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Exploratory Investigation of Energy Use Metering and Data Analysis Methods for Multifamily Buildings in the Pacific Northwest

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/CON-304

Energy Division

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Date published — May 1991

Research Sponsored by the
Bonneville Power Administration

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

Acknowledgments

This study was supported by the efforts of staff from the Bonneville Power Administration and others. Several sources provided the data needed to conduct this project. Mark Halverson of Pacific Northwest Laboratory was instrumental in retrieving and sending us the ELCAP data. Richard Gillman and Megan Taylor of Bonneville provided backup information on the ELCAP buildings. Jane Selby of Bonneville arranged for delivery of the RSDP data and described important factors affecting the data, and Mark Schuldt of United Industries Corp. provided results and insight regarding the MHEUS data and results. The overall project benefitted from the support and encouragement of Pam Brandis of Bonneville, who managed the effort and helped arrange many of the data transfer operations.

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SUMMARY

This investigation focused on analyzing energy data for all-electric (single-fuel) multifamily buildings (MF) in the Pacific Northwest from the Residential Standards Demonstration Program (RSDP), the End-use Load and Consumer Assessment Program (ELCAP), a study of building energy retrofits by Seattle City Light – the Multifamily Hourly End Use Study (MHEUS), and from a previous evaluation of energy savings from the Model Conservation Standards (MCS) in new, low-rise multifamily (MF) buildings in Tacoma, Washington (Tonn et al 1989). The purpose was to search for insights that could guide future field energy measurement studies and analyses of MF conservation potential, with better evaluations of the MCS in MF buildings being a driving influence.

The Tacoma MCS study pointed to some significant problems in analyzing energy use and savings in MF buildings. The primary difficulties are caused by inaccuracies in estimating heating energy use in single-fuel (all-electric) buildings and variations in tenancy of MF buildings, especially variations resulting from vacancies (see also Ivey et al 1988). Vacancy is a particularly acute problem in new buildings which begin empty and add tenants over time. Results from this study highlight the issue that, for MF buildings, both weather and occupancy normalizations can be important.

Understanding energy use in all-electric MF buildings in moderate climates is complicated by the increased importance of end uses other than heating. MF buildings typically have a lower percentage of total energy used for heating since multiple residences are in the same building, and each residence has a higher density of occupants compared to SF buildings. Thus, an important issue is what type of index to use to compare energy use between MF buildings. A two-dimensional index is proposed here: heating energy use per sq ft of floor area by nonheating energy use per residence. The energy use index is referred to as the MF building energy performance Index (MFI). The proposed units are kWh/ft^2 (space heating or H) by MWh (nonheating or O) for each residence, with the time period typically being annual. Estimation of the MFI for the previous Tacoma MCS evaluation study data supports the statistically determined building-level space heating energy improvement estimate (Tonn et al 1989) of 0.8 kWh/ft^2-yr attributable to the MCS. With these heating savings fixed, the Tacoma MCS buildings also used about one MWh/yr less nonheating energy for each apartment unit.

Examination of MFI values for the buildings in this study indicates that the causes of variations in MFI should be studied. Determination of the causes of variation appears needed to define classes of buildings based on efficiency levels (or MFI) and to provide direction for future efforts to improve energy efficiency in the region. The MFI, or an index like it, should be considered for all future representations of MF energy use.

Using this index requires a reasonable knowledge of heating energy use to estimate a likely case. However, determination of heating energy use was a significant problem both in the Tacoma MCS evaluation and in evaluation studies of all-electric MF buildings in general, unless expensive metering is employed. With results from electric energy use measurement studies for MF buildings now becoming available, devising methods for estimating heating energy use in all-electric MF buildings using empirical data may be approached with more confidence.

A new empirical modeling tool for evaluating heating energy use is proposed as a result of this study. The concept for the tool was developed from analysis of the data for the Fife ELCAP MF building. The concept was strengthened by examination of the RSDP data, but the RSDP data did not permit as detailed an examination as the ELCAP data. The model represents the fraction of total energy that is used by the heating system as a translated, truncated, simple sine function. The sine function model was determined based on inspection of the data and the periodic (annual) nature of the data. More complicated representations, such as with Fourier analysis, were ruled out to keep the model simple and easier to understand. The assets of this modeling approach are simplicity and the ability to provide answers that mimic the temporal empirical behavior of heating energy use in the Pacific Northwest.

The model appears adequate for estimating annual space heating energy use in all-electric MF buildings. Use of this new model (or a variation) to examine future conservation potential in all-electric MF buildings should be evaluated further as data from more buildings become available. Future research should be considered to determine whether this model can reasonably estimate space heating energy use based on a partial season of metered data.

For any energy modeling effort, the importance of weather normalizations is recognized. For MF buildings, variations in occupancy are also important, such as during tenant turnover. Tenant turnover in MF buildings is often high. For energy studies, tenant turnover makes evaluation of changes in energy use over time more difficult. Thus, occupancy rates can affect evaluations of MF energy use. The MHEUS study provides valuable information about occupancy and weather normalizations. The work reported here corroborates that both occupancy and weather normalizations should be considered in planning any MF energy use measurement study.

Empirical energy use data are important for improving the understanding of results from energy modeling tools and of the energy behavior of buildings. Although large amounts of end use energy data have been collected for residential buildings in the Pacific Northwest, the data for MF buildings are very limited. Under ELCAP, MF buildings had "low" priority most of the time. This low priority meant that adequate resources could not be directed toward maintaining high quality data sets. As a result, the ELCAP Fife building data are worth study, but the ELCAP data for other MF buildings have significant gaps, which could make analysis results less meaningful and require additional analytical time to make the data useful The RSDP MF data are extremely difficult to use for many types of energy use analyses and should be considered with caution for the types of analyses presented here, due to the erratic and questionable nature of the data, the difficulty of performing analyses with the multiple time intervals, and the apparent lack of floor space data. If the ELCAP Fife building is the only MF building of more recent construction with end use energy consumption data considered worthy of analysis for most energy use studies, data from more buildings are needed.

Exploratory Investigation of Energy Use Metering and Data Analysis Methods for Multifamily Buildings in the Pacific Northwest

ABSTRACT

This investigation focused on analyzing energy data for all-electric (single-fuel) multifamily (MF) buildings in the Pacific Northwest. The purpose was to search for insights that could guide future field energy measurement studies and analyses of MF conservation potential, with better evaluations of energy standards for MF buildings being a driving influence. A two-dimensional index is proposed here to compare energy use between MF buildings: heating energy use per sq ft of floor area by nonheating energy use per residence. This index, or an index like it, should be considered for all future representations of MF energy use. A new empirical modeling tool for evaluating heating energy use is proposed as a result of this study. The model represents the fraction of total energy that is used by the heating system as a translated, truncated, simple sine function. The model appears capable of estimating annual space heating energy consumption in all-electric MF buildings. Results from this study also highlight the issue that, for MF buildings, both weather and occupancy normalizations are important. Finally, the available end use energy consumption data for MF buildings are limited.

INTRODUCTION

Significant activities have occurred in the Pacific Northwest to increase the energy efficiency of buildings, with most programs focusing on residential buildings. The passage of the Northwest Power Planning and Conservation Act by the U.S. Congress in 1980 provided a significant impetus to current efforts and helped to make energy conservation an important part of overall energy planning. Since 1980 the Northwest Power Planning Council (NWPPC) and the Bonneville Power Administration (Bonneville) have worked to design and implement a comprehensive portfolio of conservation programs.

Electricity is the major source of energy for buildings in the region and has been referred to as "a cornerstone of the Pacific Northwest economy" (NWPPC 1986). For residential buildings, 60–65% of site energy use (site refers to energy consumed at the building) and over 80% of source energy use (source energy includes electrical energy system losses) is electrical energy in the states of Washington and Oregon (EIA 1989a). Interested parties in the Pacific Northwest contribute to the development of a regional electricity plan (NWPPC 1986) aimed at increasing the efficiency of energy use and improving the process of developing and allocating energy resources.

The power plan calls for increased cooperation in the region by all electric power institutions "to develop and share the lowest cost resources," and energy conservation is seen as one of the important resources to be developed. (Energy conservation is allowed a 10 percent advantage in calculating estimated incremental system costs over other systems allowed in the enabling legislation.) As part of the overall effort to develop the conservation resource, Bonneville is developing a comprehensive long-range plan to monitor region-wide progress in implementing Model Conservation Standards (MCS). The MCS were developed as building code requirements and guidelines to support increased energy efficiency in new buildings.

Bonneville previously funded a study by Oak Ridge National Laboratory (ORNL) to evaluate the energy savings from the MCS in new, all-electric, low-rise multifamily (MF) buildings in Tacoma, Washington (Tonn et al 1989). The MCS are directed at saving space heating energy in new buildings. The Tacoma MCS evaluation used the Princeton Scorekeeping Method (PRISM) (Fels 1986) to obtain weather-adjusted estimates of normalized annual consumption (NAC, annual total energy use) and heating energy use from bimonthly billing data for individual apartments, which were analyzed both at the building level and at the apartment level. More extensive analyses of additional apartment-level data were also performed.

The Tacoma MCS pointed to some significant problems in analyzing energy use and savings in MF buildings. The primary difficulties are caused by inaccuracies in estimating heating energy use in single-fuel (all-electric) buildings and variations in tenancy of MF buildings, especially variations resulting from vacancies (see also Ivey et al 1988). Vacancy is a particularly acute problem in new buildings which begin empty and add tenants over time. The study described here was conducted to investigate methods applicable to all-electric MF buildings for metering and analyzing energy use and modeling that energy use to provide information on the potential energy conservation resource.

DATA AND METHODOLOGY

Large amounts of data have been collected on electric energy use in the Pacific Northwest. Data on all-electric MF buildings are available from the ORNL MCS study mentioned previously, the Residential Standards Demonstration Program (RSDP), the End-use Load and Consumer Assessment Program (ELCAP), and from a study of building energy retrofits by Seattle City Light – the Multifamily Hourly End Use Study (MHEUS).

The Tacoma MCS study data include bimonthly customer billing data histories, occupant surveys, daily ambient temperature data (from the Sea-Tac airport), and building surveys for 370 apartment units. The 370 units were available from a potential sample of 760 apartment units in 77 buildings.

The RSDP data set contains approximately biweekly data over a one-year period on total, space heating, and hot water energy use and average indoor and outdoor temperatures for the period of the readings. These readings were made by the occupants and there is considerable variability in the consistency of the readings.

RSDP data for MF residences were available for the states of Idaho, Montana, and Washington, but the data for Idaho and Montana are not usable. Data on about 80 apartments were available for the state of Washington, of which 24 units were of interest to this study because they were two sets of 12 "matched" units – half MCS and half "standard practice."

The ELCAP data are available for some or all of the apartments in three buildings in the state of Washington and one building in Idaho, covering hourly energy consumption for end uses at a high level of disaggregation. However, not all units in all buildings have end use data. Data for one additional building in the state of Washington were collected, but the measurement apparatus was wired incorrectly and the data are not meaningful. MF buildings were usually not "high" priority during the ELCAP project, and as a result the resources directed toward maintaining quality data sets were often not adequate. Thus, if MF buildings are now of interest, MF ELCAP data will not be as helpful as ELCAP data for single family and commercial buildings.

ELCAP data from only one building, the building in Fife, Washington (outside Tacoma) were used. The data for the Fife building were the most complete and maximized the validity of the results obtained. Data were available for 8 out of 12 units for this building. Data from the Fife building had only 2% of the energy use data missing, while for the other three buildings the missing data comprised 17, 42, and 66% of the total.

The MHEUS data are available for three older buildings in Seattle covering pre- and post-retrofit energy use. The data are of high quality and have been used to help simulate the energy performance of the buildings under varying conditions. Although the MHEUS data are not directly applicable to the MCS since the buildings were older, the methods and results of the MHEUS project have significant import for future study of the energy conservation resource in MF buildings in the Pacific Northwest.

This study focused on analyzing the ELCAP, RSDP, and MHEUS data to search out insights that could guide future field energy measurement studies and analyses of MF conservation potential and MCS progress. Limited additional analysis of the Tacoma MCS data was also performed, and a comparison with RSDP data on single family (SF) buildings contained in an informal report to Bonneville from Ecotope, Inc., is also presented (Palmiter et al 1988).

Possible analysis methods considered in this study include empirical models of actual energy use data, such as PRISM, and theoretical models, such as SUNDAY (a simple one-node thermal simulation model) and engineering heat balance equations. Important considerations affecting the course of this study are: potential impacts on the course of future energy measurement studies, the capabilities of modeling approaches for providing enhanced knowledge and insights about the conservation resource, the reliability and stability of methods, and the potential for use with SF residential buildings.

REPRESENTING MULTIFAMILY ENERGY USE

Understanding energy use in all-electric MF buildings in moderate climates is complicated by the increased importance of end uses other than space heating. Space heating energy was found to be about 50% of total energy use in the all-electric Hood River homes (Hirst and Goeltz 1986), with the percentage decreasing as more wood is used for heating. Data examined for this study and previous work by Seattle City Light (SCL) for the MHEUS study indicate that heating energy in MF buildings in the Pacific Northwest is likely to be only 25-35% of total use for reasonably efficient buildings. (Heating energy, as used here, is the energy consumed by the primary system for heating the building.) Heating is still the dominant winter energy use (see Esterberg 1986), but other energy uses are important on an annual basis. This lower annual percentage of heating energy for MF buildings has important implications for the MCS, since they are primarily directed at heating energy.

MF buildings typically have a lower percentage of total energy used for heating since multiple residences are in the same building, and each residence has a higher density of occupants compared to SF buildings. As buildings become larger to accommodate more residences, the amount of building envelope exposed to outdoor temperatures relative to the floor space of the building decreases. This tends to lower the heating requirements per sq ft of floor area. Higher occupant density is shown in national data on characteristics of residential buildings, where multifamily residences have almost twice as many occupants per sq ft as single family residences (EIA 1989b). This means the MF buildings should have higher internal gains than SF buildings, which also reduces heating requirements, and that more energy is used per sq ft for purposes other than heating (such as for hot water). These factors make comparisons with SF buildings complicated and indicate the potential need to analyze MF buildings differently than SF buildings.

One important issue is what type of index to use to compare energy use between MF buildings. A two-dimensional index is proposed here: heating energy use per sq ft of gross floor area by nonheating energy use per residence. Many other indexes could be proposed, and each index might have specific advantages and validity, but for purposes of this presentation the above index will illustrate the potential of a new MF energy index.

Advantages of the proposed index for studying MF energy use can be seen from a re-examination of the Tacoma MCS evaluation results (Tonn et al 1989). A comparison of MCS and standard practice (SP) buildings using this index indicates a distinct improvement for MCS buildings. The comparison is shown graphically as a possibility space in Fig. 1 based on mean values of normalized annual consumption (NAC, see Fels 1986 for definition) developed by Tonn et al (1989) for each of the MCS and SP building samples. The 'Fh' term used in the figure refers to the mean fraction of NAC (or of total energy use in other cases) used for space heating.

The mean NAC values were obtained using PRISM in the previous study for both sets of apartments in the MCS and SP buildings. The data points shown in Fig. 1 were calculated using (arbitrarily selected) values of Fh from 0.3 – 0.5 for the MCS set of apartments and the SP set. The "likely" combination of these fractions is circled in the figure. The "likely" case was determined from examination of the Fife ELCAP data, the MHEUS results, and calculations for three MCS and three SP buildings from the Tacoma evaluation (see Modeling MF Energy Use with SHEAF,

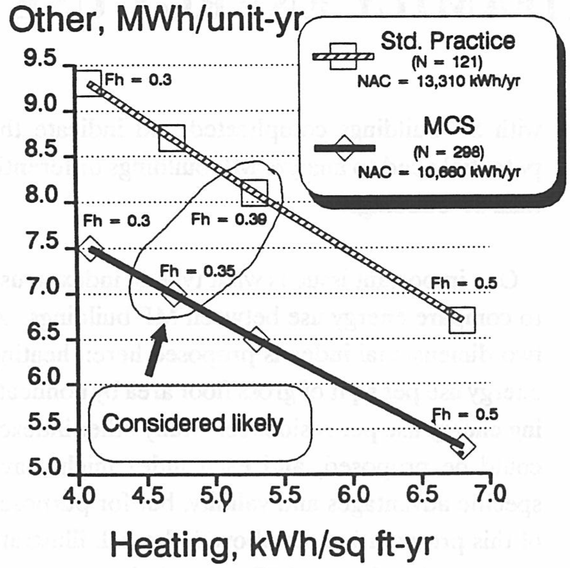

Fig.1 – MF energy index possibility space for MCS and SP MF datasets from the Tacoma MCS evaluation (Tonn et al 1989).

Application to Datasets with Billing Data, following). The "likely" difference in heating energy consumption, 0.6 kWh/ft^2-yr, is in the same range estimated for building-level savings by Tonn et al (0.8 kWh/ft^2-yr).

This index appears to be an important concept for comparing MF buildings – especially all-electric buildings, and it allows the comparison to be made based on values of NAC. However, basing this index on NAC requires a reasonable knowledge of heating energy use to estimate a likely case, and the estimation of heating energy use was a significant problem both in the Tacoma MCS evaluation and in evaluation studies of all-electric MF buildings in general, unless expensive metering is employed. With results from electric energy use measurement studies for MF buildings now becoming available, devising methods for estimating heating energy use in all-electric MF buildings using empirical data may be approached with more confidence.

The energy use index will be referred to as the MF building energy performance Index (MFI), and the MFI is two-dimensional. The units used here are kWh/ft^2 (space heating or H) by MWh (nonheating or O) for each residence, with the time period typically being annual. For the likely case shown in Fig. 1, the mean MFI for MCS residences is 4.7 kWh/ft^2-yr (H) by 7.0 MWh/yr (O), while the mean MFI for SP residences is 5.3 kWh/ft^2-yr (H) by 8.1 MWh/yr (O). The estimated MCS energy efficiency improvement for each residence is 0.6 kWh/ft^2-yr (H) by 1.1 MWh/yr (O). This index, or an index like it, appears to offer the best potential for comparing energy use between MF buildings. Presenting MFI values based on NAC depends completely on determining a value for Fh. If Fh were better determined, the MFI would provide a more useful breakout of heating and nonheating energy.

The comparison of the MCS and SP sets of apartments would be quite different if the MFI had the nonheating (O) energy use expressed as kWh/ft^2-yr – the two sets of apartments would be almost identical. The total energy use for both sets of units was about 13.6 kWh/ft^2-yr. (The points on the two lines in Fig. 1 line up vertically for the same values of Fh because the total energy use per ft^2 is almost the same.) Expressing 'O' as MWh/unit-yr causes the 'O' dimension of the MFI to increase as 'O' energy use increases, regardless of floor area. If 'O' energy use should be reasonably independent of floor area, this behavior is desirable, and floor area will have no impact on the value of the 'O' dimension of the MFI. The presentation here is based on keeping the 'O' dimension of the MFI virtually independent of floor area. (Thus, 'O' is expressed in units of MWh/yr instead of kWh/ft^2-yr.)

Since the MCS is directed at saving space heating energy, the cause of the difference in 'O' energy use between MCS and SP can be questioned. No con-

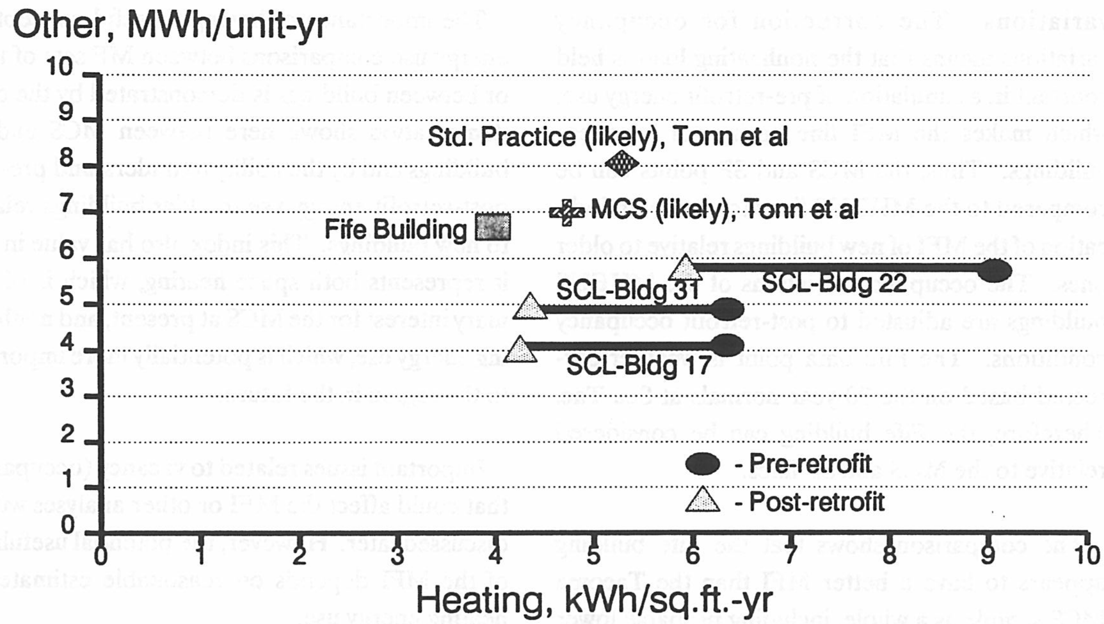

Fig. 2—Comparison of MHEUS buildings MFI values before and after retrofit to the likely points estimated for the Tacoma MCS and SP datasets and to the ELCAP Fife building.

crete cause can be identified from previous work, but some discussion will highlight the complexities. In addition, Tonn et al (1989) "[controlled] for housing and demographic factors related to energy use."

A higher number of occupants were living in MCS residences than in SP residences (1.9 vs 1.7 family members). MCS households had lower annual income ($20,500 vs $25,000). MCS households were more likely to have air conditioning (22% vs 7%). SP households had significantly more clothes washers (92% vs 51%) and clothes dryers (93% vs 50%), while MCS units were slightly more likely to have laundry facilities in the building (10% vs 8.5%, although separately metered laundry facilities were not included in the estimation of NAC). SP units were much more likely to have devices running that removed air to the outside (80% vs 13%). MCS units were more likely to have waterbed heaters (30% vs 14%). Finally, the occupancy rate for MCS units was lower (77% vs 82%, see Normalizations section). Overall, there are a variety of factors to account for in reasoning why the MCS units used less 'O' energy, but the previous analysis still indicated that less 'O' energy was used by MCS residences.

A further comparison of MF residences to demonstrate the use of MFI is shown in Fig. 2, where data from the MHEUS study (Schuldt 1989) buildings are shown together with the MFI data points considered "likely" from Fig. 1 and a data point for the ELCAP Fife building. The MHEUS data lines indicate the MFI before and after the buildings were retrofitted, with the rightmost end point being the pre-retrofit condition and the leftmost the post-retrofit. The MHEUS data are corrected both for weather (Typical Meterological Year, TMY, weather data from Sea-Tac) and for occupancy variations. The correction for occupancy variations means that the nonheating load is held constant in a simulation of pre-retrofit energy use, which makes the MFI line horizontal for these buildings. Thus, the MCS and SP points can be compared to the MHEUS lines to obtain an indication of the MFI of new buildings relative to older ones. The occupancy variations of the MHEUS buildings are adjusted to post-retrofit occupancy conditions. The Fife data point is weather-corrected based on the 30-year normals at Sea-Tac. Therefore, the Fife building can be considered relative to the MCS and SP lines.

The comparison shows that the Fife building appears to have a better MFI than the Tacoma MCS sample as a whole, including probable lower heating consumption. MHEUS buildings 31 and 17, which are essentially identical, also appear to have better MFIs than the Tacoma MCS sample, while building 22 is more similar to the MCS sample. The performance of these older buildings relative to the MCS sample indicates that *some study is needed of the causes of better MFIs*, regardless of whether the building is an MCS or other type of building. Knowledge of the causes of better MFIs should allow better decisions to be made regarding future improvements to the MF stock.

The importance of having a useful concept for energy use comparisons between MF sets of units or between buildings is demonstrated by the clear demarcation shown here between MCS and SP buildings and by the ability to understand pre- and post-retrofit energy use in older buildings relative to new buildings. This index also has value in that it represents both space heating, which is of primary interest for the MCS at present, and nonheating energy use, which is potentially more important to the region in the future.

Important issues related to vacancy (occupancy) that could affect the MFI or other analyses will be discussed later. However, the potential usefulness of the MFI depends on reasonable estimates of heating energy use.

MODELING MF HEATING ENERGY USE

To improve understanding of overall MF building energy use and potential impacts of the MCS, the most important end use to model is space heating energy. Of the potential methods available for modeling and analyzing MF heating energy, two categories will be used to facilitate discussion: engineering and empirical.

An engineering model is developed from an understanding of the expected physical data and principles that govern energy flows to calculate expected energy use for a given building. This can be considered a "forward" process. An empirical model is based on actual energy data to model how a building implicitly performs, and this can be thought of as an "inverse" process (see Rabl et al 1986).

A combination of approaches can be used to provide information from both directions, and the best examples are "calibrated simulation models" (Cleary 1986, Cleary and Schuldt 1986, Schuldt 1989, MacDonald and Wasserman 1989). Some of these terms will be used below to indicate categories of models and relationships between approaches.

PRISM

The PRInceton Scorekeeping Method (PRISM) is a valuable modeling tool that has the benefit of widespread understanding and relative ease of use and which provides important information on total energy use. However, the use of PRISM for determining heating energy use is subject to known inaccuracies (Burnett and Lesser 1986, Fels et al 1986, Lee and Hadley 1988, Hwang 1989, Tonn et al 1989) caused by coincidence of a portion of all other energy use with heating energy as a function of outdoor temperature (or heating degree days, HDD).

Efforts to develop corrections to PRISM estimates of heating energy for SF buildings in the Pacific Northwest (Hwang 1989, Lee and Hadley 1988, Burnett and Lesser 1986) have important potential benefits for studying the impacts of the MCS. However, one of the advantages of PRISM was having a physical understanding of the parameters determined by the regression model, and some of the approaches to correcting PRISM obscure this advantage unless important explanations are derived that provide a physical basis for the models.

Lee and Hadley (1988) provided some physical interpretation, but the result involved engineering "judgment" regarding many physical factors in the residence and, on the whole, remains a problematic approach because of the inherent difficulties. Hwang (1989) developed a constant multiplier correction factor that is applied to the PRISM heating slope. This factor was based on a regression analysis of a large sample of residences, but this approach departs from improved physical interpretation of the initial PRISM parameters. What is needed are methods to complement these approaches that retain or improve the physical understanding of heating energy as a fraction of total energy use.

The approach of correcting the heating slope parameter estimates has some benefit, but there may be as much or more benefit in developing a procedure for correcting the reference temperature (see Fig. 3). The PRISM parameters can be affected by random fluctuations of the data being modeled, especially fluctuations around the reference temperature. Overall, significant benefits

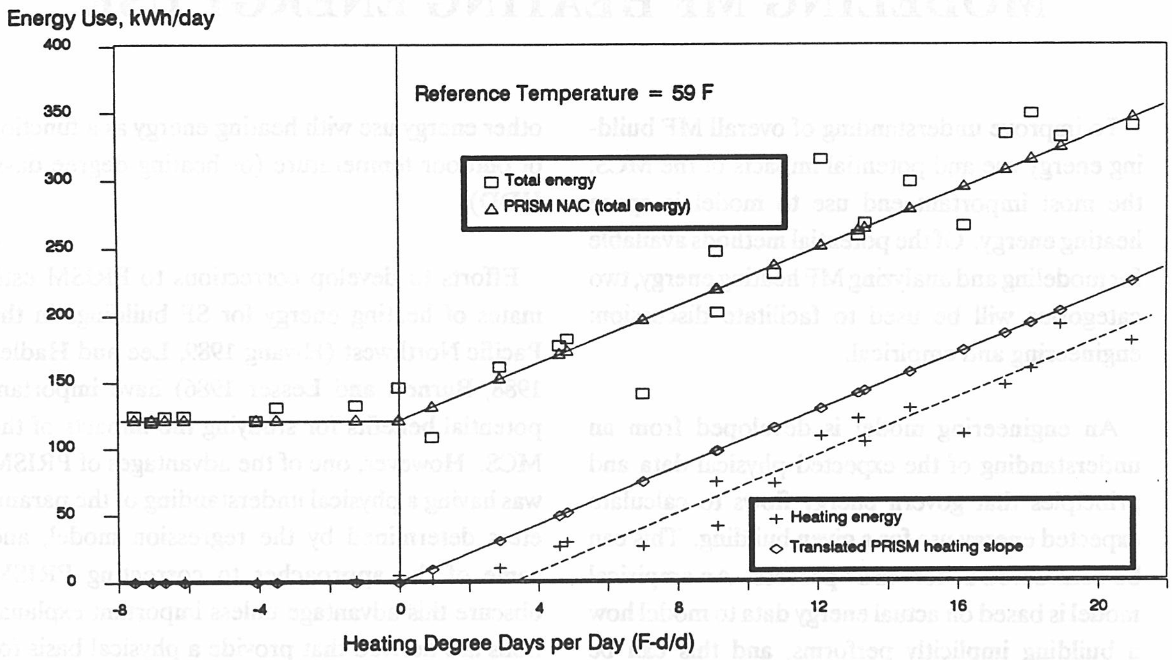

Fig. 3 – PRISM NAC (total) model, translated heating slope (PRISM heating), and metered data for Fife ELCAP building for total and heating energy use for 1988 shown graphically. As expected, the PRISM NAC (total) estimates the actual data well, but the translated heating slope is affected by seasonality. Methods for correcting PRISM heating estimates have included a simple constant multiplier (which for these data would be approximately 0.7). However, examination of the data here suggest that a correction to reference temperature would be more appropriate, since the slope is not far different from the metered data. Further refinement might include both an adjustment to reference temperature and an adjustment of slope.

would be possible if a useful correction procedure could be developed to provide better heating estimates, but a directed research effort is needed to develop the procedure and goodness of fit criteria. For the present, the NAC is the most valuable output of PRISM, and estimates of heating energy will be based on statistical corrections developed from large samples of residences with submetered heating data.

SUNDAY AND OTHER ENGINEERING MODELS

SUNDAY (or more complicated simulation tools such as DOE-2) have a valuable role to play in understanding MF heating energy use. These tools provide analysts substantial flexibility in modeling "idealized" energy use that allow parametric examination of factors impacting increases or decreases in energy use. In addition, these tools can provide calibrated simulations of real buildings that allow critical quality control checks and normalizations of energy use measurement data that can improve analysis results. However, the application of complicated simulation tools such as DOE-2 can be time consuming and expensive.

The application of these tools can be enhanced by better understanding of empirical data. Empirical data on energy use patterns can be compared to the "idealized" data from simulation tools. Variations in energy use patterns between the two can be studied to determine when and if corrections are needed for either the simulations or the interpretations of the empirical results. Thus, empirical and simulated data can each serve as a check on the other, and both the forward and inverse processes can be used to support one another. However, an empirical model is needed to allow this cross-checking and support to occur.

Heat loss equations or methods are essentially a subset of simulation models. The standard heating degree day method (ASHRAE 1989) or any of its variants offers a simple way to use heat loss estimates to obtain annual heating energy estimates. However, these methods are too simplistic to apply without significant research to determine what the appropriate correction factors are for large samples of buildings. These simpler methods should be used only after results from the more capable simulation tools are available for comparison.

SHEAF: A NEW EMPIRICAL MODEL

A new empirical modeling tool was developed in this study in order to improve the understanding of: (1) empirical energy use data and (2) how empirical results relate to simulated results. In particular, the tool was developed from analysis of the data from the Fife ELCAP MF building. The parameter modeled is heating fraction, Fh. The model represents Fh as a translated, truncated, simple sine function. The sine function model was determined based on inspection of the ELCAP data and the periodic (annual) nature of the data. More complicated representations, such as with Fourier analysis, were ruled out to keep the model simple and easier to understand.

This model will be called the Sinusoidal HEAting Fraction model (SHEAF) in the discussion below. The model is "idealized" but can be calibrated to provide close estimates of space heating energy for specific buildings or groups of buildings. However, the assets of this modeling approach are simplicity and the ability to provide answers that mimic the temporal empirical behavior of heating energy use in all-electric MF buildings in the Pacific Northwest. These assets appear to be important for studies of the MCS, where answers are needed regarding future impacts based on sometimes incomplete data for buildings evolving toward full occupancy. Further discussion of the model and results obtained for this study are presented in the following section.

MODELING MF ENERGY USE WITH SHEAF

SHEAF is an idealized model in that it represents complex phenomena seen in MF energy use data in a simplified form. More detail or exactness can be added in the future as needed, such as with temperature correction. For the present the model appears adequate for modeling heating energy use in all-electric MF buildings. The simple functional representation of space heating energy in this model can be incorporated in load forecasting or conservation resource models, if such an adaptation appears worthwhile.

The concept for the tool was developed from analysis of the data from the Fife ELCAP MF building. The concept was strengthened by examination of the RSDP data, but the RSDP data did not permit as detailed an examination as the ELCAP data. The model was developed graphically at first.

DESCRIPTION

The model is a truncated, translated, sinusoidal representation of Fh, and the heating energy use for any monthly or bimonthly period is estimated by multiplying the total energy use for that period by the value of Fh estimated by the model. Values of Fh for the ELCAP Fife building derived from a 28-day moving average of daily Fh, bimonthly Fh (determined from sums of daily consumption values for heating and total energy use), and the sinusoidal model are shown in Fig. 4. The model depicted below was estimated for the Fife ELCAP building by trial-and-error. The sinusoidal representation of heating fraction allows estimation of heating energy over the approximately two-year period shown for this building within 4% of measured, when monthly or bimonthly billing data

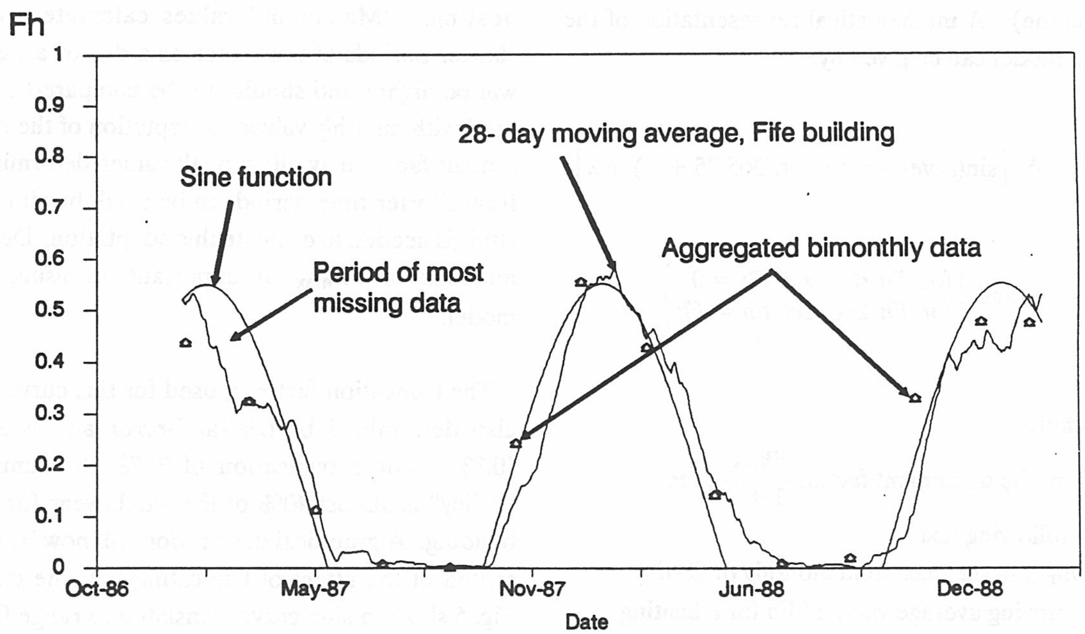

Fig. 4 – Aggregated bimonthly heating fractions, 28-day moving average of daily heating fractions, and sinusoidal model (SHEAF).

(total energy use) are multiplied by the estimated heating fraction for that month and summed over the whole period.

This model represents the increasing use of heating energy in the winter (as a fraction of total energy use) and the minimal use of heating energy in the summer. The 'truncation' of the curve defines the summer (nonheating) 'valley' seen in Fig. 4 where heating energy use is small. The truncation sets all values of Fh to zero in the valleys. The amount of truncation determines whether the valley is larger (higher truncation) or smaller (lower truncation). Fh_{max}, defined below, scales the curve to the appropriate maximum value, and the 'translation' of the curve moves it vertically to match the level of truncation and the value of Fh_{max}.

The sine curve and the bimonthly data in Fig. 4 lag the 28-day moving average by 14 days since the 28-day average was for the previous 28 days. Fh can be thought of simply as: $Fh = Fh_{max} \cdot$ (sine function). A mathematical representation of the sine model can be given by:

$$Fh = \delta \cdot \left[\sin(date{-}time \cdot 2\pi/365.25 + \varphi) + \lambda\right]$$

$$\text{and} \begin{Bmatrix} \text{for } Fh < 0, \textit{ set } Fh = 0 \\ \text{for } Fh \geq 0, \textit{ set } Fh = Fh \end{Bmatrix}$$

where

$\delta =$ the decrement factor, $\dfrac{Fh_{max}}{1+\lambda}$, see following text

$Fh_{max} =$ the maximum monthly or 28-day moving average value of Fh for a heating season, dimensionless

$date{-}time =$ a date-time serial value (e.g., Jan. 1, 1900 = 1 and Jan. 1, 1989 = 32,509)

$\varphi =$ the phase angle to bring the date-time serial value angle in phase with heating energy use (adjusts the sine function to "real time")

$\lambda =$ the translation factor to bring the sinusoidal curve to the proper relative position, $1 - 2t$

$t =$ the truncation factor, see following text

If the sine curve time adjustment (or phase angle, φ) is held fixed for a given climate – which appears reasonable from the data examined for this study, the translated, truncated sine curve can be determined completely by Fh_{max} and the truncation factor, t. For the sine curve in Fig. 4, the date-time serial value used for January 1, 1989, is 32,509, and the phase angle, φ, is $+0.3767\pi$ (1.1834) (determined by trial-and-error).

The value of Fh_{max} was determined by inspection to be 0.55, and this value is an average value over a period of about a month. Thus, in the middle of winter, about 55% of the monthly energy is used for heating. "Maximum" values calculated over shorter periods of time, such as a day or a week, will be higher and should not be compared to or used with monthly values. Adaptation of the decrement factor may allow peak values determined from shorter time periods to be used, but further study is needed to evaluate this adaptation. Determination of Fh_{max} is important for using this model.

The truncation factor, t, used for this curve was also determined by trial-and-error and is 33% (0.33). For a truncation of 33%, the summer "valley" is almost 40% of the whole year for this building. A graphical description will now be presented of the effect of truncating the sine curve. Fig. 5 shows a sine curve translated to range from zero to two vs the date-time serial values and with the same phase angle used in Fig. 4. The portions

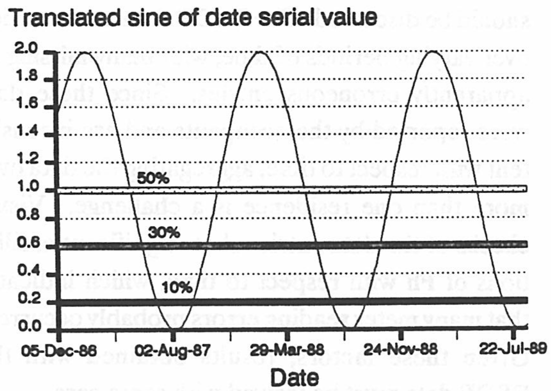

Fig.5 – Illustration of sine translation and location of truncation lines.

of the sine curve above the solid lines drawn across the sine curve indicate how much of the curve would be used for 50%, 30%, and 10% truncation.

The truncated curve is then moved (translated) and scaled to range from zero to some maximum value. Negative values are set to zero with the truncation. The effect of translation and truncation is shown in Fig. 6 for the 50%, 30%, and 10% truncation values of Fig. 5 – and a maximum value of one – on the same date-time serial axis as in Fig. 5. Lower values of truncation spread the curve out, and in the case of Fh, imply that the heating season is longer. The complete sine curve (truncation equals 0%) would imply that the heating season lasted all year and went to zero at one point (as in Fig. 5 for the full curve).

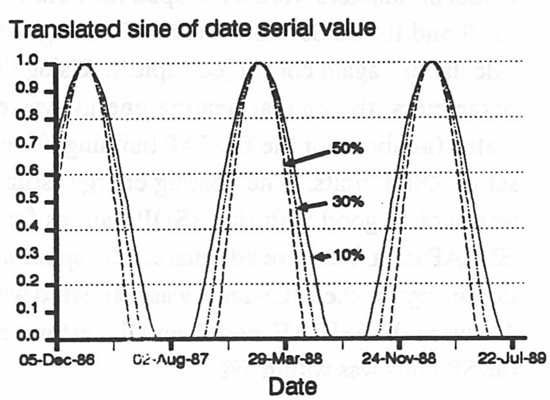

Fig.6 – Illustration of effect of truncation.

Nonlinear regression methods can be used to determine the required values of the model, if heating energy is metered separately and Fh values for monthly (or bimonthly) periods can be calculated. Aggregated monthly data from the Fife ELCAP building were analyzed to determine model parameters for a sinusoidal model of Fh using a computerized nonlinear regression technique. The model involves Fh as the dependent variable (monthly values) and time as the independent variable, with the model parameters being δ, φ, and λ. The results are promising in that the model parameters converge rapidly (when given the values determined above by inspection and trial-and-error as starting values) and can provide a reasonable representation of Fh for this building. The regression results were: $\delta = 0.2725$, $\varphi = 1.319$, and $\lambda = 0.78$ (the value of Fh_{max} is 0.48). With these parameters in the sinusoidal model, heating energy was calculated within 0.2% of actual over the whole period of data collection, using monthly data, as opposed to the 4% obtained with the trial-and-error method above.

For estimating space heating energy, the sine curve estimate of Fh at a time corresponding to the midpoint of a monthly period is multiplied by the total monthly electricity use for that monthly period to calculate a monthly heating energy value. The monthly values are summed over 12 months to arrive at the annual heating energy use estimate.

A major problem with the regression above is known periods of missing and questionable data, which were determined from extensive inspection and checking for consistency and correctness. The period from December 1986 - March 1987 has significant problems with heating consumption values that do not appear to make sense and are often zero or very low. There may have been difficulties with energy monitoring equipment during this period. Similarly, though not as obvious, there appeared to be problems with the data in the period from December 1988 - January 1989. Therefore, any regression results would have to be tempered with the knowledge that data during these periods were questionable. The value for Fh_{max} of 0.48 determined above reflects the lower values of the data points during the problem periods identified. Although the model provides very good estimates of heating energy to match the available data, the actual peak heating fraction is expected to be higher.

A second regression, with the first four months and the second and third to last months removed (which correspond to the problem periods), gave more reasonable results ($Fh_{max} = 0.52$). This model matched heating energy data within 3% and is probably a better representation of the building. The residual sum of squares for this revised model was 0.04 (N = 17), which is comparable to the 0.06 (N = 23) obtained for the model with all data points included.

APPLICATION TO DATASETS WITH SUBMETERED DATA

The SHEAF concept was used with data from MF residences in the RSDP data base. MFI data points for the RSDP data could not be shown in Fig. 2, because floor area data were not available for these residences. Also, the nonheating energy use for the RSDP data would be incorrect, since the data covered less than a full year.

The intent of this portion of the work was to check whether SHEAF would estimate space heating energy, given available submetered space heating data, as well for the RSDP units as for the ELCAP units. In other words, does the sinusoidal model make sense for more than one set of MF residences.

The difficulty of working with the RSDP data should be discussed. The RSDP data are recorded over varying periods of time, with many missing or apparently erroneous entries. Since these data were reported by the occupants and are inconsistent with respect to time, aggregating the data over more than one residence is a challenge. Visual checks of the data entries show significant oscillations of Fh with respect to time, which indicates that many meter reading errors probably occurred. Given these factors, results obtained with the RSDP data must be viewed with some care.

Despite these problems, the data for the 12 MCS and 12 SP units used here did not appear unreasonable when all units were aggregated to one data set for MCS and one for SP at a monthly level. In part this was possible because the variations in meter reading time intervals for these two sets of data were minor compared to the incredible variation found for other groups of residences. However, even though the data appeared reasonable, the RSDP data for the SP units appeared to have more missing data or erratic data and lower occupancy compared to the MCS units (based on examination of indoor temperature data).

Using the aggregated monthly Fh data (all units were aggregated over time for all units combined), nonlinear regression estimates of the SHEAF model parameters were developed for both the 12 MCS and the 12 SP RSDP units. The regression calculations again converged rapidly. Using these parameters, the annual heating energy was estimated (as above for the ELCAP building) for each set of RSDP units. The heating energy estimates were not as good with the RSDP data as for the ELCAP data, but were adequate. The space heating energy for the MCS units was estimated within 2% using the SHEAF model, and the estimate for the SP units was within 5%.

For this subset of the RSDP data, the SP set of residences used less total energy and less space heating energy than the MCS residences. This difference (see Table 1) is probably influenced by the apparent lower occupancy of the SP residences. The calculated value of Fh_{max} based on the SHEAF regression parameters was also lower for the SP residences (0.57 vs 0.60). This comparison showed that the sinusoidal model appears to perform adequately, but further testing is needed. The comparison also raised questions about the "usability" of the RSDP data and reinforced the importance of occupancy correction in interpreting MF metered energy use data.

Table 1. Comparison of the RSDP MF sets of MCS and SP residences.

	MCS	SP
No. of units	12	12
Total energy, MWh/unit-yr	10.3	8.3
Heating energy, MWh/unit-yr	4.0	3.1
Fh_{max}	0.60	0.57
Regression parameters		
δ	0.31	0.32
φ	1.63	1.70
λ	0.91	0.78

The sinusoidal model was also applied to data for a group of single family RSDP residences, including both MCS and SP residences, obtained from an informal progress report to Bonneville (Palmiter et al 1988). Data are available in this report for average heating energy and total energy use by month for a set of 95 residences that have received considerable analysis by the Washington State Energy Office and by Ecotope (again, the data do not cover a complete year). The SHEAF model parameters were estimated using nonlinear regression for the available data. The resulting SHEAF model was used to estimate monthly space heating energy for this set of residences, and the monthly estimates were summed to a heating season total. The space heating energy seasonal sum was within 1.5% of the Ecotope results for this set of residences, which again showed the adequacy of the sinusoidal model.

The regression-based ($\delta = 0.27$, $\lambda = 1.18$) calculated value of Fh_{max} for these SF residences was 0.59, which is similar to the values for the RSDP MF residences. Interestingly, the truncation was −9%, which indicates that the sine curve is lifted above zero for all points (the entire sine curve is used and no truncation is needed). The negative truncation indicates that, on average, these single family residences require heating for the whole year, which is in line with the earlier discussion on higher occupant density and internal loads in MF buildings.

APPLICATION TO DATASETS WITH BILLING DATA

The potential for determining SHEAF model parameters with only utility billing data available was also considered. Many assumptions and simplifications may be necessary for this approach to work. If the assumption is made that appropriate truncation factors can be determined for different classes of MF buildings, the model could be determined with only peak Fh. Different methods for estimating peak monthly Fh were tested in a heuristic manner. Of the methods tested, the method that provided the best estimates of peak monthly Fh is described by the equation:

$$Fh_{max} = 1 - \frac{e_{6-9}}{e_{12-3}}$$

where

e_{6-9} = the total energy use for the months of June – September divided by the number of days in this period

e_{12-3} = the total energy use for the months of December – March divided by the number of days in this period

Use of this method would presume that significant changes were not occurring in the building during the months that were used to make the calculations, but problems with major changes in a building affect most energy analysis methods.

This method was applied to the Fife building and the RSDP MF and single family residences. The results for the Fife building were reasonable, with Fh_{max} estimated to be 0.56, which is very close to the peaks from the 28-day moving averages (0.55 is the value used for Fig. 4). The estimated peak for the RSDP single family data was 0.59, which is identical to the value obtained from the regression-based estimate based on the Ecotope data.

The estimated value for the RSDP MCS MF data was 0.60, which is also identical to the regression-based estimate. The estimated value for the RSDP SP MF data was 0.53 – lower than the regression-based value of 0.57, but not unreasonable. The possibility of approximating SHEAF model parameters from billing data appears interesting, but further testing of this idea is also needed before it can receive much use.

Although no submetered data were available to compare with estimates, peak monthly Fh values were also calculated using billing data for seven MF buildings from the Tacoma MCS study (Tonn et al 1989) – three SP and four MCS. The Tacoma data were explored to see what insights might be gained.

One of the MCS buildings had significant increases in occupancy for the period when billing data were available, and the Fh values were negative. This building also has a negative heating slope coefficient from PRISM. For the remaining three MCS and the three SP buildings, an interesting mix of values was obtained. The MCS buildings showed peak monthly fractions of 0.48, 0.45, and 0.55, while the SP buildings showed peak fractions of 0.34, 0.55, and 0.54.

The peak fractions give some idea of how space heating energy use compares to total energy use, but the magnitudes of the space heating consumptions are not known. Fh_{max} can change either because the building is more efficient in use of space heating energy or because nonheating energy use increases. The SP building above with a peak fraction of 0.34 appears to have low heating energy use, but in fact this building has a high energy consumption. The heating fraction is low because the nonheating energy is extremely high. The variations in Fh_{max} seen here are instructive, and causes for these types of variations should be explored further.

DISCUSSION

SHEAF provides a visual representation of the way heating energy is used and the magnitude of the annual fraction of total energy used for heating. Thus, part of the benefit of using this model is to present the energy behavior symbolically for improved comprehension by people viewing the model – including less technically oriented people. This representation can be used to describe different "classes" of buildings based on energy use characteristics represented by the model.

If future study indicates that sinusoidal representation of heating energy use is useful for the Pacific Northwest and that "classes" of building can be defined which can be represented by some default parameters for the sinusoidal model, data collection requirements for modeling MF buildings may become more simplified (see MacDonald and White 1990). Significant study is still needed to determine the effects of weather patterns on results obtained with this model and to determine whether "classes" of buildings can be defined. However, if this approach proves useful, the ease of understanding space heating energy use and overall changes to MFI should improve.

The value of the sinusoidal model of Fh appears to lie in the potential classification of buildings according to peak monthly heating fraction, Fh_{max} (and truncation). The ability to determine certain model parameters using billing data could also be important. If buildings can be modeled with the SHEAF concept using simplifications which make application of the approach easier, improvements in future field study methods and simplification of MF field study energy use data collection requirements are expected.

This model may also prove important for checking the quality of measured energy use data obtained in field studies. Because the model mimics actual heating energy behavior over time, heating and total energy use data can be checked for variations from expected behavior forecast by a model of the building being monitored. (This technique was used in this study to examine the MF RSDP data, where graphs of Fh showed zero values in the middle of winter, values of one or more, and oscillations that sometimes indicate meter reading errors.) The capability to compare a time-domain model of expected empirical results with actual data could be an important tool for quality control.

NORMALIZATIONS

The importance of weather normalizations in energy studies is recognized. For MF buildings, variations in occupancy are also important, and this importance has been mentioned several times in this report. Tenant turnover in MF buildings is often high (Goldman et al 1988), which means that all the units in a building may not be occupied all the time. For energy studies, different numbers of units may be occupied during different time periods, which makes evaluation of changes in energy use over time more difficult. Thus, occupancy rates can affect evaluations of MF energy use, and previous work has indicated the potential problems from occupancy variations (Goldman et al 1988, Ivey et al 1988, Schuldt 1989, Tonn et al 1989).

A distinction should be made between *new* and *existing* buildings. Occupancy in new MF buildings includes the initial period when tenants begin moving in, as well as tenant turnover after the initial move-in period. Comparing a building that is in the initial moving in phase with one that has already reached a more stable occupancy is often not practical. Tonn et al (1989) identified MF buildings that had negative heating slopes from PRISM analysis, which can occur if occupancy rates increase significantly from winter to summer. Thus, some care must be exercised when examining new buildings.

Tonn et al (1989) developed a measure of "occupancy rate" to specifically account for vacant units (low energy use) in buildings, and they found occupancy rates of 77% in their sample of MCS units for the time period they investigated and 82% for SP units. The occupancy rate of a MF building is often one of the biggest occupancy factors affecting variations in MF energy use, and normalization for occupancy can thus be important.

SF buildings can also be expected to experience changes in occupants during the course of an energy evaluation, and removing such buildings from the sample used in an evaluation is considered good practice (Goldberg 1986). Evaluations of MF buildings cannot typically benefit from such a procedure, if the whole building is to be evaluated. Therefore, normalizations that account for occupancy effects become more important for MF buildings.

Occupancy effects can also be caused by the behavior of occupants, and significant literature exists on behavior and its relation to energy impacts (see for example ACEEE 1988). With the larger number of occupants in MF buildings relative to SF buildings, the increased potential for behavioral effects on energy use may mean some normalization of these effects is needed.

A method of accounting for occupancy (and behavioral) impacts on energy use was developed previously for the MHEUS work (Schuldt 1989), and an example of the type of normalizations used in that work is shown in Fig. 7, where weather and occupancy normalizations are shown for building 17 from the MHEUS study.

One of the benefits of the MHEUS study is that it shows the effects of different normalizations, adjusting for weather and occupancy, on study results. The normalizations were accomplished by calibrating simulations from the DOE-2 program to the metered energy use data and performing additional simulations using normalized (standard) weather and two adjustments for variations in occupancy. The weather normalization in Fig. 7 is always performed first. The lines in Fig. 7 show the pre- and post-retrofit conditions, as indicated. A description of the retrofits can be found in Ivey et al (1988), but the building number is different. Buildings 23 and 24 in Ivey et al are buildings 17 and 31 discussed here (Schuldt 1989).

The line labeled 'Measured' in the figure represents the metered data results with no normalizations for weather or occupancy. The line labeled 'TMY' (for Typical Meterological Year) shows the results normalized for standard year weather *at the airport*. The 'Pre-TMY' line shows the results with standard airport weather and the occupancy effects (both tenancy and behavior) held similar to those in the pre-retrofit condition, while the Post-TMY shows the results for standard airport weather and post-retrofit occupancy conditions (also shown in Fig. 2). The resultant effects of occupancy on heating energy savings is more important than weather for this building and also for Building 31. Results for Building 22 were predominantly affected by weather and not by occupancy changes, although there reportedly were significant changes in tenants for this building.

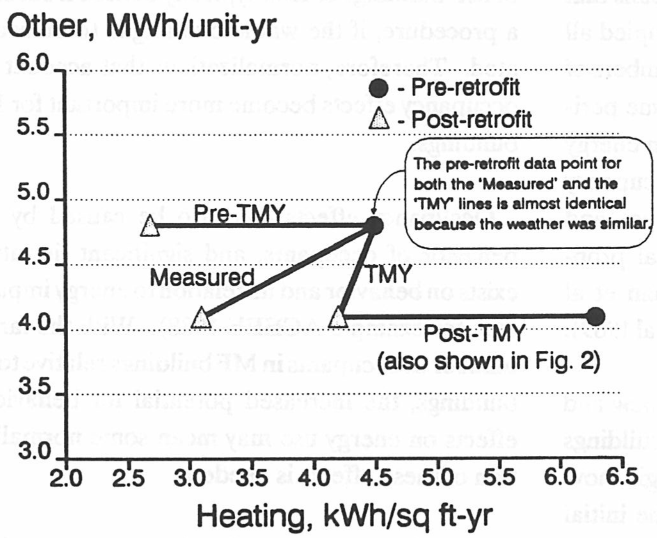

Fig.7 – Comparison of MFI pre/post-retrofit lines for MHEUS Building 17 for different normalizations.

These results show graphically that, for MF buildings, both weather and occupancy normalizations can be important.

More work could be done to examine different approaches for normalizing energy use to account for variations caused by occupancy effects and weather. The methods used in the MHEUS study seem to provide one reasonable approach that accomplishes the normalizations. However, the multiple results mean that an analyst must still choose the most "appropriate" result for a given study.

Further work has been conducted by Bonneville to analyze potential energy use differences between *new* MCS and SP buildings (UIC 1989). This work builds on the MHEUS normalization methods and will not be discussed in detail here.

The MHEUS study also confirmed the significant variation in microclimate (weather) that occurs in the coastal areas of the Pacific Northwest, and standard weather at the airport may not be standard at other locations. Thus, one issue for weather normalizations is the impact of microclimate variations. Normalizing results to the airport may be important for region-wide studies looking at utility impacts, but microclimate impacts are more important to an owner or other party who wants to understand savings impacts *for their building*. If the owner's or occupant's (or other decision-maker's) perspective is important for attempting to motivate energy-saving actions in an energy conservation program, then microclimate becomes more important in evaluating potential cost savings for the Seattle area, with its large population and varied microclimates.

IMPLICATIONS FOR ENERGY PLANNERS

Although heating is the cause of winter peaks, energy planners cannot ignore the "other" energy use for MF buildings if annual energy savings are important, because the other uses are greater on an annual basis (see also Meier et al, 1989, re single family buildings). Regional estimates of potential residential energy conservation savings for energy uses other than space heating are about as much as for the MCS (NWPPC 1986). Future consideration of energy efficiency must focus on all energy uses.

ANNUAL LOAD FACTOR

The data evaluated for this study show a lower percentage of annual total energy use for heating and a shorter apparent heating season for MF buildings compared to SF buildings. These factors indicate that MF buildings can be expected to have lower annual load factors (annual kWH divided by peak monthly kWh times 12) than SF buildings for heating energy use. Therefore, where peak energy use in the middle of winter is a problem, large populations of MF buildings may be more important heating-energy-saving targets than SF buildings.

NORTHWEST POWER PLAN

An attempt was made to apply what was learned in this study to energy savings data for MF buildings contained in the *1988 Supplement to the 1986 Northwest Conservation and Electric Power Plan, Appendix S1, Economic Forecasts for the Pacific Northwest*. However, the data in that appendix on MF buildings appeared to indicate lower than expected heating energy consumption (kWh/yr) for a given heat loss value (UA, Btu/h-F), and thus the intended application was impractical.

Information concerning the Fife ELCAP building (which seems to be a fairly efficient building) indicates, for each unit, a typical UA of about 1750 Btu/h-F and a typical consumption of 3300 kWh/yr for heating. Fig. 8 shows the data from Table 30 of the Power Plan Appendix and a data point for the Fife building, which is near Seattle. The dashed lines show an approximate extension of the data from the Power Plan. The heating energy use goes to zero at what appears to be an unreasonably high value of UA. The Power Plan data are also low compared to the actual data for the Fife building, which provides some confirmation that the lower than expected values need to be checked.

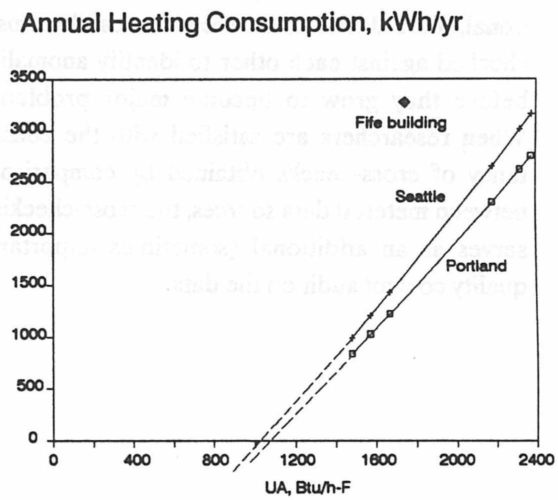

Fig.8 – Comparison of Power Plan UA and heating energy use data with Fife building data.

FIELD MEASUREMENT STUDIES

Future energy measurement field studies cannot ignore the problems with data collection observable from the MF ELCAP and RSDP data. Only one ELCAP MF building was considered usable for this study (due to low priority and resulting inadequate resources), although the ELCAP contribution was still extremely important. The RSDP data had several limitations, but chief among them is the erratic nature of entries and apparent or real missing values (also mentioned as significant problems in Palmiter et al 1988). Analysis of the RSDP data is much more difficult because of the erratic readings, missing data, and questionable data values. Some form of improved quality control is needed to assure that data make sense as collected and can be used in future analyses related to the MCS and energy savings potential for the region.

Based on ORNL experience with metering energy use in commercial buildings, end use energy measurement studies can benefit from redundant metering approaches using electric billing meters as a control total on other (usually more detailed) metered data. The billing meter data and the additional, more detailed, metered data can be cross-checked against each other to identify anomalies before they grow to become major problems. When researchers are satisfied with the consistency of cross-checks obtained by comparisons between metered data sources, the cross-checking serves as an additional (sometimes important) quality control audit on the data.

Cross-checking between metered data sources should be considered for all energy use measurement studies. The MHEUS study benefitted from using an approach with multiple data sources and cross-checks between sources (Schuldt 1989), and a major energy metering effort being planned in the state of Texas also includes such an approach (Haberl 1989).

Finally, the selection of end uses to be measured in field measurement studies should be based on benefits derived from an evolution in knowledge. At present, knowledge regarding heating energy use is limited, and for studies primarily interested in heating impacts, heating should be the only end use that is metered separately. If knowledge concerning hot water use is also important, hot water use should also be metered separately. Knowledge of heating energy use is needed now, and knowledge of hot water use should be valuable in the near future. The incremental cost of measuring each end use should be weighed against the need for incremental knowledge, current analysis priorities, and of course, availability of resources.

CONCLUSIONS

This has been a wide-ranging study that has examined many topics. A new index for representation of MF energy use, MFI, is proposed and explained. This index, or an index like it, appears to have important potential for all-electric MF buildings to improve the understanding of energy use and improve comparisons of energy use between buildings. Calculation of the MFI possibility space, based on PRISM NAC values obtained in the previous Tacoma MCS evaluation study, supports the statistically determined building-level space heating energy improvement estimate of 0.8 kWh/ft^2-yr attributable to the MCS. With these heating savings fixed, the Tacoma MCS buildings also used about one MWh/yr less non-heating energy for each apartment unit.

MFI should be useful for improving understanding of the energy use of MCS residences relative to SP residences, and use of the MFI will help maintain the distinction between space heating and other energy consumptions. MFI, or an index like it, should be considered for all future representations of MF energy use in all-electric buildings.

Examination of MFI values for the buildings in this study indicates that the causes of variations in MFI should be studied. Determination of the causes of variation appears needed to define classes of buildings based on efficiency levels (or MFI) and to help provide direction for future efforts to improve energy efficiency in the region.

The MFI also appears useful for improving the understanding of changes in energy use due to retrofits. The MFI can be used with PRISM NAC values if a reasonable estimate of heating energy use can be made. At present, PRISM heating energy estimates do not appear to be acceptable.

Although large amounts of end use energy data have been collected for residential buildings in the Pacific Northwest, the data for MF buildings are very limited. Under ELCAP, MF buildings had "low" priority most of the time. This low priority meant that adequate resources could not be directed toward maintaining high quality data sets. As a result, the ELCAP Fife building data are worth study, but the ELCAP data for other MF buildings have too many gaps. The RSDP MF data are extremely difficult to use for many types of analyses and are probably not worth future consideration, due to the erratic and questionable nature of the data, the difficulty of performing analyses with the multiple time intervals, and the apparent lack of floor space data.

If the ELCAP Fife building is the only MF building of more recent construction with end use energy consumption data considered worthy of the type of analysis conducted here, data from more buildings are needed for these types of analyses. In addition, fruitful study of the potential use of engineering simulation models such as DOE-2 or SUNDAY for modeling MF energy use in buildings of this type must wait for the additional data.

These data limitations also serve to increase the value of the data collected for the previous Tacoma MCS evaluation. Some thought should be given to expanding the analysis of these buildings and including the results from these buildings in a longitudinal study of the MCS.

MF energy use can be modeled using both engineering models and empirical data models. Both engineering and empirical data models are needed, and results from both the forward (engineering) and inverse (empirical) approaches should be used to support improved knowledge on MF energy use. Calibrated simulations use empirical input to improve simulation results, and this approach should have high priority for future studies of MF energy use.

However, the use of calibrated simulations for making comparisons between new MCS and SP buildings is not the same as comparing pre- and post-retrofit energy performance. Some thought must be given to how comparisons of occupancy effects and nonheating energy use will be made. The reasons for the differences must still be understood.

The MHEUS study has provided a valuable contribution in continuing the calibrated simulation approach used by Seattle City Light, and the lessons about occupancy and weather normalizations from the MHEUS study should be considered in planning any MF energy use measurement study. The use of DOE-2 for the simulations should only be considered for initial studies. As experience with calibrated simulations of MF buildings grows, research should be conducted to calibrate simpler simulation tools, such as SUNDAY, to the DOE-2 simulations and to empirical data.

Some improvements to weather normalizations may be needed. Normalizing energy use to airport weather may not make sense in some cases for coastal areas like the metropolitan area of Seattle. Normalizing to the weather for specific years may be more useful in longitudinal studies of MCS impacts when more detailed microclimate data are available, as this allows an improved comparison with other historical data on regional energy consumption.

The importance of occupancy normalizations in studies of energy retrofits in MF buildings suggests that more occupancy data may need to be collected in field studies. Potential benefits of occupancy surveys, occupancy reporting by month, or occupancy sensors deserve further consideration in planning of future studies. Occupancy data are needed to develop models of occupancy, which appear to be needed to improve modeling of MF energy use.

A brief examination of PRISM results for the ELCAP Fife building indicates that using a constant multiplier for correction of heating energy estimates does not appear to be the best correction approach. Correction to the reference temperature appears more appropriate to retain the physical significance of the PRISM parameters. Research study in this area would be useful to improve use of PRISM for determining heating energy use in MF buildings.

A new empirical model, SHEAF, was developed that may have the ability to provide simple, quick estimates of space heating energy use for all-electric MF buildings in the future. This model appears to give reasonable estimates of heating energy use over a year for a given "class" of buildings (yet to be determined) with only monthly total energy use and the peak heating fraction (Fh_{max}) known. This implies that metering studies might only require submetered heating energy use for three to six weeks in the coldest part of the winter, in addition to billing data for a year, to obtain an annual heating estimate. SHEAF also appears to have benefits for checking the quality of measured data and appears to provide significant self-correction with respect to weather (year-to-year variations appear to be small). This weather normalization is accomplished through the changes in total energy use that occur as heating increases or decreases. Further research on more buildings with better data is needed to verify the potential benefits of this modeling approach.

The assets of SHEAF are its simplicity and ability to mimic the temporal patterns of empirical data. SHEAF may have the potential for defining classes of MF buildings based on the determining values of the SHEAF parameters. SHEAF (or some derivative) may have important use in parametric studies of energy conservation potential in MF (and perhaps SF) buildings when different classes of buildings have been defined.

Heating is perhaps the most important end use from a winter peaking view, but heating appears to be only 30 – 40% of total energy use for most MF buildings. Therefore, an improved understanding of the nonheating energy use and the relative efficiencies of different end uses in MF buildings is needed. In addition, if the population of MF buildings increases relative to SF buildings, lower annual electric load factors for space heating energy use may result.

An attempt at applying the results of this study to data from the Northwest Power Plan was not completed due to a significant discrepancy between plan data on one hand and actual data from the ELCAP Fife building and expected values based on experience on the other hand.

Some form of improved quality control is needed to assure that data collected in energy use measurement studies of MF buildings make sense as collected and can be used in future analyses related to the MCS and energy savings potential for the region. The problems with MF data from the ELCAP and RSDP programs should teach a lesson about quality. Current experience also indicates that redundant metering approaches using electric billing meters as one source of metered data, with cross-checks between metered data sources, should be considered for all energy use measurement studies. These cross-checks should be conducted as near to "real-time" as practical, i.e., as soon as possible after the data have been collected.

The selection of end uses to monitor should be based on benefits derived from an evolution in knowledge about specific end uses, proceeding from the most important to the least important. Knowledge regarding heating energy is needed most now. Knowledge of water heating energy use will probably be useful in the near future.

RECOMMENDATIONS

The new building energy performance index proposed for representing MF energy use, or an index like it, should be considered for all future representations of MF energy use. Energy planners must give more consideration to the understanding of energy use patterns in MF buildings and the causes of variations. Energy uses other than heating must be understood if improvements in annual energy use are important, especially since this study indicates that MCS buildings used less "other" energy than the SP buildings. A study of the causes of variation in MFI should be conducted to better inform future energy planning for MF buildings. In addition, study of the apparent anomalies in the Northwest Power Plan on conservation potential for MF buildings should be considered.

End use energy data are needed for more MF buildings to support evaluation and improvement of the MCS. The ability to adequately model MCS buildings using simple simulation tools such as SUNDAY also depends on obtaining the additional data. Therefore, energy use measurement studies should be conducted to obtain the needed data.

The use of SUNDAY for MF buildings should be predicated on verification of energy loads using more sophisticated tools such as DOE-2. Calculations using DOE-2 should be calibrated against empirical data, which would allow calibration of SUNDAY both to DOE-2 and to the empirical data. Use of DOE-2 or another sophisticated tool would allow a parametric study of the causes of variations in loads, which would improve confidence in the knowledge of the ability of SUNDAY to model variations in MF energy use loads. Any available parametric studies of MF buildings using DOE-2 (or other sophisticated tool) should be reviewed, and a new study may be needed to examine causes of energy use load variations. The results of parametric studies should be used to conduct a study of the ability of SUNDAY or other simpler simulation tools to model MF heating energy use.

Future energy use measurement studies should be planned with the need for occupancy and weather normalizations in mind. The benefits of calibrated simulations for making occupancy and weather normalizations of metered data from field studies must also be considered during project planning. A research study of the appropriate methods to use for these normalizations is needed. A study of potential methods to use for obtaining occupancy data also appears to be needed to support development of occupancy models.

Redundant metered data sources with ongoing cross-checking between sources for near-real-time analysis and quality control should be a high priority for energy use measurement studies. This cross-checking implies that some analysis by knowledgeable individuals should be conducted as the data are collected. In addition, a research study of current methods being used around the country to accomplish this cross-checking should be conducted to describe current thinking and define the leading edge in this field. This study would provide benefits for planning future energy metering studies in the region.

A longitudinal study of the MCS should be considered using the results from the previous Tacoma MCS evaluation and any future evaluations. Such a study could show changes in MCS and SP buildings over time, and the use of the previous results is enhanced by the corroboration of the previous building-level space heating savings estimate reported here and by the use of the MFI.

Corrections to PRISM heating energy estimates based on adjustment of reference temperature should be pursued. If PRISM can be used to generate acceptable heating energy use estimates, it would provide an important method for energy planners to use for estimating potential heating energy conservation potential and would also make use of the new energy index easier.

Use of the SHEAF model (or a variation) to examine future conservation potential should be evaluated further as data from more buildings become available. Future research should be considered to determine whether SHEAF can reasonably estimate space heating energy use based on a partial season of metered data.

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