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Author
Meier, A.K.

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Alan K. Meier

Buildings Energy Data Group
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720 USA

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Alan K. Meier
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720 USA

ABSTRACT

This paper describes several compilations of measured energy performance of buildings and equipment. These compilations cover new, low-energy residential buildings, residential retrofits, new commercial buildings, and commercial retrofits. The databases contain measured energy consumption from over a thousand studies, consisting of about 50,000 buildings. The principal goals of the compilations are to develop techniques for characterizing measured building energy performance and identifying successful, cost-effective conservation and solar strategies. Some results of the compilation of new, low-energy homes are presented.

INTRODUCTION

A great variety of technologies to save energy in buildings have been developed and implemented. Most of these new techniques have been justified on the basis of theoretical calculations or simulations rather than measured energy consumption. Others have been field-tested under very limited conditions. Yet theoretically successful conservation strategies may not be successful in practice owing to poor quality control, rapid degradation in performance, or user-resistance. It is essential to monitor the performance of low-energy technologies in the field as a means of providing feedback to the buildings community. Three major issues must be addressed:

1. which measures save energy?
2. do the measures save as much as predicted?
3. which measures are cost-effective?

The Buildings Energy Data Group (BED) seeks to increase the energy efficiency of buildings and equipment by compiling measured performance data and disseminating analyzed results to the buildings community. BED presently collects data and maintains five major data bases. These data bases are called Building Energy-Use Compilation and Analysis, or BECA. The BECA data bases (and their most recent associated report) are:

BECA-A	measured energy consumption of new, low-energy homes (Busch et al, 1984)
BECA-B	measured energy savings from residential retrofits (Goldman, 1984a, 1984b)
BECA-CN	measured energy consumption of new, low-energy commercial buildings (Wall et al, 1984)
BECA-CR	measured energy savings from commercial retrofits (Gardiner et al, 1984)
BECA-D	measured energy consumption of water heating systems (Usibelli, 1984)

Each data base contains measured building energy consumption data plus building and occupancy characteristics in consistent formats on a commercially available database system (DEC-Datatrieve). The commercial buildings data bases (BECA-CN and -CR) contain several hundred buildings, while the residential retrofit compilation (BECA-B) contains tens of thousands of houses.

CHARACTERIZING BUILDING ENERGY PERFORMANCE

Evaluating the energy performance of new buildings and the energy savings from conservation measures involves more than simply tabulating utility bills. In order to identify successful conservation measures, we need to be able to compare the energy use of different buildings. Thus, we require **indicators of building energy performance.** Such indicators are similar to the miles per gallon ratings for autos which enable a consumer to compare fuel economy of different vehicles. It is relatively easy to compare the performance of autos because a standard driving cycle can be simulated on a dynamometer. Each auto can be placed on the dynamometer and a fuel economy rating determined. True, the fuel economy may be greater than that actually obtained on the road, but one auto's rating is nevertheless comparable to that of other autos.

The indicators of building performance will enable us to compare new buildings as well as a single building prior to and following a retrofit. However, the procedure is much more complicated than for autos. Here, we are given the energy consumption for each building under different conditions; our goal is to normalize the consumption so as to reflect its performance under standard conditions. This is analogous to being told how much gasoline an auto consumed in a year with some information regarding operating conditions, and then be asked to predict its performance on the standard driving cycle on the dynamometer. Standardization procedures must account for many factors, including climate, internal loads, and occupancy patterns. The challenge is to develop reliable standardization procedures while relying on the least possible data. An example of building energy performance indicators, as well as the standardization procedures, is given below for the BECA-A data base of new, low-energy homes.

THE MEASURED ENERGY PERFORMANCE OF NEW, LOW-ENERGY HOMES (BECA-A)

New homes represent a great energy-conservation opportunity. It is simpler and cheaper to save energy by designing cleverly than retrofitting at a later date. A variety of designs and technologies have been used in new homes to conserve space heating energy. Initially, one could identify a few major designs: active solar, passive solar, superinsulated, and earth-sheltered. Now, however, the distinctions are becoming less clear-cut as new designs tend to incorporate a little of each technology. Which designs perform best? Which designs are most cost-effective? The analysis of the BECA-A data base seeks to answer these questions. The BECA-A data base currently consists of 319 houses. We have monthly submetered furnace consumption, building characteristics, and some operating data for most of them. Details of the BECA-A data base and the analytical techniques are discussed by Busch et al (1984).

Indicators of Building Performance

We use two indicators building energy performance in the analysis of new, low-energy houses, the "k-value" and the balance temperature. We begin by regressing the monthly fuel consumption against the average outside monthly temperature for each building. An example is shown in Figure 1. In some cases, we have weekly data, but the number of points used in the regression is typically between 8 and 20. The slope of the regression line is the k-value. The k-value corresponds to more than the overall conductivity (UA) of the envelope because it also includes, infiltration, and the building's ability to exploit solar gain and thermal mass.

The x-intercept of the regression line is the balance temperature, that is, the temperature below which heating energy must be supplied by a furnace. The true heating degree-days "seen" by that house must be calculated using the balance temperature as a base instead of the standard 18.3°C (65°F).

Standardization Procedures

Unfortunately, the k-value and balance temperature for one house cannot be directly compared against another because they do not reflect variations in operating practice. We developed three standardizations of the raw data to adjust the raw data to reflect standard conditions. First, furnace input must be converted to furnace output through multiplication by the furnace efficiency. In many houses, furnace efficiency measurements were made or nameplate efficiencies were provided. (Note that the vertical axis of Figure 1 is furnace output.)

Second, we adjust internal gains to a standard of about 1 kW. If a house has internal gains greater than 1 kW we add the excess to space heating consumption. The performance of a house with low internal gains will be improved due to this adjustment. On the other hand, we identified several houses claiming to be energy-efficient that, once adjusted for very high internal gains, were in fact poor performers.

Third, we adjust the balance temperature to reflect inside temperature. We cannot fairly compare two houses' balance temperatures when the occupants maintain the inside temperature at a cozy 22°C while the occupants of one of the other keep their home at a chilly 13°C. We use 20°C as the standard inside temperature. In practice, we adjust the mean outside temperature to reflect the 20°C standardization. The adjustments are shown graphically in Figure 1.

The adjustments described above for furnace efficiency, internal gains, and inside temperature, are made prior to the regression. The k-value and balance temperature derived from the regression thus reflect the standard operating conditions of inside temperature and internal gains. We can then compare buildings using these values. Histograms of the k-values and balance temperatures are shown in Figures 2 and 3.

Results

The results of our analysis are shown in Figure 4 and Table 1. We plotted each building's heating energy consumption against annual degree-days. We estimated the buildings' energy consumption using standardized internal gains and inside temperatures. Thus Figure 4 shows estimated energy consumption for all the buildings assuming that they were all operated in the same way. Note that we used a degree-day base of 13°C rather than the standard 18.3° because (as Figure 3 shows) most houses in the data base begin heating below that temperature.

Figure 4 shows that most new, low-energy houses are in fact energy efficient when compared to current practice, although the response to severity of the climate is less than than might be expected. In other words, energy consumption in new, low-energy houses is relatively constant across a wide range of climates. Since 1 kW of internal gains is roughly equal to 300 MJ/m^2-yr, space heating consumption was comparable to the energy used for appliances and water heating. The careful attention devoted to adjustment of internal gains appears to be warranted.

We examined the performance of the major building designs individually to determine which design performed most successfully. These results are displayed in Table 1. The average balance temperature and k-value for the entire data base indicate the overall quality of the buildings in the data base. These results emphasize the unsuitability of 18.2°C as a reference temperature for low-energy houses, since, on the average, they did not need furnace operation until the temperature fell below 13°C.

As a group, the earth-sheltered buildings performed best. However, the small sample size precludes a strong statement. Passive solar houses performed nearly as well as the earth-sheltered houses. The balance temperatures are nearly identical, but the passive solar group had a higher k-value and much greater spread in k-values (as reflected in the standard deviations). Superinsulated homes had a slightly higher k-value and a surprisingly high balance temperature. On the other hand, the superinsulated homes were more consistent in performance than any other group of houses. The active solar houses had the poorest k-value but a balance temperature slightly lower than the superinsulated houses. This possibly reflects more attention to thermal storage and less attention to the envelope in active solar houses.

We obtained incremental cost data for 132 houses. We calculated the cost of conserved energy (CCE) (Meier, 1983) using the incremental cost and the energy savings from the current practice. (Estimates of energy consumption using current practice is based on a series of computer simulations rather than collected data because no data base similar to BECA-A exists for current practice.) Current energy prices for comparison are 7 cents/kWh for electricity and $7/GJ for natural gas. Passive solar and superinsulated homes appear to be very cost-effective since the CCE is considerably less than the price of natural gas or electricity anyplace in the United State. Active solar houses, though still cost-effective at 5.7 cents/kWh, appear to be much poorer investments. No cost data are available for earth-sheltered houses.

CONCLUSIONS

The data base and analytical procedures outlined here for BECA-A is one example of our attempt to critically compile building energy performance data and to extract meaningful conclusions. Our analysis also emphasizes the need for certain kinds of information, namely, submetered furnace consumption, internal temperatures, and cost data. We excluded wood-heated houses because we could not accurately estimate the wood heat contribution. Monitored houses must either prohibit wood heating or carefully monitor the fuel input. We have assisted in the development of a sensor (Modera, 1984) to permit us to include wood-heated homes in future compilations.

The other data bases are at different stages of evolution. The residential retrofit data base, for example, contains many more buildings, but uses a less sophisticated analytical procedure. Both commercial buildings data bases contain several hundred buildings, but use very crude indicators of energy performance. We invite readers to contribute building energy data or to contact us prior to monitoring a building. We are also developing monitoring protocols to assist researchers and ensure that sufficient information is collected to confidently answer the technical questions.

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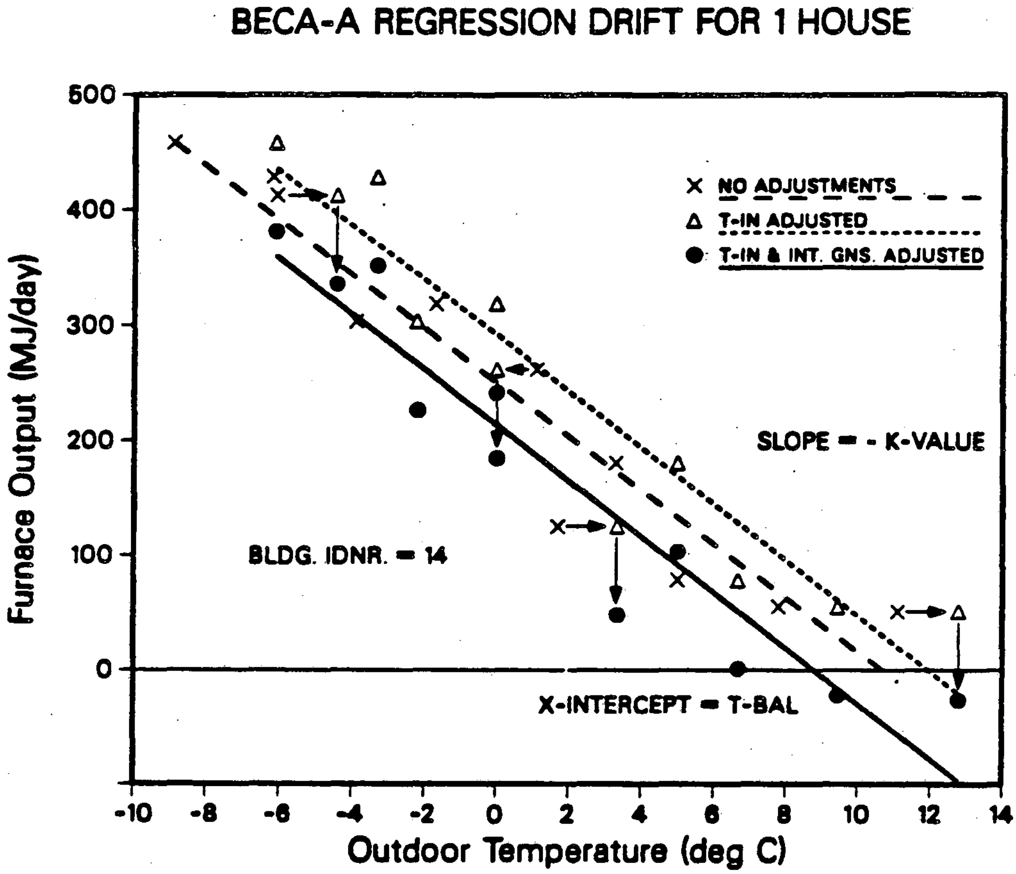

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Figure 1. Example of changes in balance temperature and k-value due to adjustments for inside temperature and internal gains for a single house. The three lines are regression fits for measured data with successive adjustments to standardize performance. The slope of the line is the negative of the k-value and the x-intercept is the balance temperature. The measured monthly consumptions versus outside average temperatures are plotted as 'X's. These values are then adjusted for inside temperature and plotted as triangles. There is a horizontal shift in the line which best fits the adjusted values; this is shown by arrows for four sample points. Note that the adjustment may be either positive or negative. The values are finally adjusted for internal gains, shown by solid circles. This results in a vertical shift, shown by arrows for four sample points. Again, the adjustment may be either positive or negative. In this house, adjustment for a lower inside temperature raised the balance temperature (from that indicated by the raw data), and adjustment for lower-than-average internal gains substantially lowered the balance temperature. The R^2 for the final regression for this house using both adjustments was 0.91.

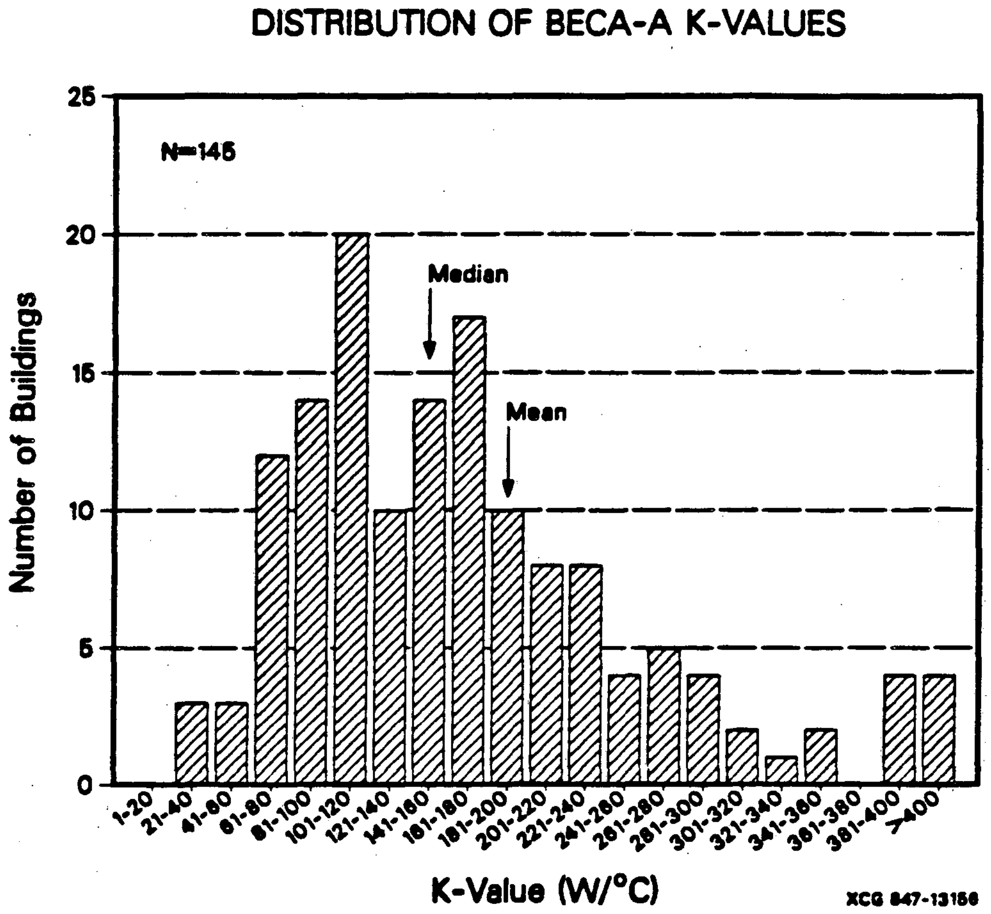
DISTRIBUTION OF BECA-A K-VALUES

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Figure 2. Distribution of k-values for 145 low-energy houses with $R^2 > 0.50$ and $t_b \leq 20^oC$. The mean value was 188 Watts/^oC, while the median value was 156 watts/^oC. Note that a k-value derived from measured energy consumption data and average monthly temperatures includes the contribution of infiltration, and to a limited extent solar gain and thermal storage.

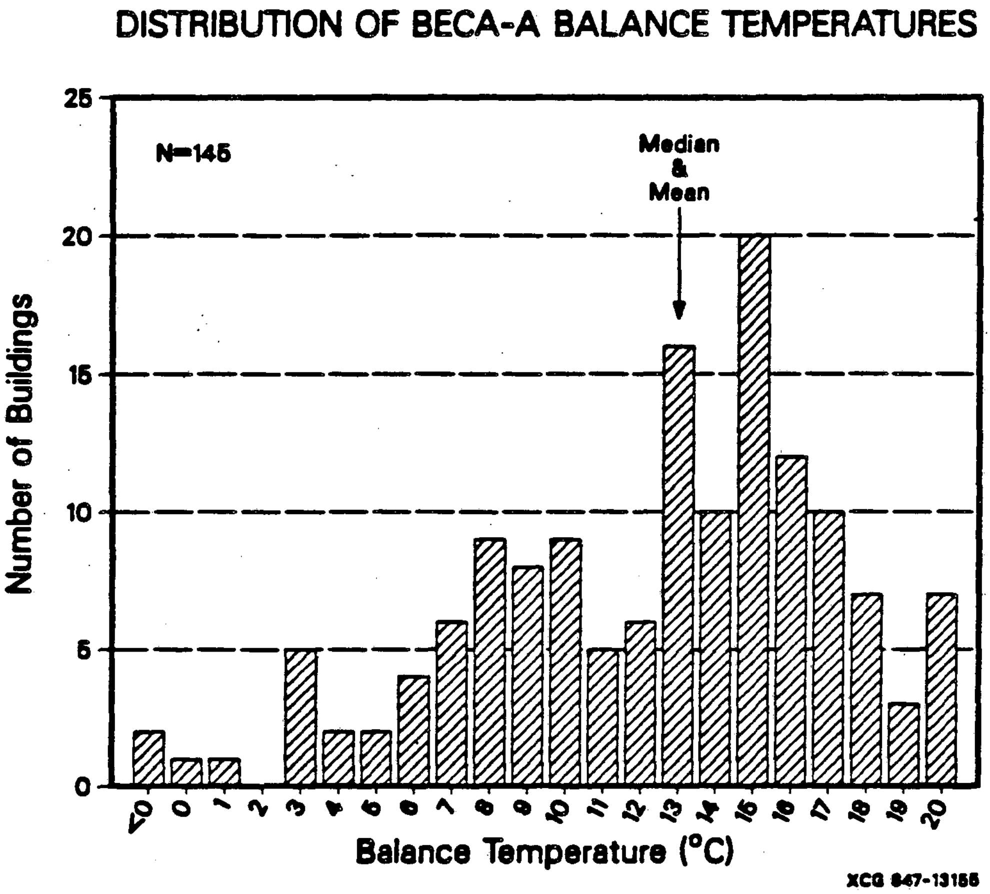

Figure 3. Distribution of balance temperatures for 145 low-energy houses with $R^2 > 0.50$ and $t_b \leq 20^{\circ}C$. This is the temperature at which the furnace must turn on in order to maintain 20° in the house. The average and median balance temperature is 13°C, which contrasts with the ASHRAE assumption of 18°C. Most of the houses have balance temperatures well below the ASHRAE value, however a few perform worse, indicating that the reported data was faulty or that they are not, in fact, low-energy homes.

ENERGY PERFORMANCE OF BECA-A BUILDINGS

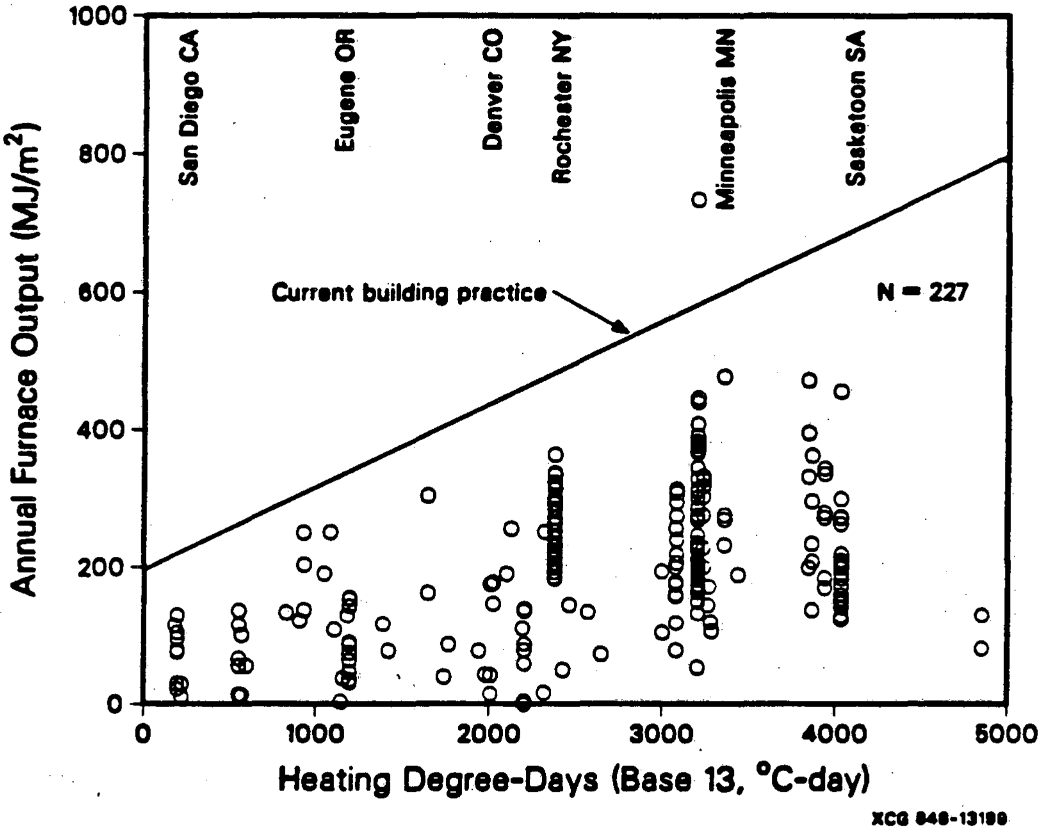

Figure 4. Annual furnace output versus degree-days (base 13°C) for 189 low-energy homes. The solid line is a best fit of computer-simulated loads of homes with average thermal characteristics as determined by a 1980 NAHB survey (see text), and represents our baseline for subsequent analysis. The degree-day scale used here is only a proxy for climatic severity; the reference temperature was chosen to coincide with the average of our compilation's balance temperature (see Figure 3). It appears that several alleged low-energy houses actually perform worse than current practice.

Table 1. Summary of results of the BECA-A database. These results are based on 319 homes with monitored energy consumption data. Many homes employ more than one conservation strategy, hence the total of homes for each strategy exceeds 319. The earth-sheltered homes appeared to perform the best, that is, have the lowest k-values and balance temperatures, however, the sample size is too small to be certain. Passive solar buildings perform nearly as well. The economic performance of the buildings is expressed in terms of their cost of conserved energy. We estimated the incremental energy savings and additional costs from conventional new homes. A conservation measure is cost effective if its cost of conserved energy is less than the price of the energy which it displaces. Note that the sample of buildings with cost data is much smaller than that listed for each design strategy.

Summary of BECA-A results*

				cost of conserved energy	
category	#	k-value (W/^{o}C)	bal. temp. (^{o}C)	elec. homes (¢/kWh)	gas homes ($/GJ)
all homes	319	188. (103)	12.9 (4.7)	2.8 (2.8)	5.01 (2.58)
superinsulated	196	146. (74)	15.0 (4.0)	2.1 (2.9)	3.92 (2.7)
passive solar	197	132. (98)	10.1 (5.2)	2.0 (2.9)	4.20 (2.7)
active solar	26	244. (145)	13.9 (4.4)	5.7 (0.8)	-
earth sheltered	9	116. (58)	10.2 (5.6)	-	-

* Note: the terms in parenthesis are standard deviations.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720