Short-Term Energy Monitoring for Commercial Buildings

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The short-term energy monitoring (STEM) method, having been successfully applied to more than 50 residential buildings, has been extended to commercial buildings, starting with units in the 5000 to 15000 ft^2 range. The method provides the ability to disaggregate and understand building heat flows to a degree that had not previously been demonstrated and with much greater accuracy. This is done through a formal process that leads to a calibrated simulation model of the building providing the ability to separate cause and effect in complex heat flow situations. With such calibrated models, whole buildings can be commissioned and the effectiveness of individual demand-side management measures can be identified. Results from the monitoring of four commercial buildings are presented, two in detail. The multi-zone modeling approach is described and shown to notably increase accuracy. In one case, a solar renormalization was possible using a six-zone model that had failed using a one-zone model. Standard errors of all the renormalization factors and the resulting error in energy balance are reduced. The method requires careful measurement of building air flows using tracer-gas techniques in commercial building applications. The STEM method has proved to be useful for diagnosing problems with the HVAC system.

Introduction

Short-term tests (herein called STEM tests) have been performed on both residential and commercial buildings with good success. These tests, which are typically three to five days in duration, are performed with the building unoccupied. The purpose is to determine the principal thermal characteristics of the building and its mechanical system. The result is a calibrated hour-by-hour simulation model that can be used to predict future energy performance, based on typical occupancy assumptions. Other applications include building commissioning, validation of demand-side management (DSM) measures, *in-situ* measurement of HVAC performance, and using the building as a dynamic calorimeter to measure unknown heat flows.

The STEM method consists of two key elements, the test protocol employed and the method used to analyze the data. The test protocol is designed to generate data sequences, both steady-state and transient, that fit the requirements of the analysis technique. The analysis method is called Primary- and Secondary-Term Analysis and Renormalization (PSTAR). It provides a formal approach to the separation of cause and effect in the data. Nine building heat flows are calculated separately, each being heat flow into a thermal zone due to a particular cause (inside-outside temperature difference, solar gains, change of inside temperature, change of outside temperature, etc.). Three of the primary heat-flow terms are adjusted (renormalized) based on results taken during a time period when that term is predominant. The renormalized model can then be used to predict long-term performance, peak loads, or as a tool for measuring an unknown energy flow during another test period.

The STEM method has been demonstrated in STEM tests made on more than 50 houses; validated against long-term monitored data; and used to make in-situ measurements of the efficiency of furnaces and air-conditioners and the effectiveness of cooling strategies, including natural and forced ventilation and solar shading (Balcomb et al. 1993). The purpose of this paper is to describe the application of the method to commercial buildings. This paper will emphasize results from two recent tests. Results from two other tests will be summarized briefly. Significant improvements in the method have been made, greatly improving the accuracy of the results.

Testing Procedure

One or more simple data acquisition systems are temporarily installed in the building (Subbarao 1988). Hourly averages of measured channels are computed and stored. Data channels are typically as follows: several inside air temperatures, outside air temperature, one or more other temperatures (such as a plenum), outside relative humidity, global-horizontal solar radiation, global-vertical-south solar radiation, total electrical power, wind velocity, and HVAC data.

In the residential tests, a one-time air pressurization and de-pressurization test is performed on the building to determine the effective air-leakage area. This is done in the conventional way using a blower door. Leakage area is estimated from a power-law curve fit of pressure difference plotted versus air flow rate. This leakage area is subsequently used in the estimation of infiltration, based on stack and wind driving forces.

In the commercial-building tests, a tracer gas, SF_6, is injected at a known rate into the air stream of the HVAC system, and a multi-point monitor is used to measure the tracer-gas concentrations at other points. These data can be analyzed to determine the fan flow rate(s), the effective volume of the building, and the total air exchange rate of the building. The latter is used to calculate the heat flow into or out of the building associated with ventilation, due to the combined effect of infiltration and HVAC outdoor-air supply.

The typical residential test requires four days and three nights, including setup, take down, and analysis as shown schematically in Figure 1. The objective is to obtain steady-state conditions during the first night (called the 'co-heat' period), to do a cool-down test on the second night, and to calibrate the heating system on the third night. The second- and third-night tests are started at midnight after a steady-state lead-in period. Daytime data are used to determine the effect of solar gains. Insofar as practical, equipment not required to perform the test and lights are turned off during the entire test. Until midnight on the third night, the furnace is off and all heat comes from several portable electric heaters individually switched on and off by the data acquisition computer to maintain the nearby measured temperature constant. Control is based on the closest measured room temperature. After midnight on the third night, heat is supplied from the installed heating system, operating in response to the normal house thermostat.

The test protocol for commercial buildings is usually much the same as for residences, but variations are made to accommodate special needs, such as operation of the HVAC system in various modes.

Audit Model

An approximate thermal simulation model of the building is developed, based on an audit. NREL has used the SUNCODE simulation program (Palmiter 1985), although, in principle, one could use any simulator. The advantage of starting with a detailed simulation model of the building

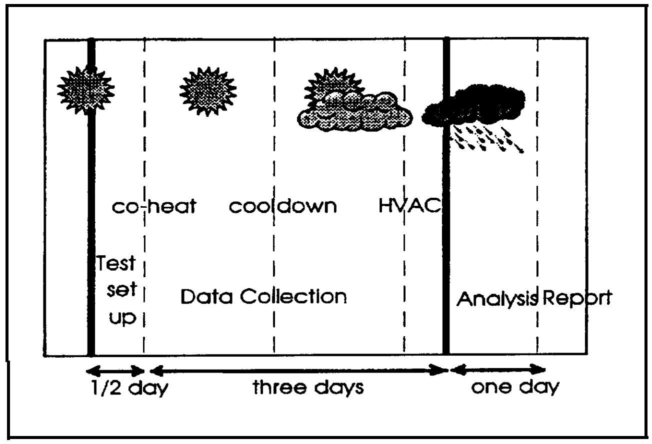

Figure 1. Typical Residential STEM Test Sequence, Sometimes Modified Slightly for Commercial Buildings

is that known building characteristics amenable to direct observation are imbedded in the model. Of primary importance are the distribution of primary mass elements and the size, orientation, and shading of all windows. The former allows one to predict an appropriate mix of fast and slow dynamic responses, and the latter allows data from a short-term test carried out during one season to be used to predict performance in another season, even though sun angles may be quite different. Accurate modeling of other details, such as thermal bridges and the effectiveness of insulation, is not as important because the building loss coefficient will subsequently be renormalized.

Data Analysis

PSTAR provides a mathematical formalism for separating building energy flows into convenient categories (Subbarao 1988). This separation allows the user to identify the three primary thermal characteristics of the building: 1) the building loss coefficient, 2) the effective building mass, and 3) the effective solar gain area. The PSTAR method virtually eliminates crosstalk between the three renormalizations, an important advantage.

Heat flow into the room air is mathematically separated into nine terms relating to the effect causing the heat flow. This disaggregation of terms is central to the PSTAR method. During the test, these are the only terms considered. Therefore, if energy is to be balanced, the sum of the nine terms should be equal to zero at each hour. The terms listed below use the sign convention that heat flow into the room air is positive.

Primary terms to be renormalized:

Q_l The building conduction gain to room air from outside air under steady-state conditions, calculated by multiplying the building loss coefficient (BLC) times the outside-inside temperature difference. Q_1 is negative when the outside temperature is less than the inside temperature. BLC is determined from the audit model.

Q_z The heat flow to the room air due to changes in inside air temperature. This can be positive or negative depending on whether the building mass is discharging or charging, and is calculated from the model.

Q_3 The heat flow to the room air due to solar gain. This includes the prompt effect of solar gains through windows, heat absorbed by light-weight materials, heat stored in building internal mass that is subsequently discharged into the room, and heat flow through the external walls due to solar absorption. Always positive, Q_3 is calculated using the simulation model by setting the inside and outside temperatures equal and constant; the calculated cooling load is Q_3.

Primary terms usually not renormalized:

Q_4 Measured heat flow to the room air due to internal gains. Q_4 includes all electrical energy into the building, such as the electric space heaters, and is positive.

Q_5 Heat flow to the room air due to heating of infiltration and/or supply air. In residential tests this has been calculated using the Sherman-Grimsrud model. In the commercial-building tests air-flow results based on tracer-gas data are used directly. Q_5 = (flow rate) (volumetric air heat capacity) (inside-outside temperature difference).

Secondary terms (usually not renormalized):

Q_6 Heat flow to the room air due to changes in outside temperature. Either positive or negative, Q_6 is calculated from the model.

Q_7 Extra heat to the room air due to the depression in sky temperature below outside air temperature. Normally negative, Q_7 is calculated using Martin-Berdahl model (Martin and Berdahl 1984) as described by Subbarao et al. (1988). Sky temperature is estimated based on the measured outside temperature and relative humidity.

Q_8 Heat flow to room air due to conduction from an adjacent buffer space, such as a crawl space or basement. Usually negative, Q_8 is calculated from the model as a static term, $Q_8 = (T_{space} - T_{room}) L_{room\text{-}to\text{-}space}$, where $L_{room\text{-}to\text{-}space}$ is the conduction coefficient between the room and the space.

Q_9 Average heat flow to the ground due to direct earth contact. Usually negative, Q_9 is measured using heat-flux meters placed on the slab or basement-wall surface.

Each of the Q_i is multiplied by an associated renormalization factor, p_i. For example, Q_1 is multiplied by p_1. The nominal value of each p_i is unity. Renormalization consists of determining non-unity values of one or more of the renormalization factors. In most cases, we have renormalized only the first three terms determining values of p_1, p_2 and p_3, leaving the other values equal to unity.

The sum of these heat flows is the net heat flow, $Q_{net} = p_i Q_i$. In the absence of other heat flows, Q_{nett}. should be zero. Non-zero values indicate the error in the heat balance at each hour.

Renormalization of the first three terms is done in three steps. In each step the previously determined values of renormalization factors are used.

Step 1 is performed during a period of 2 to 4 hours at the end of the night when the inside temperature has been maintained reasonably steady (called the co-heat period). During this period, Q_1, Q_4, and Q_5 are the dominant terms. The heat input from the electric heaters and other electric input (such as fan energy) should approximately balance the heat losses by conduction and infiltration. The dynamic terms, solar gains, and other effects are small, *but not negligible.* The value of p_1 is adjusted to force the average value of Q_{net} to equal zero during the co-heat period.

Values of p_z and p_3 are determined in steps 2 and 3. In both cases it is desirable to evaluate the renormalization factor using data taken from the entire analysis period because the values of Q_2 and Q_3 are zero or very small except when these terms are important. The value of Q_2 is small except during a room-temperature transient. During the cool-down period the primary heat flow into room air is from the discharge of building mass because the electrical heat input, Q_4, is zero, or at least small. During this period Q_2 and Q_1 are usually the dominant terms in the heat balance. During the daytime hours a major heat input is usually from solar gains so Q_3 is large and electric heat is correspondingly reduced. Q_3 is small during non-daytime hours. In both step 2 and step 3 values of p_2 and p_3 are determined that minimize the root-mean-square (RMS) value of Q_{net}.

Steps 1 to 3 are repeated until the three renormalization factors stabilize. In a successful test the value of Q_{net} is small throughout the test period. The average value of Q_{net} is close to zero; the RMS variation is typically 100 Btu/h at night and 1700 Btu/h during the daytime in a residential test.

The entire PSTAR procedure is embedded in a PC program called STEM-1.2 (Subbarao et al. 1989). A complete walk-through of the method as applied to one house (Fredericksburg) is described by Subbarao et al. (1988). Future plans call for making this program, which is now quite idiosyncratic, more user friendly.

If the renormalization values from a test are different than unity then temperature predictions made using the audit model will be in error. The renormalized model will correct this, usually to within a 1°F to 2°F range of errors.

The thermal modeling approach that is used in the PSTAR method is based on frequency-domain technique developed by Subbarao (1984). Thermal admittances of the building are calculated as a function of driving frequency by vector addition of the transforms of each building element. These complex functions are then fit at selected frequencies (depending on the time constants of the building) to obtain a reduced model containing only a few terms. The resulting Z transforms are converted to a simple-but-accurate time-domain recursion equation that relates current heat flows to temperatures, heat flows, and solar gains at the current and a few previous hours. Advantages of this approach are: 1) it allows the desired disaggregation of heat flow terms, 2) the detailed microdynamic description of a building is reduced to a simple macrodynamic model without significant loss of accuracy, and 3) computing time is reduced.

The simulation model is a hybrid in the STEM 1.2 software; the solar-gain term (Q_3) and sky-temperature depression term (Q_7) are pre-calculated using a proprietary simulation model (Palmiter 1985), and the dynamic analysis is done using the reduced model described above.

Residential Results and Validation

Results from several residential tests and validations are given by (Balcomb et al. 1993). The conclusions are that the renormalization factors are repeatable from test to test and that long-term data agree with predictions made using the renormalized model. Standard root-mean-square (RMS) errors (σ) of the renormalization factors are: BLC renormalization, p_1, σ = 0.03, mass renormalization, p_2, σ = 0.13, and solar-gain renormalization, p_3, σ = 0.05. (The p_i are dimensionless; the σ_i are relative to unity; thus σ = 0.03 represents a 3% RMS variation.) The bias error in matching the long-term heat required is 2% and the standard error from predictions made using results from individual tests is 5%. Additional validations are presented. Most notably, the Q_{net}. term closely matches the measured heat removed from a building by a vapor-compression chiller (within 5%).

Results from 10 residential tests indicate typical values and variations in the renormalization factors. The BLC renormalization factor, p_1, averaged 0.86 with a variation (σ) of 0.16; the thermal-mass renormalization factor, p_2, averaged 1.34 with a variation of 0.28; and the solar-gain renormalization factor, p_3, averaged 0.88 with a variation of 0.21. Comparisons of long-term extrapolations made with the simulation model, both before and after renormalization, indicated that the average value of annual heat required did not change much (4%) but the variation was large (34%).

Multi-Zone Analysis

Although we have been using the single-zone model to analyze commercial buildings with some success, a major objective of the current commercial-buildings STEM project has been the development of a multi-zone model to cope with the complexities of larger buildings.

A multi-zone model is needed because temperatures of different parts of a building often exhibit intended or unintended spatial variations. For our purposes, a thermal zone is defined as a space whose temperature can be reasonably approximated as homogeneous. The thermal zones may or may not be the same as the HVAC zones. In the one-zone approximation, a weighted average of the measured temperatures, T_{in}, is used as *the* building temperature. The heat-flow sum of the zone can be written as follows:

$$p_1 L(T_{in} - T_{out}) + p_2 Q_2 + REST = Q_{net}$$

where the first term is $p_1 Q_1$ in the previous formulation, L is the BLC, and $REST$ is the sum of the remaining 7 terms. In the multi-zone approach, the individual thermal zones are treated separately, each having its own heat-flow sum:

$$p_1 L_1(T_{in}(i) - T_{out}) + p_2 Q_2\ (i)$$

$$+ \sum_j Q_{interzone}(i,j) + REST_i = Q_{net}(i)$$

where we have made the p_i the same for each zone. The inter-zone heat flows are the product of the temperature differences between zones times the appropriate inter-zone conduction coefficients. Although in theory these equations could be considered individually, there is usually not enough information in the data to obtain individual zone-by-zone renormalizations. Instead, we consider a whole building energy balance obtained by adding up the multi-zone flows to obtain a single energy imbalance term:

$$Q_{net} = \sum_i Q_{net}(i)$$

In the limiting case of all zone temperatures being the same, the multi-zone analysis reduces to a one-zone analysis. The advantage of the multi-zone analysis is that it provides a way to introduce the measured individual zone temperatures into the analysis.

Commercial Building Tests

This paper reports on STEM tests done in four commercial buildings. Results from the two most recent tests are presented in some detail followed by brief conclusions from the other two.

Ft. Riley Building

Two short-term tests were performed on a 12,500 ft^2, single-story battalion headquarters building at the Fort Riley Army Base in Kansas. The building is moderately massive and is divided into 20 offices and other rooms. Heating or cooling energy for the building is extracted from water that is heated or cooled using a boiler or chiller located in an adjacent building. Distribution of heated or cooled air and ventilation of the building is achieved using a multi-zone air-handling unit serving 6 zones in the building. The first test, March 5-9, 1993 was to evaluate the building in the winter heating mode and to demonstrate the multi-zone model. The second test, September 1-8, 1993, was to evaluate the building in the summer cooling mode. Primary testing was over weekends during which the building was nearly unoccupied.

Winter Test. In the winter test, the inside-outside temperature difference was sufficient to permit renormalizing the simulation model using the normal STEM technique, described previously. Temperatures were measured in 18 rooms using probes connected to the data acquisition systems. Additionally, 10 temperatures were measured using small stand-alone monitors. Comparisons at a few locations proved that the stand-alone monitors produced the same results, demonstrating their value for augmenting the connected probes.

Figure 2 shows measured temperatures. Individual measurements taken at the 28 locations have been combined into six groups representing the six thermal zones chosen for the multi-zone analysis. Note that these temperatures are not as equal nor as steady as we would like, at least when compared with most tests that we have performed. Because of the massive nature of the building, small temperature variations lead to large values of the transient heat flow terms Q_z and Q_6.

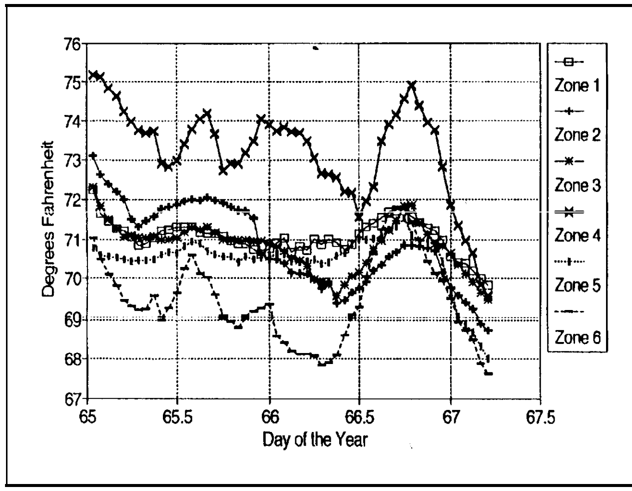

Figure 2. Room Temperatures During the Ft. Riley Winter Test [1]

The renormalization results show a major improvement from using the six-zone model compared to using the one-zone model (see Table 1.). This shows up as reduced standard errors (sigma) and reduced RMS error in Q_{net}. The one-zone model is not able to reconcile the solar gains. Parameter p_3 shows up as a negative value with a sigma that is greater than the value, signifying that the result is meaningless. The solar renormalization is successful with the six-zone model, giving a reasonable sigma. Note that the loss-coefficient renormalization, p_l, changes significantly. The six-zone results are a credible set; the one-zone results are questionable. The RMS error is remarkably low, considering the size of the building. RMS errors in the range of 1.0 Btu/h per sq ft of floor area have been typical of residential test results. Note that this error is about 65% less than a typical residential building.

The value for p_1 indicates that the audit description underestimates the building losses by 4.4%. The audit building loss coefficient is 2432 Btu/hour-F. Thus, the best-estimate for the actual BLC is 2432 x 1.044 = 2539 Btu/h-°F. This includes the effect of infiltration which is estimated separately based on the air-exchange rate measured by tracer-gas techniques as 620 Btu/h-°F.

The value for p_2 indicates that the actual effective building mass is only 57.5% of the audit value. The building is quite massive, having a slab on grade floor with no carpeting, a massive internal wall on the west side of the central hallway, and significant internal walls and

Table 1. Renormalization Parameters for Ft. Riley. Best estimates are shown in bold.

Factor	Description	Single-Zone		Six-Zones	
		Value	Sigma	Value	Sigma
p_1	Total BLC ratio	0.927	0.021	**1.044**	0.016
p_2	Internal mass ratio	0.580	0.047	**0.575**	0.022
p_3	Solar gain ratio	-0.044	0.115	**0.314**	0.076
RMS	Root-mean-square error in Q_{net} Btu/h	5844		**3853**	

equipment. The effective mass accounts not only for the amount and thermal properties of the building materials coupling is difficult to estimate, and it is not too surprising to find that the original estimate is high.

The value for the solar-gain renormalization, p_3, is 0.314. There are several possible explanations for this, including the fact that the windows are small, deeply recessed, and many are shaded inside by blinds (the recesses and blinds are not accounted for in the simulation). Because of these complexities, we believe that the low value of solar gain is credible and probably correct within the indicated error band of ±0.076. It is worth noting that the windows are primarily on the east and west sides of the Fort Riley building. The temperature data indicate that the east side room heats first in the morning and the west side warms up only after noon, as expected. The multi-zone model provides a means for rationalizing these changes; whereas, the one-zone model averages everything together.

The principal measure of PSTAR success is to obtain a small energy imbalance, Q_{net}. The RMS value of Q_{net} before renormalization is 19125 Btu/h and after renormalization is 3853 Btu/h, indicating that there a significant benefit to renormalization. In Ft. Riley, the most important changes are due to the solar and mass renormalization (because the loss-coefficient renormalization is close to unity *in this case).* Based on these results, we should expect to be able to accurately deduce other energy flows in the building, using the building as a dynamic calorimeter, with an expected RMS error of about 4000 Btu/h. This is about 5% of the largest heat-flow terms.

It is always instructive to study plots of the individual heat-flow terms. These are shown in Figures 3 to 5.

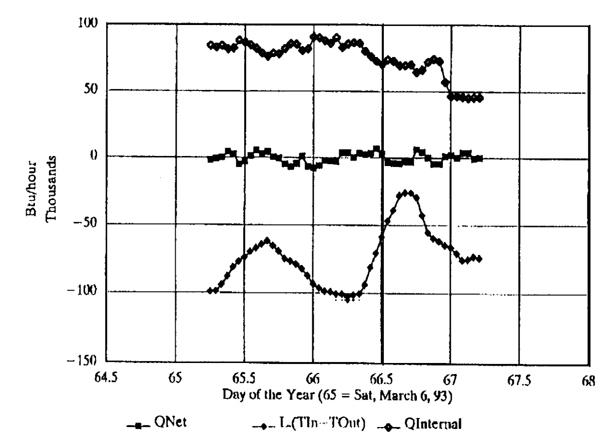

Figure 3. Calculated Heat Flows During the Ft. Riley Test[2]

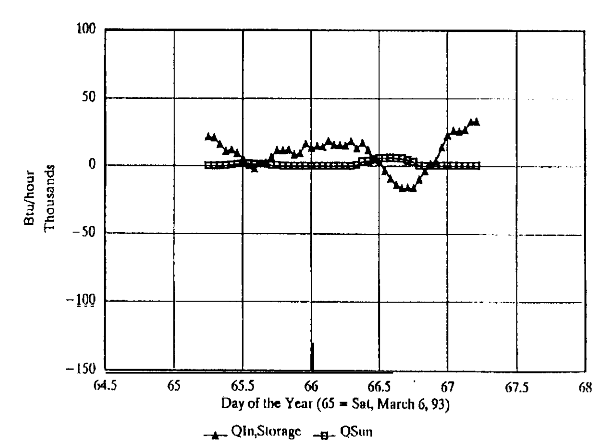

Figure 4. Calculated Heat Flows During the Ft. Riley Test (with the same scale as Figure 3)[3]

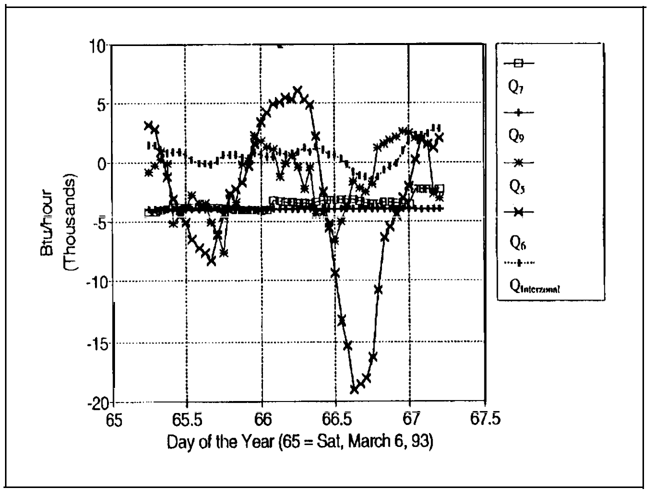

Figure 5. Other Heat Flows During the Ft. Riley Test (note the change in scale)[4]

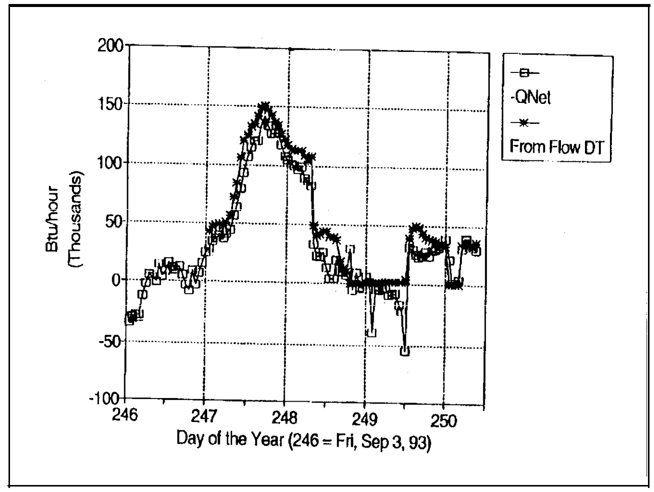

Figure 6. Results of the Ft. Riley Summer Test[5]

Summer Test. Outside temperatures in September were still reasonably high in Kansas for the summer test. No attempt was made to obtain data suitable for renormalizing the building simulation model because this had already been done. The main purpose was to obtain data during a time when the building was being mechanically cooled.

Figure 6 shows a comparison of cooling energy delivered to the building. One curve, labeled 'measured', is the energy removed from the building calculated from the temperature rise of the water and the product of the water flow rate into the building from the chiller—each direct measurements. The second curve, labeled 'model' is Q_{net}, calculated using the renormalized six-zone simulation model based on all of the measured input temperatures, solar gains, air-exchange rates, and other data.

The close agreement of these two completely independent measurement of the same quantity is a verification of the PSTAR technique. The error band on the measured data is at least equal to the difference between the two curves. This difference is about twice the RMS error expected in the Q_{net} term, based on the winter tests.

Gunnison Building

A short-term test was performed on the Aspinal-Wilson Conference Center, a 9600-ft^2, building at Western State College in Gunnison, Colorado. The building is single story and has extensive vertical and sloped glazing resulting in large solar gains. The building is ventilated by two separate air-handing units serving the east and west portions. A boiler provides hot water for space heating to individual terminal boxes and also to radiant ceiling panels along the perimeter. The test period, October 7-12, 1993, provided data for evaluating the building in the winter-heating mode. No cooling-mode tests were performed because cooling is generally not needed during the mild Gunnison summers (at 7700-ft elevation), although the building does have an evaporative cooler. The test was carried out over a weekend during which the building was unoccupied, although data were logged from Wednesday afternoon through Tuesday morning.

We were more successful in obtaining steady and uniform temperatures in Gunnison than we had been at Ft. Riley, as shown in Figure 7, Data on either of two nights could be used for the co-heating analysis. The renormalization results are shown in Table 2.

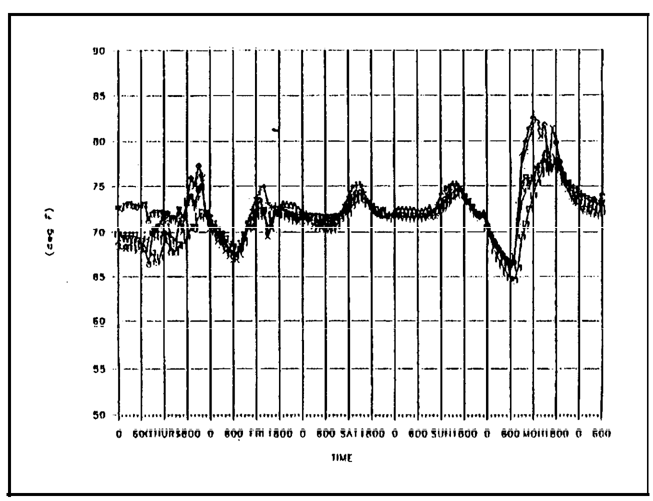

Figure 7. Room Temperature During the Gunnison Winter Test[6]

The values of all renormalization factors are similar to those obtained in residential tests. Of more significance than the values themselves (since the correct values are not known) are the small values of the standard errors,

Table 2. Renormalization Parameters for Gunnison Based on Six-Zones

Factor	Description	Value	Sigma
p_1	Total BLC ratio	**1.05**	0.005
p_2	Internal mass ratio	**1.63**	0.075
p_3	Solar gain ratio	**0.67**	0.027
$p_{3'}$	Solar gain shift, hr	**-0.60**	0.070
p_5	Air exchange ratio	**0.94**	0.047
RMS	Root-mean-square error in Q_{net}, Btu/h	**8721**	

sigma, indicating a very robust fit to the data. The value for p_1 indicates that the audit description underestimates the building losses by 5%. The audit building loss coefficient is 2168 Btu/hour-F. Thus, the best-estimate for the actual BLC is $2168 \times 1.05 = 2268$ Btu/h-°F. This includes the effect of infiltration which is estimated separately based on the air-exchange rate measured by tracer-gas techniques as 395 Btu/h-°F (during the co-heat period). The building is well insulated and the close agreement of the measured and predicted values indicates the success of the insulation strategy in the building.

The value for p_2 indicates that the actual effective building mass is 63% greater than the audit model. The building is quite massive, having a slab on grade floor, and several internal brick walls. The difference between p_2 and unity is somewhat larger than seen in residential tests, where the buildings were lightweight.

The value for the solar gain renormalization, p_3, is 0.67. Solar gains are large in this building, driving temperatures up a few degrees during the day. An additional term was added to the analysis to shift the solar-gain term forward or back in time. In this case the value of $p_{3'}$ indicates the time shift in hours. The best fit to the data (to minimize the RMS error) is a backward shift of 0.60 hours. Since the data are not actually shifted in time, the most likely explanation is that the thermal coupling between solar gains and the internal mass surfaces and air temperature has not been modeled correctly. Although this is not a major problem, it does indicate a potential direction for model improvement. In any case, the solar-gain renormalization of 0.67 is toward the bottom of the range not greatly different than the 0.88 average p_3 measured in residential tests.

The good data and tight fit in the Gunnison data permitted renormalization of the heat-flow term due to infiltration, Q_5. The value that minimizes the RMS error is 0.95. This is credible, considering the complexity and uncertainty of the tracer-gas data analysis based on two injection points and six tracer-gas concentration measurement points. The 0.047 standard error also indicates credibility.

The root-mean-square (RMS) value of Q_{net} before renormalization is 38,725 Btu/hr and after renormalization is 8721 Btu/hr. This indicates that, as usual, there a significant benefit to renormalization. Again, the most important changes are due to the solar and mass renormalization. The observed Q_{net} values, as a fraction of the maximum heat-flow values, are typical of those observed in residential tests.

Heat-flow results (after renormalization) are shown in Figures 8 and 9.

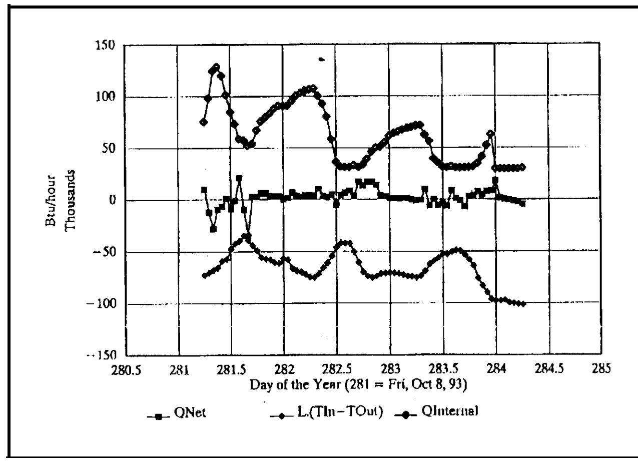

Figure 8. Calculated Heat Flows During the Gunnison Test[7]

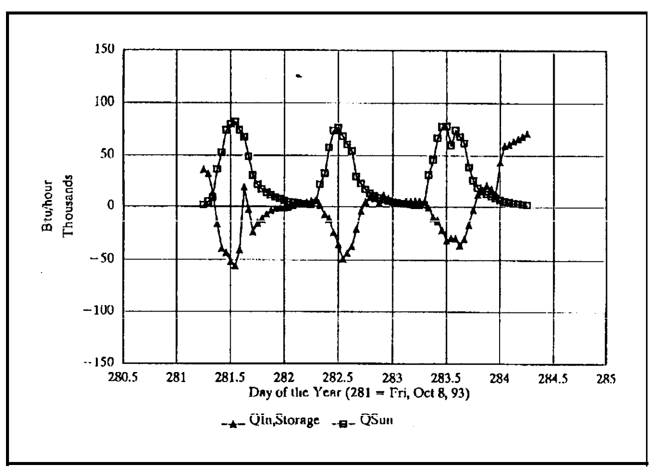

Figure 9. Calculated Heat Flows During the Gunnison Test (with the same scale as Fig. 8)[8]

After the weekend tests, the electric heaters were turned off and the building was operated with heat from the boiler. Boiler output was not measured directly because there was not an installed water flow meter as there had been at Ft. Riley. The total gas input to the boiler was measured and compared to the integral of Q_{net} over the same period. This comparison indicates that the overall system efficiency of the boiler and distribution system is 56%, a credible value.

Princeton Building

A STEM test was done on a 130,000 ft^2 building in Princeton. Results are given in (Burch et al., 1990). The most significant finding was that the BLC is nearly twice the predicted value, largely explaining the excessive heating observed.

East Idaho Building

A STEM test was done on the 5300 ft^2 East Idaho Credit Union building in Idaho Falls. This building had been the subject of three demand-side management investigations: improved shell construction, low-e windows, and four split-system air-to-air heat-pumps. The renormalization factors indicate that the BLC is 26% lower than predicted, indicating the success of the improved insulation and advanced window strategies. Solar and mass renormalizations showed no unusual results.

In-situ measurement indicated that the *overall* COP of heat-pump system was 0.86. Follow up tracer-gas studies revealed that excessive ventilation air was being drawn into the building, resulting in the poor performance. Ventilation was adequate without this air. It was recommended that the outdoor air dampers be closed and the fans operated in the 'unoccupied' mode at all times.

HVAC System Observations

We found serious problems in the operation of the HVAC systems in all of these commercial buildings. Tracer-gas results were particularly useful in diagnosing the problems, although thermal observations based on PSTAR results proved useful to uncover more subtle issues. In this paper we have not had space to describe the considerable complexity of the tracer-gas/air-flow analysis employed.

At Ft. Riley, we found that the belt on exhaust-air fan was slipping, resulting in poor fan performance and air being drawn in through the exhaust duct. In Gunnison, there was no exhaust fan installed and a large amount of air was being drawn in through the exhaust duct. Ventilation was far greater than required for fresh air. The exhaust-air grill was covered for our tests, bringing the total ventilation into line. Other serious design and control problems were observed and reported to the building owners.

Clearly a major value of these tests has been in uncovering HVAC problems by separating shell from systems performance. When operating properly, the HVAC performance seems to be reasonable. One value of the STEM tests is in measuring end-to-end, whole-HVAC-system performance. Unsatisfactory performance results, as found in the East Idaho building, provide a reason to look within the HVAC system for an explanation.

These results indicate that STEM tests could be a valuable tool in operation and maintenance of a building. In particular, an indication of poor performance of the HVAC system could lead to further tests that would pinpoint the problem. It is also possible to conceive of a continuous on-line diagnostic during normal operation. The diagnostic would be based on making a current PSTAR calculation. For example, HVAC performance could be evaluated continuously; low values indicating abnormal behavior could be used to flag the need for investigation.

Conclusions

- The STEM method has enabled us to disaggregate and understand building heat flows to a degree that had not previously been demonstrated and with much greater accuracy. This provides the ability to separate cause and effect in complex commercial buildings. The effectiveness of individual DSM measures can be identified.

- The multi-zone modeling approach increases the accuracy of the STEM method. In one case, a solar renormalization was possible using a six-zone model while it had failed using a one-zone model. Standard errors of all the renormalization factors and the resulting error in Q_{net} are reduced.

- The robustness of the STEM method observed in the residential results can be carried over into commercial buildings. This requires careful measurement of building air flows using tracer-gas techniques and is helped greatly by evaluating heat flows using a multi-zone model.

- The STEM method has proved useful for diagnosing problems with a building's HVAC system.

- We still depend on electric co-heating to obtain data for renormalizations. However, in cases in which the HVAC system supplies heated or chilled water it seems likely that *accurate* measurement of both water flow and water Δ T would allow us to substitute the boiler or chiller for electric co-heating (or co-cooling). (In the future, we will investigate the use of the building's electric lights for co-heating.)

Future Work

STEM is an on-going program at NREL. Monitoring of additional residential and commercial buildings, from small to large, is scheduled. Capability to renormalized HVAC performance is being programmed into the software. Programming of the STEM 2.0 program is underway to incorporate the multi-zone and HVAC capability and to make the program suitable for distribution to and use by trained teams of building engineers. Long-range plans call for merging the program with a building design tool so that monitoring becomes the logical last step in the building design and construction process.

Acknowledgments

This monitoring is part of the research being performed under the Short-Term Energy Monitoring program funded by the US Department of Energy (Federal Energy Management Program), the Western Area Power Administration, the Bonneville Power Administration, and the US Army. The project is carried out within the Buildings and Demand-Side Management Branch at the National Renewable Energy Laboratory under the direction of Louis Abernethy and the Department of Mechanical Engineering at the Colorado State University under the direction of Douglas Hittle. Ren Anderson is program manager at NREL.

The assistance of Larry Stillwagon, Mark Imel, and Linda Eslinger at Ft. Riley is gratefully acknowledged. The assistance of Richard Tonnessen, Joe Winegardner, Nancy Anderson, Terry Zerger, and Ken Coleman in Gunnison is gratefully acknowledged. Jim Miller and Janette Manke assisted with the tests.

Endnotes

1. Average outside temperature is about 42°F. Each curve is a suitable average of several measured data channels combined to represent one thermal zone of the building. The cool-down, which is not large, occurs toward the end. The temperature drop is small because the building is quite massive and the fan heat, which was on during the entire test, is quite large.

2. The top curve is Q_4, the internal heat, mostly electric heat from the heaters and the fan. The bottom curve is p_lQ_l, the loss coefficient times the inside-out AT. The middle curve is Q_{net}, the net error in the renormalized-model heat balance. This averages zero during the co-heat period, early on day 66.

3. The squares show p_3Q_3, the solar-gain term. This shows how small the solar signature really is (after multiplying by the 0.314 factor). The diamonds show p_2Q_2, the heat flow due to changes in inside temperature. The large rise at the end is the cool-down period.

4. These are small, but not negligible. The largest signature is Q_6, the heat flow into the room due to changes in outside temperature. The total interzonal heat flow is also shown.

5. The stars show the heat extracted from the chilled-water line entering the building from an adjacent building ('flow- Δ T'). The squares show Q_{net}. These should be equal-they are totally independent measures of the same quantity. The close agreement indicates that the STEM method can be used to measure total heat removal, using the building as a calibrated calorimeter.

6. Average outside temperature is about 40°F. Each curve is a suitable average of several measured data channels combined to represent one thermal zone of the building. The cool-down occurs toward the end, on Sunday night.

7. The top curve is Q_4, internal heat, mostly electric heat from the heaters and the fan. The bottom curve is p_lQ_l, the loss coefficient times the inside-outside Δ T. The middle curve is Q_{net}, the net error in the renormalized-model heat balance. This averages zero during the co-heat period, early on day 283.

8. The top curve is p_3Q_3, the solar-gain term. The three days shown were quite sunny and there is a very large solar signature. The bottom curve is P_2Q_2, the heat flow due to changes in inside temperature. This falls during the day as the room temperature rises. The large rise at the end is the cool-down period.

References

Balcomb, J. D., J. D. Burch, and K. Subbarao (1993), "Short-Term Energy Monitoring of Residences", *ASHRAE Trans.* V. 99, Part 1 (DE-93-14-3).

Burch, J. D., K. Subbarao, A. Lekov, M. Warren, and L. Norford (1990), "Short-Term Energy Monitoring in a Large Commercial Building", *ASHRAE Trans.* V. 96, Part 1. (AT-90-26-2).

Martin, M., and P. Berdahl (1984), "Summary of Results from the Spectral and Angular Sky Radiation Measurement Program," *Solar Energy* Vol. 33, pp. 241.

Palmiter, L. (1985), "SUNCODE-PC Building Load Simulation Program", Ecotope, Inc., 2812 East Madison, Seattle, WA 98112.

Subbarao, K. (1984), "BEVA - A New Hour-by-Hour Building Energy Simulation with System Parameters as Inputs", SERI/TR-254-2 195, Golden, CO: Solar Energy Research Institute.

Subbarao, K. (1988), "PSTAR - Primary and Secondary Terms Analysis and Renormalization", SERI/TR-254-3175, Golden, CO: Solar Energy Research Institute.

Subbarao, K., J. D. Burch, C. E. Hancock, A. Lekov, and J. D. Balcomb (1988), "Short-Term Energy Monitoring (STEM): Application of the PSTAR Method to a Residence in Fredericksburg, Virginia", SERI/TR-254-3356, Golden, CO: Solar Energy Research Institute.

Subbarao, K., J. D. Burch, J. D. Balcomb, C. E. Hancock, and A. Lekov (1989), "Short-Term Energy Monitoring, STEM 1.1 User Manual", SERI/TR-254-3613, Golden, CO: Solar Energy Research Institute.