OUTDOOR-INDOOR TEMPERATURE RELATIONSHIPS

Bruce Nordman and Alan Meier
Lawrence Berkeley Laboratory

ABSTRACT

We investigated the relationship between outside and inside temperatures for several hundred houses in the Pacific Northwest. While the analysis was initially adopted as an efficient means of detecting faulty data, it also revealed unusual patterns of inside temperatures. These patterns included large fluctuations in weekly average inside temperature and a drop in inside temperature corresponding to drops in the outside temperature. The inside temperature pattern for most houses appeared to fall into two regions. At low temperatures, the thermostat settings dominated the behavior but at warmer outside temperatures, the float dominated the inside temperature. In order to determine if the observed patterns were due to simple thermostat management, we performed computer simulations of similar houses to generate synthetic inside temperatures. These simulations demonstrated that observed outside-inside temperature patterns could be explained by thermostat setbacks and floating. The results improve our understanding of thermostat behavior and permit more realistic estimates of heating energy use for houses operated with thermostat setbacks.

OUTDOOR-INDOOR TEMPERATURE RELATIONSHIPS

Bruce Nordman and Alan Meier
Lawrence Berkeley Laboratory

INTRODUCTION

Heat losses in buildings are driven primarily by the difference between inside and outside temperatures. There has been considerable progress in accurately describing outside temperature behavior. These techniques include degree-days, hourly bins, and, more recently, hourly weather data. On the other hand, data regarding the inside temperatures are much less developed. Most of the research on inside temperatures has been directed towards surveys of thermostat settings, such as that by Vine[1], or determination of thermal comfort[2] rather than their influence on heating requirements.

Most estimates of heating (or cooling) loads incorporate relatively simplistic assumptions regarding indoor temperatures. For example, computer simulations of residential building energy use typically assume a constant indoor temperature or a simple thermostat schedule. This is in part due to the strong influence of unpredictable individual behavior. How do these temperature assumptions compare to actual field situations? What kinds of errors are introduced by simplifications? We found that certain analyses of temperature data provided considerable insight into what initially appeared to be anomalous temperature behavior in monitored houses. Moreover, it was possible to duplicate inside temperature patterns with computer simulations.

As part of a monitoring program, the Residential Standards Demonstration Program (RSDP), we analyzed measured energy and temperature data from several hundred homes in the Pacific Northwest.[3] The primary goal of the program was to determine the space heat energy savings when houses were constructed to much higher levels of insulation. We performed thermal analyses in order to determine the energy savings. At the same time, this program provided excellent data on residential heating patterns. The energy use, and inside and outside temperatures were monitored in each house for up to three winters.[4] The project also metered energy use of the furnace, water heater, and total appliances. The houses were audited and the occupants were asked to report their thermostat habits.

---

[1] E.L. Vine, "Saving Energy the Easy Way: An Analysis of Thermostat Management,", Lawrence Berkeley Laboratory Report #18085, Berkeley CA (April 1985).

[2] P.O. Fanger, *Fundamentals of Thermal Comfort: Analysis and Applications in Environmental Engineering*, New York, McGraw-Hill (1972).

[3] A. Meier, B. Nordman, C. Conner, and J. Busch, "A Thermal Analysis of Homes in the Bonneville Power Administration's Residential Standards Demonstration Program", Lawrence Berkeley Laboratory Report LBL-22109, Berkeley, CA (October 1986). Several papers in this Conference discuss other aspects of this project.

[4] Several filters were used to process the synthetic and field data. For both the synthetic and field data, inside temperatures were rejected if below 13°C or above 30°C. Outside temperatures were rejected if below -10°C or above 30°C. Periods lying far from the regression line were rejected; for synthetic data, outliers greater than 0.75°C were rejected and, for field data, outliers greater than 1.5°C were rejected. DOE-2 assumed a venting routine that, at summer temperatures, did not correspond to typical behavior; we therefore truncated the scatterplot 1°C below the highest average inside temperature to remove the periods containing a significant fraction of venting hours.

OUTSIDE-INSIDE TEMPERATURE SCATTERPLOTS AS A DIAGNOSTIC TOOL

Prior to the thermal analysis of the RSDP houses, we developed several automated procedures to screen the data for transcription errors and equipment failures. This included a graphical procedure, in the form of a scatterplot, to permit rapid manual scanning of the input data. In this diagnostic scatterplot, we plotted the inside and outside temperatures for each period. [5] Two examples are shown in Figures 1 and 2.

Certain patterns were apparent in the scatterplots:

- Average inside temperatures fluctuated from week to week. Houses were rarely maintained at a constant inside temperature throughout the winter.
- The inside temperatures in many houses appeared to fall with the outside temperature. The relationship appeared to correspond to those homes with temperature setbacks or intermittent occupancy.
- At higher outside temperatures, a second pattern emerged. Inside temperature appeared to climb much more rapidly.
- Inside temperature patterns for some houses changed markedly from winter to winter.
- Some houses appeared to have temperature patterns that varied with the season. In other words, different inside temperatures were maintained during the spring and fall for the same outside temperature.

We were curious to know the extent to which these patterns had straightforward thermostat-based explanations, and were not due to other, occupant-related factors. For this reason, we compared temperature data from field measurements and simulations (or "synthetic data").

EXPLORING OUTSIDE-INSIDE TEMPERATURE RELATIONSHIPS WITH SYNTHETIC DATA

"Synthetic" data were developed to examine the relationship between the outside and inside temperatures without the uncertainties introduced by field data. Houses similar to those monitored were simulated with the hourly building energy simulation, DOE-2. The hourly temperature data from the weather tape and the DOE-2 output were aggregated into weekly averages.[6] These weekly averages were plotted on an outside-inside scatterplot. A sample scatterplot of synthetic data is shown in Figure 3.

The points on the scatterplot fall into two distinct regions: one with a weak outside temperature dependency and one with a strong outside temperature dependency. We used a regression procedure to find the lines best fitting the points in the two regions. These lines are shown as the "Winter slope" and "Summer slope" lines in Figure 3. The winter line represents the range of temperatures in which the inside temperature is principally determined by the thermostat setting; the summer line represents the range where the house is floating above the thermostat setting a significant fraction of the time. A vocabulary is useful in describing the parameters of the outside-inside temperature scatterplot. These are labeled on the figure and explained in Table 1.

---

[5] This error-detection technique is very efficient and is recommended. Numerous periods which appeared on the surface to be acceptable for the regression were in fact defective and appeared as highly visible outliers on the outside-inside plot. This technique is capable of detecting transcription errors and hardware failures; however, it does not catch more subtle errors such as calibration drift.

[6] The applications of synthetic data are described in:
A. Meier, C. Conner, and J. Busch, " Testing The Accuracy Of A Measurement-Based Building Energy Model With Synthetic Data, *Energy and Buildings*, 12 77 (1988).

Larry Palmiter and Mark Toney, "The Effect of Solar Gains on Degree-day Regression Results", Proc. American Solar Energy Society Conference, Portland OR, July 1987.

Table 1. Explanation of Outside-Inside Scatterplot parameters.

Parameter	Dimen-sion	Explanation
Winter Slope	°C/°C	Slope of line for region dominated furnace heating.
Summer Slope	°C/°C	Slope of line for region of intermittent heating and inside temperature float.
Elbow	°C	The outside temperature at which the regression lines for the low slope and high slope intersect.
Base	°C	Outside temperature which divides the two regions. It is chosen so that the difference between the base and elbow is minimized.
Equal Temperature Line	°C/°C	Line showing equality between outside and inside temperatures. This is a reference line to permit comparison of inside with outside temperature.
Root	°C	The inside temperature at which the regression lines for the low slope and high slope intersect.

The "elbow", that is, the outside temperature at which the two lines intersect, indicates where the transition from a range where the thermostat provides the dominant temperature control to a range where floating is the dominant behavior. We calculated the balance temperature for these houses using the weekly energy and temperature data from DOE-2 using a simple regression technique. The elbow temperature was on average three degrees lower than the balance temperature. Figure 8 shows the relationship between the elbow and balance temperature based on synthetic data. For some of the Missoula homes, the balance temperature was as much as 7°C higher than the elbow. Thus, part of the heating season occurs during the float period.

One unique feature of the scatterplot is the positive slope of the Winter line, indicating that the average inside temperature falls with outside temperature. In this house, the average inside temperature falls about 1°C for every 10 °C fall in outside temperature (slope = +0.1). There is a simple explanation for this phenomenon: the simulation assumed that the house's thermostat was set 21°C during the day and 13°C during the night (70°F/55°F). Every winter evening the inside temperature decays and converges to the nighttime thermostat setpoint. The decay rate — hence the number of hours at lower temperatures — depends on the inside-outside temperature difference, and the decay constant of the house. So the colder the outside temperature, the more rapid the nighttime decay, and the greater fraction of hours at lower inside temperatures.

We simulated houses under other conditions to better understand the outside-inside temperature relationships. These conditions included other thermostat settings, different levels of insulation, passive solar design, and other climate zones. Two more scatterplots with synthetic data are presented in Figures 4 and 5. Table 2 summarizes some of the parameters extracted from the synthetic data.

Table 2. Elbow Parameters and Balance Temperature from Synthetic Data

TMY Site	House type	Internal Gains *(W)*	Thermo-stat	Elbow *(°C)*	Slopes Winter	Slopes Summer	Root *(°C)*	T_{bal} *(°C)*
Missoula	Base Case	586	setback (21°C/13°C)	9.8	0.10	0.47	20.8	13.2
Missoula	Passive Solar	586	setback	2.1	0.09	0.34	20.7	9.3
		1114		-0.3	0.07	0.34	20.7	7.6
		1700		-0.5	0.09	0.58	21.0	4.1
Missoula	Well Insulated	586	setback	4.4	0.06	0.32	20.7	11.2
		1114		4.1	0.07	0.44	21.0	8.7
		1700		1.9	0.08	0.63	21.1	4.7
Missoula	Base Case	586	constant (18.3°C)	5.8	0.01	0.49	18.5	11.2

The synthetic data show that a house with higher insulation levels has a shallower winter slope. This result is physically reasonable because the inside temperature will decay slower when the house is better insulated. The elbow, that is, the temperature at which floating is the dominant inside temperature condition, occurs at consistently colder temperatures for a well-insulated house.

The slope is also sensitive to the amount of internal gains. The winter slope becomes steeper as the amount of internal gains increases. This result is counterintuitive because one would expect the internal gains to retard the temperature decay during setback periods (hence shallower slope). The higher internal gains increase the inside temperature near the elbow and lowers the elbow. These points shift the regression sufficiently so that it overwhelms the shallower slope at colder temperatures.

Note that houses with passive solar features (i.e., a higher fraction of south-facing glazing and thermal mass) had significantly different behavior. The distinction between the winter and summer slopes is less distinct. The inside temperature begins floating at much lower outside temperatures.

The synthetic data results show how houses respond under ideal, consistent operation. It is useful to see how closely real houses duplicate these patterns.

OUTSIDE-INSIDE TEMPERATURE RELATIONSHIPS IN REAL HOUSES

We examined the temperature scatterplots of 558 real houses to see if similar trends appeared.[7] Houses built to current practice (Control) and to a new thermal standard (MCS) were monitored. Some

[7] The field data consisted of weekly average temperatures. The outdoor sensors were located at the house sites, and the indoor sensors were located in the main living space of the houses. Hourly temperature readings were stored and averaged by a multi-channel accumulator and read weekly by the occupants. Sensor calibration errors were of unknown magnitude, but while they would affect the average temperature, slope parameters (as described below) would be unaffected. Transcription errors of significant magnitude have been filtered out. Neither deletion is expected to introduce any bias into the results.

typical scatterplots are shown in Figures 6 and 7. The results are summarized in Table 3.

Table 3. Elbow Parameters and Balance Temperatures from RSDP Field Data.

Zone*** /Type	Number Houses	Elbow (°C)	Slopes Winter	Slopes Summer	Root (°C)	Seasonal* T_{in}(°C)	T_{bal}** (°C)
Zone 1	348	10.7	0.106	0.412	20.4	19.8	14.5
MCS	139	10.3	0.105	0.379	20.7	20.3	13.8
Control	209	10.9	0.107	0.434	20.1	19.5	14.9
Zone 2	99	7.4	0.072	0.289	21.3	20.9	13.5
MCS	57	6.9	0.072	0.254	21.6	21.3	13.5
Control	42	8.0	0.072	0.336	20.7	20.3	13.5
Zone 3	110	5.9	0.063	0.298	20.8	20.5	13.5
MCS	49	5.4	0.066	0.297	21.1	20.7	12.6
Control	61	6.3	0.061	0.299	20.6	20.3	14.3

**Seasonal Average T_{in} is the average temperature over the heating season for a Typical Meteorological Year at the house's Elbow, Root, and Winter Slope. For this purpose, the winter slope is extended past the elbow.*

***Balance Temperatures are computed from a subset of 348 houses for which they are available.*

****Zone 1 is the warmest region, with <3300 °C-days (base 18.2°C), while Zone 3 is the coldest, with >4,400°C-days.*

Many of the houses exhibited an inside temperature pattern very similar to those found in the synthetic data. The Winter and Summer slopes were clearly distinguishable, as were the elbows.

The difference in winter slopes observed in the synthetic data between the MCS and Control houses did not appear in the real houses. This is no surprise because many houses in the group maintained a constant inside temperature. The slopes did, however, drop in colder climates (as was also observed in the synthetic data). Since Controls in Zone 3 were more efficient than MCS in Zone 1, this is to be expected. Future work will compare only those houses whose occupants reported thermostat setbacks; we expect that the slopes will increase markedly for this group.

The balance temperatures for the real houses were consistently higher than the elbow temperatures (see Figure 8). This suggests that the houses were already floating a significant amount of the time below the balance temperature. This could seriously distort estimates of heating load based on the inside temperatures and balance point.

CONCLUSIONS

The outside-inside temperature scatterplot approach provides a new perspective in building energy analysis. It can be used as a powerful diagnostic procedure to detect faulty field data from building monitoring. Moreover, it can detect errors that could not otherwise be detected because it links two data items that, individually, are reasonable yet together form an outlier.

Analysis of the temperature patterns with synthetic data suggested that there were two distinct regions of temperature behavior. In one, the Winter line, the thermostat controlled the inside temperature almost exclusively. The slope of the winter line varied with the amount of the thermostat setback and thermal features of the house. At warmer temperatures, floating occurred such that the inside temperature remained above the thermostat settings a significant amount of the time. The transition to the float-dominated condition consistently occurred several degrees below the regression-derived balance temperature.

Field data demonstrated that inside temperatures are rarely constant, but a relationship between outdoor-indoor temperatures was observed in several hundred real homes. Although the scatter was greater with real data, the winter and summer lines were clearly distinguishable in many homes. At the same time, houses with constant thermostat settings and setbacks were easily recognizable. The elbows occurred several degrees below the regression-derived balance temperatures indicating that houses undergo significant floating below the balance point. However, further work is still needed to better reconcile the difference in elbow and balance temperatures and its effect on regression-based normalization models.

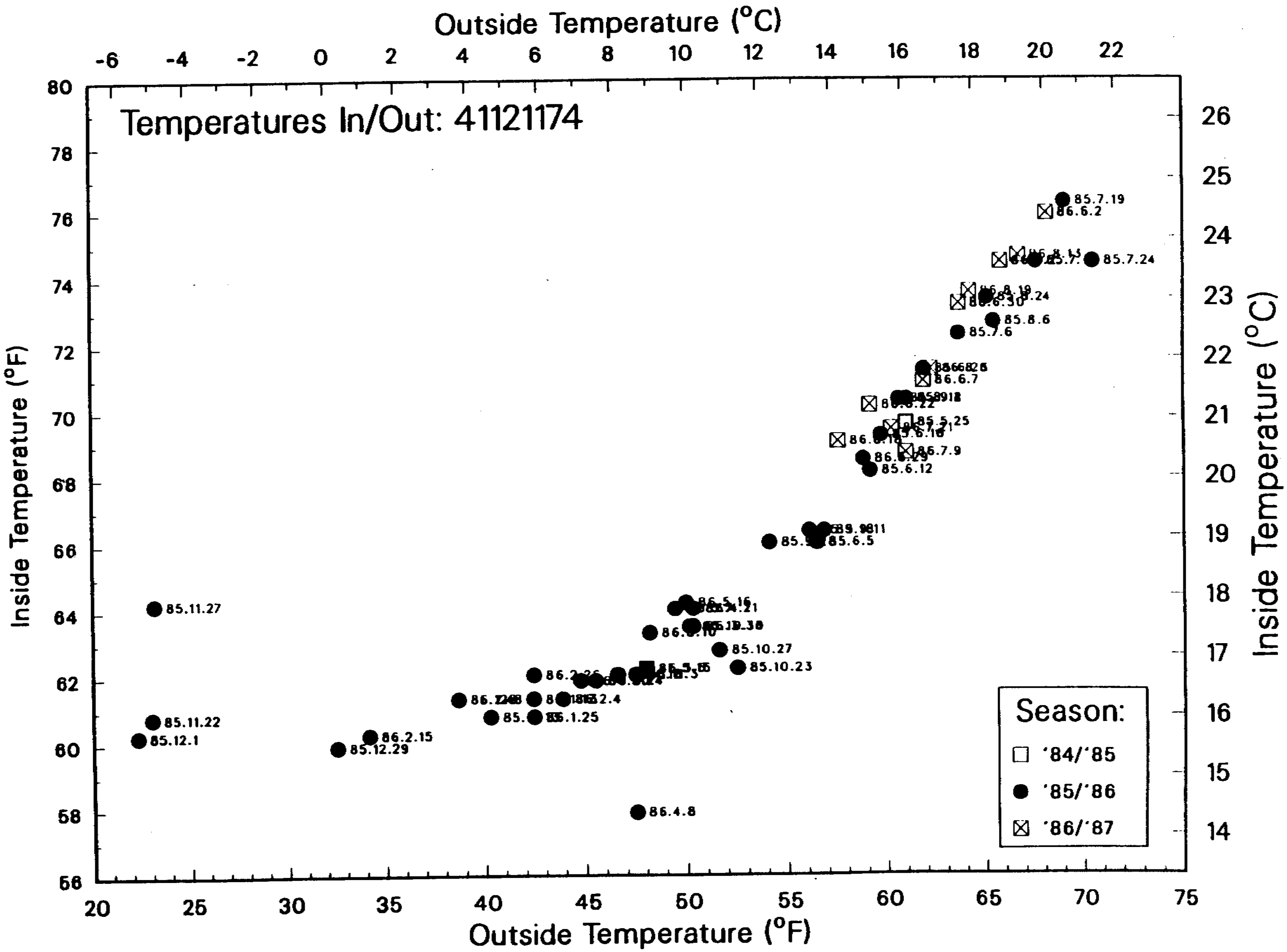

Figure 1. Outside-inside scatterplot for RSDP house 41121174. The end-date of each weekly period is printed next to the point. Note that the temperature behavior in the 86/87 winter very closely paralleled the 85/86 winter although data collection ceased before the coldest part of the second winter occurred. The outlying points at 85.11.27 and 86.5.8 suggest unusual behavior during these periods. In both cases, it appeared that the occupant incorrectly recorded the date.

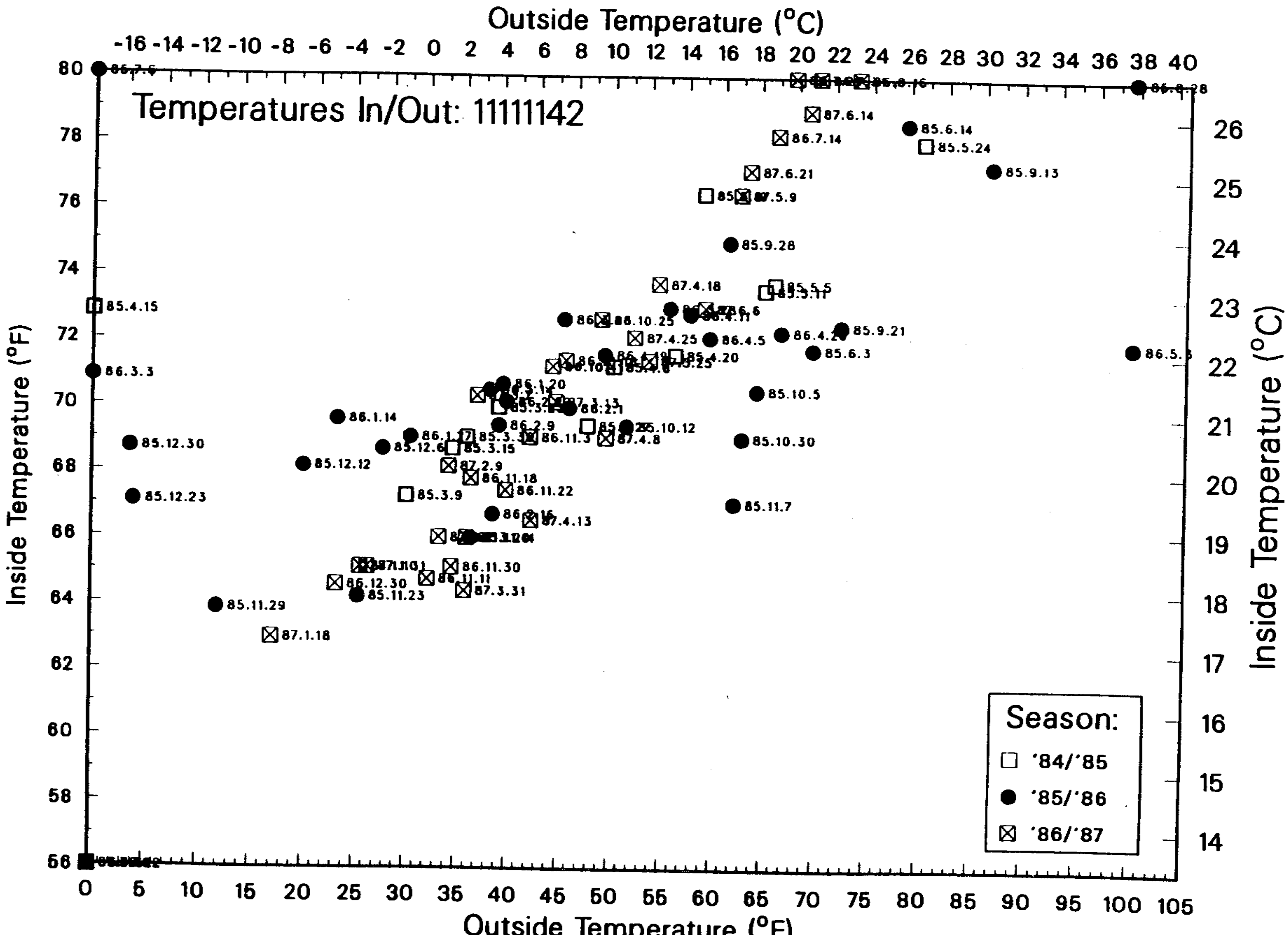

Figure 2. Outside-inside scatterplot for RSDP house 11111142. The end-date of each weekly period is printed next to the point. Outlying points were frequently caused by errors in data collection or transcription. The individual values were not unreasonable in themselves (and therefore were not detected by our error-detection programs) but the pair of values were highly unlikely, especially when linked to the reported date of occurrence. In this case, several points were incorrectly transcribed as 0 instead of no entry. The point at 86.5.3 is also an error since it is unlikely that the outside temperature averaged 100°F in early May. Note the inside temperature "excursions", such as at 85.11.29 and 85.11.23, where the occupants clearly operated the house differently for two weeks. The occupants also operated the house significantly differently in the second winter, probably with a greater thermostat setback.

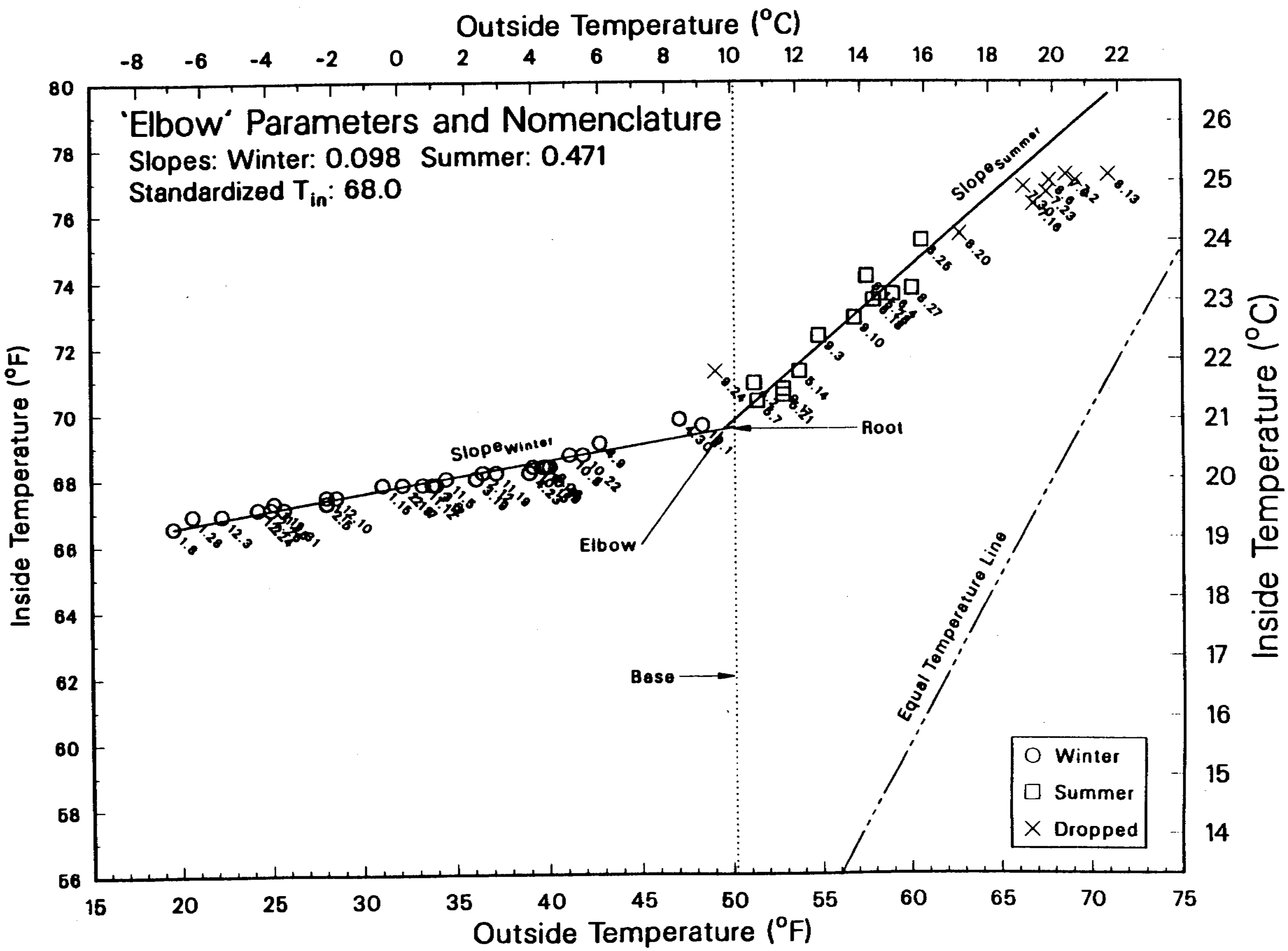

Figure 3. An outside-inside temperature scatterplot using synthetic data. The end-date of each weekly period is printed next to the point. This house was operated with a daytime thermostat setting of 21°C and a nighttime thermostat setting of 13°C (70°F/55°F). The model parameters are explained in Table 1. Periods marked with an 'X' were dropped from the regression. The venting routine assumed in DOE-2 is responsible for the leveling off of inside temperatures at higher outside temperatures; these were also dropped prior to the regression.

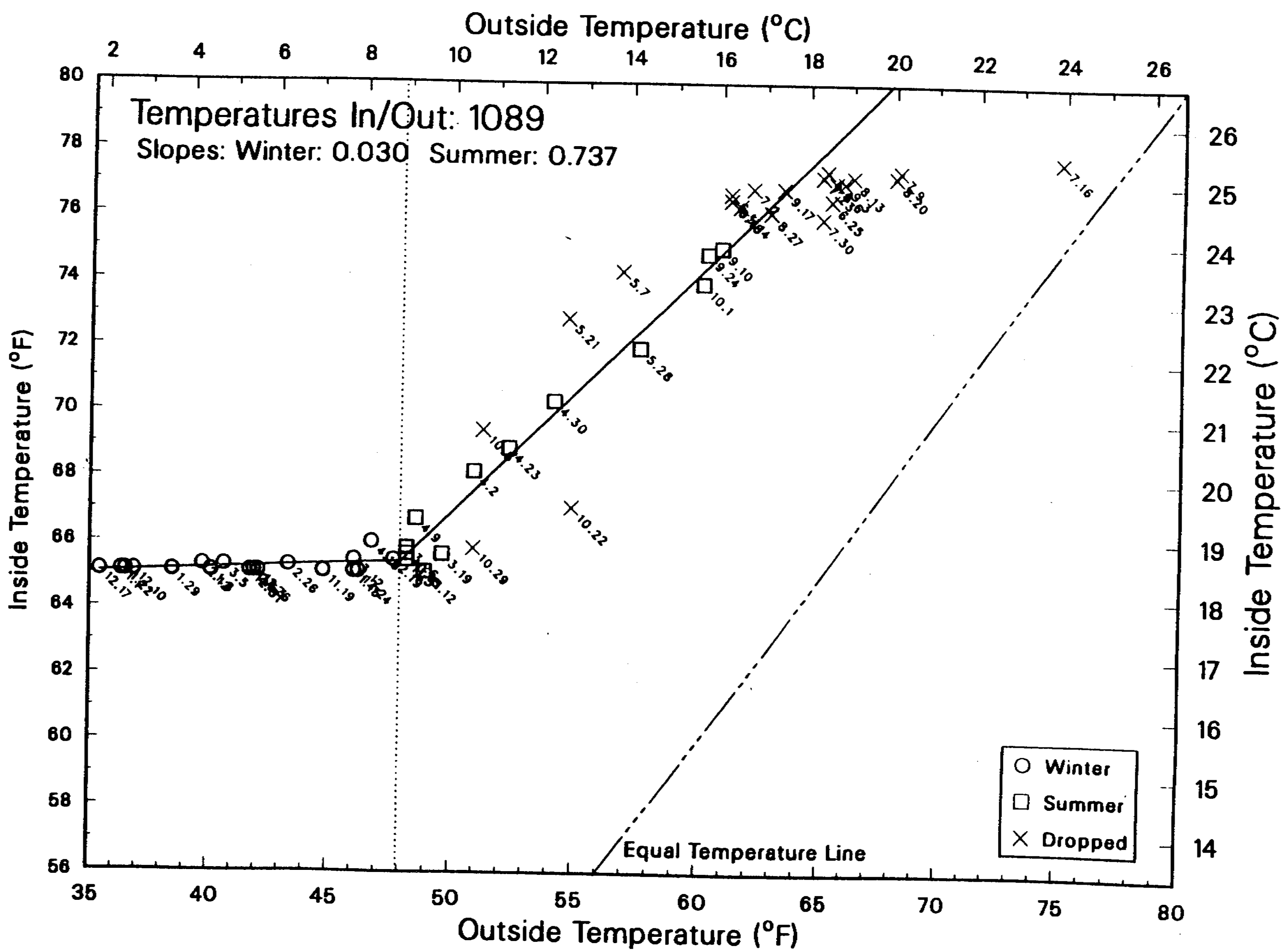

Figure 4. An outside-inside temperature scatterplot for a house based on synthetic data. The end-date of each weekly period is printed next to the point.

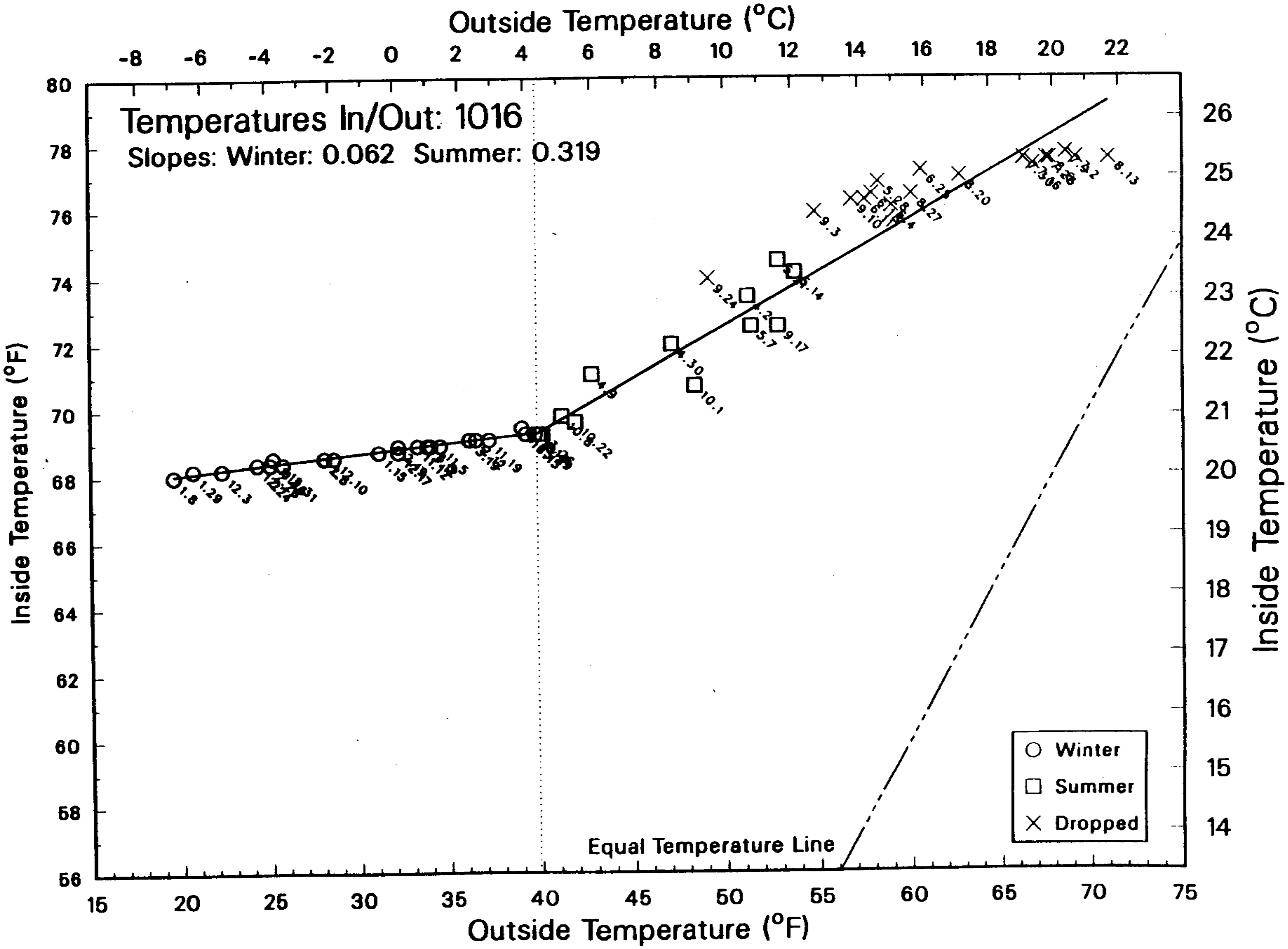

Figure 5. An outside-inside temperature scatterplot for a house based on synthetic data. The date of each period is printed next to the point.

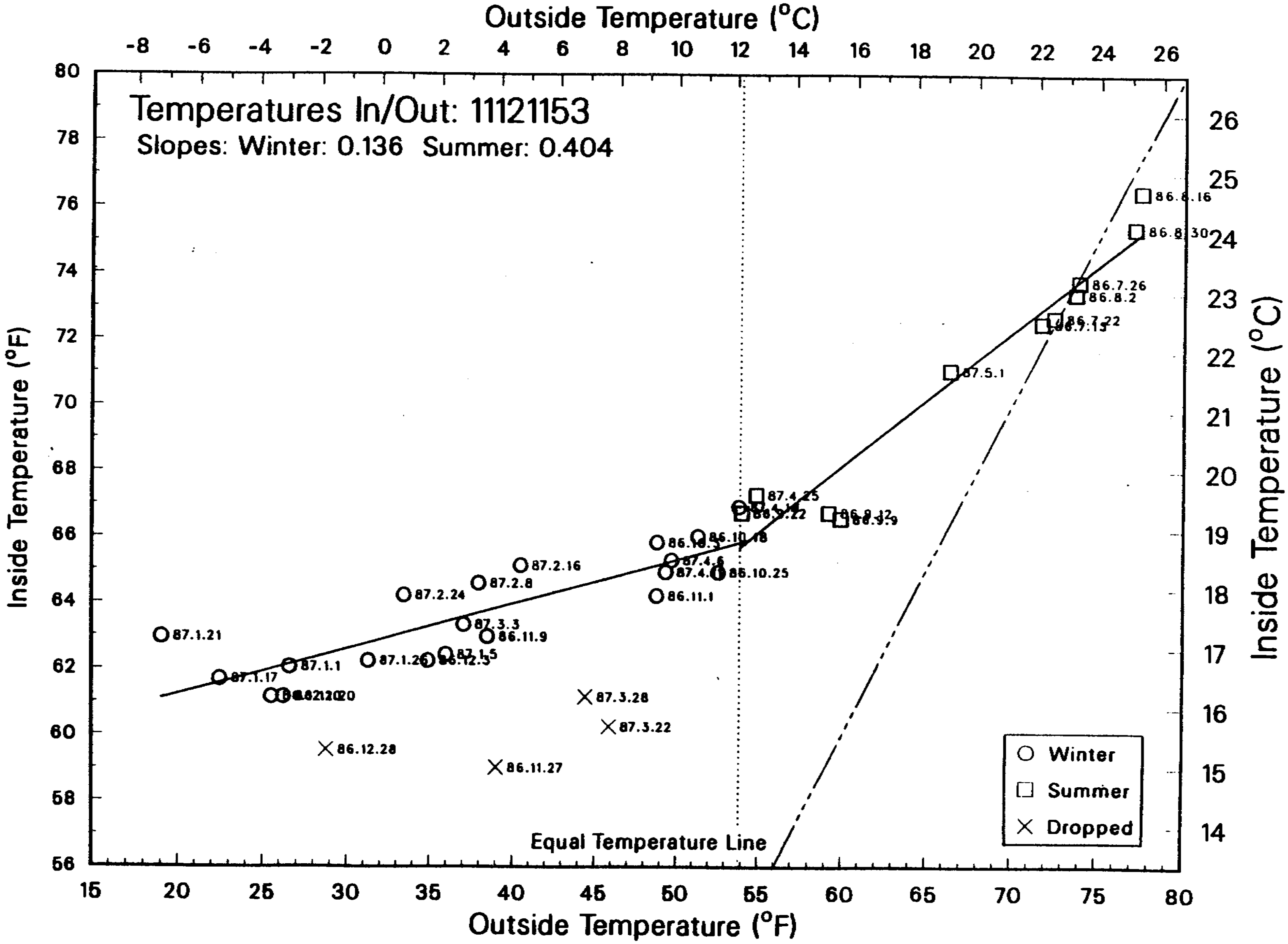

Figure 6. Scatterplot of outside-inside temperatures for a RSDP house. The scatterplot shows the Winter and Summer regression lines. Note the slope of the Winter line, suggesting that the occupants set back the thermostat.

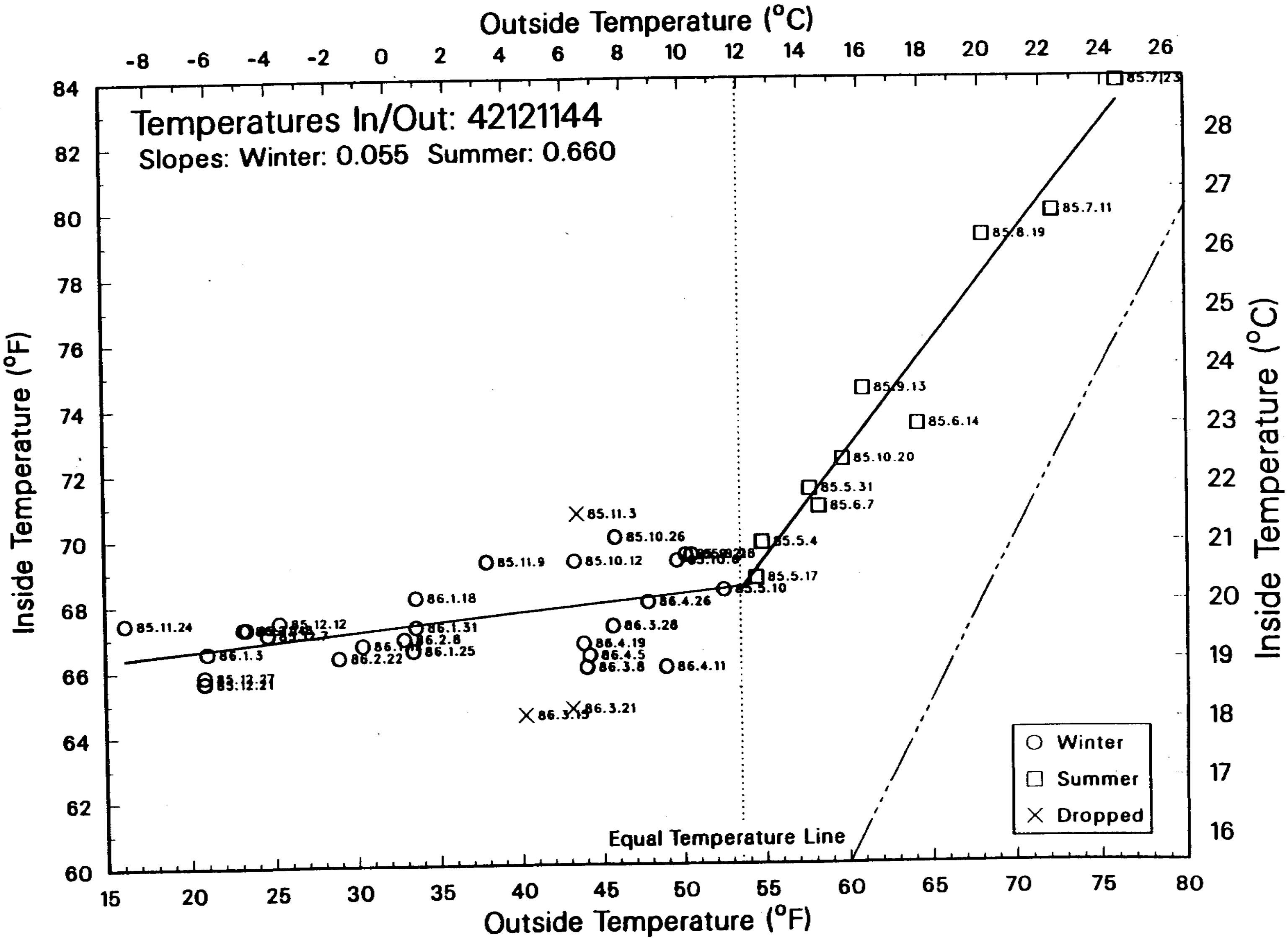

Figure 7. Scatterplot of outside-inside temperatures for a RSDP house. The scatterplot shows the Winter and Summer regression lines. The shallow slope of the Winter line suggests that the occupants maintain a relatively constant indoor temperature.

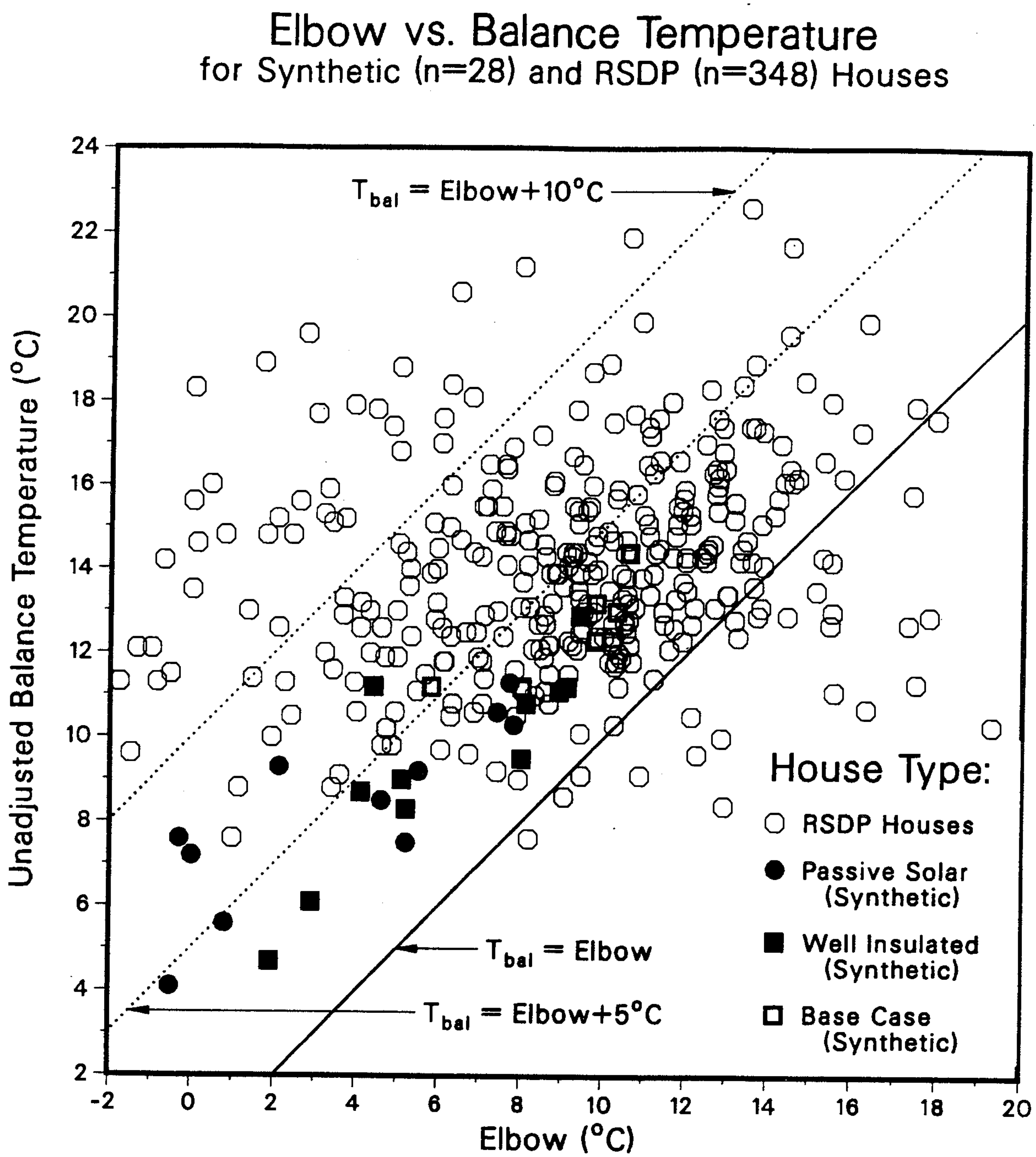

Figure 8. Elbows vs. Balance temperatures for real and synthetic data. The regression-derived balance temperatures lie several degrees above the elbow temperatures. This suggests that significant floating is already occurring in the homes below the balance temperature. Similar trends were seen in both the synthetic and real data.