# As-Operated Heat Loss Coefficients of Residential Buildings in the Pacific Northwest—An Analysis of Empirical Space-Heating Energy Data

**R.G. Lucas** **R.G. Pratt**

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## ABSTRACT

*Previous research of residential electrical space-heating data has revealed that the heat loss coefficients obtained from empirical data ("as-operated" UAs) are, on average, about 25% below the UA calculated from the shell construction of each building. This as-operated UA is obtained from a linear regression of the measured space-heating energy consumption versus the inside-outside temperature difference. This finding indicates that simple steady-state calculation techniques for heating energy consumption utilizing only UAs may be inaccurate in estimating annual consumption.*

*The purpose of this research was to study how climate, construction, and occupant variables may affect the as-operated UA and, therefore, the annual heating energy consumption. Specifically, the goal is to gain a greater understanding of how and why the as-operated UA differs from the construction-based nameplate UA. Multiple seasons of daily heating data from 131 occupied single-family residential sites were analyzed. A multiple linear regression was used to generate a model that utilizes the construction-based UAs and other characteristics of individual residences to predict an as-operated UA that better estimates annual heating energy.*


## INTRODUCTION

Past analyses of monitored heating data have revealed discrepancies between the theoretical thermal performance of Pacific Northwest residential buildings and the actual achieved performance determined from the measured energy and temperature data. These analyses have indicated the "as-operated" UA, or effective building resistance to heat loss, is often significantly lower than building construction indicates (Miller et al. 1988). This phenomenon has important implications for forecasting future space-heating energy use, as the *UA* is commonly utilized for this purpose.

This paper examines the performance of residential buildings using monitored data from the End-Use Load and Consumer Assessment Program (ELCAP). Detailed electrical end-use data were collected during several years for more than 400 residences. A linear regression used in earlier ELCAP research (Miller 1988) was used to obtain as-operated *UA*s. A multivariate regression model using the as-operated *UA*s as the dependent variable is developed here to adjust the nameplate *UA* to account for building-specific characteristics such as heating system type and foundation type. This regression model improves the prediction of as-operated heat loss coefficients from the nameplate.

## METHODOLOGY OVERVIEW

The steady-state heat balance for calculating the energy required from a mechanical space-heating system (e.g., a furnace or wood stove) for a building is

$$Q = UA \cdot (T_{in} - T_{out}) - (IG + SG) \qquad (1)$$

where

| | | |
|---|---|---|
| $Q$ | = | heat required, Btu/h; |
| $UA$ | = | sum of the products of thermal transmittance per unit area, Btu/ft$^2$·h·°F (W/m$^2$·°C), and the area of the building envelope components, ft$^2$ (m$^2$), including heat transfer by air transport (infiltration); |
| $T_{in}$ | = | indoor temperature, °F (°C); |
| $T_{out}$ | = | outdoor temperature, °F (°C); |
| $IG$ | = | internal heat gains from people and appliances, Btu/h (W); |
| $SG$ | = | solar heat gains into the building, Btu/h (W). |

An additional term, known as the "balance temperature," is defined as the ambient temperature at which $Q$ = 0 and is calculated based on the indoor temperature and "free" internal and solar heat gains:

$$T_b = T_{in} - (IG + SG)/UA. \qquad (2)$$

When the outdoor temperature is below the balance temperature, supplemental mechanical heating is required. Combining Equations 1 and 2 and adding a correction factor to account for overall heating system efficiency,

$$Q = UA \cdot (T_b - T_{out})/k \qquad (3)$$

where

$k$ = correction factor for seasonal equipment efficiency.

**Robert G. Lucas** is a development engineer and **Robert G. Pratt** is a staff scientist at the Pacific Northwest Laboratory, Richland, WA.

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Coupled with widely available hourly or daily outdoor air temperatures, Equations 1 through 3 typify simple techniques of calculating yearly mechanical heating energy consumption, such as the variable-base degree-day (VBDD) method (ASHRAE 1989). (Chapter 28 of the 1989 *ASHRAE Handbook—Fundamentals* uses the term "building loss coefficient" [*BLC*] instead of *UA*.) The yearly calculation is done by integrating the positive difference between the balance temperature and the outdoor temperature over the full year.

Figure 1 shows an example of heating energy dependence on temperature, where measured daily average heating power data over several years for one house are plotted against daily average indoor-outdoor temperature differences. In the figure, and in the regression analysis, only days with heating energy use above 4,100 Btu (1.2 kWh or 50 average watts) and with average outdoor temperatures below 65°F (18.3°C) are included to minimize the nonlinear "tail" at the lower left corner. Each point is the average of one day of hourly data.

According to Equation 3, heating loads are proportional to the difference between the outdoor temperature and the balance temperature. In Figure 1, the change in heating energy divided by the change in outdoor temperature (the slope) can be used as an estimate of the *UA*. This slope in Figure 1 is the "as-operated" *UA* and is estimated from measured data by a linear regression of average heating power on the average daily temperature difference seen across the shell of the building, as shown by the line in Figure 1. Note that the as-operated *UA* implicitly includes the efficiency of the heating system. The balance temperature difference for the house in Figure 1 is indicated by the x-intercept of the regressed line, which is shown to be about 8°F (4°C) (i.e., $T_{in} - T_{out}$ must be greater than 8°F [4°C] before heating is required).

The as-operated *UA* along with the regression-based "as-operated" balance temperature reproduce the mean annual heating energy for any given site. This paper focuses on the *UA* only and does not address balance temperatures. As mentioned in the introduction, the as-operated *UA*s for ELCAP sites have been determined usually to be lower, indicating less heat loss, than would be expected based only on the envelope construction. There is an assortment of factors that may be biasing the regression results away from the construction-based heat loss coefficient. The construction-based *UA* and simple VBDD calculation techniques do not account for the variation of parameters that affect the heating energy consumption (e.g., solar gains) with inside-outside temperature difference (the VBDD method does contain the correction factor *k* for heating system effects). Also, VBDD techniques do not give credit for the capacitance effect of heat storage in massive materials. Additionally, occupant-related effects such as unheated zones within houses (referred to as zoning) can effectively change

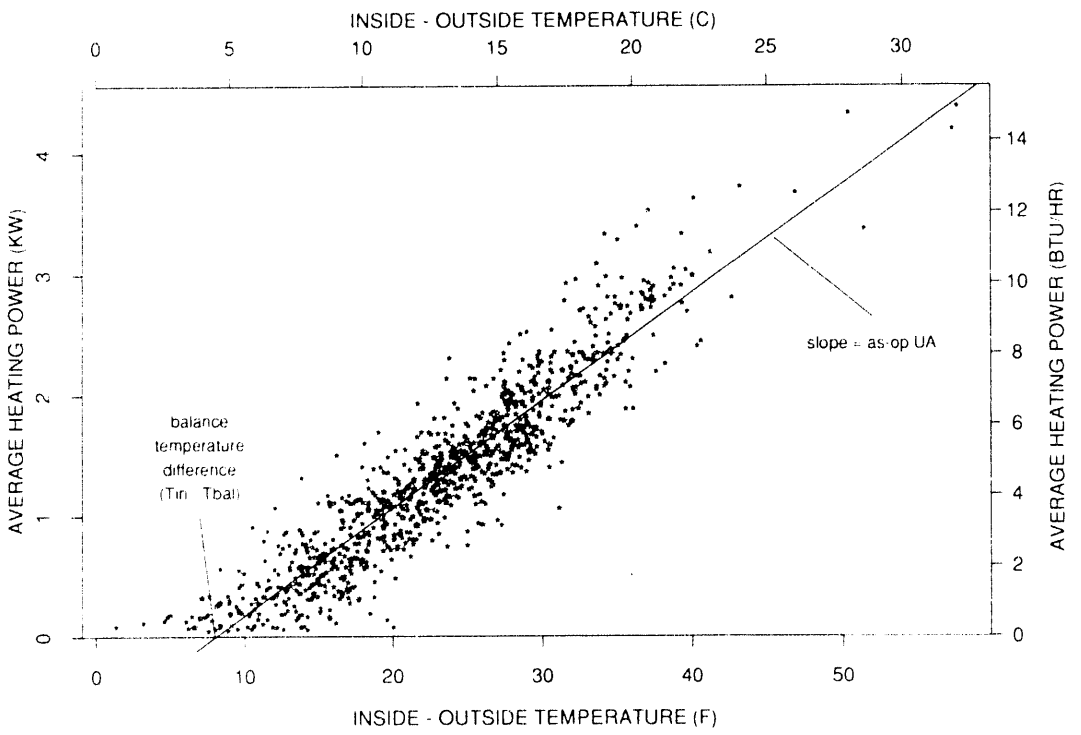


***Figure 1*** *Daily average heating power vs. daily average temperature difference across building shell for one ELCAP site.*

the envelope *UA*. This paper uses the monitored data to help understand and quantify the effects of parameters not accounted for in steady-state VBDD techniques.

## SUMMARY OF PREVIOUS RESEARCH

As-operated steady-state resistance to heat loss (*UA*) was previously estimated to be only 76% of the calculated "nameplate" *UA*s on the average (Miller et al. 1988) (the nameplate *UA* is based on the envelope construction and is described later). Some common attributes of the sites with lower than expected *UA*s were revealed when building characteristics were examined (Miller 1987). By electrical heating system type, houses with baseboard and radiant systems, in particular, performed better (i.e., much lower as-operated *UA*s than nameplate *UA*s). When the foundation types were examined, houses with basements and slabs had lower ratios of as-operated to nameplate *UA*s than houses with other foundation types.

A parametric analysis comparing nameplate and as-operated *UA*s for Pacific Northwest climates using simulated data has been conducted by Lucas (1991). These parameters included solar and internal gains, infiltration, and foundation types, among others. No clear systematic bias was found that indicates the as-operated *UA*s can be well below the nameplate *UA*s. Many of the parameters appear to produce offsetting effects on the as-operated *UA*.

Experimental measurements of combined radiation, conduction, and infiltration heat transfer mechanisms indicate that, for certain conditions, the standard *UA* calculation may overestimate the effective envelope *UA*s. Liu and Claridge (1992) measured reductions in the nameplate *UA* of up to 25% for a test cell under favorable infiltration conditions. In these tests, diffuse infiltration allowed solar heat gains to be carried into the cell, effectively lowering the *UA*.

## EMPIRICAL DATA ANALYSIS

This section describes the analysis of an extensive data set of monitored heating energy data from 131 occupied houses throughout the Pacific Northwest. Additional conditions confounding the empirical data are examined with a multilinear regression to create an improved predictive model of the heat loss performance of the ELCAP sites.

The analysis of the ELCAP monitored data presents many difficulties and uncertainties. The *UA* calculation of the ELCAP buildings has some degree of uncertainty due to incomplete inspection data. The nameplate *UA* is calculated based on audit information for component constructions, along with a fixed estimate (0.4 air changes per hour [ach]) of infiltration effects (Conner et al. 1990). The *UA*s of the ELCAP houses were calculated with considerable detail. Inspections of each house were made to collect information on construction details. In the *UA* calculation, the heat flow through the wooden framework and doors was accounted for and the heat flow through the ground was estimated. Even though considerable care was taken to calculate the *UA* for each house, there are a number of uncertainties in the nameplate *UA* calculations. Not all of the insulation levels were known for all components in all houses, and default values based on the vintage and location were substituted. The nameplate *UA*, by definition, is based only on envelope construction and does not account for other factors affecting heating energy consumption such as solar and internal gains, zoning, and heating system efficiencies.

The effect of the occupants on heating energy consumption is significant but very difficult to ascertain. For example, the occupants may turn baseboard heaters off in some rooms, lowering the heating energy use. An extensive effort was made to eliminate sites that were not well understood or that had attributes, such as non-electrical heating, that are not included in the monitored data. The site selection process, where 131 sites were selected from the pool of more than 400 sites, is described by Lucas (1991).

Figure 2 shows the as-operated versus nameplate *UA* for the 131 sites (these data have a regressed R-squared of 0.58). The majority of the sites have as-operated *UA*s that are lower than the nameplate *UA*. The dashed regressed line has a slope of only 74% compared to the 100% slope of the solid line, indicating equality of the as-operated and nameplate *UA*s. The greatest area of uncertainty in the nameplate *UA* is the infiltration factor, which is based on 0.4 ach. This is only 19% of the total *UA* on average, a conservatively low estimate, particularly for older houses. Even with an assumption of *zero* infiltration, the nameplate *UA*s still exceed the as-operated *UA*s by 9% on average.

A multivariate linear regression analysis was performed to study the effects of building-specific parameters that may influence heating energy use. An array of characteristics data for each house was used to attempt to explain the as-operated heat loss performance of the buildings. Table 1 shows the characteristics examined. Seven characteristics are properties of each building while four are principally occupant controlled.

In the regression, the product of the nameplate *UA* and other characteristics of each of the 131 sites are the independent variables, and the as-operated *UA* is the dependent variable. The explanatory variables are thereby assumed to effectively scale the nameplate *UA*. The regression computes coefficients for each of the independent variables such that the right side of Equation 2 most closely matches the known as-operated *UA* across all sites (minimizing the sum of the square of residuals).

$$UA_{as\text{-}op} = UA_{namepl} \cdot (c_1 + c_2 \cdot X_1 + \ldots + c_{n+1} \cdot X_n) \tag{4}$$

where

$c_1 \ldots c_{n+1}$ = regression coefficients,

$X_1 \ldots X_n$ = explanatory (independent) variables.

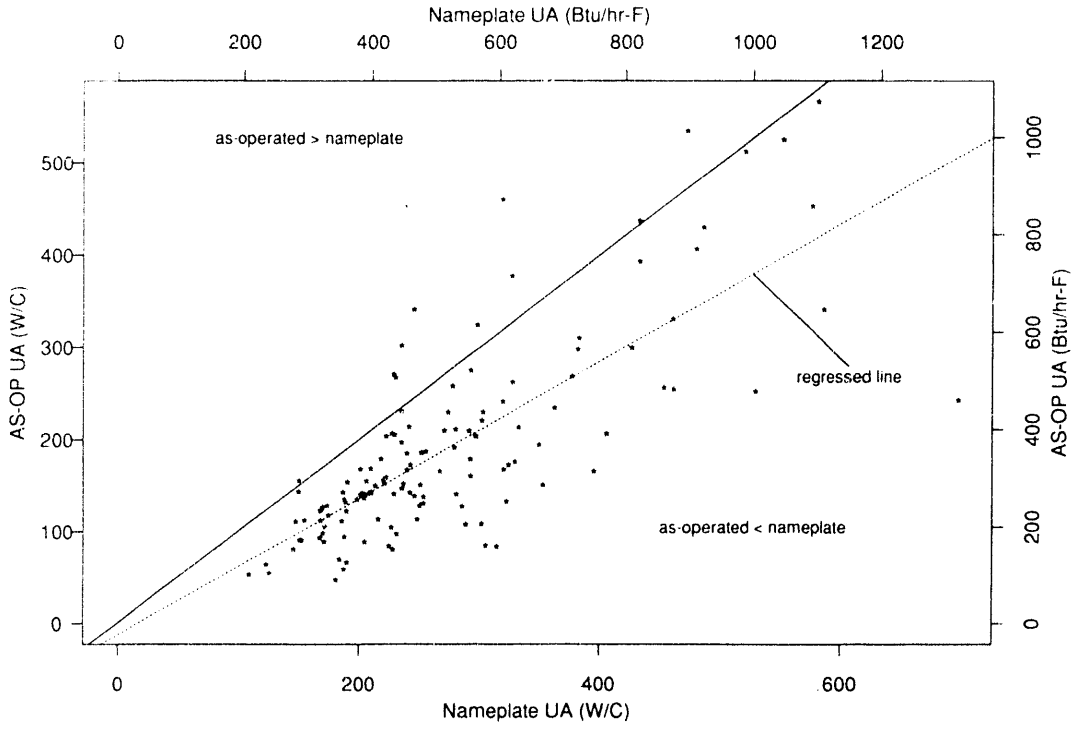


*Figure 2* *As-operated vs. nameplate* UA*s for 131 ELCAP residential sites. Each point represents one site. The solid line is the line of equality where as-operated equals nameplate.*

**TABLE 1**
**Characteristics Examined**

| | |
|---|---|
| Total window area | Outside air temperature |
| South-facing window area | Magnitude of internal gains |
| Presence of fireplace | Seasonality of internal gains |
| Major wood-burning equipment | Electric heating system |
| | Reported zoning |
| Foundation type | Measured zoning |

Table 2 shows the results of the final regression. The analysis showed that some of the characteristics listed in Table 1, such as south-facing window area and internal gains, were not statistically significant and were discarded. A *T*-statistic with an absolute value of 2 or more indicates that the coefficient differs from 0 at the 0.025 level of significance or better. Variables 1 through 8 are binary variables with a value of 1 if yes and 0 if no. The relative magnitudes of the coefficients for variables 1 through 8 indicate the extent to which the variable results in a lowering or raising of the as-operated *UA* relative to the nameplate *UA*. A negative coefficient indicates that the variable tends to lower the as-operated *UA*, while a positive coefficient means that the variable tends to raise the as-operated *UA*.

This regression model (Equation 4 with the coefficients in Table 2) explains 78% of the variance, with the nameplate *UA* alone accounting for 58% of the variance. The individual correlations between the independent variables in Table 2 are generally quite low, with no correlation above 0.50. The first observation to be made from Table 2 is that for the default condition (houses with crawlspaces and baseboard heat), the as-operated *UA* is only 59% of the nameplate *UA*. The default conditions are the least problematic conditions and should give the most accurate results in a VBDD technique (e.g., baseboards are 100% efficient at all conditions). Although most of nondefault parameters raise the as-operated to nameplate percentage, there is still a large discrepancy, and this indicates that the calculated nameplate building loss coefficients do not equate to

**TABLE 2**
**Coefficients and T-Statistics for Multiple Linear Regression**

| Independent Variable | Coef. | T-Statistic | n |
|---|---|---|---|
| Intercept | 0.594 | 10.609 | |
| 1. Pure conditioned basements | −0.197 | −3.287 | 18 |
| 2. Mixed conditioned basements | 0.097 | 1.587 | 13 |
| 3. All unconditioned basements | −0.019 | −0.312 | 14 |
| 4. Slab-on-grade | 0.078 | 1.611 | 71 |
| 5. Central electric furnace | 0.11 | 2.551 | 31 |
| 6. Air-to-air heat pump | −0.042 | −0.869 | 16 |
| 7. Fireplace | 0.175 | 4.289 | 53 |
| 8. Major wood-burning equipment | 0.079 | 1.759 | 20 |
| 9. Reported fraction of house zoned | −0.119 | −1.598 | 131 |

observed building heat loss coefficients (i.e., other parameters in addition to the nameplate *UA* are significant).

Variables 1 through 4 are foundation types. Variable 1 is conditioned basements, variable 2 is conditioned basements mixed with other foundation types, variable 3 is unconditioned basements (both full basements and basements mixed with other foundation types), and variable 4 is slab-on-grade foundations. The default condition for foundation type (i.e., if none of the above four types applies) is crawlspace. Pure conditioned basements have an as-operated *UA* about 33% lower than crawlspaces and have a strong T-statistic. This decrease is similar to the decrease seen in simulation runs (Lucas 1991) and suggests that conditioned basements are typically zoned as occupants close ducts, turn off baseboards, etc. Both slabs and mixed basements raise the as-operated *UA* about 8% to 10%, though the low T-statistics indicate weak confidence in these coefficients. It is interesting that pure conditioned basements and mixed conditioned basements have opposing effects on the as-operated *UA*. This may be the result of bias in the foundation component of the nameplate *UA* calculation.

The default heating equipment type is baseboards. The central furnace results in an 18% increase in the as-operated *UA* relative to baseboards. This increase is likely due in part to the heat losses caused by the distribution duct system. The coefficient and T-statistic for heat pumps indicates that heat pumps did not have an effect demonstrably different from baseboards on the as-operated *UA*. This lack of improvement over baseboards may seem surprising because for certain operating conditions heat pumps can have efficiencies of two or more. However, the nonlinear nature of heat pump efficiencies as a function of the operating temperatures differs from the assumption of linearity in the as-operated *UA* calculation. In fact, the higher efficiency of heat pumps may be accounted for in the balance temperature rather than the as-operated *UA* for linear regression models (Lucas 1991).

Both fireplaces and major wood-burning equipment have an adverse effect on the as-operated *UA*, as indicated by the positive coefficients in Table 2. This finding does not appear to be related to wood burning, as sites with extensive wood use were initially filtered out of the analysis. Also, previous ELCAP research (LeBaron 1988) shows that wood burning peaks in midwinter, which should tend to lower the as-operated *UA*. The wood-burning equipment may directly increase the envelope *UA* (wood-burning equipment is not accounted for in the nameplate *UA* calculations). Metal or brick chimneys provide a path of low thermal resistance and, possibly more important, are an infiltration source. The basic fireplace increases the as-operated *UA* more than major wood-burning equipment, indicating a fireplace may be more of an energy loser than major wood-burning equipment.

There is an indication that zoning as reported by the occupants may be lowering the as-operated *UA*, although the T-statistic is marginal. The range of the zoning variable is from 0 to 0.8 with a mean value of 0.22. The fraction of the house zoned was scaled by the average conductance of the envelope of each house divided by the average envelope conductance of all houses combined. The reasoning for this scaling is as follows. The heat transfer through zoned spaces will normally be through two paths: internal and external surfaces. With all other factors equal, zoning will have a greater impact in structures with looser envelopes as the resistance from internal walls will provide a larger fraction of the overall resistance.

Figure 3 shows as-operated versus nameplate *UA*s like Figure 2 but with the nameplate *UA*s adjusted by the multiple linear regression equation (Equation 4). The data points are now centered around the diagonal line, which represents as-operated *UA*s equal to the adjusted nameplate *UA*s. However, the regression explains only 78% of the variance (R-squared = 0.78) from this line of equality, and this divergence is the amount of the as-operated *UA* not explained by the regression analysis.

## CONCLUSIONS

Using empirically derived as-operated *UA*s, a multiple linear regression model improved the correlation of nameplate *UA*s and as-operated *UA*s for the 131 sites. Forced-air systems are clearly observed as energy losers relative to other electrical systems. This poor performance is suspected to be attributable to heat loss from the ducting system. Pure conditioned basements perform much better than other foundation types, indicating these zones may be commonly left unheated by occupants. Interestingly, wood-burning equipment, when not heavily used by the occupant, appears to increase the as-operated *UA* and, therefore, electrical heating energy consumption. A final finding from the empirical data is that reported occupant zoning appears to help lower the as-operated *UA*.

The examination of the empirical heating data has not fully answered the mystery of the low as-operated heat loss coefficients in the ELCAP data. This is particularly perplexing given the wealth of detailed characteristics information employed in this analysis. A possible source of error that may cause the divergence of the as-operated and nameplate *UA*s is the nameplate *UA* calculation itself. However, the authors found little evidence that suggests the *UA*s may have been greatly or even moderately overestimated.

Recommended future work includes performing a case-study analysis to better understand individual houses. Examination of other monitored residential heating energy data sets would be useful. Further study of regression methodologies for determining as-operated *UA*s is also needed. Preliminary additional research done here on linear regression methods indicates eliminating daily heating data below an inside-outside temperature difference cutoff (such as 12°F [7°F] in Figure 1) raises the as-operated *UA* about 7% on average.

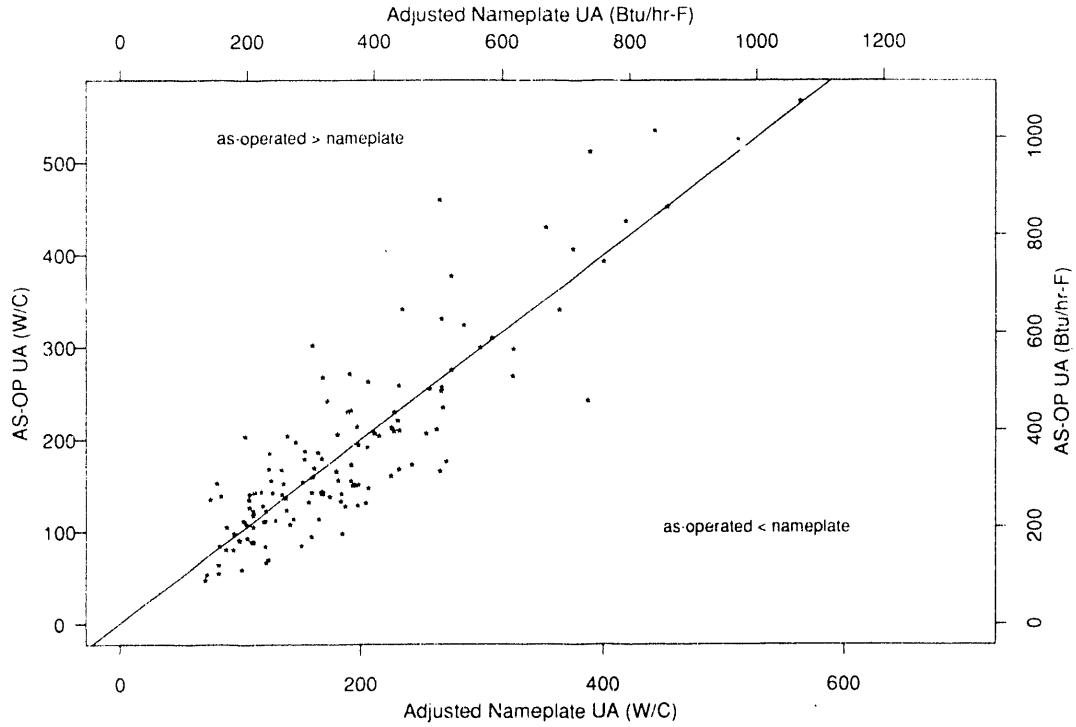


*Figure 3* *As-operated vs. nameplate* UAs *adjusted by multivariate regression equation for 131 ELCAP residential sites. Each point represents one site. The solid line is the line of equality where as-operated equals nameplate.*

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