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MONITORED PERFORMANCE OF NEW, LOW-ENERGY HOMES: UPDATED RESULTS FROM THE BECA-A DATA BASE*

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ABSTRACT

We compiled and analyzed energy consumption data, construction details, and operating characteristics for over three hundred new, low-energy homes. Over two thirds of the buildings incorporated solar features. A sequence of standardization procedures were developed to compare the energy performance of the buildings. The procedures adjusted the reported heating energy consumption for variations in the climate, floor area, internal gains, and reported indoor temperature. Two indicators of thermal performance were developed, the balance temperature and a k-value, which roughly corresponds to the overall UA of the building but also includes the ability of the house to exploit solar gains and thermal mass. The buildings in the data base have an average balance temperature of 12°C and a k-value of 114 W/°C. Earth-sheltered buildings perform best, but only slightly better than passive solar and superinsulated buildings.

INTRODUCTION

Widespread interest in solar and energy-efficient homes began after the 1973 oil embargo. There have been only scattered attempts to measure the performance of these buildings since then. Earlier reports from the Buildings Energy-Use Compilation and Analysis[1,2] were among the earliest compilations of measured performance of low-energy residences. These reports compared the thermal performance and construction costs of low-energy buildings for a collection of active solar, passive solar, and superinsulated homes. In this report, we have greatly expanded the number of buildings in the compilation and improved procedures for comparison of thermal performance. We limited this compilation to space heating energy use, although we have begun work on a parallel effort for cooling.

Why should energy performance data be compiled? In the past decade builders have employed an enormous variety of designs to reduce a home's energy consumption. Innovation in solar designs has been especially great. Yet the differences in location, size and operating characteristics have made it nearly impossible to make valid comparisons among houses, and thus to identify successful designs and conservation measures. Those designs and measures that do in fact save energy will not be adopted (nor the failures discarded) without adequate analysis and feedback.

Even though some technologies are successful at saving energy, they are not cost-effective. That is, the initial construction cost is not justified by the subsequent energy savings. Solar heated "zero energy houses" are technically feasible (and has been achieved in many locations) but the cost will be high. Thus, a second, stricter, goal of this compilation is to estimate a house's **economic** performance. Where possible, we collect data on the incremental cost of the energy-conserving features so as to calculate the cost-effectiveness of those measures. Those designs and strategies that reduce the life cycle costs deserve widespread adoption.

The energy performance of houses is much more difficult to measure and compare than is automobile mileage. It is relatively simple to measure an auto's fuel consumption in a standard driving cycle and to rank autos in terms of fuel economy based on the standard test conditions. In contrast, energy performance data for occupied houses are based on widely varying operating conditions and weather. In general, we cannot expect the occupants to operate their home according to "standard conditions", nor is it always physically possible (e.g. with built-in equipment). Instead, the reported data must be analytically adjusted to these standard conditions to permit comparison between buildings. These adjustments must account for variations in thermostat settings, internal loads, and floor area -- all of which are factors that significantly affect space heating requirements.

Comparing the Performance of Low-Energy Homes to Conventional Homes

It is of course illuminating to compare low-energy houses, but it is also important to compare the class of low-energy houses to conventional design and construction. Are the additional costs of low-energy homes justified by their lower heating bills? Unfortunately, no comparable database exists on the measured energy performance of *conventional*, new homes to use as a benchmark. Thus, we estimated a baseline energy consumption level for conventional new houses based on survey data from the National Association of Homebuilders[3] survey data. The survey compiles average insulation levels and construction details of new houses (built by participating NAHB members) for every state. Using the building energy simulation computer program, DOE-2, we modeled the energy use of typical new houses with average thermal characteristics reported for each major climate zone[4]. The NAHB survey does not collect data on some important thermal parameters (such as infiltration rate or thermostat setting) so appropriate values were used in the simulations.

Comparing measured performance to computer simulations (with incomplete input data) is always hazardous[5]. Nevertheless, informal validation studies suggest that the DOE-2 predictions of energy use are probably within 20% of actual use. While we are not fully satisfied with this procedure, we feel that it is much better than no comparison at all. In the future, we hope to compile analogous measured performance data for conventionally-built, new homes.

Where low-energy homes have been constructed near conventional homes with a similar design, we have a natural energy and investment baseline. In a forthcoming paper we will analyze the heating performance of energy-efficient tract homes in several California subdivisions as compared to each builder's "standard" model.

Description of the Database

We have collected data on building design and energy consumption for 319 solar and superinsulated homes in the U.S., Canada, and Europe. The overwhelming majority are single-family houses, although there are also some multi-family and manufactured buildings. The buildings were all constructed during the last decade and use a variety of design strategies including passive and active solar, earth-sheltering, double-envelope, and superinsulated. Early designs tended to be "purist", emphasizing a single design strategy. More recent designs, while predominantly one type, tend to incorporate some elements of the other strategies, so the distinctions are evaporating every year. For instance, most recent superinsulated homes have extra glazing area on the south side and most active solar homes are now more heavily insulated. Over 60% of the houses had either passive solar or superinsulated features (see Table I).

The level of monitoring detail varies from highly instrumented research houses employing hundreds of sensors and continuous data logging to large samples of similar homes where only the total monthly billed energy usage is available. Wherever possible, we collect information on the building physical characteristics, occupancy characteristics (e.g., thermostat settings and number of occupants), energy consumption for heating and other end-uses, actual and long-term-average (LTA) weather, the incremental construction costs for the conservation features, and local energy prices. The metered time increments vary in duration from 7 to 60 days, but are typically one month and we have, in some cases, multiple seasons of data.

We rejected data for all houses heated with wood stoves because we could not establish accurate estimates for net heat output or fuel input. We expect to include them in subsequent analyses as new monitoring techniques permit reasonably accurate estimates of woodstove heat output [6].

METHODOLOGY

Evaluating measured performance of low-energy houses requires more than simply tabulating utility bills. Quantifiable indicators of performance must be developed from the data available for each building. Furthermore, these indicators must be sufficiently flexible to accommodate a wide variety of building characteristics. This section describes our technique for generating several indicators of building energy performance and the procedures used to adjust the data to a standard operating condition. We suggest that the reader first scan the flow chart (Figure 1) outlining the determination and adjustment procedure.

Determination of Building Performance Indicators

We begin with the basic equation for the heat balance across a building envelope, where the rate of heat gain equals the rate of heat loss, excluding heat storage. (The storage effects are ignored because we assume a steady-state condition exists when flows are averaged over a period of a week or more). The heat gains are broken into two components: 1) the furnace heat output, H, and 2) the "free heat", F, consisting of internal gains, I, from people, appliances, and hot water, plus the solar gains, S. The losses, L, are described using the overall heat loss coefficient, k, multiplied by the indoor-outdoor temperature difference. In this model, the k-value represents the overall "lossiness" of the building envelope, that is, the sum of the conduction and infiltration losses. Thus,

$$H + F = L \quad k(t_i - t_o) \tag{1}$$

where,

$$H = E \ \eta \tag{2}$$

and,

$$F = S + I \tag{3}$$

The energy input to the heating system, E, and the outside temperature, t_o, are always measured values. The heating system efficiency (or COP in the case of a heat pump), η, is either measured or assigned a default value according to the system type. Rearranging equation (1),

$$H = k(t_i - t_o) - F = k \left[(t_i - \frac{F}{k}) - t_o \right] \tag{4}$$

where,

$$t_b = t_i - \frac{F}{k} \tag{5}$$

by substitution we have,

$$H = k(t_b - t_o). \tag{6}$$

The "balance temperature", t_b, is defined as the outside temperature above which the free heat alone is sufficient to maintain the inside temperature at t_i. The value, $\frac{F}{k}$ is often called the "degrees of free heat." In other words, the furnace output is needed only when the outside temperature falls below t_b, and is proportional to $(t_b - t_o)$. In contrast, the shell heat loss is proportional to the larger value, $(t_i - t_o)$. Note that the balance temperature used here is a time-weighted average value taken over the monitored period. The instantaneous balance temperature will depend, to a large extent, on the instantaneous solar and internal gains and tends to fluctuate over the day.

Without further normalizations (see below) we can determine initial values for k and t_b by inserting measured monthly values for t_o and H, and performing a least-squares regression. The slope of the straight line that best fits the points is the negative of the k-value and the line's x-intercept is the balance temperature. An example of such a fit is shown as the middle (long dashed) line in Figure 2.

Adjusting the Indicators for Variations in Operating Conditions

The initial regression fit described above does not account for important variations among buildings in operating conditions. These variations include house size (i.e. the surface area exposed to outside weather), internal and solar heat contributions, and indoor temperature settings. Failure to compensate for these factors can understate the performance of a very efficient house or overstate that of a poorly built one. Our goal is to compare the energy performance of buildings as if they were operated under similar conditions. We therefore employ several procedures to normalize the energy consumption of a house. Normalizing for building size is relatively simple, but normalizing for internal gains, internal temperature and long-term-average weather is more involved. We describe these procedures below.

Internal Gains Correction. Recall from equation (3) that the free heat is provided by two sources: solar gains through windows (or other glazings), S, and internal gains, I. For most buildings we lack sufficient design details and solar radiation data to normalize the solar gain component, but we see no reason to "penalize" a building that successfully exploits solar energy. Instead, the credit will appear as an enhanced (i.e. lower) k-value and balance temperature. We normalize internal gains by defining a correction term,

$$\Delta I = I_a - I_s. \tag{7}$$

I_a is the actual internal gains calculated from the number of occupants and measured energy consumption by appliances, water heater, lights, etc. An example of the internal gains adjustment is shown in Figure 2. I_s is a floor-area weighted standard internal-gains value, which we estimate using the formula,

$$I_s = 706 + 3.24A \tag{8}$$

where A = heated floor area (m^2). For a typical 110 m^2 house, I_s is about 1000 W. Note that I_s is only weakly dependent on floor area. The values and algorithms used in determining I_a and I_s are described in Ribot.[2]

Indoor Temperature Correction. We also define a correction term for normalization with respect to indoor temperatures,

$$\Delta t = 20\,^{\circ}C - t_i \tag{9}$$

where we use 20°C as the standard indoor average temperature during the heating season. After incorporating our two correction factors into equation (6), we have,

$$(H + \Delta I) = k \left[t_b - (t_o + \Delta t) \right]. \tag{10}$$

We now perform a least-squares fit of the "adjusted" H as function of the "adjusted" t_o. Note that the correction for internal gains appears as an adjustment to the space heating value and the indoor temperature correction appears as an adjustment to the outside temperature. For example, to analyze a house with an average indoor temperature of 18°C (2° lower than "standard"), we simply raise the average outside temperature by a corresponding 2°. Similarly, an internal gain value lower than I_s will be treated as if the furnace output were lesser by the amount ΔI. The regression yields a "standardized" k and t_b, as shown for a specific house in Figure 2, where the arrows drawn in connecting several sets of points show the "drift" accompanying normalization.

Determination of Annual Performance Factors

Using these parameters, k and t_b, and equations (1) and (10), we can sum the "monthly" furnace output, H, and the shell loss, L, over the entire heating season to get annual performance factors,

$$AH = \sum_{p=1}^{n} H(p) \tag{11}$$

$$AL = \sum_{p=1}^{n} L(p) \tag{12}$$

where A stands for "annual" and p is each metered period and n is the number of periods in the heating season. To normalize our results with respect to long-term-average weather, we use long-term average (monthly) values for t_o instead of the actual year's data for each winter month in equations (11) and (12). The sequence of these calculation procedures is shown in the flow chart in Figure 1.

We designed the above normalization procedure for conditions when data on inside temperatures, appliance and hot water energy use and certain building and occupancy characteristics are available. In many cases, some data are unavailable. When data are absent, we rely on default values based on the literature and our own estimates.

RESULTS

Table 1 summarizes the performance of the 319 new, low-energy buildings presently in our compilation. Of these, 54 were corrected for either indoor temperatures or internal gains and 85 were corrected for both. We grouped the homes by major design strategy. Since many homes incorporated several strategies, they may appear in more than one group. More detailed information on the inputs and calculated results are found in Busch et al.[7] We discuss the energy performance and cost-effectiveness of the buildings in separate sections below.

Energy Performance of New, Low-Energy Homes

Our two thermal performance indicators, the area-normalized k-value and balance temperature, provide the primary basis for comparisons among houses. The distribution of k-values for a subset of the database is shown in Figure 3. The mean k-value for the entire sample is 114 W/$^{\circ}$C, while the median is 99 W/$^{\circ}$C. Balance temperatures are similarly presented in Figure 4. The mean and median balance points are 12°C. The R^2 for the regressions used to estimate the k-value and balance temperature range between 0.01 and 0.99. In Figures 3 and 4, we display only houses having an R^2 greater than 0.50 and a balance temperature below 20°C. The low R^2 values reflect the problem of acquiring accurate and consistent data from disparate sources. We generally accept submitted data as correct; however, we use low R^2 values (and common sense) to identify buildings with questionable data. We hope to include these buildings in the future after making appropriate corrections.

The nine buildings with earth-sheltering appear to perform better than other design types; however, this result is not conclusive because the sample size is small. The 26 active solar buildings are the worst performers, perhaps indicating a lack of attention to the building shell. Again, however, the sample is small. Houses with passive solar (197) and superinsulation (196) features -- our largest categories -- have roughly comparable performances. Note, however, the low balance temperatures in the passive solar homes, which is consistent with our earlier assertion that the solar contribution to the free heat is embedded in the k-value and balance temperatures. Not surprisingly, the k-values and balance temperatures tend to vary in the same direction; that is, the better houses have low values for both performance indicators.

We plot annual furnace output versus heating degree days (base 13°C) for 227 buildings in Figure 5. This figure also includes buildings for which we only have annual performance data. We chose base 13°C as the reference temperature because it closely corresponds to the mean balance temperature for the houses in our compilation. This base represents a scale of climatic severity most accurately reflecting the weather a low-energy house experiences, as opposed to the commonly used base 18°C. Almost all of the homes fall below our baseline representing current building practice. Note that some of the alleged low-energy homes actually perform worse than current practice. Even among low-energy houses, however, the variability is high, especially in the colder climates.

We do not calculate a value for the average amount of heat consumed per degree-day because (as Figure 4 shows) there is a very wide range in balance temperatures; no single degree-day base would be appropriate.

Attributing a building's performance to specific components generally requires more detailed data than we receive. However, in two cases we have quantitative measures of components which permit us to evaluate their influence on energy consumption.

We received infiltration measurements for 73 houses, where researchers estimated infiltration with tracer gas or blower door tests. We converted the reported values into average infiltration heat loss (in W/$^{\circ}$C). Figure 6 shows the comparison between the infiltration heat loss and the overall heat loss, that is, the k-value. Points below the dashed line represent houses where infiltration accounts for more than half of the overall heat losses. To the extent that the one-time measured infiltration rates reflect seasonal infiltration, the figure suggests that builders have achieved mixed success in limiting air infiltration.

South-facing glazing represents another "component" influencing building energy performance. Figure 7 shows the correlation between the percentage south-facing glazing to floor area and the k-value. Numerous studies have suggested that there exists an optimum amount of south-facing glass because conduction heat loss offsets solar gains. Our results appear to support these predictions. Homes with glass area distributed roughly equally on all four walls fall into the 0 - 5% range; these are primarily superinsulated houses. The k-value is suitably low for this group. Passive solar designs have the majority of their glass area facing south; these buildings appear in the bins above five percent. After discounting the highest bin because of its small sample size, the passive solar homes appear to achieve maximum thermal performance with south-facing glass area between ten and fifteen percent of floor area.

Cost-Effectiveness of New, Low-Energy Homes

Is the additional investment to build a low-energy home justified in terms of future energy savings? To determine cost-effectiveness we compared the incremental energy savings and incremental cost to those of typical, conventionally-built homes. For about one third of the homes, the builders or researchers provided estimated incremental costs for the energy conservation features We derived the incremental energy savings from the DOE-2 simulations of "typical" new houses as determined by the NAHB survey (discussed earlier).

We selected the "cost of conserved energy" as our indicator of cost-effectiveness. The characteristics of this indicator are discussed in detail by Meier [8,9].

The cost of conserved energy (CCE) is defined as,

$$CCE = \frac{I}{E} \cdot \frac{d}{1-(1+d)^{-n}} \tag{13}$$

where,

I = incremental investment ($)
E = annual energy savings (GJ/yr)
d = annual discount rate
n = lifetime of investment (years)

The right-hand term is the capital recovery formula, and converts the incremental investment to an annual payment. If the annual energy savings are expressed in GJ/year, then the CCE has the dimensions of $/GJ. A conservation measure is cost-effective if its CCE is less than the price of the energy it displaces. In this case, the conservation measures displace electricity or natural gas, whose average delivered prices in the U.S. are $19/GJ and $5/GJ, respectively. (Note that $19/GJ corresponds to 7 cents/kWh and that $5/GJ converts to about 50 cents/therm.)

The chief advantage of the CCE is its independence from energy prices. Energy prices vary widely, especially between fuels, but also with location. Thus, our indicator of the cost-effectiveness is not tied to any particular location or fuel. It does, however, require assumptions regarding the discount rate and lifetimes of the conservation measures. We used a three percent real discount rate and assumed that the lifetime for all conservation measures is thirty years.

The economic results are summarized in Table I. We plotted the estimated incremental cost of 132 low-energy homes (as reported by the builder or researcher) against their CCEs in Figure 8. Electrically-heated houses are shown as squares and fuel-heated houses are shown as open circles. We drew two price lines for reference, the average US electricity price and the average US natural gas price.

The average CCE for all electrically-heated homes was $7.81/GJ, considerably less than the average U.S. electricity price. The average CCE for all gas-heated homes was $5.01/GJ, somewhat less than the average U.S. gas price. Essentially all of the houses whose incremental construction costs were less than $5000 were cost-effective (compared to national average fuel prices), whereas investments over $12000 appear cost-ineffective, with mixed results occurring in between. We had no incremental cost data for earth-sheltered homes, so we cannot make any conclusions regarding their cost-effectiveness. Houses with passive solar and superinsulated features had similar CCEs. The electrically-heated homes were especially cost-effective, suggesting that additional conservation measures would have been justified. Active solar homes had a high CCE, over $15/GJ, which still makes them cost-effective at average US electricity prices. We also compared each building's CCE to the *local* energy price. On the average, the CCE was $2.58 less than the price charged for the local fuel.

CONCLUSIONS

We have developed what we believe to be the world's largest compilation of monitored performance data for new, low-energy homes. We presented a technique for standardizing the performance of these buildings and applied it to buildings for which we had sufficient data.

In general, the low-energy homes in our compilation are consuming significantly less energy than those built using current practice. But there is a wide range in performance, even after taking account of variations in climate. As a group, buildings with earth-shelter features appeared to perform best, that is, had the lowest k-values and balance temperatures, but the sample size is too small to be conclusive. Furthermore, cost-effectiveness could not be verified. Buildings with passive solar and superinsulated features have only slightly inferior performance. More important, the life-cycle cost analysis indicates that investment in energy saving features is cost-effective as compared to both electric and natural gas prices. Houses with active solar features performed significantly worse than the other homes; their k-values were roughly twice those of the earth- sheltered homes. The active-solar houses had a high cost of conserved energy, nearly three times that of passive and superinsulated homes, indicating that active-solar houses are relatively poor investments. Again, the small sample size means that these conclusions should be accepted cautiously. We continue to collect data on measured performance of new, low-energy houses, and ask our readers to submit case studies.

ACKNOWLEDGMENTS

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Above all, we want to thank the hundreds of persons who have contributed case studies to this compilation. Within LBL, we gratefully acknowledge the assistance of Ernest Chang, Chuck Goldman, Jeff Harris, Art Rosenfeld, and Jeana Traynor.

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Table 1.

Summary of BECA-A Results*

category and number of homes	k-value W/°C**	bal. temp. (°C)	cost of conserved energy: elec. homes ($/GJ)	cost of conserved energy: gas homes ($/GJ)
all homes 319	114. ±68	12.2 ±4.5	7.81 ±7.7	5.01 ±2.58
passive solar 197	104. ±55	11.0 ±4.9	5.63 ±8.1	4.20 ±2.7
active solar 26	163. ±110	12.9 ±3.8	15.9 ±2.0	-
earth sheltered 9	91. ±32	7.6 ±1.7	-	-
superinsulated 196	96. ±50	12.9 ±4.0	5.8 ±8.0	3.92 ±2.7

* standard deviations are listed below values

** all k-values have been normalized to 100 m^2

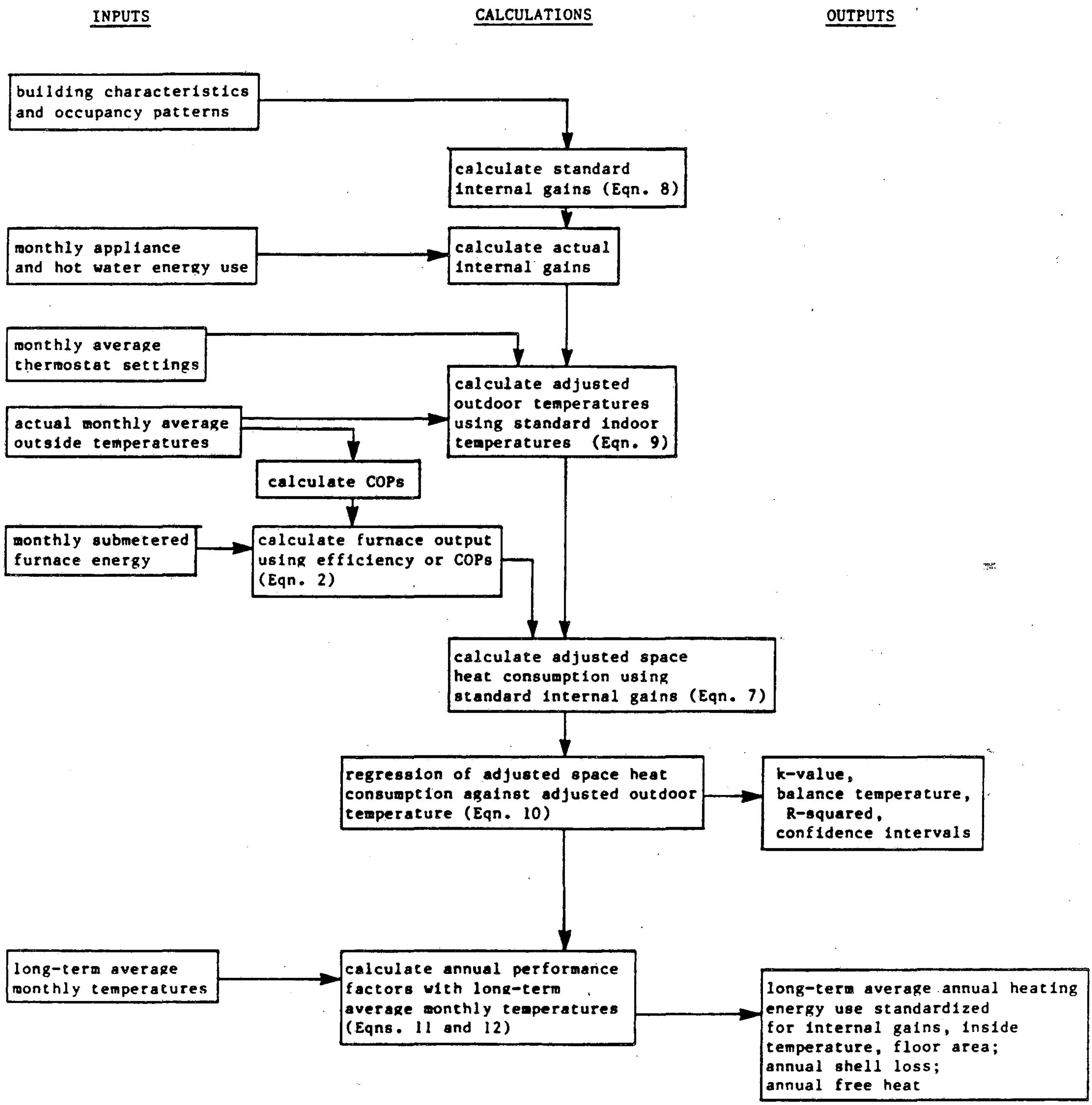

Fig. 1. Flow chart of the steps used to calculate indicators of thermal performance for new houses in BECA-A and to adjust the performance to standard conditions. Data inputs are given on the left side, calculations in the middle, and outputs on the right side.

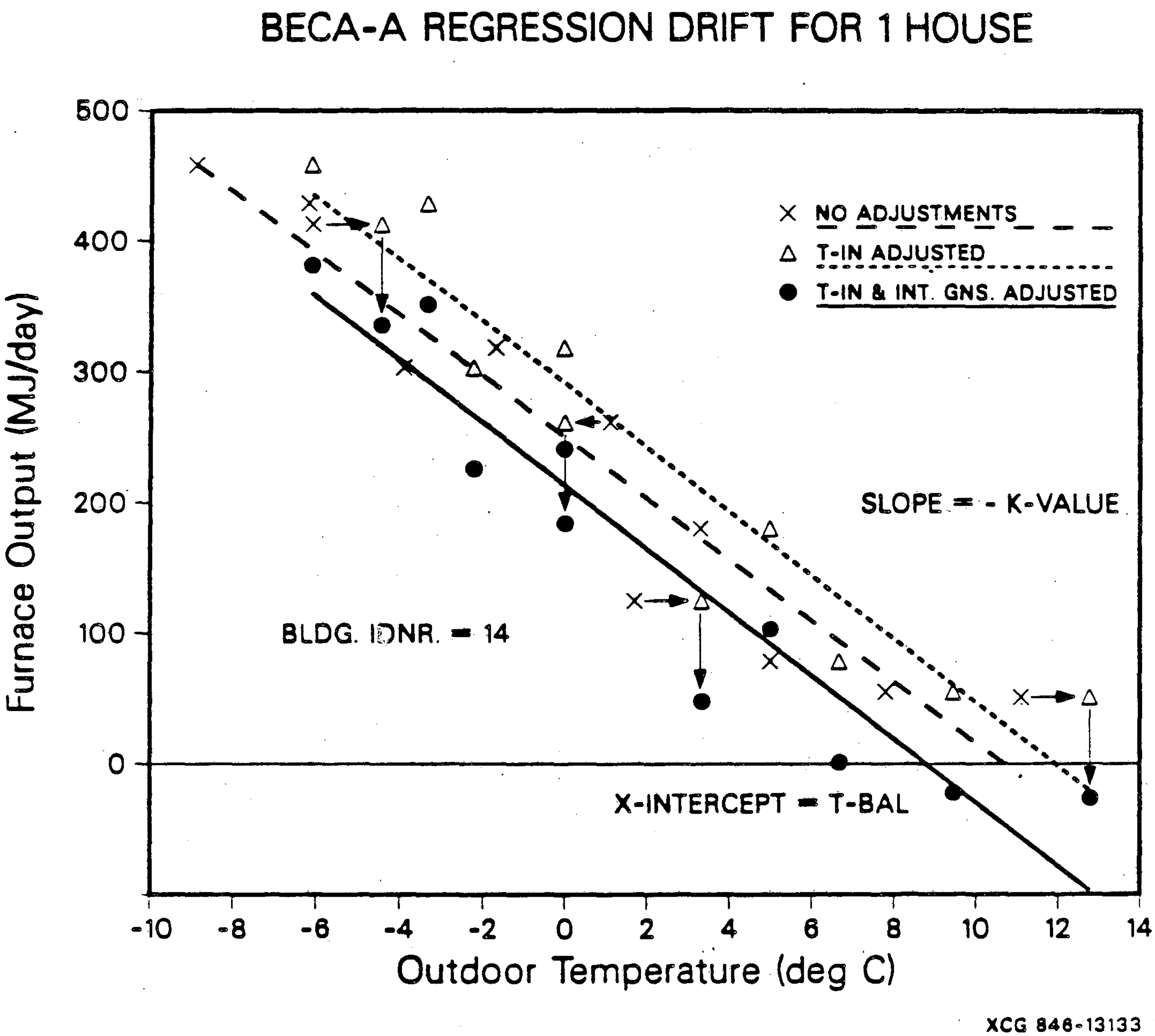

Fig. 2. Example of changes in balance temperature and k-value due to adjustments for inside temperature and internal gains for a single house. The three lines are regression fits for measured data with successive adjustments to standardize performance. The slope of the line is the negative of the k-value and the x-intercept is the balance temperature. The arrows show the effect of adjustments for four sample data points. The R^2 for the final regression for this house using both adjustments was 0.91 .

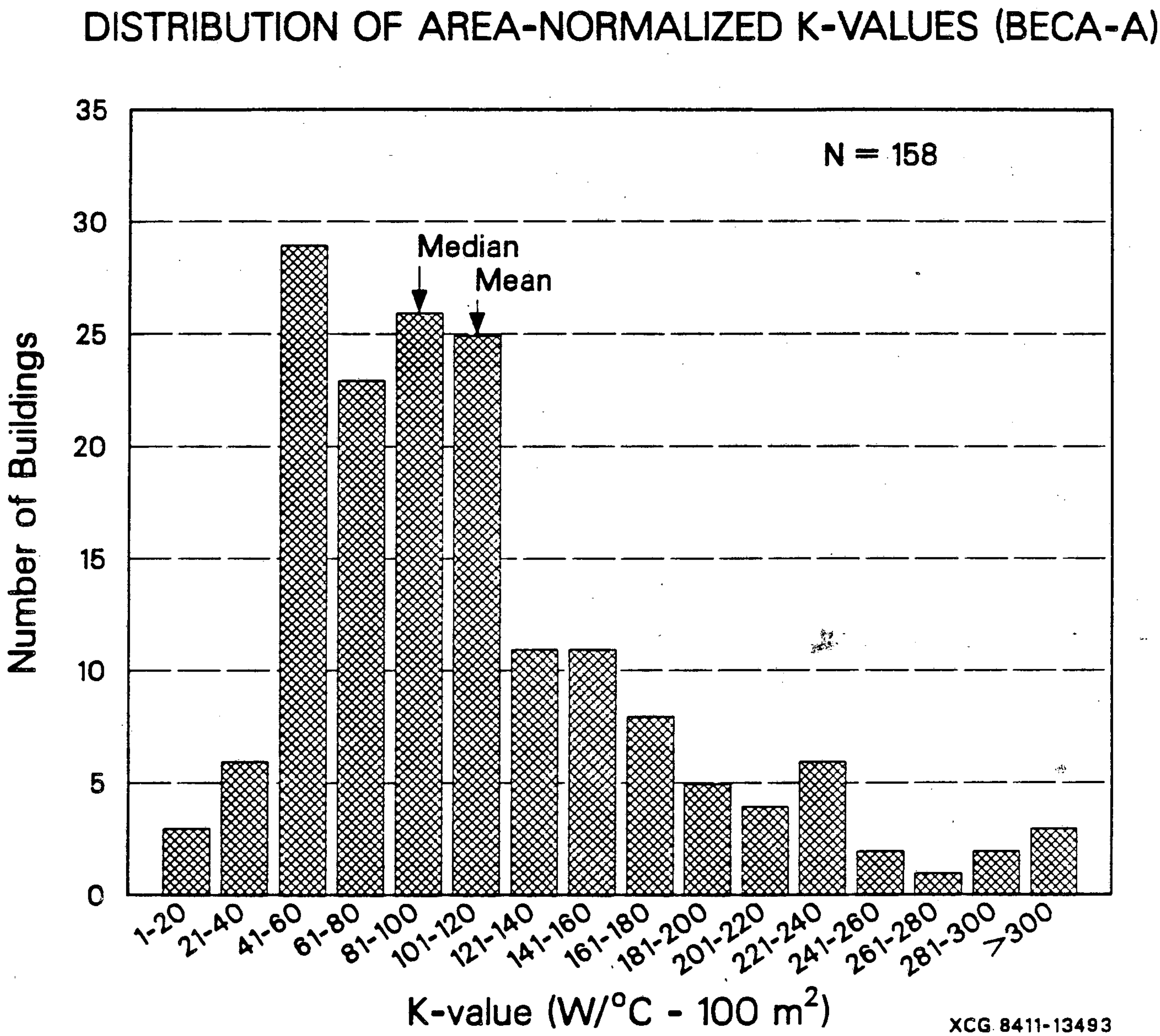

Fig. 3. Distribution of floor-area-normalized k-values for 158 low-energy houses with $R^2 >$ 0.50 and $t_b \leq 20^oC$. Note that a k-value derived from measured energy consumption data and average monthly temperatures includes the contribution of infiltration, and to a limited extent solar gain and thermal storage.

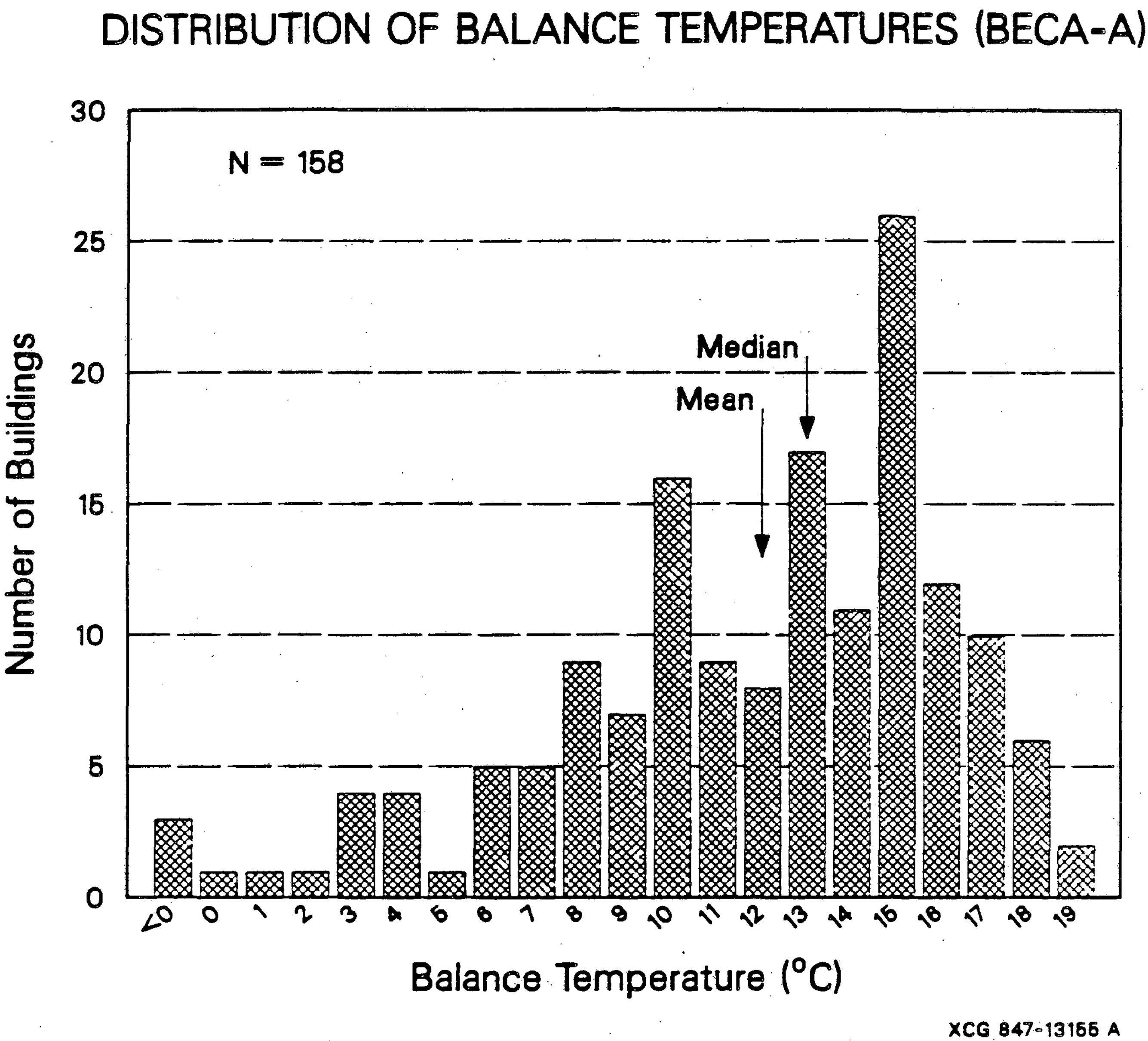

Fig. 4. Distribution of balance temperatures for 158 low-energy houses with $R^2 > 0.50$ and $t_b \leq 20^{\circ}C$. Most of the houses have balance temperatures well below the ASHRAE assumption of $18^{\circ}C$.

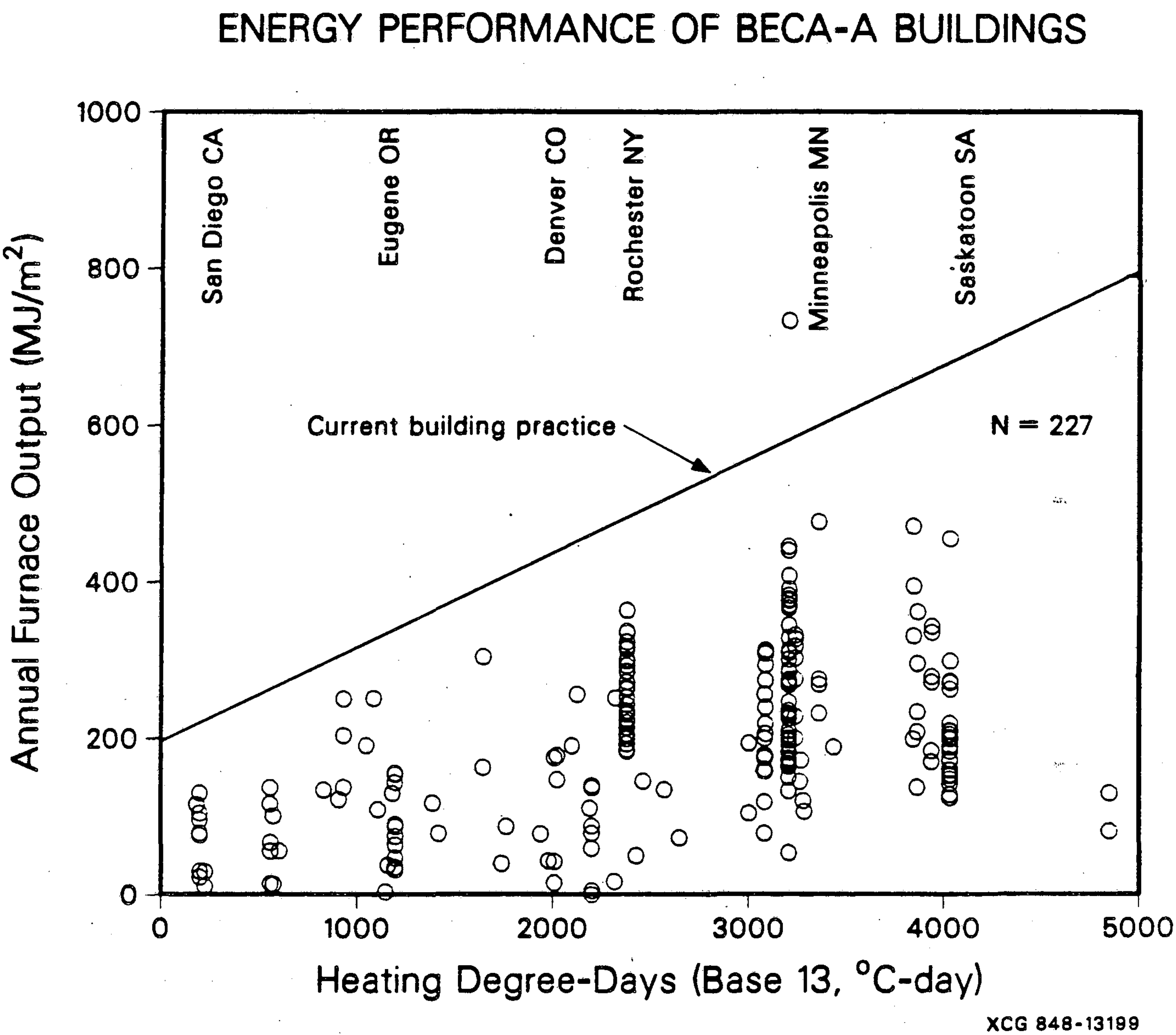

Fig. 5. Annual furnace output versus degree-days (base 13°C) for 227 low-energy homes. The solid line is a best fit of computer-simulated loads of homes with average thermal characteristics as determined by a 1980 NAHB survey (see text), and represents our baseline for subsequent analysis. The degree-day 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 4).

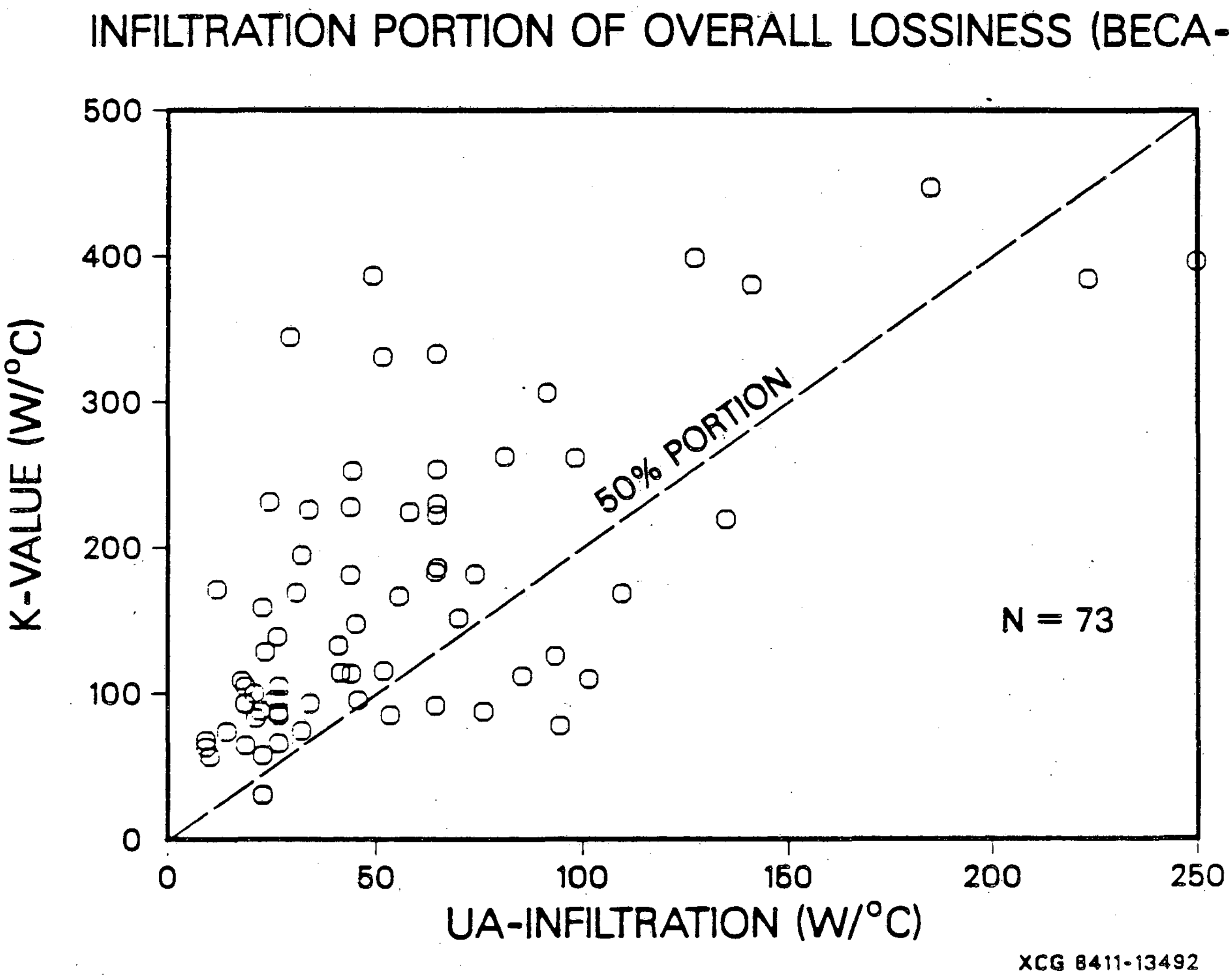

Fig. 6. Infiltration portion of overall lossiness for 73 low-energy houses. Infiltration values are calculated from blower door or tracer gas measurements. Note that for buildings whose points fall below the dashed line, infiltration accounts for more than half of the total heat loss.

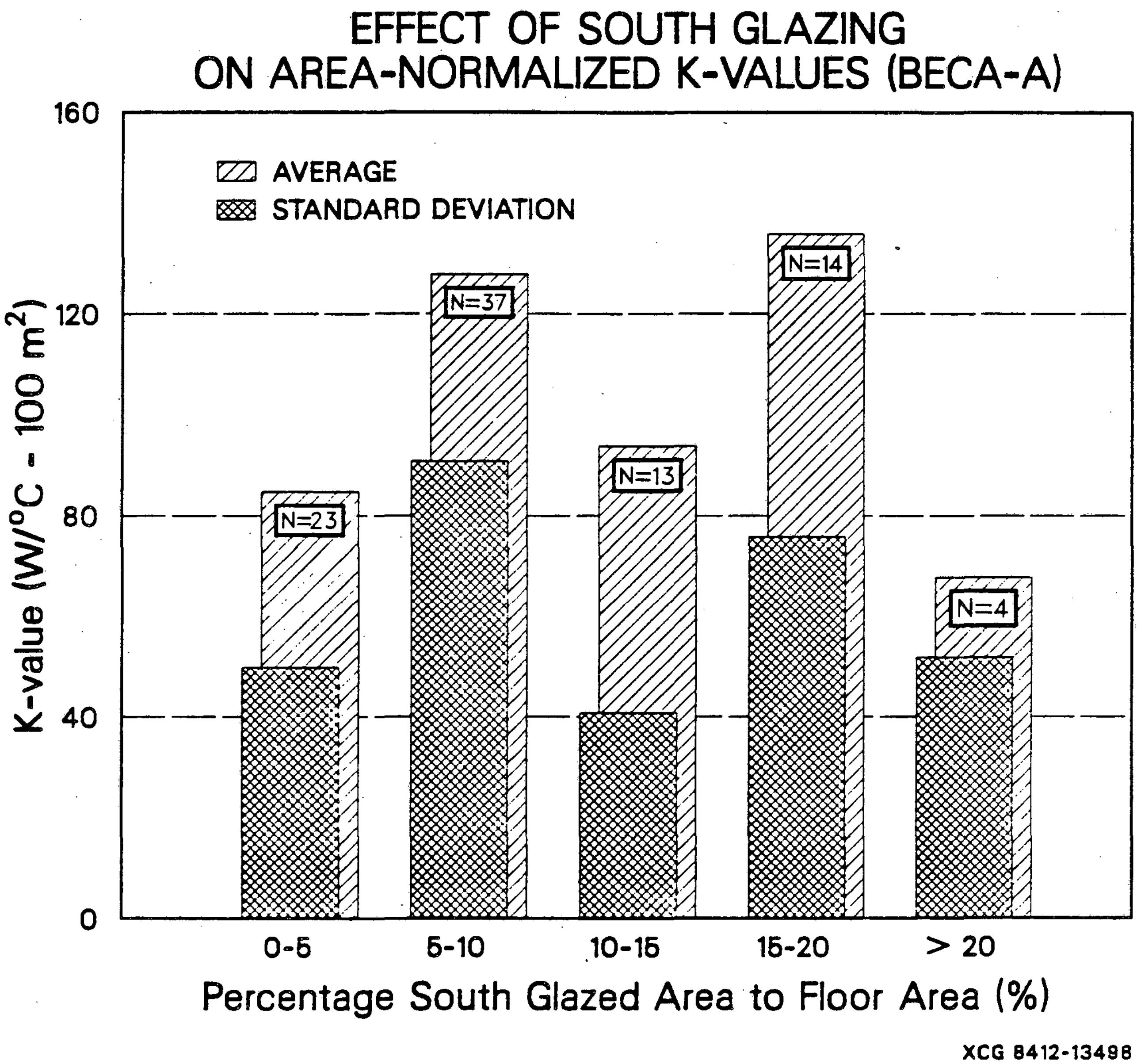

Fig. 7. Effect of south glazing on the energy performance of 91 low energy residential buildings.

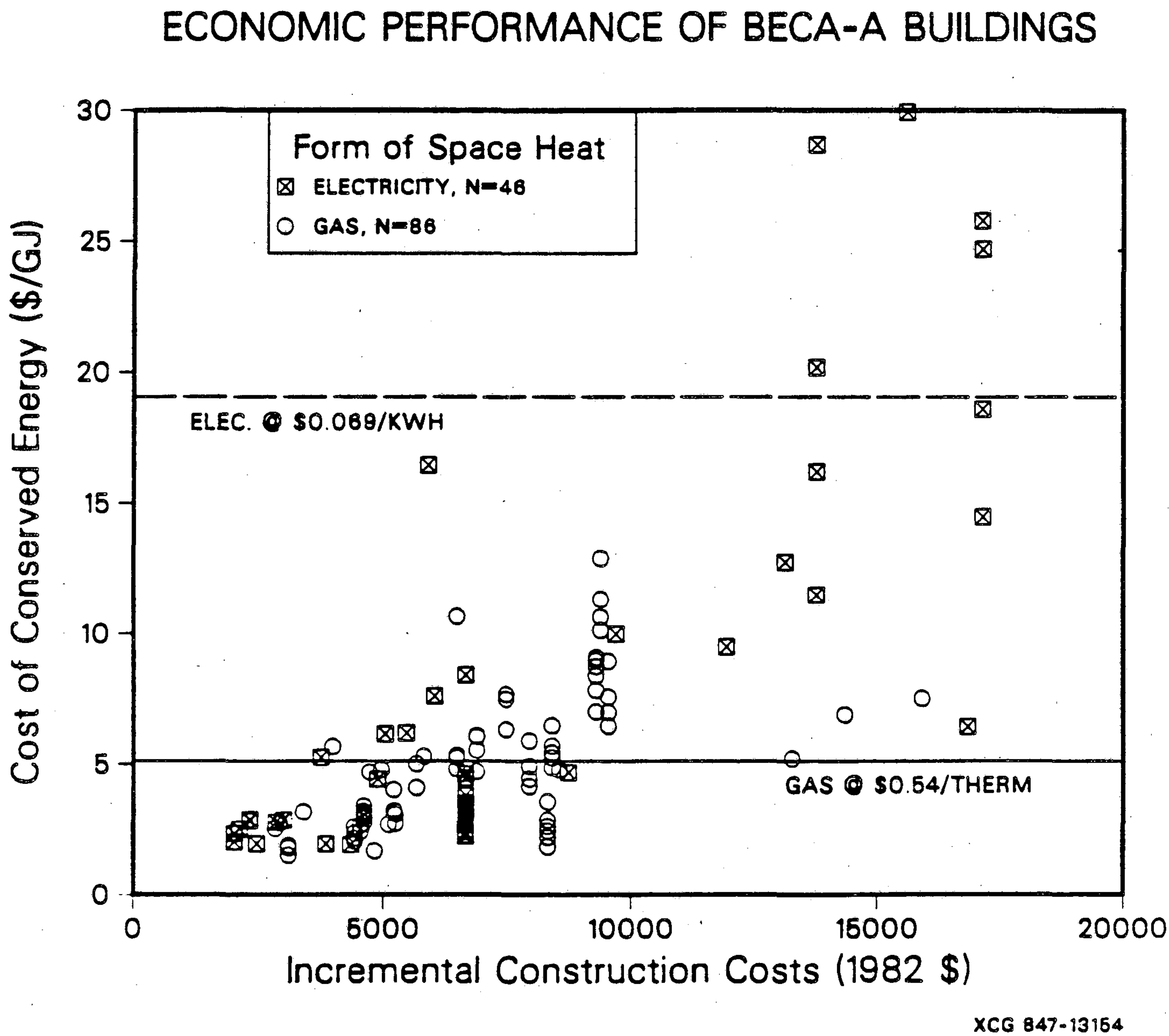

Fig. 8. Cost of conserved energy (CCE) versus incremental contractor cost for 132 low-energy homes. The investments to achieve efficient energy performance are cost-effective when the cost of conserved energy is less than the price of the saved energy. National average prices of electricity and natural gas are plotted as horizontal lines for comparison. The CCEs and the scatter rise for houses with high incremental cost, suggesting larger investments do not save proportionally more energy.