

The three parameters, p_o, p_{in}, and p_{sun}, are determined from a linear least squares fit (usually, the residuals are autocorrelated; using generalized least squares provides an improvement). There are certain requirements on the data to elicit the renormalization parameters. These requirements, in turn, are translated into a test protocol. The protocol follows from the renormalized energy balance Eq. 2-2.

This linear least squares fit implies several assumptions. For example, the $Q^{in}_{storage}(t)$ term has only a scale factor, therefore, the time phasing of the charging and discharging given by the audit description is not subject to modification. This can be easily accommodated by further decomposing the $Q^{in}_{storage}$ (t) term and introducing independent renormalization of the various parts. If it is necessary to modify the time phasing of $Q_{sun}(t)$, it is handled somewhat differently. One nonlinear parameter known to be in the range 0 to 1 is introduced. One can perform a linear fit with this parameter held at various values in the range 0 to 1 and the best bit picked. In other words, the important property of linearity is maintained at all stages, achieving an unambiguous estimation of parameters.

There are several obvious generalizations. For example, if the building is heated by a furnace and if the heating system (i.e., furnace plus distribution system) has a constant efficiency η, then the Q_{aux} term can be written as η times the gas input $Q_{gas}(t)$. The system efficiency η can be obtained as an additional parameter in the linear regression.

Once the parameters are determined, Eq. 2-2 allows the building to be used as a dynamically calibrated calorimeter. If, for example, all terms except Q_{vent} are known, the ventilation term can be determined. Long-term extrapolation with thermostatic constraints is straightforward.

2.2 Second Example Building

The second building to be considered is a residential building with a basement. Much of the discussion for the first example is applicable here with some modifications. The heat balance equation for the living zone is now modified to be

$$\begin{aligned} Q_{int}(t) = {} & L[T_{in}(t) - T_{out}(t)] + Q^{in}_{storage}(t) + Q^{out}_{storage}(t) \\ & - Q_{sun}(t) + Q_{vent}(t) - Q_{aux}(t) + L_B\,[T_{in}(t) - T_B(t)] \\ & + Q_B^{storage}(t) + Q_{sky}(t)\ , \end{aligned} \qquad (2\text{-}3)$$

where the subscript B denotes the basement. The living zone is now driven by two temperatures, the outside temperature and the basement temperature. Because the basement temperature tends to be relatively constant, the $Q_B^{storage}$ (t) term will be quite small.

Equation 2-3 must be supplemented by an energy balance for the basement. Because the basement temperature tends to be a constant and because many of the thermal characteristics of the soil are unknown, a simple model is usually adequate. One such model was discussed. The main reason for performing an energy balance for the basement is to predict the basement temperature. If this temperature is known from measurements, or is estimated from some other means, it is not necessary to perform an energy balance for the basement.

As usual, renormalization factors are introduced as necessary for the primary heat flow terms in Eq. 2-3.

The above procedure was extended to multizone buildings. By identifying combinations of heat flows that are primary and secondary, it is easy to introduce renormalization parameters for the primary heat flows.

Note that at every stage of the calculation (fitting the admittances at multiple frequencies and estimating parameters), only a solution of linear equations is involved. Thus, the often insurmountable problems of solving nonlinear equations are avoided.

The PSTAR approach entails an intricate synergistic combination of microdynamical calculations, macrodynamical calculations, and performance data. This synergism allows for the complexities needed to model buildings realistically and maintain a small, manageable number of parameters to be estimated from performance data. This synergism can be expected to be equally important in analyzing performance data from other complex systems such as active systems, and moisture absorption, desorption, etc.

3.0 WORKED EXAMPLE

The PSTAR process consists of the following steps:

- Identify all the heat flows relevant for the building (Eqs. 2-1 and 2-3). Identify each term as primary, secondary, or measured.
- Obtain the audit description needed to calculate the primary and secondary heat flows.
- Determine a test protocol to elicit the renormalization parameters as well as to obtain the measured heat flows.
- Obtain the test data.
- Calculate the heat flows for the test period.
- Obtain the renormalization parameters for the primary terms from linear least squares (generalized linear least squares may be necessary if the residuals are autocorrelated).
- Use the renormalized energy balance equation for the intended application: long-term extrapolation, building-as-a-calorimeter, or predictive load control.

Let us demonstrate a simple example using computer-generated performance data.

- The building is a one-zone structure with two types of walls subject to an artificial weather with constant T_{out} and no solar radiation. The only terms of interest are Q_{int}, $L(T_{in} - T_{out})$, and $Q^{in}_{storage}$; the first term is measured and the latter two are primary. The energy balance equation is

$$Q_{int}(n) = L\,(T_{in}(n) - T_{out}) + Q^{in}_{storage}(n) \ . \qquad (3\text{-}1)$$

- Table 3-1 gives an audit description of the building. The two walls combine enough complexity to highlight some of the main features.
- The issue of optimal protocol for a given application is quite intricate. Some general considerations as well as suitable protocols are discussed in the longer report. For this simple example, we will use data under normal operation of the building.
- Figure 3-1 depicts test data over a 54-hr period.

Table 3-1. Audit Description of Example Building

Layer	Material	Thickness (ft)	Conductivity (Btu/h·ft·°F)	Density (lbs/ft^3)	Specific Heat (Btu/lb)
a. **Frame Wall:**	Inside film conductance: 1.7 Btu/h ft^2 °F				
1	Drywall	0.0417	0.3	50	0.24
2	Insulation	0.293	0.032	3.5	0.17
3	Sheathing	0.0417	0.035	10	0.2
4	Wood Siding	0.0833	0.08	20	0.3
b. **Storage Wall:**	Outside film conductance: 3.5 Btu/h ft^2 °F Inside film conductance: 1.7 Btu/h ft^2 °F				
1	Concrete	0.3	1.2	80	0.2

Outside film conductance: 0.4 Btu/h°F (corresponds to double glazing)

Area of Frame Wall: 1000 ft^2
Area of Storage Wall: 500 ft^2

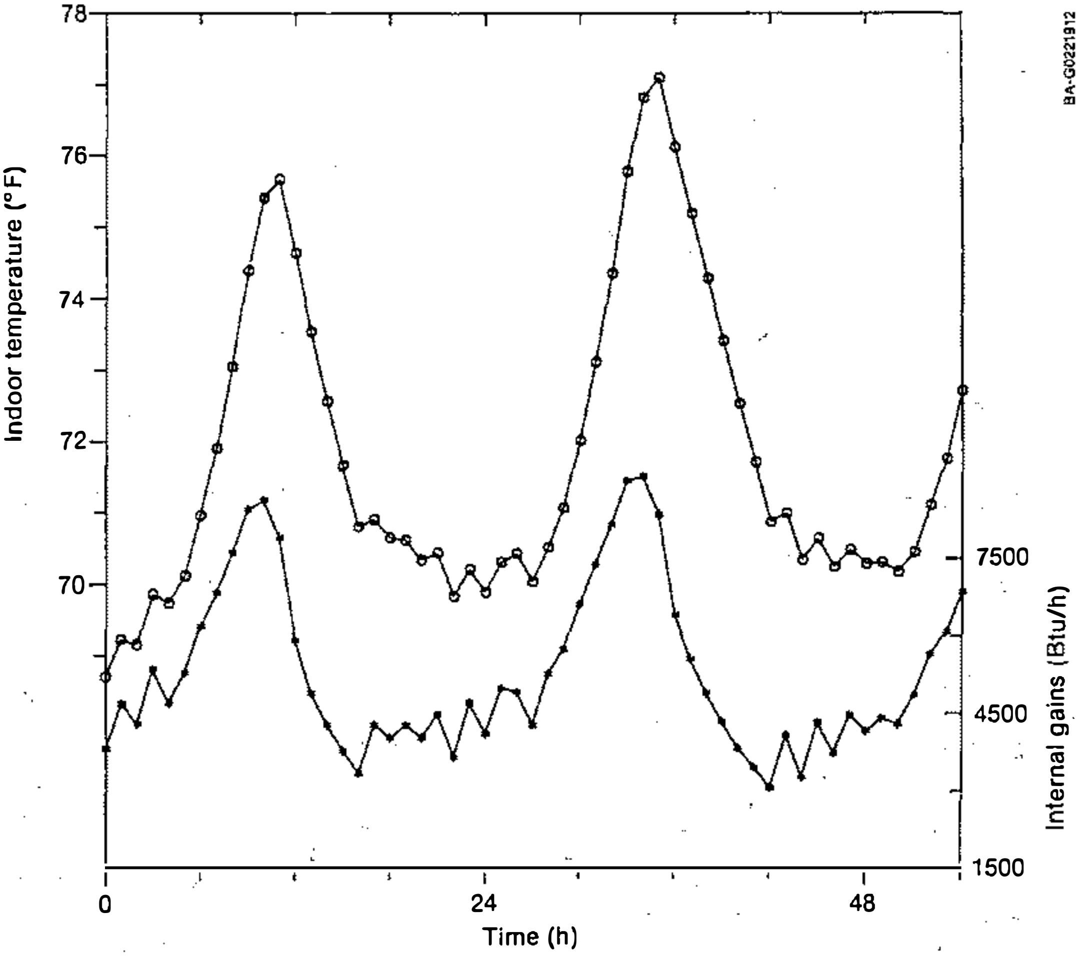

Figure 3-1. Performance Data for the Example Building. (The outdoor temperature is a constant at 45°F and solar radiation is set to zero.)

- The loss coefficient of the audit building is calculated to be 230.4 Btu/h °F. The term 230.4$[T_{in} - T_{out}]$ is given in Figure 3-2. Also given in Figure 3-2 is $Q^{in}_{storage}(n)$. This is calculated by fitting the admittance with respect to inside temperature at two frequencies, the 4-day cycle and the 12-hr cycle (for reasons discussed in the longer report). The storage term can be written as

$$\begin{aligned} Q^{in}_{storage}(n) = {} & \beta_1 T_{in}(n) - (1-\alpha_1) [T_{in}(n-1) + \alpha_1 T_{in}(n-2) + \dots \\ & + \alpha_1^{n-3} T_{in}(2)] - \alpha_1^{n-2} T_{in}(1) \\ & + \beta_2 T_{in}(n) - (1-\alpha_2) [T_{in}(n-1) + \alpha_2 T_{in}(n-2) + \dots \\ & + \alpha_2^{n-3} T_{in}(2)] - \alpha_2^{n-2} T_{in}(1) \end{aligned} \qquad (3\text{-}2)$$

with $\alpha_1 = -0.3252$, $\alpha_2 = 0.6643$, $\beta_1 = 644.7$, $\beta_2 = 508.8$.

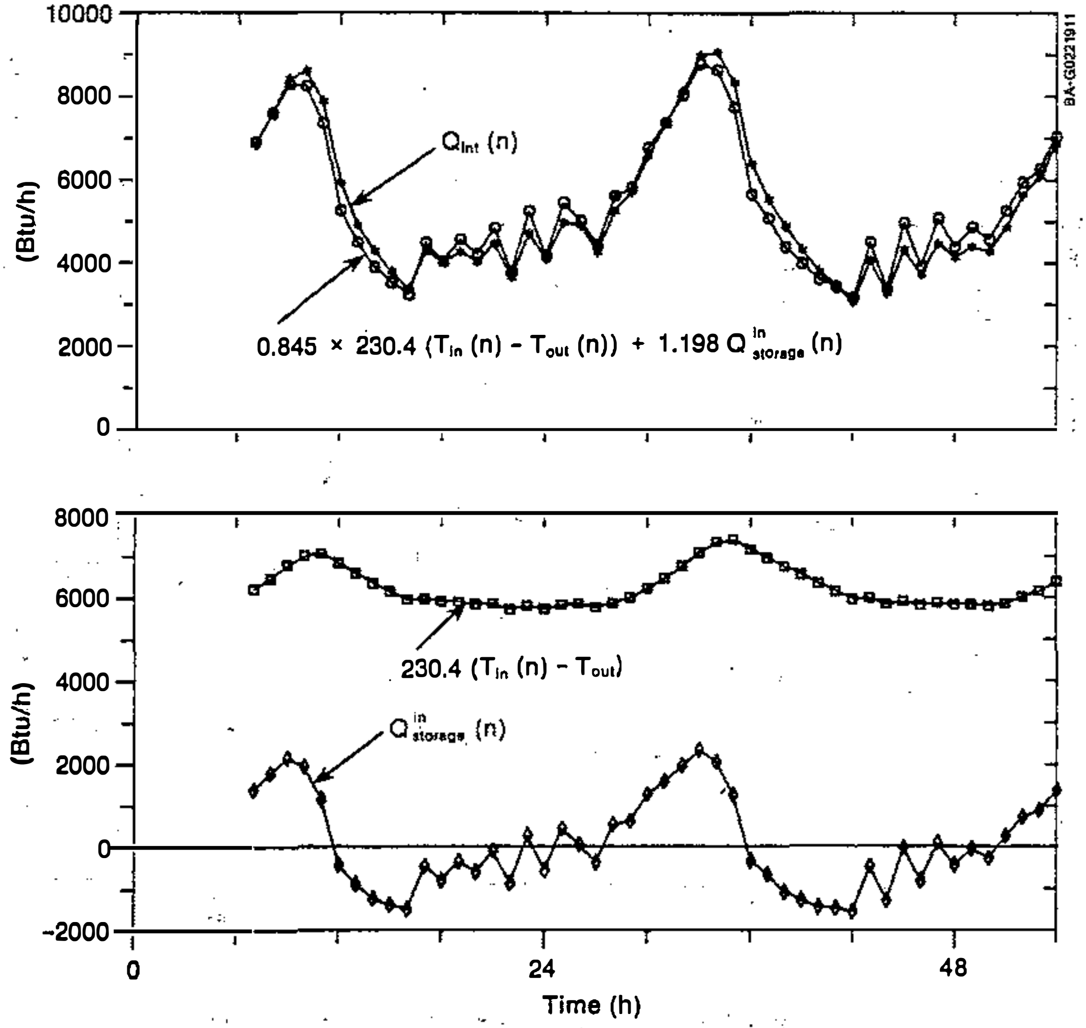

Figure 3-2. The Individual Heat Flows and a Linear Least Squares Fit to Q_{int}

- The renormalized energy balance equation is

$$Q_{int}(n) = p_o L \left[T_{in}(n) - T_{out}\right] + p_{in} Q^{in}_{storage}(n) \qquad (3\text{-}3)$$

  A linear least squares fit is performed between the hours of 7 and 54. The first six hours of data are used to minimize the effect of the initial conditions. By introducing additional parameters to account for initial conditions, we can use all the data. It is sometimes simpler to have fewer parameters while using up some of the initial hours of data. (In the longer report, additional parameters were introduced to estimate the initial state of the building, and the fit was done between the hours of 1 and 54. This accounts for the small differences in the numerical results as well as the graphs between this summary and the longer report.) This gives $p_o = 0.845$ and $p_{in} = 1.198$.

  This tells us that the performance data require that the actual building have a loss coefficient of 0.845 times the audit value, i.e., a value of 194.7 Btu/h °F. The heat storage efforts of the actual building are 1.198 times that obtained from the audit description.

- Equation 3-2 provides a complete description of the building for a variety of applications.

Before closing, we will give a way of improving the building parameters without introducing additional parameters. This is based on a signal enhancement principle. From Figure 3-1 we can see that there is a dominant diurnal frequency component. So let us write

$$Q_{int} = Q_{diurnal}(n) + Q_{residual}(n) \; . \qquad (3\text{-}4)$$

Let $T^{residual}_{in}(n)$ be the temperature response to $Q_{residual}(n)$ as given by Eq. 3-3. Then $T_{in}(n) - T^{residual}_{in}(n)$ is the response to $Q_{diurnal}(n)$. The quantity $T_{in}(n) - T^{residual}_{in}(n)$ should be a diurnal sine wave; one can fit this to a diurnal sine wave. From the magnitudes and phases of $Q_{diurnal}(n)$ and the diurnal fit to $T_{in}(n) - T^{residual}_{in}(n)$, we can determine the admittance at the diurnal frequency. The value obtained from this signal enhancement procedure is usually quite accurate. In the example building, a value of $733.4 \times |\underline{37.7}^\circ$ was obtained. This is a significantly better value than the admittance at the 24-hr cycle implied by Eq. 3-2.

The numerical data were actually generated by a simulation of a building with two walls of quite different material properties than those in Table 3-1. The loss coefficient of this actual building was 192.8 Btu/h °F and the diurnal admittance was $728.3 \; |\underline{38.2}^\circ$.

The quantitative values of the loss coefficient and the diurnal admittance can be combined with the qualitative information of mass distributions, given from an audit description, to provide the response at any frequency that, in turn, can be used to provide improved estimates of $Q^{in}_{storage}$ for practical calculations.

Note that if we posited a one-resistor—one-capacitor model for the building, we do not need any audit information. A regression of $Q_{int}(n)$ versus $T_{in}(n) - T_{out}$, and $T_{in}(n) - T_{in}(n-1)$ gives, respectively, the loss coefficient and the capacitance. The PSTAR analysis, by combining audit information and a complex building model, better accounts for the complexities of the heat transfer process in buildings.

4.0 REMARKS

Equation 2-1 contains some of the commonly considered heat flows. It is easy to include additional terms, as necessary. A formulation for multizone buildings that regroups the heat flows into primary and secondary flows is given in the longer report.

For the example building, no special test protocol was necessary. More generally, in the presence of variable ambient temperatures and solar radiation a proper protocol is necessary. For example, during a period of constant inside temperature at nighttime, the term $L(T_{in} - T_{out})$ dominates over other terms, and thus its renormalization factor (and consequently the loss coefficient) is expected to be well determined. During a cool-down period at night, the $Q^{in}_{storage}$ term (in addition to $L[T_{in} - T_{out}]$) dominates, and its renormalization factor is expected to be well determined. A period of sinusoidal heat input (away from the diurnal frequency) gives an excellent determination of the admittance at that frequency with respect to the inside temperature. We can then adopt a protocol in which there are "windows" of data in which a smaller number of parameters are determined, and design an analysis that sequentially and iteratively determines all the parameters. Feasibility of the test as well as the importance of a parameter for a given application lead to an appropriate protocol.

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By combining realistic building models, simple test procedures, and analysis involving linear equations, PSTAR provides a powerful tool for analyzing building energy as well as testing and monitoring. It forms the basis for the Short-Term Energy Monitoring (STEM) project at SERI.

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