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ENERGY USE IN A HIGH-RISE APARTMENT BUILDING--A PROGRESS REPORT

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Abstract

Although much residential housing in urban areas is found in multi-unit buildings, especially in the older cities of the northeastern United States, the technical and behavioral aspects of energy use in such structures are virtually unknown. Structures of two or more units comprise 20 million households in the United States and account for 20% of residential energy use. A significant potential for energy conservation exists in multi-unit buildings, but if energy savings are to be realized from them, information must be obtained about their energy use characteristics.

In June 1982, the Energy Performance of Buildings group of the Applied Science Division at Lawrence Berkeley Laboratory initiated a study in a 328-unit, 15-story high-rise apartment building in Oakland, California, to investigate energy use patterns in such a structure. The units are heated electrically and all have similar complements of electric appliances. Natural gas for domestic hot water and cooking is supplied through a common meter. Hence, it was possible to analyze the electric billing information to determine electricity use patterns.

We found a 20 to 1 range in baseload electricity consumption and a 40 to 1 range for space heating in a sample of 207 units. Units with an eastern orientation used less electricity for space heating than did those facing other directions. Other technical features for which we were able to devise tests were found not to account for any part of the observed variation. Our analysis suggests that some occupants may be using their gas ranges for space heating, although our results are not conclusive on this point. A second major cause of the variations may be differences in occupants' temperature preferences.

Energy Use in a High-Rise Apartment Building--A Progress Report

Introduction

Although much residential housing in urban areas, especially in the older cities of the northeastern United States, is found in multi-unit buildings, the technical and behavioral aspects of energy use in such structures are virtually unknown. Structures of two or more units comprise 20 million households in the United States and account for 20% of residential energy use (1). A significant potential for energy conservation exists in multi-unit buildings, but if energy savings are to be realized from them, information must be obtained about their energy use characteristics (2).

In June 1982, the Energy Performance of Buildings group of the Applied Science Division at Lawrence Berkeley Laboratory (LBL) initiated a study in a high-rise apartment building in Oakland, California, to investigate energy use patterns in such a structure. The building, named City Center Plaza, was selected because of several attractive characteristics: 1) in 1980, the management installed electric submeters on all units; 2) the quantity of data available from the building was potentially quite large; 3) in each apartment, electricity is used only for space heating and a few appliances; and 4) it is near LBL. We analyzed electric submeter readings from the building to determine the influence of various technical and behavioral factors on energy use. From this, we hoped to learn about the energy requirements and consumption patterns of the individual units and the effect of behavior on energy use in an apartment building.

City Center Plaza's Board of Directors gave us the electric billing data for the units, requesting only that we work closely with the building manager and keep him informed of our progress. Our work, to date, has concentrated on analysis of the utility data, rather than on field measurements of energy use in the building. This report relates the results of an analysis of electric utility data from City Center Plaza. The report is organized as follows:

1. A discussion of the project's rationale and goals;
2. A description of Oakland's climate;
3. A description of the building's design, the apartments, and their energy use characteristics;
4. A description of some demographic characteristics of the building's occupants;
5. A description of the data and possible factors affecting electricity use;
6. A description of data analysis and results; and
7. A discussion of the results.

Project Rationale and Goals

We initiated this project to understand how energy is used in a large residential building located in a relatively mild climate. We settled on three primary goals for our research. First, we wished to determine which, if any, of various technical and behavioral factors affect gross electricity consumption and space heating in the building. Second, we hoped to discover the relative significance of each factor in variability of electricity use. Finally, we wanted to understand how energy was being used in the building so we could recommend conservation measures to the management.

In order to know how closely energy use in an individual unit follows a theoretical estimate based on building components, appliances in each unit, weather, etc., and to know by how much this estimate differs from both actual consumption and the average for all units, we needed to find out whether certain design factors, such as apartment height above ground, window area, orientation, and neighboring units, affect energy use and might account for observed variations. If technical features were unable to account for the variations, we would like to discover what other factors (such as behavioral ones) were more probable causes.

A common approach to building energy analysis is to correlate monthly or daily energy use with the difference between indoor and outdoor temperatures and other weather features--for example, wind velocity and direction (3). In this project, we inspected graphs of raw data from groups of similar units (with the same floor plan but with different floor levels, orientations, etc.). We analyzed the data using linear regressions to study variations from the group average. We also tried to separate baseload from space-heating electricity use. We developed a list of factors--both technical and behavioral--that might account for the observed variations and tested the data for those effects for which tests could be devised. We assumed that any remaining variations were caused by unknown technical or behavioral factors.

The difficulties involved in analyzing energy data from many units in a single building are not trivial. While there are some similarities to the more familiar problems with single-family dwellings, there are also major differences. Modelling energy use in a multi-family building should be somewhat easier than in a single-family house because the apartments have only one or two exposed surfaces, many units have identical floor plans, and the entire building experiences the same climate. Furthermore, the shielding effects of nearby geographic features and buildings do not vary from unit to unit. However, there are other, complicating problems not present in single-family structures--heat flows and infiltration between adjacent units, the effects of wind and solar gain on opposite sides of the building, the effect of the ventilation and exhaust systems on energy use, and so on. The nature and significance of these complications cannot be determined without extensive instrumentation, measurements, and occupant surveys, all of which were beyond the scope of this project.

The reader should be aware, therefore, that our analysis must be considered preliminary and that there are aspects of energy use that we did not or could not fully consider. This document constitutes a progress report of work that, although not presently funded, may be resumed in the future.

Oakland's Climate

Oakland is located on the eastern shore of San Francisco Bay, about 10 miles from the San Francisco peninsula and 15 miles from open ocean. The Bay Area experiences a cool, rainy season extending approximately from November to May and a warm, dry season from June to October, but local weather is highly variable because of microclimates induced by the region's geography.

Along the Pacific Coast runs a ridge of low hills that offers the Bay Area some protection from ocean winds and weather. The Golden Gate, however, is a conspicuous breach in this ridge and allows the summer fog to flow into the Bay and ashore. The fog can turn a sunny, mild day into a cold, gray one, with temperatures dropping from 70° to 55°F in a matter of minutes. Consequently, heating during the summer months is not uncommon (4). To the east of Oakland is another range of low hills that blocks the hot summer air from California's Central Valley. As a result, temperatures rarely exceed 75 °. During the winter, Pacific storms move into the area every few days, usually interspersed with periods of sunny, mild weather. Temperatures rarely drop below 45°F, but the high winter humidity makes space heating desirable, although not essential. As a result of these climatic variations, Oakland's 2800 heating degree days are spread over the entire year, although most occur during the winter months (November through March; see Figure 1).

The Building

City Center Plaza, completed in 1975, is a 15-story, 328-unit building located near downtown Oakland (Figure 2). It is one of the tallest buildings in the immediate area and is unobstructed and unshielded on all sides except the northeast. Figure 3 shows the building's surroundings.

City Center Plaza is T-shaped, with the leg of the T facing 30° west of south. The building's linear dimensions are sketched in Figure 4. The construction is conventional steel frame with three-inch-thick prestressed concrete slab floors and partition walls. The building's exterior skin is concrete on the three ends of the T and glass and metal on the long surfaces of the T. The concrete floors and walls extend outward from the building to form balconies. There is a three-level garage under the building. The ground floor (approximately 28,000 square feet) is used for office and commercial space. Floors 2 through 15 (approximately 397,000 square feet) are residential. The apartments on floors 2 through 11 are located on double-loaded corridors, with each floor having 25 units of varying area and design. Floors 12 and 14 each have 39 two-story townhouses; thus, there are no corridors on floors 13 and 15. Figure 5 shows the arrangement of apartments on the floors.

There are four basic apartment plans in City Center Plaza, designated A, B, C, and D. Each is further divided into subtypes, such as C1, D2, and so on. For the purposes of this analysis, we usually have assumed all units with the same letter designation to be identical, although Table 1

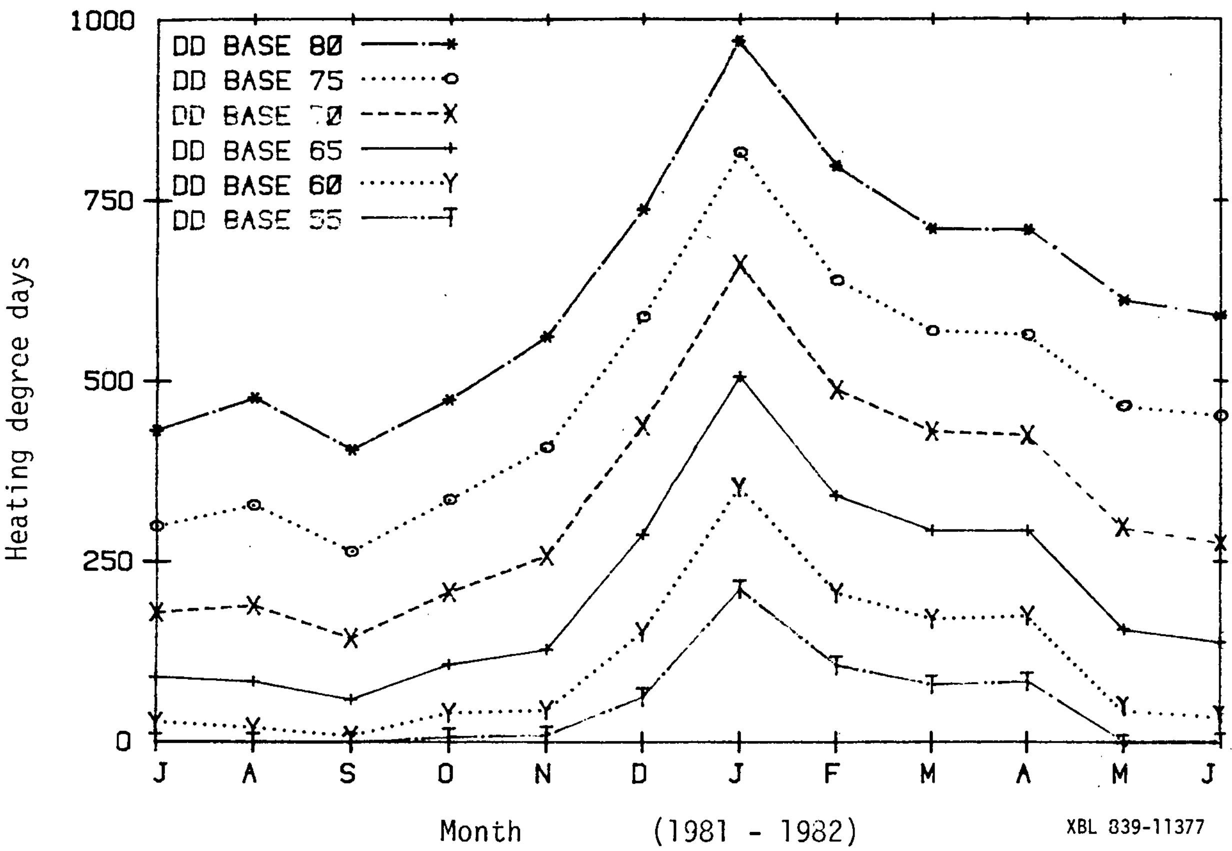

Figure 1: Monthly heating degree days in Oakland, California, calculated from varying temperature bases. Note that heating degree days (base 65°F) occur even during the summer months.

CBB 838-7594

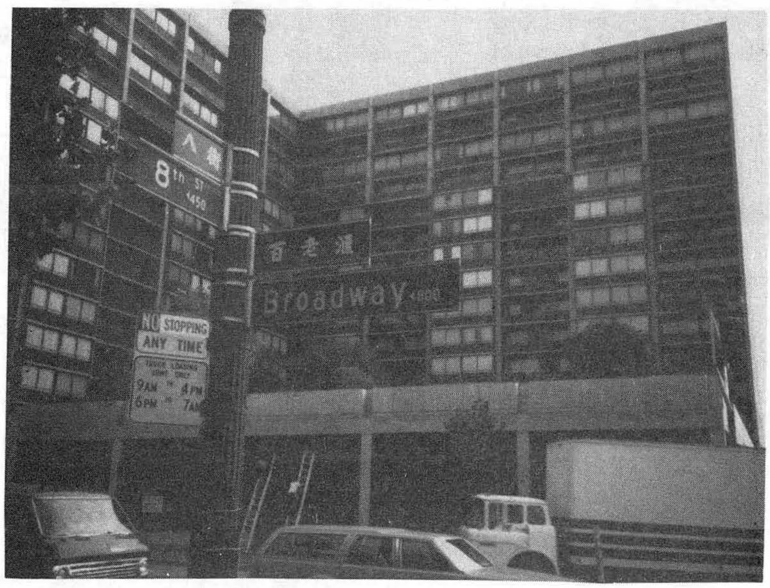

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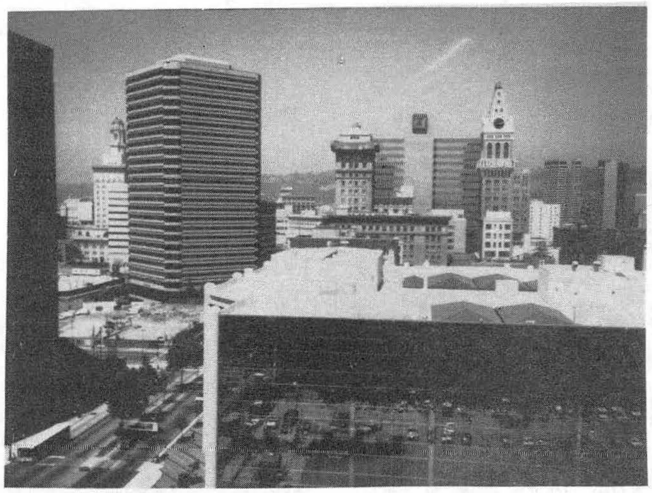
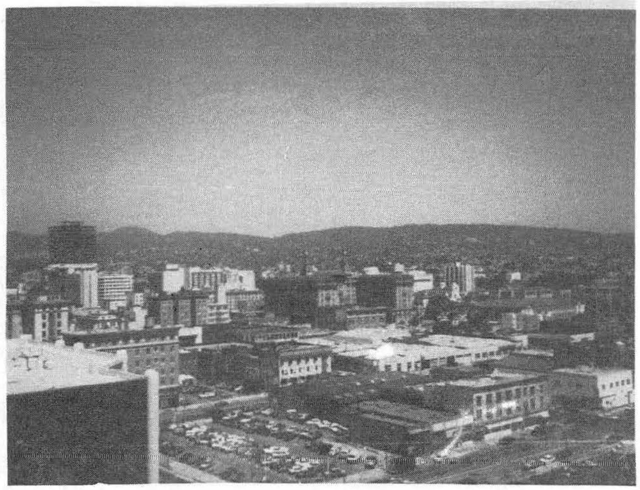
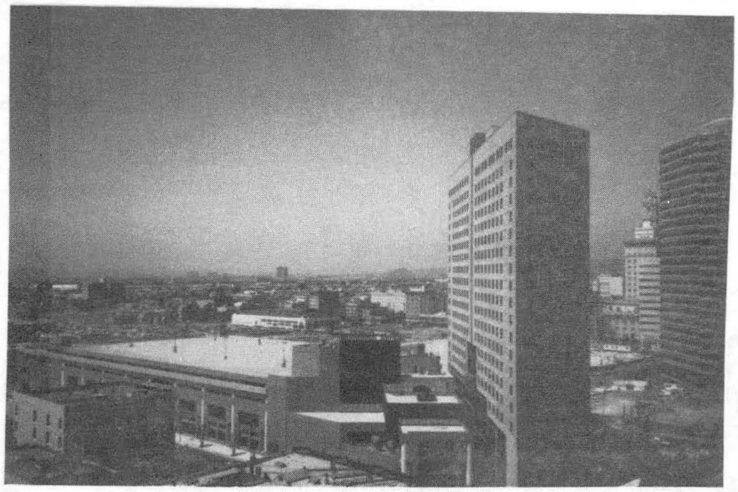
Figure 2: Two views of City Center Plaza: north side (top) and southwest side (bottom).



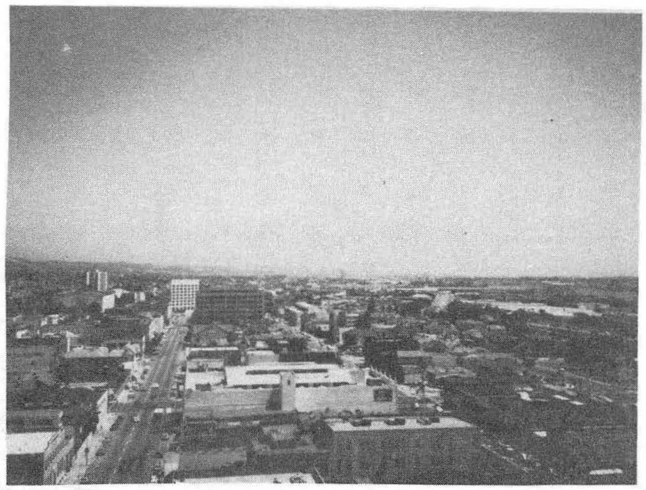
Northeast CBB 838-7584



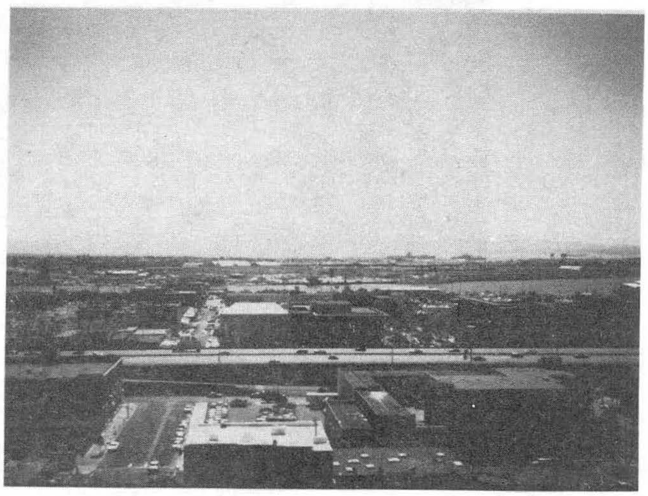
East CBB 838-7582



North CBB 838-7588



Southeast CBB 838-7586



South

CBB 838-7596

Figure 3: City Center Plaza's surroundings as seen from the building roof.

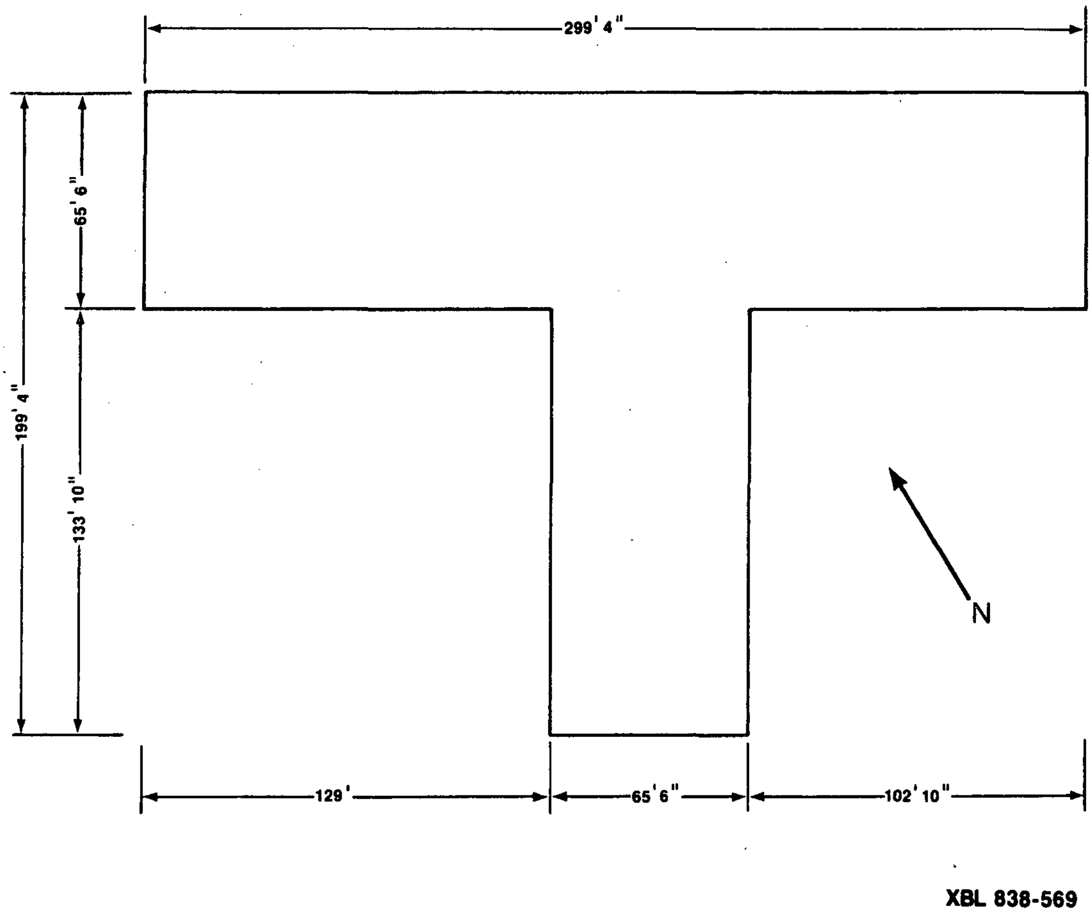
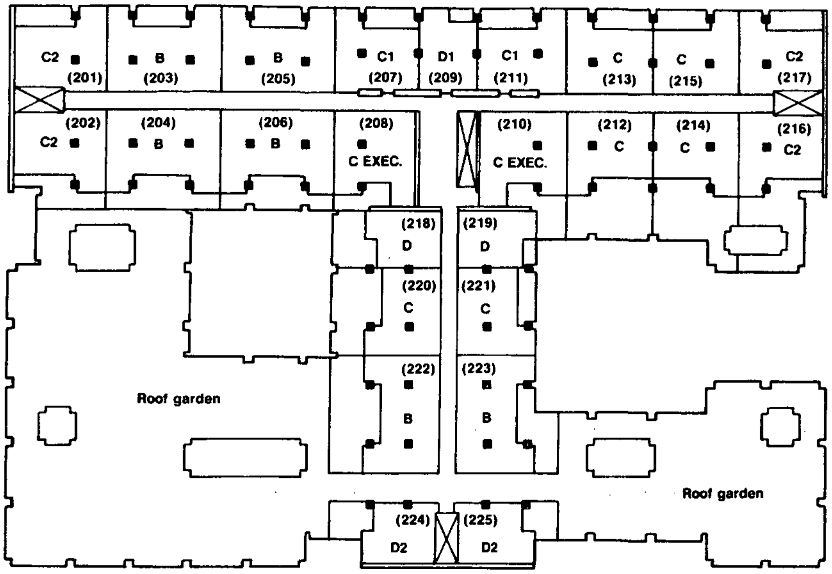
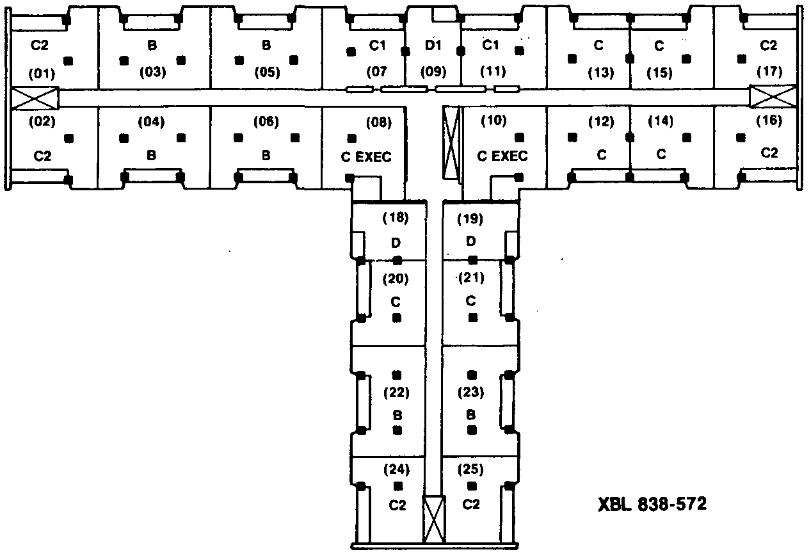


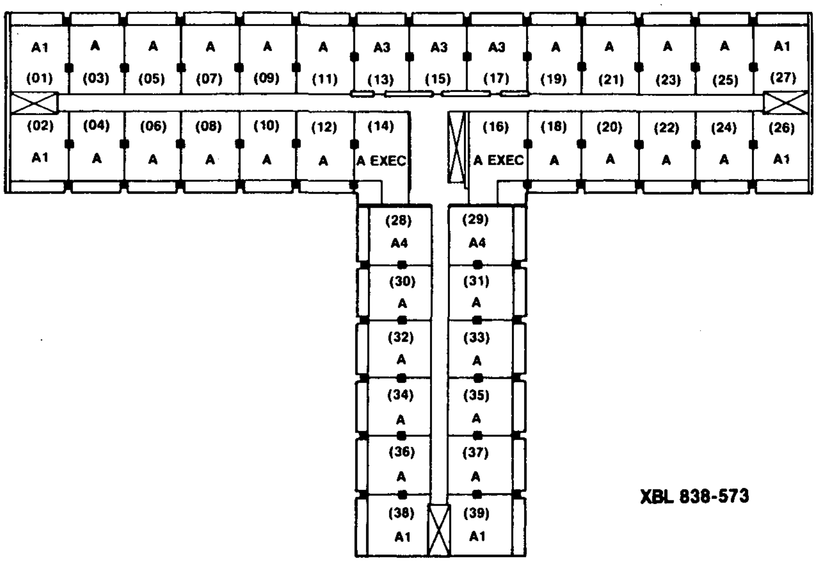
Figure 4: City Center Plaza's linear dimensions.



XBL 838-574



XBL 838-572



XBL 838-573

Figure 5: The arrangement of apartments in City Center Plaza. Floors 3 to 11 are identical; floors 12 and 14 are two-story townhouses. The second floor differs slightly from those above it.

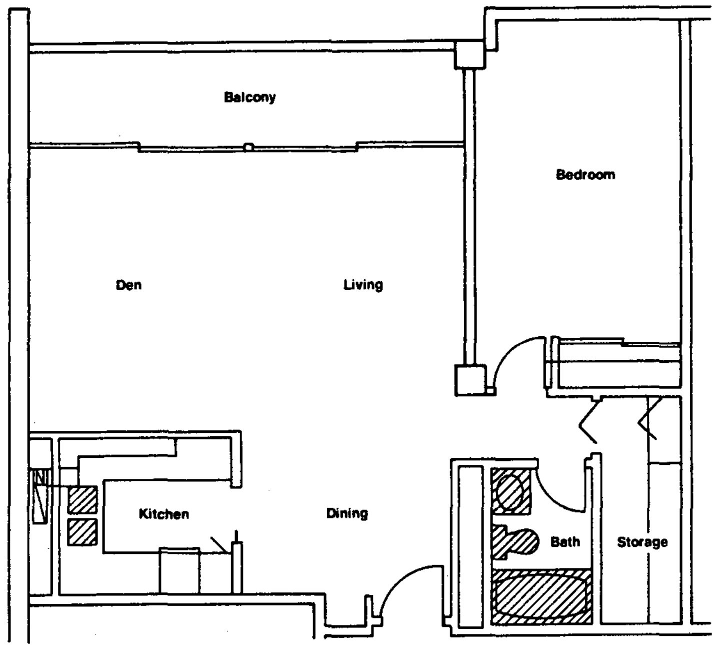
shows that there are minor differences in floor area and design within each of the four categories. Floor areas range from an average of 592 square feet (ft^2) for D units to 1232 ft^2 for B units. All apartments have balconies. They also have fairly large windows, ranging in size from 19 to 28% of gross floor area. In the living room of each unit, the exterior wall (opening onto the balcony) is floor-to-ceiling glass. In the bedroom(s), glass takes up about two-thirds of the exterior wall. Other information about the apartments can be found in Table 1. Two apartment floor plans are shown in Figure 6.

The Building's Occupants

All units in City Center Plaza are privately owned. Two-thirds of the apartments are owner-occupied; the rest are sublet. According to the building management, the annual turnover in occupancy, concentrated in the rental units, is about 33%. The average number of occupants in an apartment is 1.8 and their average age is about 44 years. The average length of occupancy for all units is 3.3 years. The racial makeup of the building (again, according to the management) is approximately 49% Asian and Asian-American, 19% Black, and 31% Mexican-American and Caucasian (5). Because the rents for sublet units at City Center Plaza are relatively high for Oakland and the units are privately owned, occupants can be categorized as middle to upper-middle income. These data summarize what we know about the building's occupants. Some additional information is available from the building management, but we did not request it. To avoid influencing energy use patterns, we postponed occupant surveys until we better understand those patterns.

Table 1: City Center Plaza Apartment Data.

Unit type	No. of units per floor	No. of units in bldg.	Floor area (ft^2)	No. of bed-rooms	No. of bath-rooms	Window area (ft^2)	Window/floor area
A1	6	12	1054	2	2	277	0.26
A	26	52	1145	2	2	264	0.23
A3	3	6	1109	2	2 & utility	262	0.23
A4	2	4	1090	2	2 & utility	229	0.21
Aexec	2	4	1335	2	2 & utility	272	0.20
Avg.		78	1133			264	0.20
B	6	60	1232	2	1	258	0.21
C	6	60	784	1	1	209	0.27
C1	2	20	753	1	1	209	0.28
C2	6	58	764	1	1	217	0.28
Cexec	2	20	992	1	1	197	0.20
Avg.		160	799			210	0.26
D	2	20	590	1	1	109	0.18
D1	1	10	590	1	1	125	0.21
D2	-	2	605	1	1	133	0.22
Avg.		32	592			116	0.20



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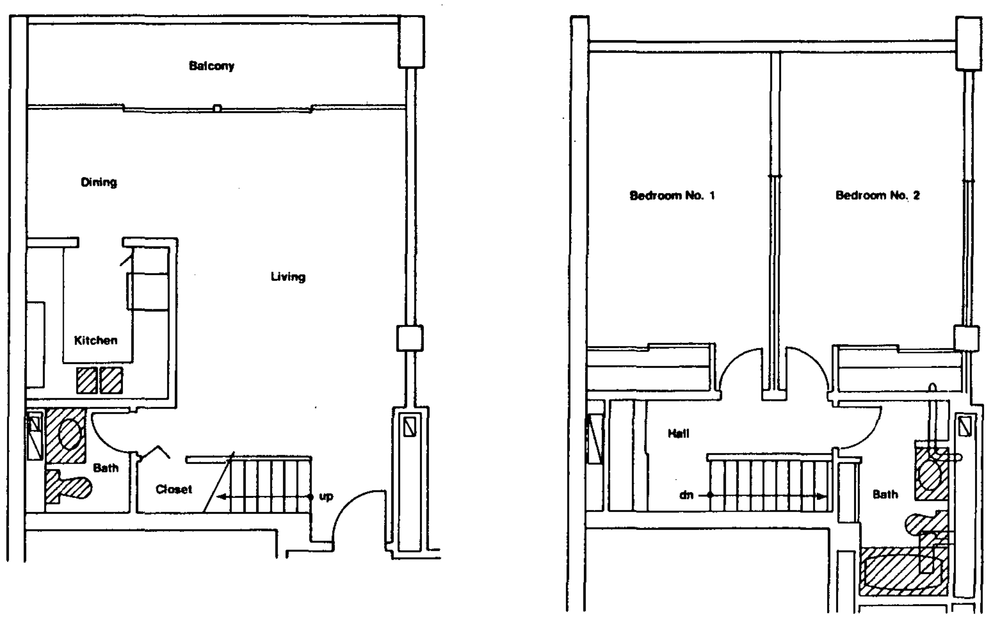


LOWER LEVEL

UPPER LEVEL

XBL 838-570

Figure 6: Floor plans for two of City Center Plaza's 13 apartment types. The top plan is a C-type unit; the bottom, an A-type townhouse.

The Apartment Energy Systems and Loads

We have identified three major paths of energy loss from the City Center Plaza apartments. The first is through the concrete floors and walls, which protrude from the building like fins and act as heat radiators. The second major path is through the windows and exterior walls, and the third is through the ventilation and exhaust systems.

The apartments are heated by wall-mounted electric resistance heaters rated at two to three kilowatts (kW) for a total of 7 to 11 kW per unit. Each heater is separately wired and thermostated, with a continuous "low" to "high" adjustment that can be set to a fixed, although unknown, temperature. All apartments in the building were originally equipped with the same model of refrigerator and dishwasher. Some of the larger units have compact electric clothes washers and dryers. Only a few built-in lighting fixtures are present in each unit. Each unit has a gas range and receives domestic hot water from a central gas-fired boiler. An important fact is that all natural gas for the entire building is supplied through a single common meter. To summarize: electricity for heating, lighting, and appliances is paid directly by the occupant; natural gas for domestic hot water and for cooking is paid by the owners' association (to which occupants pay a flat monthly maintenance fee).

City Center Plaza has a central air supply and exhaust system to the hallways and separate multiple exhaust shafts that keep the apartments under negative air pressure. Makeup air enters each unit through leaks in the windows and cracks around the entrance door to the corridor. There are no air supply ducts into the units nor any obvious air-flow paths between apartments. Each apartment has exhaust vents in the kitchen, bathroom, and sometimes the dining or living room. According to blueprints, the total design exhaust flow through these vents is approximately 350 cubic feet per minute (cfm), although the few random measurements we made suggest that actual flows might be lower (on the order of 75 to 240 cfm). Most of the flow takes place through the kitchen exhaust vent.

We estimate the heat-loss coefficient through the opaque walls and floor of a typical apartment (due to the fin efect) to be about 50 Btu/hr-^{o}F. This is small by comparison with heat loss through the windows, which is about 200 Btu/hr-^{o}F for a unit of average size. However, ventilation appears to be the greatest source of heat loss. Assuming an average apartment volume of 8000 cubic feet, the design ventilation rate of 350 cfm amounts to 2.6 air changes per hour, equivalent to a heat-loss coefficient of 380 Btu/hr-^{o}F. The total heat loss coefficient is approximately 630 Btu/hr-^{o}F. With a temperature differential of 20 to 40^{o}F between indoors and the outside, the winter heating load for a typical unit therefore ranges from 3.7 to 7.4 kW. This is somewhat less than the full-power output of the complement of electric resistance heaters found in the average unit (see the calculation in Table 2).

<u>Utility Data Description and Preparation</u>

As noted earlier, only electricity use is submetered at City Center Plaza. Because the system does not meet the operating standards of Pacific Gas and Electric Company (the local utility), the building management has maintained and read the meters since their installation in 1980. Major advantages of this arrangement are the availability of a large quantity of data from a single source and lack of any bias in the data that could result from our interaction with the building's occupants. Among the disadvantages are meter reading errors and meter malfunctions that required correction of some of the data and elimination of certain units from the data sample (this is discussed further below).

Table 2: Cursory Heat Load Calculation for a Typical City Center Plaza Apartment.

Floor area:	1000 ft^2
Window area:	200 ft^2
Exterior wall area:	40 ft^2
Apartment volume:	8000 ft^3
Bathroom exhaust flow (design):	100 cfm
Kitchen exhaust flow (design):	250 cfm

Total ventilation flow: 350 cfm x 60 min/hr = 21,000 ft^3/hr
(equivalent to 2.6 air changes/hour)

Heat transmission by mechanical ventilation: 21,000 ft^3/hr x 0.0183 Btu/ft^3-^oF =	380 Btu/hr-^oF
Window heat transmission: 200 ft^2 x 1.0 Btu/hr-ft^2-^oF =	200 Btu/hr-^oF
Wall heat transmission: 40 ft^2 x 0.67 Btu/hr-ft^2-^oF =	27 Btu/hr-^oF
Floor heat transmission: 30 ft^2 x 0.81 Btu/hr-ft^2-^oF =	24 Btu/hr-^oF
Total heat transmission:	630 Btu/hr-^oF

Assume temperature difference of 20 to 40^oF:

20^oF x 630 Btu/hr-^oF = 12,600 Btu/hr equal to:	3.7 kW
40^oF x 630 Btu/hr-^oF = 25,200 Btu/hr equal to:	7.4 kW

The heating load for a typical unit (for a inside-outside temperature difference of 20 to 40^oF) is 3.7 to 7.4 kW.

The meters are read monthly and the raw data are entered into a computer where the appropriate multiplication factors (there are three types of meters) and electricity costs (the utility charges an increasing block rate) are figured in. The resulting output is used to bill apartment occupants. Figure 7 shows a billing sheet. We received these sheets for the period from June 1981 through July 1982. Earlier data are unavailable due to startup problems with the system prior to this date.

Monthly electricity consumption data for individual units on each floor were checked for accuracy before analysis. Where obvious meter reading errors had been made--for example, a positive reading followed by a negative one--the data were corrected by subtracting the smaller number from the larger and averaging the difference over the two months. When possible, zero or small anomalous readings were corrected to reflect an average of the preceding and following months. We estimate that we had to correct 1-2% of the meter readings in this way. Units whose readings could not be corrected were eliminated from the sample.

After correcting the data, we copied the 12 monthly readings for each apartment from the billing sheets into arrays organized by floor. The arrays were entered into a microcomputer and rearranged into 13 apartment subtypes (C1,C2, etc.). These files were manipulated to generate the arrays used in subsequent analysis.

Our first step in analyzing the data was to generate month-by-month electricity consumption profiles for all units remaining in our sample (after correcting the data). Following this, we applied linear regression techniques to the data. Generally, a dependent variable such as monthly electricity use is assumed to be a function of one or more independent variables. One common independent variable is "degree days", which is

CITY CENTER PLAZA ELECTRICITY BILLING 5/ /82

UNIT	OPEN	CLOSE	DIFF	FACT*	KWH	RATE	AMT	FLAT	BILLED	CITY	STATE	CURRENT	PRIOR	TOTAL
[redacted]	533	550	17	20	340	.06925	23.55	.00	23.55	1.30	.07	24.92	.00	24.92
[redacted]	5980	6220	240	1	240	.06925	16.62	.00	16.62	.91	.05	17.58	.00	17.58
[redacted]	451	462	11	20	220	.06925	15.24	.00	15.24	.84	.04	16.12	.00	16.12
[redacted]	4666	4991	325	1	325	.06925	22.51	.00	22.51	1.24	.07	23.82	.00	23.82
[redacted]	12946	13290	344	1	344	.06925	23.82	.00	23.82	1.31	.07	25.20	.00	25.20
[redacted]	9460	9757	297	1	297	.06925	20.57	.00	20.57	1.13	.06	21.76	78.72	100.48
[redacted]	10051	10225	174	1	174	.06925	12.05	.00	12.05	.66	.03	12.74	.00	12.74
[redacted]	5964	6111	147	1	147	.06925	10.18	.00	10.18	.56	.03	10.77	64.72	75.49
[redacted]	5295	5421	126	1	126	.06925	8.73	.00	8.73	.48	.03	9.24	.00	9.24
[redacted]	4974	5232	258	1	258	.06925	17.87	.00	17.87	.98	.05	18.90	.00	18.90
[redacted]	222	231	9	20	180	.06925	12.47	.00	12.47	.69	.04	13.20	.00	13.20
[redacted]	10660	11075	415	1	415	.06925	28.74	.00	28.74	1.58	.08	30.40	22.29CR	8.11
[redacted]	303	323	20	20	400	.06925	27.70	.00	27.70	1.52	.08	29.30	.00	29.30
[redacted]	12452	12777	325	1	325	.06925	22.51	.00	22.51	1.24	.07	23.82	102.51	126.33
[redacted]	273	296	23	20	460	.06925	31.86	.00	31.86	1.75	.09	33.70	214.05	247.75
[redacted]	7137	7446	309	1	309	.06925	21.40	.00	21.40	1.18	.06	22.64	.00	22.64
[redacted]	3294	3599	305	1	305	.06925	21.12	.00	21.12	1.16	.06	22.34	.00	22.34
[redacted]	3398	3625	227	1	227	.06925	15.72	.00	15.72	.86	.05	16.63	18.36	34.99
[redacted]	3168	3395	227	1	227	.06925	15.72	.00	15.72	.86	.05	16.63	.00	16.63
[redacted]	5076	5259	183	1	183	.06925	12.67	.00	12.67	.70	.04	13.41	.00	13.41
[redacted]	3210	3390	180	1	180	.06925	12.47	.00	12.47	.69	.04	13.20	123.76	136.96
[redacted]	258	279	21	20	420	.06925	29.09	.00	29.09	1.60	.08	30.77	.00	30.77
[redacted]	6476	6761	285	1	285	.06925	19.74	.00	19.74	1.09	.06	20.89	.00	20.89
[redacted]	14060	14490	430	1	430	.06925	29.78	.00	29.78	1.64	.09	31.51	81.03	112.54
[redacted]	3799	3971	172	1	172	.06925	11.91	.00	11.91	.66	.03	12.60	.00	12.60

*Multiplication factor

Figure 7: A utility billing sheet from City Center Plaza for May 1982, prepared by the building management.

defined for each day as the difference in degrees (Farenheit or Centigrade) between a base temperature (usually 65°F) and the average outdoor temperature for the day. If the temperature difference is less than zero, the number of degree days is set equal to zero. The total number of degree days in a month is the sum of the degree days for each day of the month (6).

In analyzing the City Center Plaza data, we chose not to regress electricity use against degree days because we did not know the temperature differences across the building shell and were unwilling to assume constant interior temperatures throughout the year (7). Instead, we assumed that: 1) all units with the same letter designation were identical; 2) all apartments experienced identical exterior climatic conditions, and 3) average energy use for a set of units (a "group") with similar architectural features represented the "normal" response of that type of unit to the exterior climate. We therefore calculated average monthly electricity use for categories of apartments, used these averages as our independent variable, and regressed individual unit consumption against these averages. Using this approach, the slope and intercept provide indicators of an individual unit's consumption compared to the average and the R^2 calculated for each apartment is a measure of how well that apartment's actual consumption profile is represented by the average of all apartments of the same type. In the absence of direct, long-term measurements of interior temperatures in the apartments, this appears to be the best means of normalizing observed consumption data (8).

The regression was performed twice. We eliminated units having an R^2 less than 0.2 after the first run and those having an R^2 less than 0.3 after the second. This removed those units whose consumption patterns were erratic or irregular over the course of the year. By setting the required

R^2 at a low level, we tried to establish a uniform criterion to eliminate the most problematic outliers (9). A total of 207 units remained in the sample after the elimination of outliers (Table 3). We also calculated a consumption ratio representing the actual annual consumption of a particular unit divided by the average annual consumption for that type of unit; this quantity was utilized in several of our test procedures. (An example of the regression output is shown in Figure 8.)

Data Analysis and Results

A. Approach

Analysis of the City Center Plaza utility data proceeded through several stages, in a sequence determined largely by our assumptions concerning energy use in the building. Although aware of the importance of occupant effects (10), we initially established the hypothesis that variations in energy use could be partly accounted for by technical factors. We thus asked the following questions:

1. Did identical units show similar electricity consumption profiles?
2. How did consumption vary between and within apartment types?

In order to determine the nature of the variations, we graphically plotted electricity use data normalized by group and floor area. We then asked:

3. What were the patterns and levels of consumption in different apartment types?

After regressing the data against group averages, we separated baseload from space-heating electricity use. Based on the results of this analysis, we developed a list of technical and design factors that might account for the range of variation observed in space-heating electricity use. We then asked whether the variations could be attributed to:

4. heat flow between adjacent units (heat-stealing)?

Table 3: Apartment Sample Size before and after Outlier Elimination.

Apartment type	Number before elimination	Number after elimination	Percent remaining in sample
A	78	47	60%
B	60	38	63%
C	160	104	65%
D	32	18	56%
All units	326	207	63%

8.86766
10.1848
8.62598
11.2787
17.7271
29.7973
38.1133
24.1343
16.6602
16.4362
9.68839
6.7278
16.5201

[redacted]	345.885	28.8237	1.74476	1.47209	4.50456	.939042
[redacted]	174.654	14.5545	.881015	.86586	.250364	.613348
[redacted]	81.9998	6.83332	.413635	.19493	3.61304	.152825
[redacted]	292.536	24.378	1.47565	2.38892	-15.0873	.943111
[redacted]	111.755	9.31295	.563733	.570743	-.11581	.668755
[redacted]	249.532	20.7943	1.25873	.788713	7.76469	.880022
[redacted]	154.902	12.9085	.781377	.647472	2.21212	.725366
[redacted]	154.396	12.8664	.778828	.596135	3.01812	.819127
[redacted]	59.6671	4.97226	.300981	.2956	.0889006	.420469
[redacted]	316.659	26.3883	1.59734	.864443	12.1076	.803547
[redacted]	137.987	11.4989	.696054	.524874	2.82792	.625677
[redacted]	217.715	18.1429	1.09823	.587145	8.44322	.437419
[redacted]	249.801	20.8167	1.26008	.591213	11.0498	.489306
[redacted]	180.401	15.0335	.910008	.655014	4.21253	.713385
[redacted]	188.291	15.6909	.949803	.50173	7.40222	.684523
[redacted]	163.051	13.5876	.822484	.829274	-.112174	.700353
[redacted]	203.496	16.958	1.02651	1.52787	-8.28254	.679802
[redacted]	127.881	10.6568	.645077	.404564	3.97331	.509044
[redacted]	187.118	15.5932	.94389	1.14079	-3.25286	.927538
[redacted]	312.006	26.0005	1.57386	1.362	3.49998	.882304
[redacted]	76.4568	6.3714	.385675	.518184	-2.18907	.470207
[redacted]	247.673	20.6394	1.24935	2.00075	-12.4133	.944377
[redacted]	180.746	15.0622	.911746	1.32374	-6.80623	.847691
[redacted]	158.702	13.2252	.800548	1.00588	-3.39205	.714512
[redacted]	233.209	19.4341	1.17639	.924681	4.15822	.528363
[redacted]	238.365	19.8637	1.2024	1.65797	-7.52618	.714936
[redacted]	293.472	24.456	1.48037	2.3522	-14.4027	.920543
[redacted]	252.923	21.0769	1.27583	1.92502	-10.7248	.926242
[redacted]	454.061	37.8384	2.29044	2.3845	-1.55392	.915639
[redacted]	187.002	15.5835	.943303	.326513	10.1895	.857784
[redacted]	118.643	9.88693	.598477	.279266	5.27341	.372658
[redacted]	105.59	8.79916	.532632	.395931	2.25833	.765553
[redacted]	57.8341	4.81951	.291735	.337871	-.76217	.728143
[redacted]	199.132	16.5943	1.00449	.442626	9.28205	.665398
[redacted]	359.833	29.986	1.81512	3.11987	-21.5546	.732826
[redacted]	168.036	14.003	.847633	.733177	1.89082	.406755
[redacted]	93.5344	7.79453	.47182	.462455	.154713	.675341

Figure 8: A sample of the linear regression output. The column of 13 numbers at the top represents average gross electricity consumption for July 1981 to June 1982 for the group of Type-A apartments. The vertical columns represent: 1) unit number; 2) annual consumption (monthly average x 12); 3) average daily consumption (kWh/day); 4) average-to-actual consumption ratio for the year; 5) slope of the regression fit; 6) intercept; and 7) R-squared of the regression fit.

5. apartment orientation?

6. differential operation of the ventilation and exhaust systems?

We then investigated whether the variations might be related to testable behavioral factors. There are a number of occupant factors that might cause large variations in electricity use, such as:

i. Age of occupants in each unit;
ii. Number of occupants in each unit;
iii. Changes in occupancy;
iv. Whether the unit is occupied by the owner or a renter;
v. Who pays the electric bill?;
vi. Socioeconomic group, race, nationality;
vii. Use of drapes or other devices for cooling;
viii. Living patterns (e.g., whether occupants are at home during the day);
ix. Temperature preference;
x. Relationship between appliance use and space heating;
xi. Use of the gas range for heating.

These factors can be subdivided into two groups: those concerning demographic characteristics of the occupants (i-v) and those concerning living habits (vi-x). Of those factors concerning living habits, (vii) and (viii) are not measurable or testable within the scope of our study and (ix) could be measured but would require installation of instrumentation. Factors (x) and (xi) might be testable using our data. Hence, concerning behavioral factors, we asked whether:

7. units having high baseload consumption used more or less electricity for space heating than those having low baseload consumption.

8. use of gas ranges for space heating could account for some of the observed variation.

Our analysis procedure and results are discussed below.

B. Visual Analysis of Variations in Consumption

The monthly utility data were used to plot month-by-month graphs of electricity consumption for July 1981 to June 1982. Each plot depicts 4 to 6 units of the same type on the same floor; approximately 60 plots were generated. Because only architecturally identical units are depicted on each graph, such a comparison may provide visual clues to similarities and differences in patterns of electricity use between identical apartments. For example, B-type units on the tenth floor might show systematically greater consumption than identical units on the third floor, or those in the west wing of the building might use more electricity than those in the east wing.

Many units showed a flat consumption pattern during the summer months corresponding to baseload appliance use, and a peak in the winter due to space heating. However, summer use often varied by a factor of two to four between identical units on the same floor, while variations in winter consumption tended to be even greater (Figures 9 and 10). These large variations made it difficult to perceive systematic differences in electricity use that could be caused by simple differences in apartment design. Consequently, we hypothesized other causes of the variations, such as orientation, heat-stealing, etc.

In a second normalization scheme, we compared variations in electricity use from month to month within and between apartment types. We calculated average monthly consumptions for each type of unit and divided by the floor area for each category and the number of days in each billing period. Our results, expressed in units of kilowatt-hours per day per square foot (kWh/day-ft^2), are shown in Figure 11. We expected gross consumption to scale with apartment size (since larger units would require more energy for space heating) and normalized consumption to be roughly the same for all units, but we found this not to be strictly the case. Apartments in the C1 category, although not the smallest, were the highest consumers of electricity per square foot while the B units were the lowest

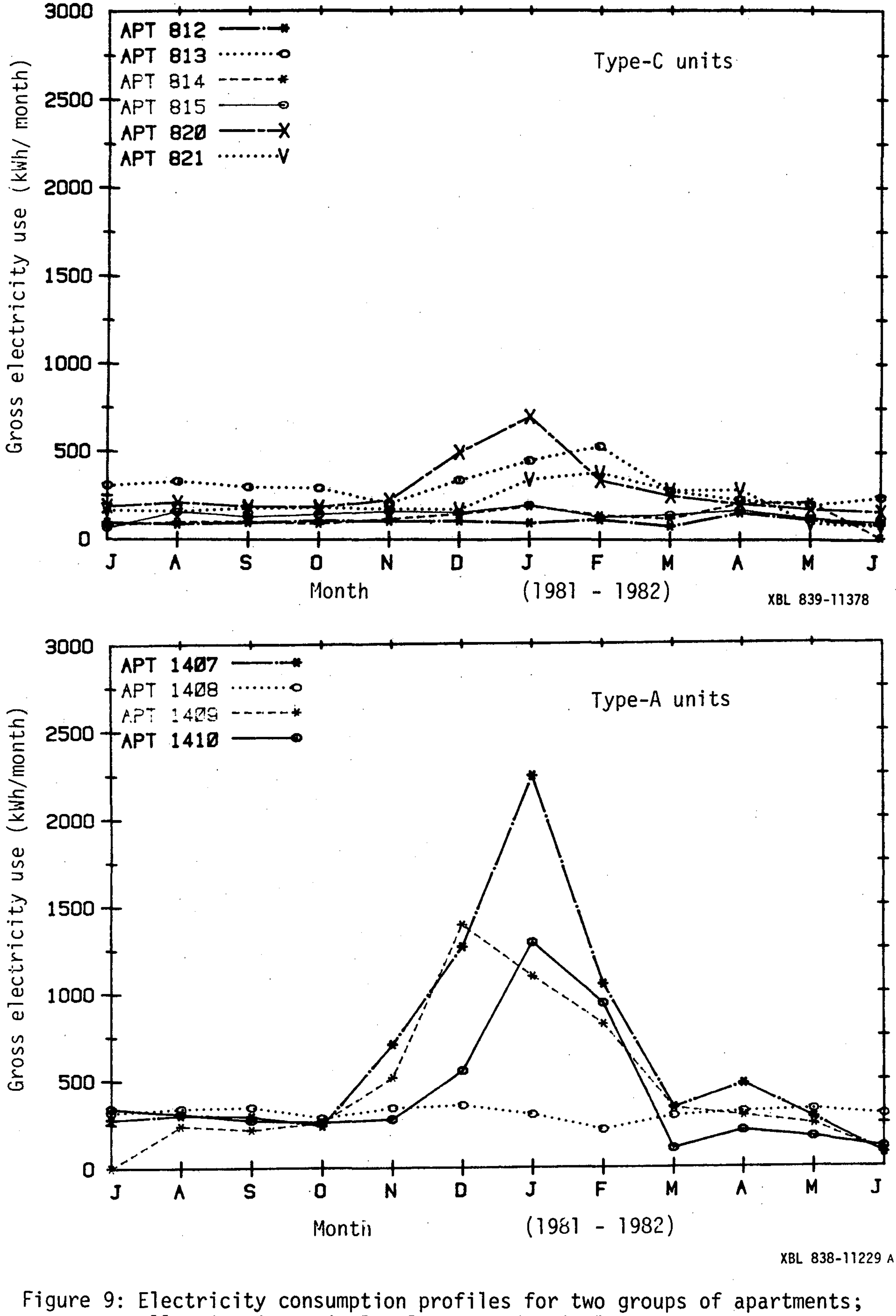
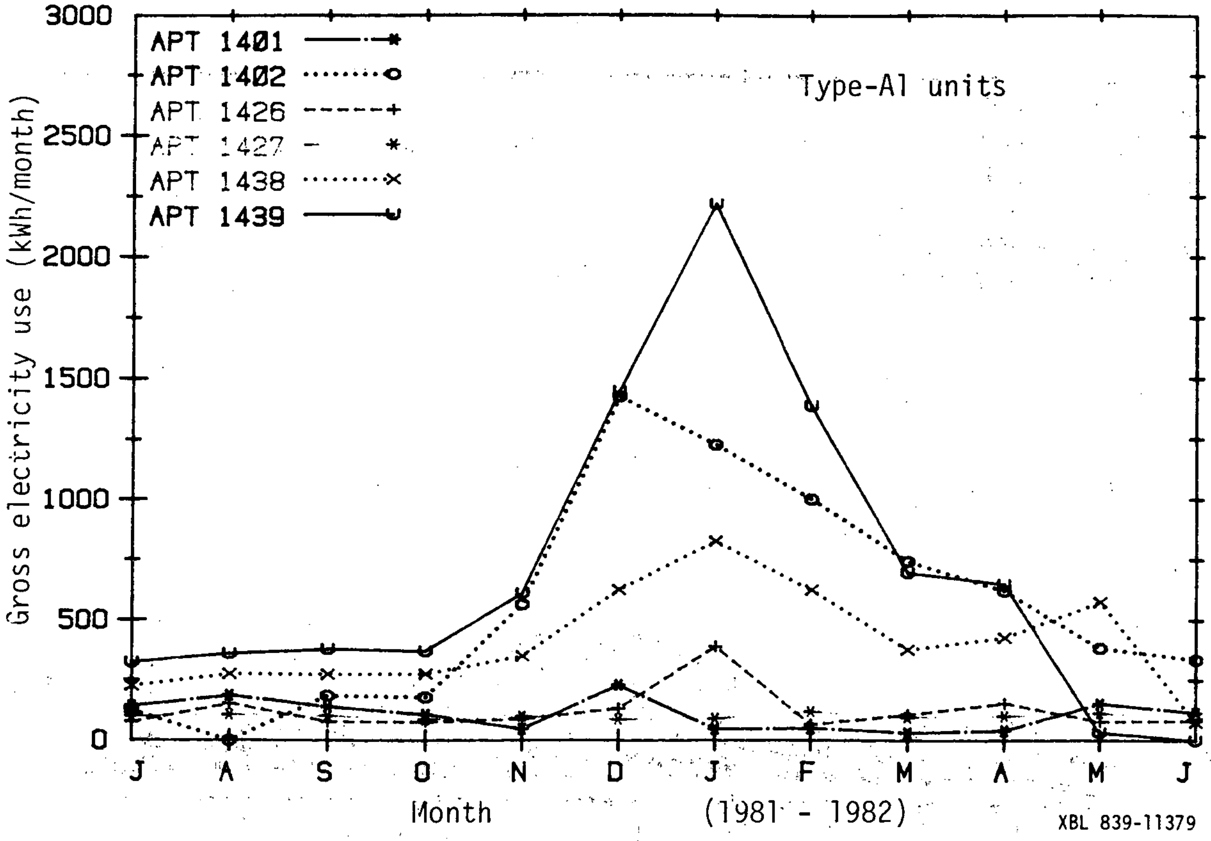


Figure 9: Electricity consumption profiles for two groups of apartments; all units in a single plot are identical.



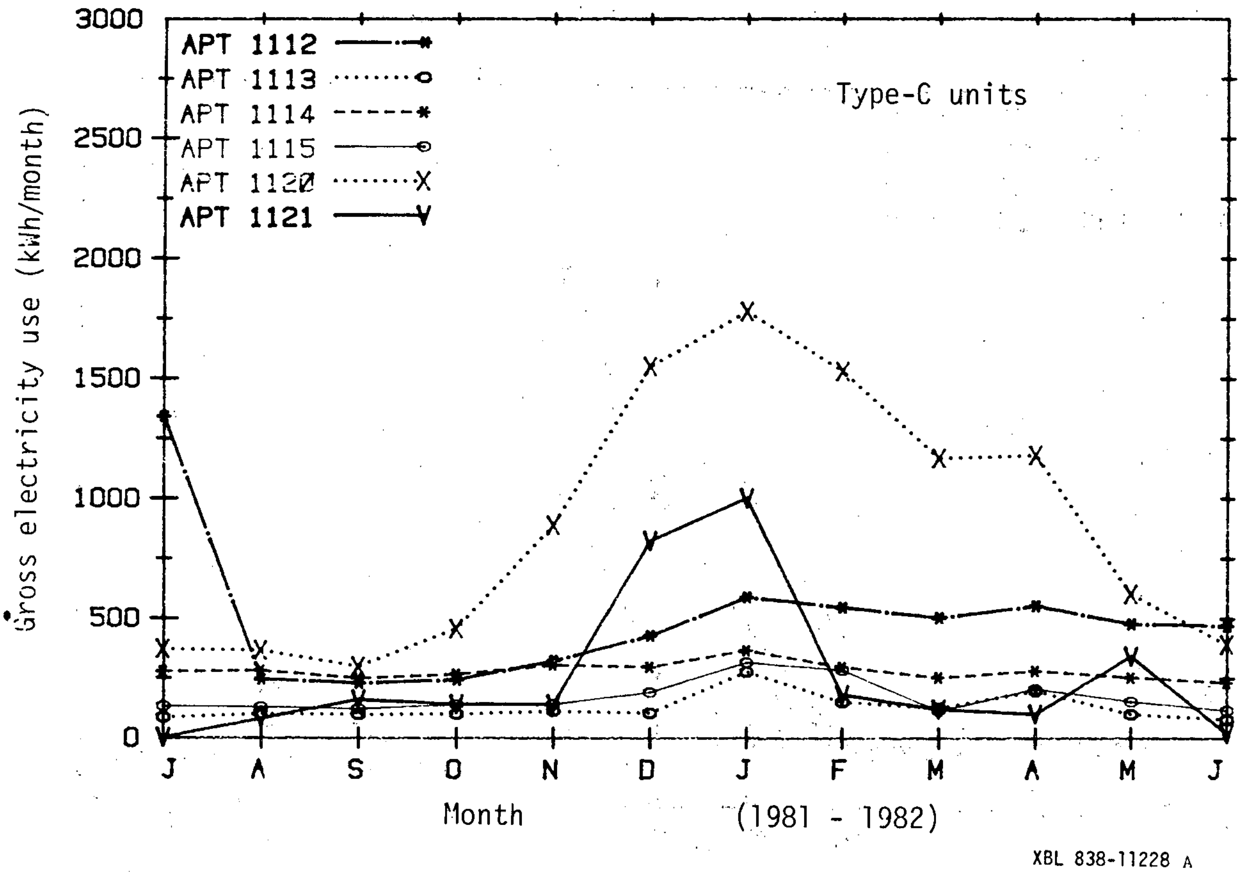


Figure 10: Consumption profiles for nominally identical units. Note the large variations among units for the summer and winter months.

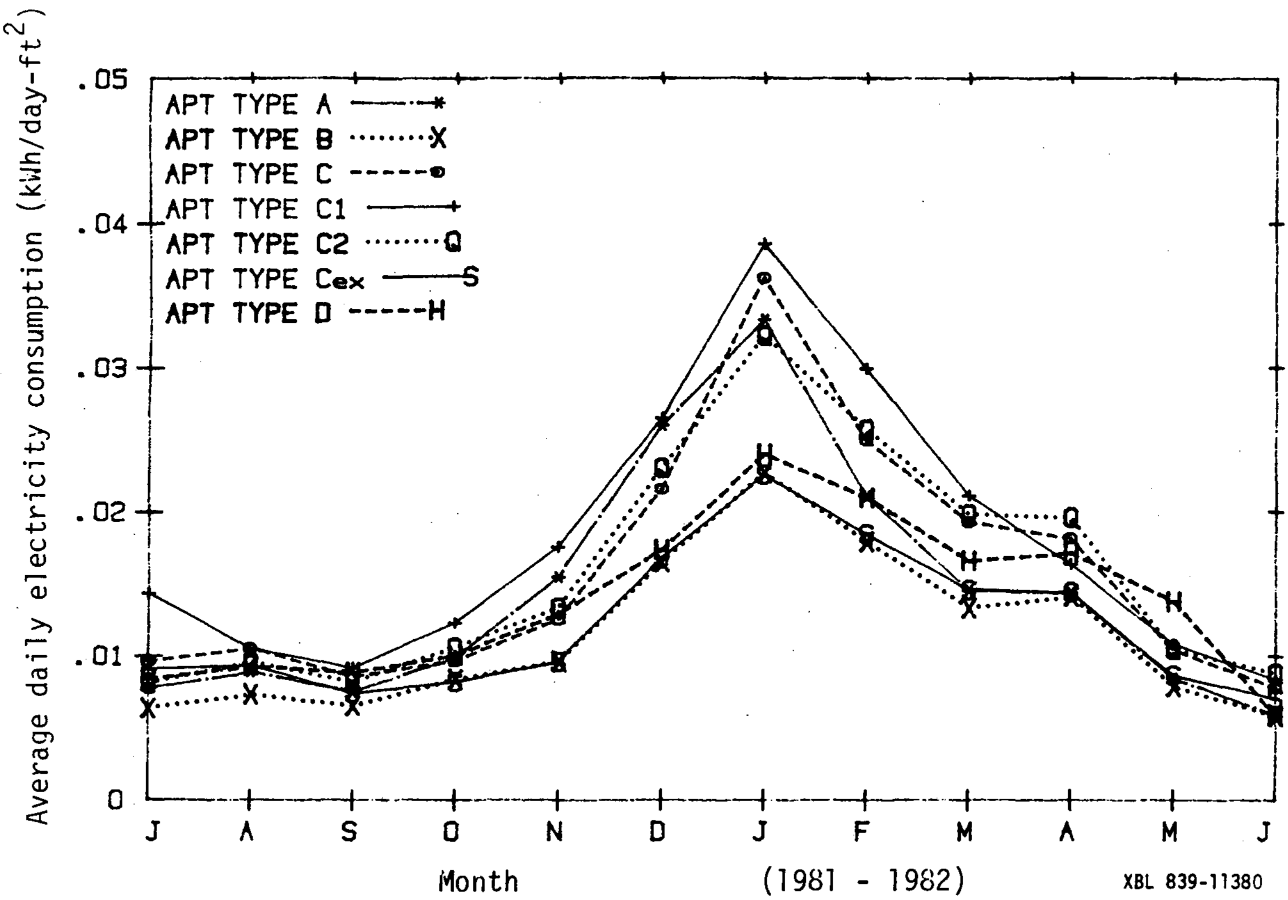


Figure 11: Average daily electricity consumption (kWh/day-ft^2) for seven of the 13 apartment subtypes in City Center Plaza. (Sample sizes for the remaining six subtypes were too small to obtain meaningful results for this normalization procedure.)

consumers. An explanation of this may be that the C1 units are located at the ends of the building and have two exterior surfaces. The B units, while the largest, have only one exterior face. The A units are on two floors and have the most exposed surface of all the units in City Center Plaza. Although they are smaller than the B units, their gross electricity consumption is higher.

C. Determination of the Range of Variation in Consumption

In order to determine the range of consumption within a particular apartment category, we used a third normalization scheme in which we compared the actual electricity use of an individual unit to the average for its category using the actual-to-average consumption ratio. This ratio indicates individual variations from the mean, making it possible to generate plots of the dispersions in electricity consumption and to quantify the range of variation from the average. Using gross electricity consumption data (in which baseload and space heating were not differentiated), we found a range in the consumption ratio of about 10 to 1 (Figure 12).

D. Differentiation between Baseload and Space-Heating Consumption

We next tried to separate baseload and space-heating electricity use. We assumed that no significant space heating took place during the summer and that electricity consumption during the months of July, August, and September represented baseload (see below for further discussion of this point). For each unit, we summed consumption for these three months and divided by the total number of days in the three billing periods. This provided a value for the daily baseload for each unit, which was subtracted from the total daily electricity use for each apartment for each of the five months of the heating season (November to March). We assumed the

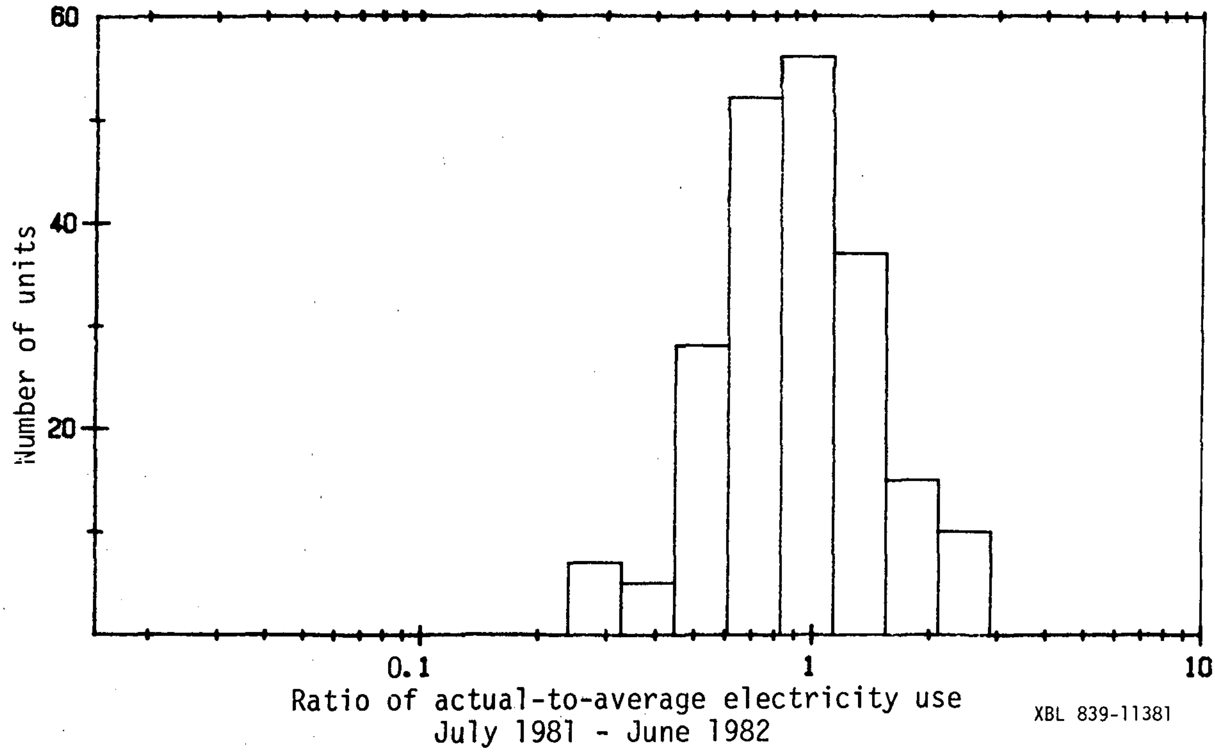


Figure 12: Distribution of actual-to-average electricity use for the 207 units in the data sample. The range of variation in this plot is roughly 10 to 1.

difference to represent electricity used daily for space heating. Averaged over the four types represented in the 207 units, baseload was found to be 7.7 kWh/day, with a range of 6.8 to 9.0 kWh/day and a standard deviation of roughly 4.2 kWh/day. Space-heating consumption averaged 12.1 kWh/day, with a range of 7.1 to 16.7 kWh/day and a standard deviation of approximately 9.7 kWh/day, as shown in Table 4.

How accurate is this estimate of baseload consumption? All the apartments in City Center Plaza have similar refrigerators and identical dishwashers. All of the A-type units have electric clothes washers and dryers. Most of the units probably have televisions and other, smaller appliances. According to the published literature (11), a typical complement of household appliances (refrigerator, dishwasher, TV, washer, dryer) consumes from 6.5 to 9.5 kilowatt-hours per day (kWh/day). We checked this against an end-use analysis of several units in City Center Plaza, where we found a baseload of 6.3 to 9.9 kWh/day (Table 5). So our baseload estimation procedure described above appears reasonable.

1. Baseload consumption: We calculated the distribution of baseload electricity use (Table 4) and plotted it as a histogram (Figure 13a). The A units show the greatest daily gross baseload, while the D units show the least. Normalized to floor area, the D units (smallest) have the greatest baseload while the B units (largest) have the smallest. This is understandable, since the set of appliances in each apartment is almost identical (except for the washers and dryers in the A units). We found a variation in the ratio of actual-to-average baseload for all apartments of about 20; this is plotted as a histogram in Figure 13b.

2. Space Heating: We calculated and plotted similar quantities for space heating (Figure 14a). We found that the A units consumed the most

Table 4: Baseload and Space-Heating Electricity Consumption in City Center Plaza.

	N	Baseload usage (kWh/day)	Space Heating usage (kWh/day)
All units	207	7.74 ± 4.18	12.11 ± 9.71
Group A	47	9.00 ± 4.40	16.67 ± 10.80
Group B	38	8.19 ± 4.56	12.78 ± 10.40
Group C	104	7.18 ± 3.75	10.67 ± 8.62
Group D	18	6.76 ± 4.64	7.07 ± 6.48

Table 5: End Use Survey of Appliances in City Center Plaza Apartments (kWh/year).

Appliance	Burnett[1]	Lipschutz et al.[2]	Survey of City Center Plaza units
Refrigerator	1600	1125	1140 - 1380[3]
Lights	not listed	1000	(500)[4]
Dryer	(950)	(900)	(804)[5]
Washer	(90)	not listed	(168)[6]
Dishwasher	370	250	365[7]
TV	400	200	(300)[8]
Total	2370 -3410	2575 - 3475	2305 - 3517[9]
Daily usage	6.5 - 9.3	7.0 - 9.5	6.3 - 9.9

Footnotes:

1. Burnett (see references).
2. Lipschutz et al. The Energy Saver's Handbook (see references).
3. Data from 1977 AHAM Directory. Refrigerator is GE No frost, model TB14DWB, 120 volts, 6 amps.
4. Represents half of value in previous column; apartments have few installed lamps.
5. From: "Domestic Electric Range and Clothes Dryer Usage Study," Potomac Edison Company Applications Engineering & Research, July 1981. Survey of 79 households. Dryer is Kenmore compact, model 110 78413100 84131. No information on ratings. Parentheses indicate that only A units have dryers and washers.
6. From: "Appliance Metering," Tennessee Valley Authority, Aug. 31, 1978. Results of measurements in 1 household, so data are probably not very good. Washer is Kenmore compact, no model number was found.
7. Assumes dishwasher rated at 1000 watts (with heater & motor), used 1 hour/day. Dishwasher is Whirlpool model SAU300P2, 800 W heater, 6 amp motor, 120 V.
8. Average of two values in columns 1 and 2.
9. Lower value represents usage without washer and dryer; higher value is with washer and dryer.

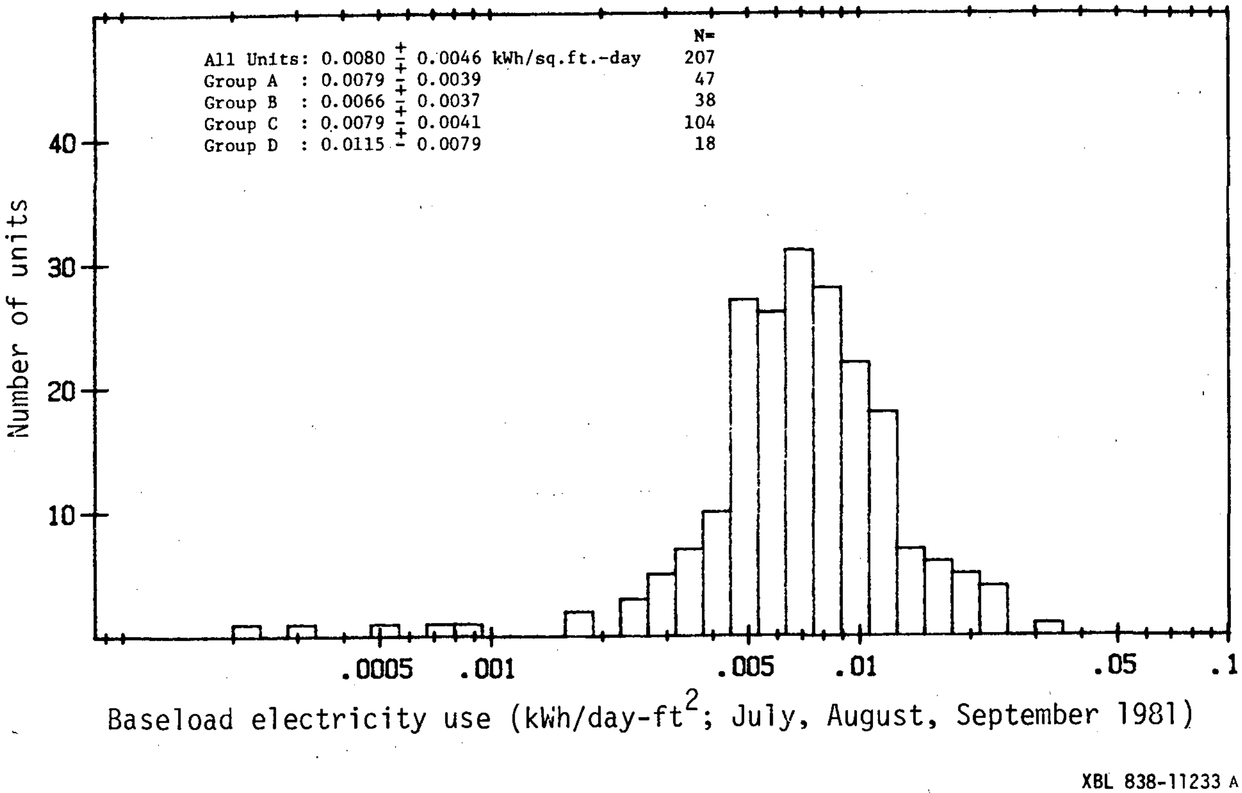


Figure 13a: Distribution of baseload electricity use for 207 units in sample.

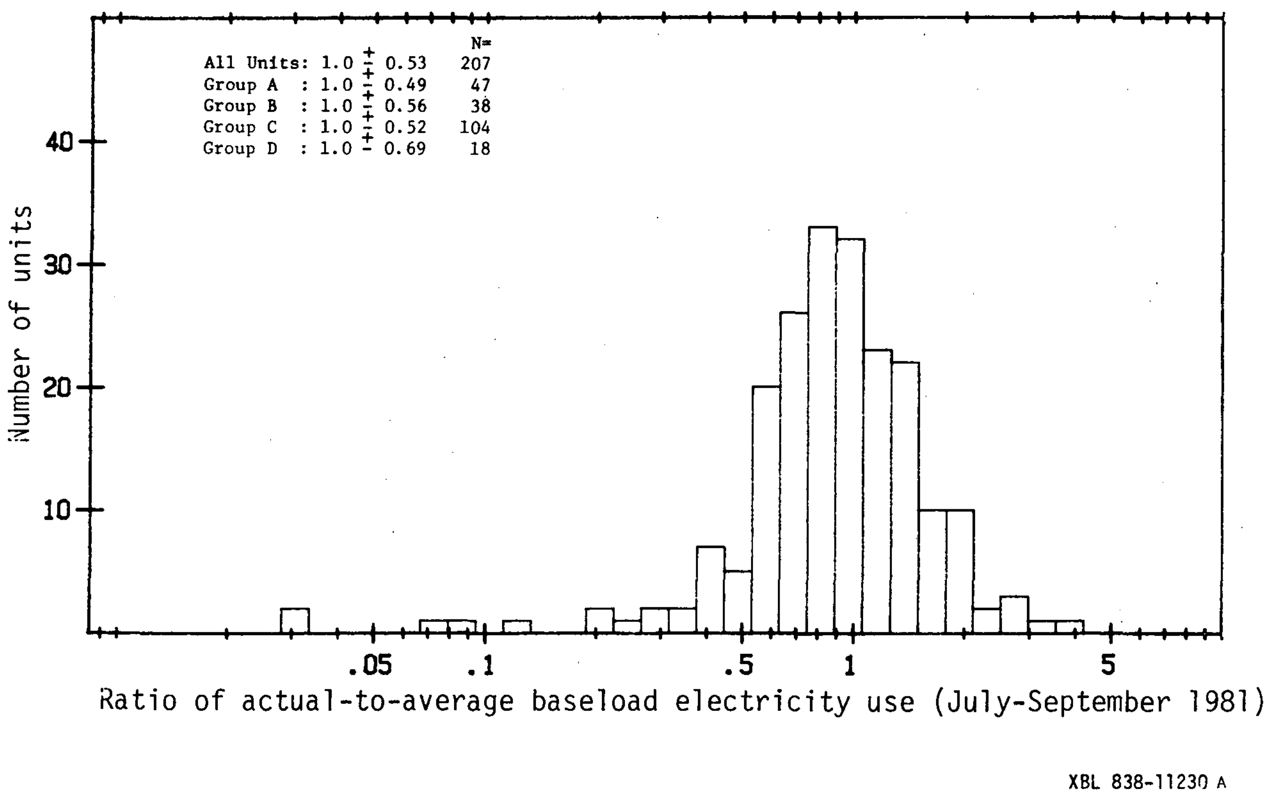


Figure 13b: Distribution of actual-to-average baseload electricity use for 207 units in sample.

electricity for space-heating (perhaps a consequence of the two-story construction), while the D units consumed the least (Table 4). Normalized to floor area, the A units also had the highest space-heating consumption. The variation in the actual-to-average space-heating consumption ratio for all apartments was about 40 (see Figure 14b).

E. Interactions Between Adjacent Units

After completing the normalization procedures, we began to investigate the effects of the various technical and behavioral factors discussed earlier. One important technical factor might be heat-stealing, the flow of heat through the walls between apartments. That is, a unit with a high level of electricity use--and, presumably, a high interior temperature--might be located next to a cooler, low-energy apartment. If so, the first apartment might provide heat to the second.

In order to test for such an effect, we compared the actual-to-average consumption ratios of gross electricity use of adjacent apartments, looking for high users located next to low ones. The maximum possible number of adjacent pairs is 198 in the horizontal direction and 223 in the vertical direction. From the 207 units in our sample we were able to construct 109 horizontal pairs and 113 vertical pairs. We plotted the actual-to-average consumption ratios of these pairs graphically, with one ratio on the ordinate of the graph and the ratio of the neighboring unit on the abcissa. If heat-stealing were present, pairs of apartments showing heat transfer should cluster toward the upper left (high-y, low-x) and the lower right (low-y, high-x) of the graph, as shown in Figure 15. Our results, plotted in Figure 16, show no such trend. This does not mean, however, that the effect is not present. Heat-stealing may be taking place between only a few units or at a very low level, and our sample size may be too small to

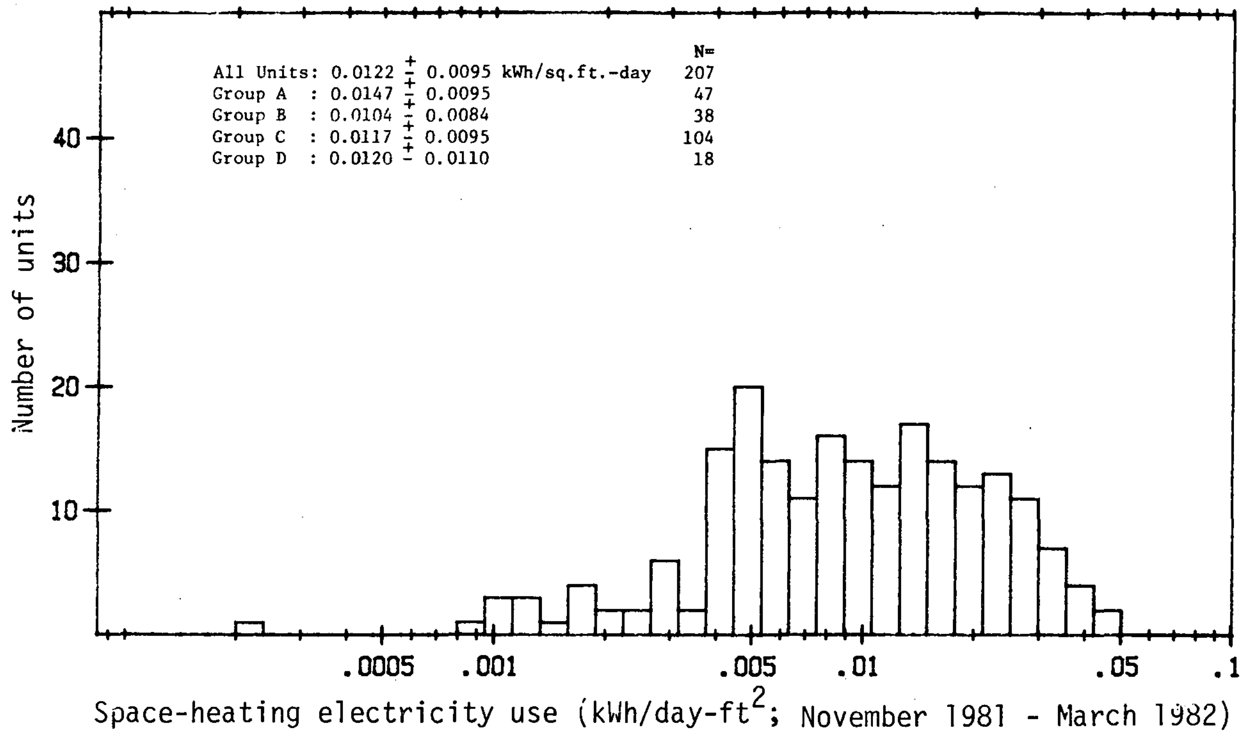


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Figure 14a: Distribution of space-heating electricity use for 207 units in sample.

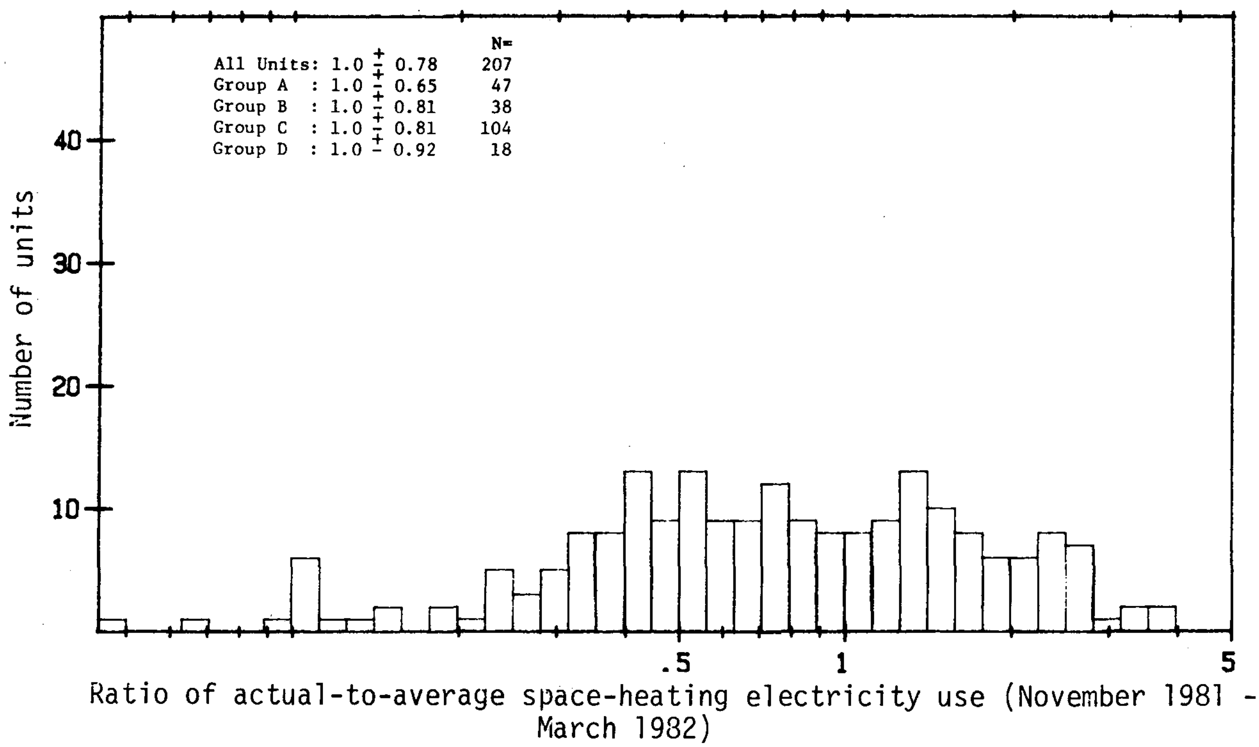

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Figure 14b: Distribution of actual-to-average space-heating electricity use for 207 units in sample.

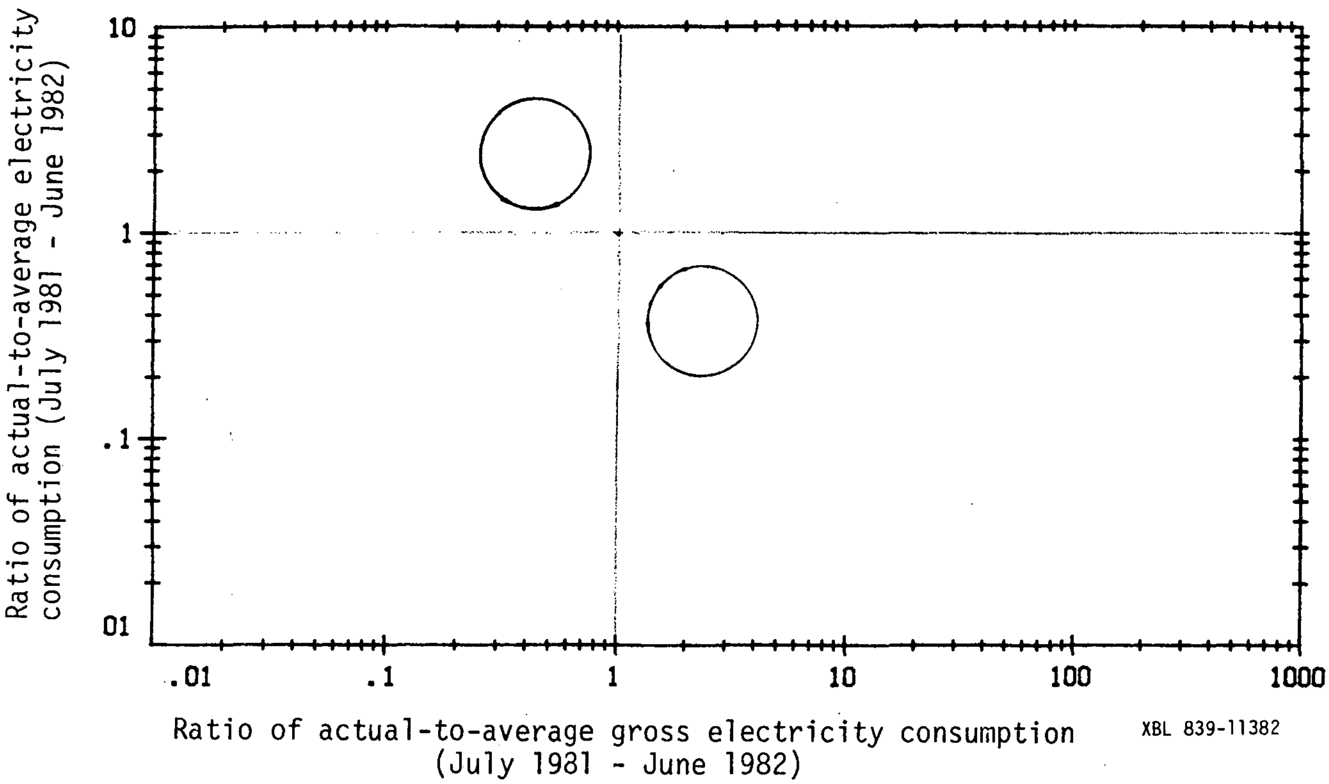

Figure 15: If heat stealing between units were taking place, we would expect to see concentrations of points in the region of the circles.

(Data not shown here.)

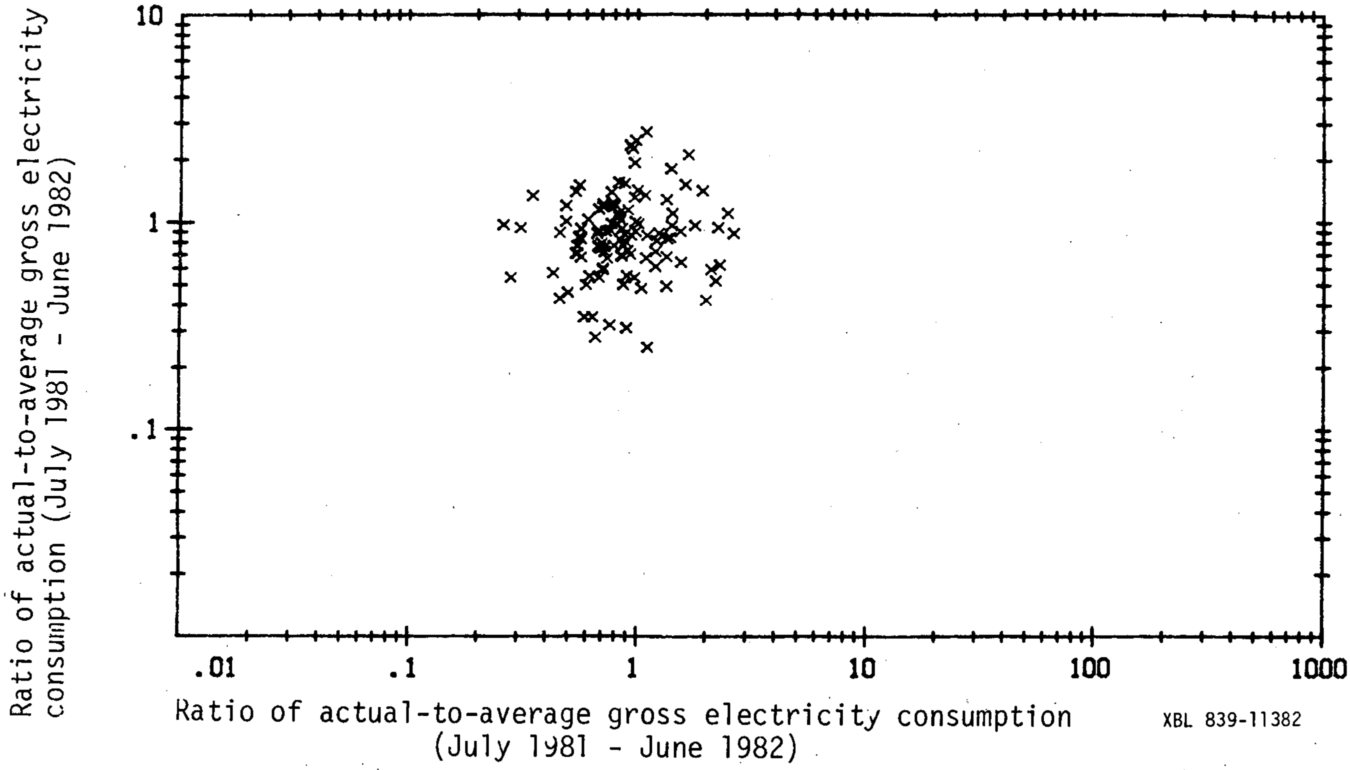

Figure 16a: Actual-to-average gross electricity use ratios for pairs of units located upstairs/downstairs. The distribution of points shows no detectable concentration as in Figure 15. Sample size is 113 pairs.

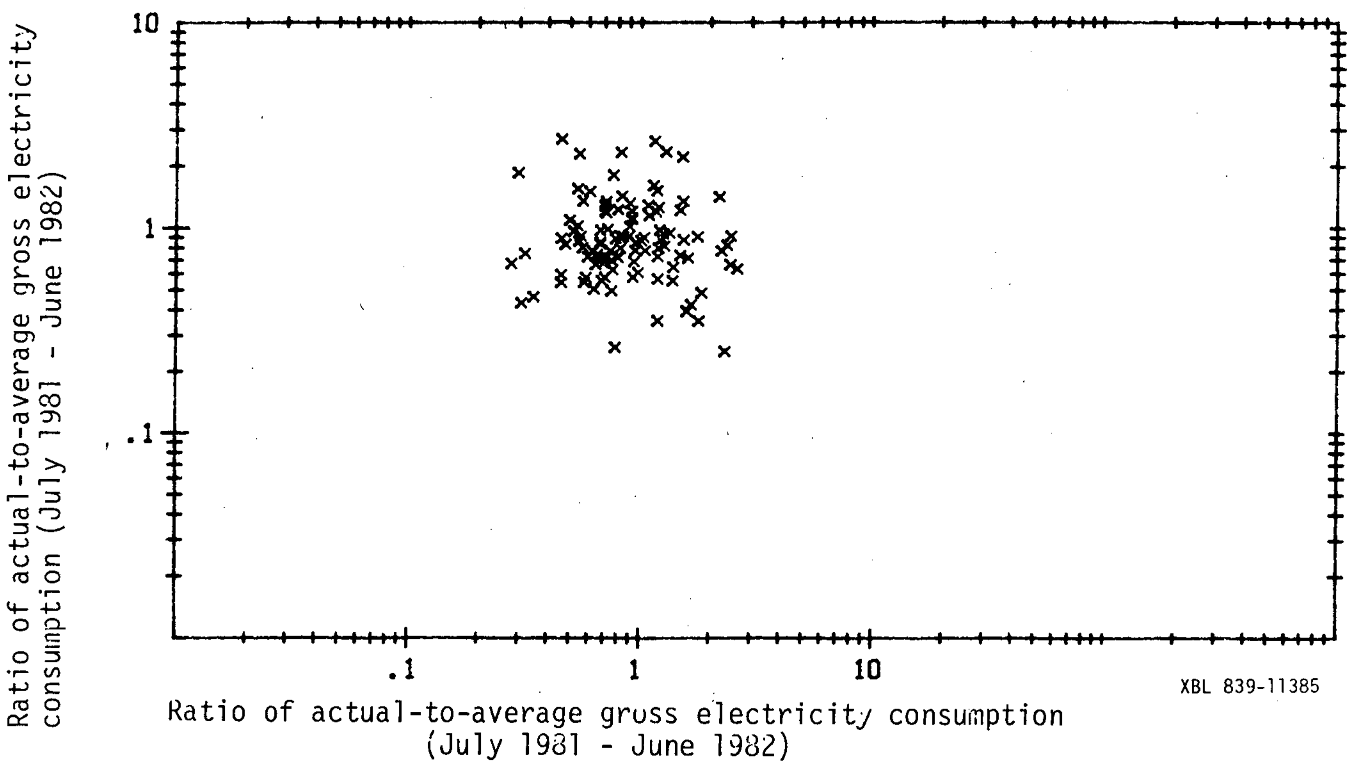

Figure 16b: Actual-to-average gross electricity use ratios of adjacent pairs of units. No concentrations of points are observable. Sample size is 109 pairs.

show it. It is also possible that a single unit may be providing heat to several surrounding ones, thus diluting the effect.

F. Effect of Apartment Orientation

To test for the effect of apartment orientation, we calculated daily electricity use per square foot of floor area for each of the 207 units and regrouped them on the basis of orientation—north, southeast (south-facing units in the east wing of the building), east, west, southwest (south-facing units in the west wing; see Figure 5). We then calculated the average consumption for each orientation. We found that east-facing units consumed about 35% less electricity in gross terms than the average for all units, an effect significant at the 99% confidence level as measured by a t-test (Table 6).

This difference might be explained by either of two factors. East-facing units appear to benefit from significant solar gain during the morning hours when the heating requirement is the greatest. Since these units face some 30° south of east, they receive the first sunlight on a winter day. However, because cold winter days tend to be overcast in the Bay Area, solar gain alone may not be sufficient to explain the effect. Alternatively, because the prevailing winter winds in the Bay Area are from the north and northwest, the northwest-facing units may be overpressured and experience an inflow of cold air and a loss of warm air, while east-facing units, being underpressured, may receive warmer air from the building corridors and have a lower infiltration rate. However, the southeast units, also on the leeward side of the building, should show a similar effect, but do not. Lacking detailed, long-term insolation and wind records from the immediate vicinity of City Center Plaza and extensive tracer gas measurements within the building, we are unable at present to

Table 6: Results of Analysis of Electricity Use on the Basis of Orientation.

<u>Gross electricity consumption</u>

Orientation	N	Ratio of actual to average elec. use	Results of T-test	Statistical significance
North	79	1.03 ± 0.50	0.73 (North vs. Southeast)	< 0.90
Southeast	24	1.13 ± 0.61		
East	40	0.77 ± 0.29	2.68 (East vs. West)	> 0.99
West	35	1.04 ± 0.53		
Southwest	33	1.05 ± 0.45		

identify positively the causes of this orientation effect.

G. Ventilation Systems

Although we made few measurements of air-flow rates through the building's supply and exhaust systems--too few to provide much useful information--we hypothesized that these systems might play an important role in the variations in electricity consumption. There are about 50 exhaust shafts in City Center Plaza, each serving approximately 10 apartments (some of the units are served by more than one shaft). Air flows could vary significantly from shaft to shaft because of: 1) differences between the performances of the exhaust fans; 2) the "stack effect" caused by the temperature gradient through the height of the building; or 3) infiltration caused by varying wind pressures across the height and width of the building that could cause air flows to vary significantly from shaft to shaft.

In order to determine whether the exhaust system had any effect on electricity use in the apartments, we calculated average baseload and space-heating consumption for units located on the same exhaust shaft. A major effect by the exhaust system on space heating would be indicated by statistically significant differences in average consumption from column to column. Although we found substantial variations in the averages for shafts serving columns of identical apartments, the associated standard deviations were large enough so that the t-test indicated these differences not to be statistically significant at the 10% level. The results of this calculation are shown in Table 7.

In any event, the ventilation and exhaust systems probably could not account for the large variations in electricity used for space heating. In calculating energy loads for the apartments, we found ventilation to

Table 7: Comparison of Electricity Consumption for Sets of Identical Apartments on Different Exhaust Shafts.

Shaft no.	Unit type	N=	Baseload (kWh/day)	Result of t-test	Significance	Space heating (kWh/day)	Result of t-test	Significance
01	C2	8	5.2 ± 2.7			17.7±17.8		
02	C2	9	5.7 ± 2.2			15.9±16.5		
16	C2	9	8.1 ± 4.6	1.68	~0.93	9.8± 9.9	1.14	< 0.90
17	C2	9	7.3 ± 5.2			14.6±13.8		
24	C2	9	6.6 ± 1.6			19.1±22.4		
25	C2	10	5.2 ± 2.5			14.2± 8.8	1.02	< 0.90
03	B	10	6.2 ± 3.9	0.65	< 0.90	17.8±17.5		
04	B	10	7.1 ± 3.5			19.6±25.3		
05	B	8	12.5 ± 8.1			20.3±18.8		
06	B	8	8.5 ± 5.7			16.8±16.8		
22	B	10	6.5 ± 1.4	2.40	0.98	21.3±15.1	1.55	~0.93
23	B	8	8.5 ± 2.0			11.7±11.2		
07	C1	9	7.4 ± 3.1	0.80	< 0.90	22.0±19.4	0.88	< 0.90
11	C1	10	9.2 ± 6.3			15.7± 9.8		
08	CE	10	7.7 ± 1.8			10.6±10.8		
10	CE	10	7.7 ± 5.5			9.4±12.8		
12	C	10	8.5 ± 6.9	1.28	< 0.90	10.9±11.6		
13	C	9	6.4 ± 4.6			10.2±10.0		
14	C	8	5.6 ± 1.8			7.8±10.7	0.98	< 0.90
15	C	8	5.6 ± 2.3			9.4±10.4		
20	C	10	6.8 ± 2.8			15.4±14.7		
21	C	9	5.7 ± 3.1			13.0±11.2		
18	D	8	6.6 ± 3.8	1.22	< 0.90	9.8± 8.4	1.15	< 0.90
19	D	10	4.7 ± 2.5			5.5± 7.2		

account for roughly 60% of the heating requirement. Assuming that air flows might vary by 50% from one exhaust shaft to another, the resulting change in the total heating requirement would be on the order of only 30%. This is much smaller than the factor of 40 we observed.

It is possible, of course, that the range of exhaust air flows is much greater than suggested by the above example. While measuring air flows in a few apartments, we found large differences between actual air flow and design specifications listed in the building's blueprints. We also discovered an exhaust vent that had been taped over, a behavioral variable that might or might not be common. Even so, the cumulative effect on the variation in electricity of such occupant actions in a few apartments could not be very large.

In order to assess the importance of the ventilation and exhaust systems, it would probably be necessary to make systematic measurements of air flows in many apartments, in the supply system, and in the exhaust shafts. The building management intends to install load controllers on the exhaust fan motors. If this conservation measure reduces the variations in electricity use, we may be able to conclude that the ventilation and exhaust systems have been important factors in electricity consumption at City Center Plaza.

H. Relationship between Baseload and Space Heating

We next analyzed several testable behavioral factors. We hypothesized that a correlation might exist between the level of appliance use in an apartment and the quantity of electricity consumed for space heating (12). In other words, would people who used appliances more than the average (or who possessed more appliances than the norm) also heat more (or less) than average? To test either of these hypotheses, we compared baseload to space-heating electricity consumption, expecting one of the two patterns shown in Figure 17. A positive correlation between the two might indicate that those occupants who own many appliances tend to be freer in their use of energy and require more space heating. A negative correlation would suggest that some apartments are heated significantly by appliances rather than space heaters. The latter is a more likely outcome.

We found no observable correlation between space-heating and baseload consumption (Figure 18) and concluded that either no relationship exists between the two or that the two opposite effects coexist but cancel each other. In other words, while the majority of City Center Plaza's occupants use appliances at more or less the same level (most within a factor of five or so), the spread in space heating is much larger in Oakland's relatively mild climate and is determined primarily by other factors.

I. Use of Gas Range for Space Heating

Based on comments by the building manager, we suspected that some of City Center Plaza's occupants were using their gas ranges for partial space heating, a suspicion confirmed by the building management. Because gas is master-metered, the occupants do not pay directly for this form of energy use. Figure 19 shows the pattern of natural gas consumption in the building during the course of a year. The winter peak is quite conspicuous. During the month of January 1983, for example, the difference between the peak and baseload amounted to approximately 130 therms per day (or 3800 kWh/day). We were assured by the building management that natural gas was used within the building only for cooking and heating of domestic hot water. A furnace used to heat supply air was disconnected in 1981; commercial and common spaces within the building are all-electric.

Because ranges are not individually metered, we can only speculate

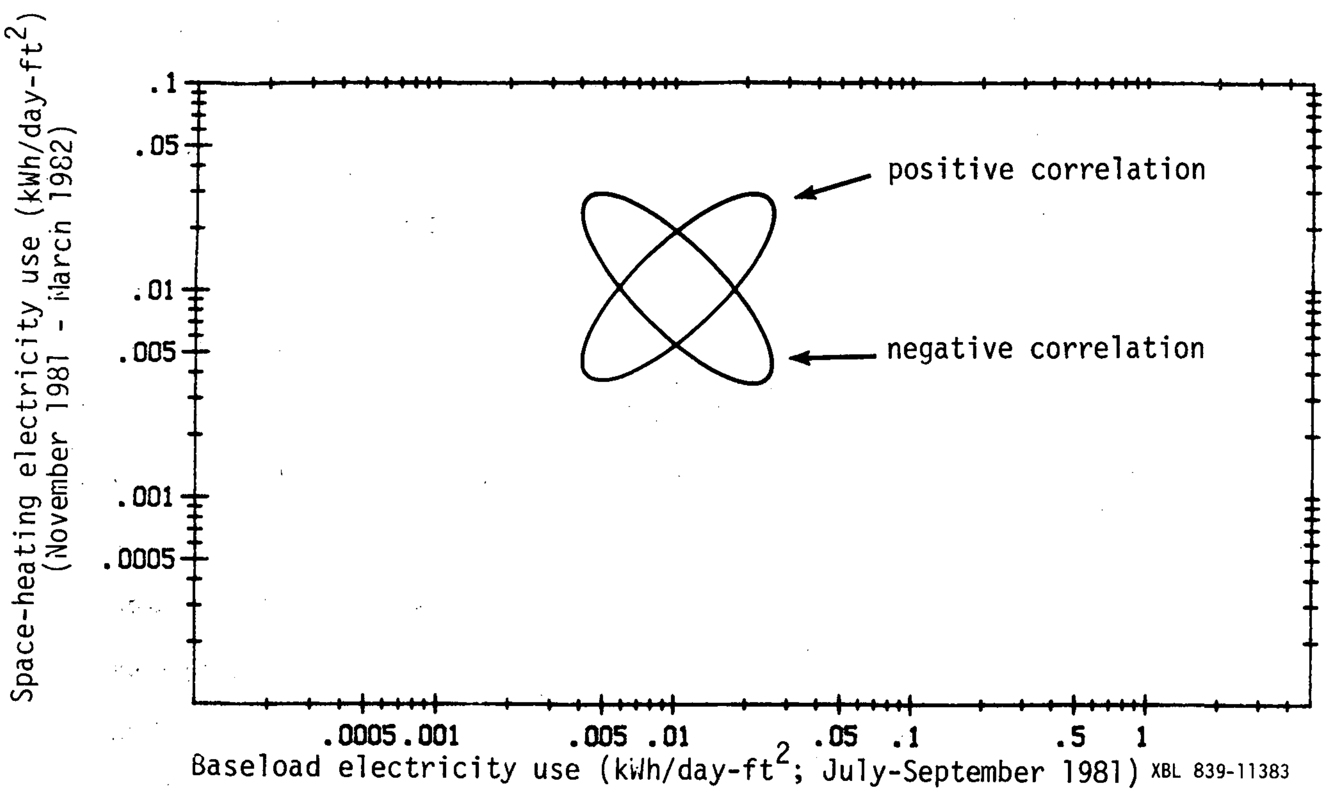

Figure 17: Possible correlations between baseload and space-heating electricity use.

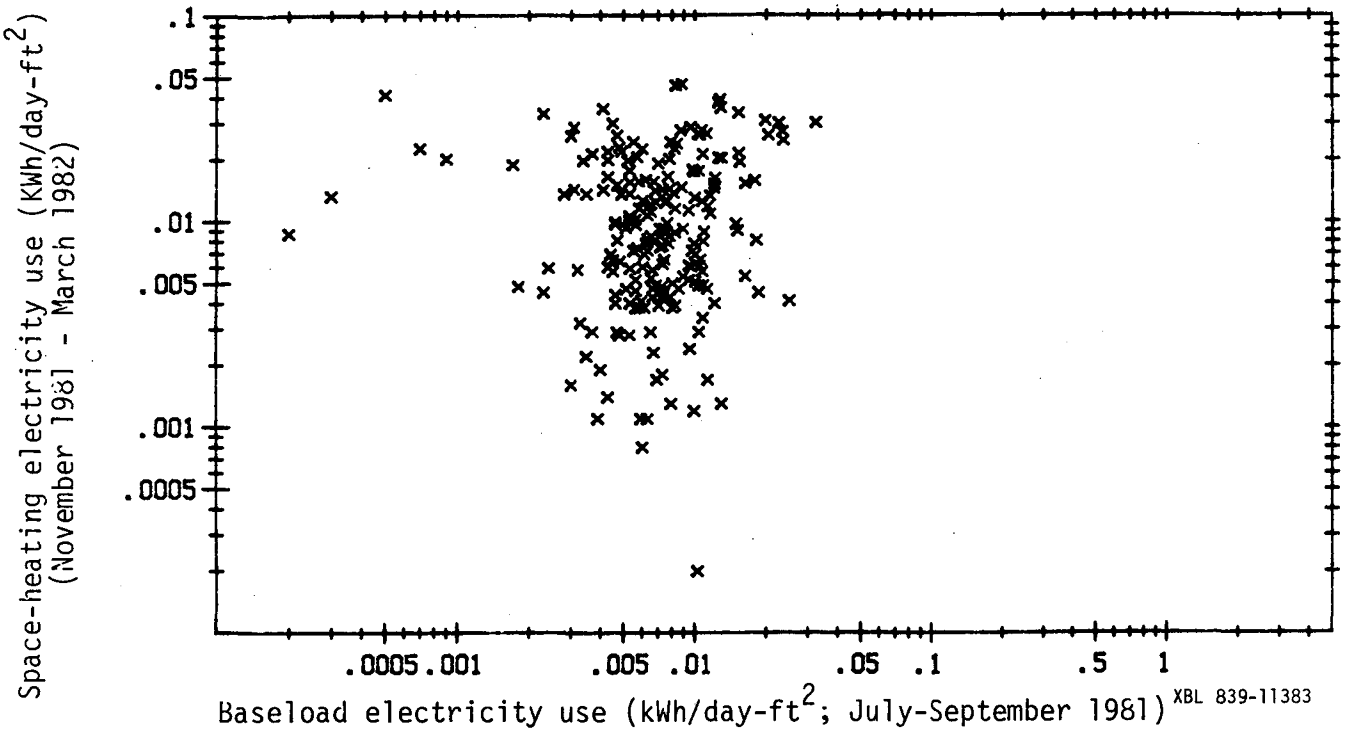

Figure 18: Comparison of baseload to space-heating electricity use for the 207 units in the sample. The plot shows neither a positive nor a negative correlation between the two quantities.

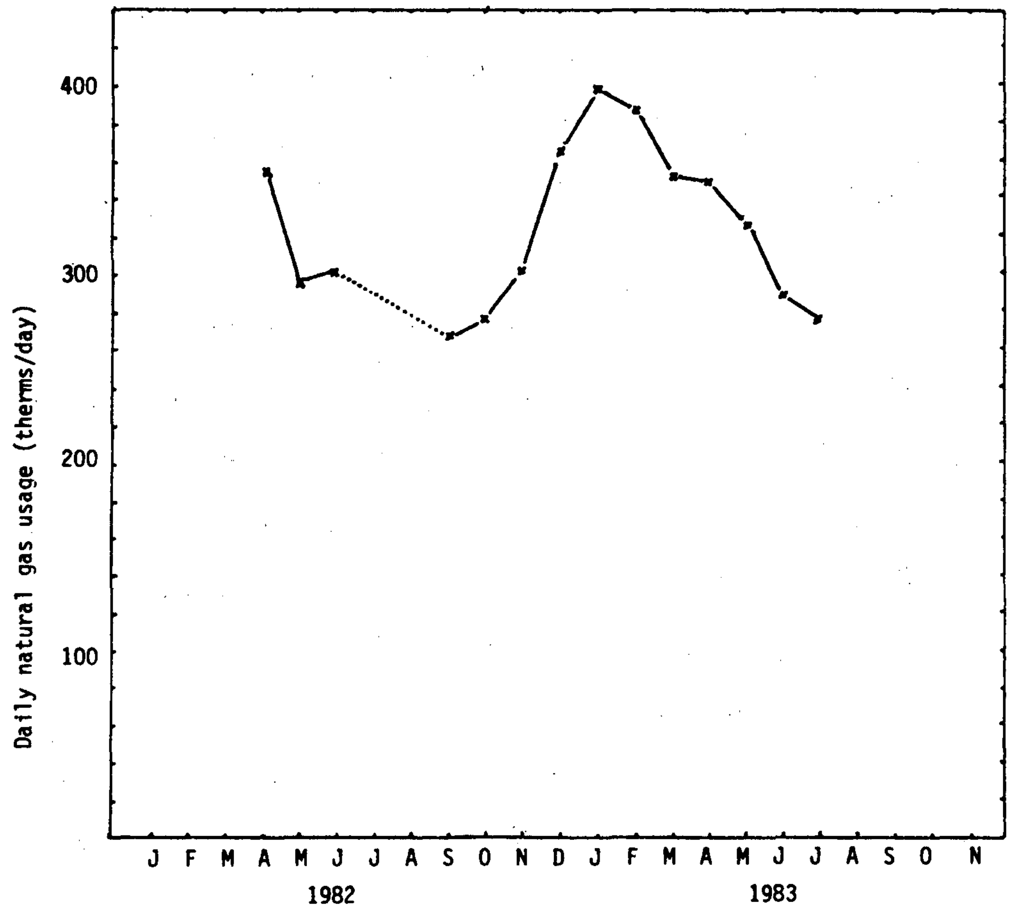

Figure 19: Daily natural gas usage at City Center Plaza, 1982-1983. Note the conspicuous winter peak.

whether heating with gas is a plausible explanation of the large observed variation in electricity consumption. If we assume (for the sake of argument) that units consuming less than a specified quantity of electricity compensate with gas heating, then this difference, summed over all of these units, may be sufficient to account for the winter peak. We found that by setting this specified quantity of electricity use at 0.5 standard deviations above average consumption for all units in the building, we could account for the entire January gas peak. (This exercise is shown in Table 8.) Implicit in this calculation is the assumption that all units below the specified level require the same total quantity of energy for space heating. Hence, we find it plausible, although by no means certain, that the winter peak may be due to surreptitious space heating with gas ranges.

The pattern of gas use assumed above is, however, quite unrealistic. The resulting distribution of total energy use (gas and electric) has a large group of users all at the same level and a small tail of higher users. We do not, of course, know the actual distribution of gas consumption but we can speculate on its shape. First, we may assume that natural gas use is negatively correlated with electricity consumption. That is:

$$G = a + bE \quad \text{(Eq. 1)}$$

where:
- G is gas consumed in a unit in excess of the average consumption for cooking and water heating (in kWh/day);
- a is the base quantity of gas consumed;
- b is the correlation coefficient between gas and electricity use ($b<0$); and
- E is the observed space-heating electricity consumption for a unit (kWh/day).

We may also assume that there exists some level of electricity consumption above which which surreptitious use of gas no longer occurs. At this point, we may construct a second equation:

Table 8: Calculation on the Use of Gas Ranges for Space Heating.

Space-heating electricity distribution (binned by kWh/day)

	0.0-5.0	5.1-10.0	10.1-15.0	15.1-20.0	20.1-25.0	25.1-30.0	30.1-35.0	35.1-40.0	40.1-45.0	45.1-50.0	50.1-55.0	55.1-60.0	60.1-65.0	65.1-70.0	70.1-75.0
No. of units	25	37	29	25	26	15	14	10	4	4	4	4	3	3	2
Cumulative no. of units	25	62	91	116	142	157	171	181	185	189	193	197	200	203	205

Summed difference between average for bin and specified level of electricity use (kWh/day)

Average daily consumption for all units: 21.0 ± 16.6 kWh/day (electricity only)

avg. + 0.5 sd =	670	807	487	295	170	47									
avg + 1.0 sd =	878	1114	728	502	393	152	71	1							

Kilowatt-hours per day summed over sample in table for:

average + 0.5 standard deviations (29.3 kWh/day): 2476 kWh/day

average + 1.0 standard deviations (37.6 kWh/day): 3839 kWh/day

Corrected for units eliminated from sample (i.e., for entire building) (kWh/day):

average + 0.5 standard deviations: 3930 kWh/day

average + 1.0 standard deviations: 6094 kWh/day

Equivalent in therms per day of natural gas (1 therm = 29.3 kWh):

average + 0.5 standard deviations: 134 therms/day

average + 1.0 standard deviations: 208 therms/day

$$Gmin = a + (b \times Emax) = 0 \quad \text{(Eq. 2)}$$

where: Gmin is the minimum possible level of excess gas use (zero);
a and b are the same as above; and
Emax is the level of electricity consumption above which no space heating with gas is taking place.

We can solve this set of equations for values of a and b (since we know G, E, and Emax) and calculate new distributions of energy use within the sample. We solved these equations setting Emax equal to 1, 2, and 3 standard deviations above the average electricity consumption for the group. Our results are shown in Table 9 and Figure 20. Note that the original distribution in Figure 20 is for electricity consumption only, while those for 1, 2, and 3 standard deviations are for total energy use.

The effect of this second exercise is to narrow the distribution of energy use. Low users are pushed toward the middle of the distribution while high users remain unaffected. The variations in total energy consumption are decreased by 30 to 50%. In other words, if natural gas is being used for space heating as suggested here, the 40 to 1 observed variation in space heating energy use might be reduced by half, similar to the range observed for baseload consumption.

This exercise is merely speculative since we do not know the actual distribution of natural gas consumption in the building. Most of it may be taking place in a small number of units at the lower end of the distribution. In particular, many of the units eliminated by the outlier criteria used in the analysis may have irregular electricity consumption patterns precisely because of space heating with gas ranges. The actual situation in City Center Plaza can be determined only through surveys of the occupants or instrumentation of gas ranges, and without such information we cannot much more of a quantitative nature in explanation of the large observed variation in space-heating electricity use. We should

Table 9: Distribution of Energy Use in City Center Plaza Apartments under Assumption that Gas is Being Used for Space Heating.

	Space-heating total energy consumption (binned by kWh/day)														
	0.0-5.0	5.1-10.0	10.1-15.0	15.1-20.0	20.1-25.0	25.1-30.0	30.1-35.0	35.1-40.0	40.1-45.0	45.1-50.0	50.1-55.0	55.1-60.0	60.1-65.0	65.1-70.0	70.1-75.0
Original distribution (electricity only): 21.0 ± 16.6 kWh/day															
No. of units	25	37	29	25	26	15	14	10	4	4	4	4	3	3	2
Distribution for upper limit on gas consumption set at average + 1 standard deviation: 37.6 kWh/day															
Average total energy consumption for new distribution: 32.3 ± 9.9 kWh/day															
No of units:	0	0	0	0	25	91	41	24	4	4	4	4	3	3	2
Distribution for upper limit on gas consumption set at average + 2 standard deviations: 53.3 kWh/day															
Average total energy consumption for new distribution: 32.3 ± 11.2 kWh/day															
No. of units	0	0	0	25	37	54	26	29	10	8	4	4	3	3	2
Distribution for upper limit on gas consumption set at average + 3 standard deviations: 70.8 kWh/ day															
Average total energy consumption for new distribution: 32.3 ± 12.6 kWh/day															
No. of units:	0	0	0	25	37	54	26	15	24	4	4	4	7	3	2

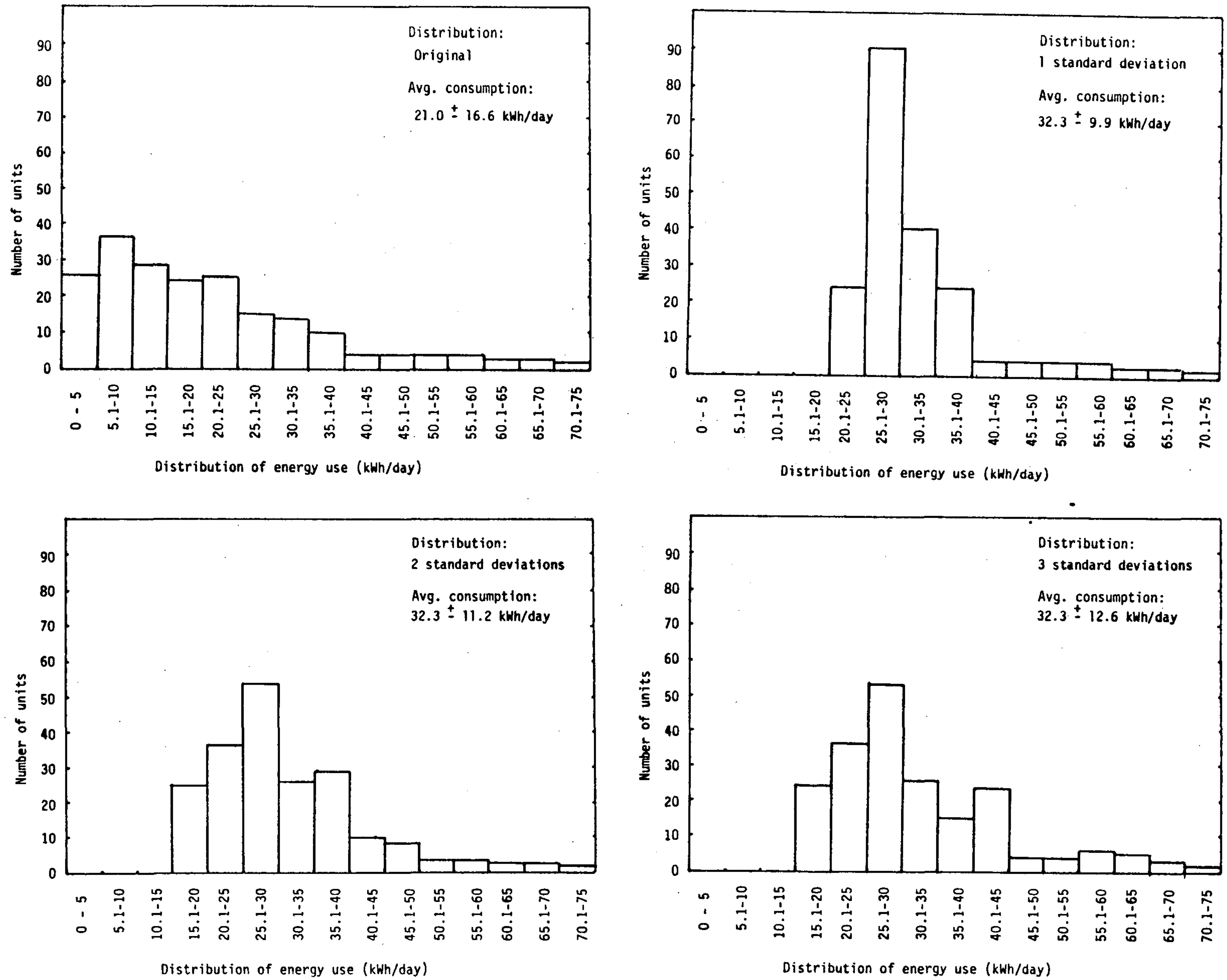

Figure 20: Histograms of distribution of space-heating energy use under the assumption that natural gas is being used for space heating (see text). Note that the original distribution is for electricity only. The other three figures represent total (gas + electric) energy use.

point our, however, that such monitoring would probably cause occupants to reduce their use of gas stoves for space heating and bias our measurements.

Explanations and Observations

An important finding of this research is the wide variation in electricity consumption between nominally identical apartments: a factor of 20 for baseload and 40 for space heating. Part of this spread may be attributable to apartment orientation and the use of gas ranges for space heating, but these factors are insufficient to explain the larger fraction of the variation. The problem of variations in energy use between identical structures is not new, and several studies have reached different conclusions regarding such variations. In the Twin Rivers study, for example, energy use in townhouses whose occupancy had recently changed was compared with those whose occupants had not moved and was found to vary by a factor of two between identical structures (13). This difference was attributed to behavioral factors. But a study of energy use in similar houses in Saskatchewan, Canada, found no such variation (14). "Identical" is a loosely-used term where detached structures are concerned. In field research projects, we have found large differences in construction quality and infiltration rates between similar or identical single-family dwellings (15). In a high-rise apartment building, with many units built at the same time, "identical" might be an accurate term. Initially, it seemed safe to assume that certain well-defined features would affect energy consumption in identical units and that variations could be associated with these features. For the most part, our analysis has not borne out this assumption but, until we are able to pursue further research at City Center Plaza, we will not be able to say with certainty that technical factors do not cause these large variations.

It is conceivable that more sensitive statistical procedures, such as multivariate regressions with carefully selected variables, and the weeding-out of certain units, could reveal correlations that have been masked by noise or the lumping together of too many variables. But, as indicated by the brief exercise on the effect of a 50% variation in exhaust air flow, a single technical feature would be unlikely to account for more than a fraction of the observed variation in electricity use. An accumulation of such factors might increase the explainable variation by a factor of 2 to 3 but not, we believe, to the level seen in our analysis.

Behavioral factors seem a more probable cause of these variations. For example, a simple calculation shows that most of the variation could be caused by differences in interior temperature preferences. Occupants who allow the temperature of their apartments to drift in response to outdoor temperatures are likely to require almost no space heating. (In Oakland's mild climate, it is possible to spend the entire winter without heating.) Other occupants may prefer to keep their apartments at 75°F. A unit kept at a temperature of 55°F during the winter will experience only about 500 degree days, while one at 75°F may experience several thousand degree days. Clearly, the quantity of electricity used by the two units will differ greatly.

Conclusions

Our analysis would suggest that, in mild climates such as Oakland's, where heating seasons are poorly-defined and outdoor temperatures are moderate, the absolute need for space heating will be determined to a large degree by individual preference. This is contrary to the situation in more severe climates, where space heating is determined to a large extent by a building's physical features (16). That is, if the average winter temperature is 25°F, a house heated to either 55 or 75°F will differ in space-heating energy use only by a factor of two. If the average outdoor temperature is 45 or 50°F for much of the year, space-heating energy use may differ by a factor of 5, 10, or even more as a consequence of differing temperature preferences. We cannot ignore the importance of other factors of which we are unsure such as the use of gas ranges for space heating. However, until we resume our research at City Center Plaza, we will not be able to assess the significance of such factors.

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4. The local utility, Pacific Gas and Electric, offers a summer lifeline rate in the Bay Area intended specifically for space heating.

5. Based on the management's survey of 204 units (62% response) in late 1982.

6. Ref. 3, op cit.

7. We have serious questions about the reliability of temperature data from the weather station located at the Art Museum in downtown Oakland. For the period July 1981 to June 1982, the Oakland station reported 2045 heating degree days and 248 cooling degree days, whereas the Berkeley station, not more than five miles away, reported 2862 heating degree days and 68 cooling degree days. We suspect this difference is due to poor placement of the monitoring equipment on the Museum's roof.

8. Expressed in terms of equations, the procedure is as follows:

$$Ai = \frac{Cij}{N} \qquad \text{(Eq. R1)}$$

where
- i represents month i;
- j represents unit j;
- Ai is average monthly consumption (kWh/day) for a specified group of apartments in month i;
- Cij is the actual consumption by unit j in month i; and
- N is the number of units in the sample.

and

$$Cij = (mj \times Ai) + bj \qquad \text{(Eq. R2)}$$

where
- mj is a constant of proportionality representing the "rate" of electricity use by unit j in relation to the group average; and
- bj is the difference between the actual baseload of unit j and the average baseload for the group.

9. We wish to thank Carl Blumstein for pointing out that the criterion for eliminating units from the data sample may throw out low, relatively level energy users. While for a perfectly straight line, the R-squared will be one, a unit with a relatively flat consumption profile but with small deviations from a straight line will yield a poor fit. The exclusion of units with R-squared less than 0.30 appears to have eliminated potentially usable low-energy units from the sample. However, the substance of our findings remains the same, since the inclusion of these units would broaden the range of variation in electricity use, rather than narrow it.

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13. Sonderegger, op cit.

14. C.P. Hedlin and M. Bantelle. "A Study of the Use of Natural Gas and Electricity in Saskatchewan Homes." SHELTER, Proceedings of the Technical Program of the 91st Annual EIC Meeting, Jasper, Alberta. National Research Council of Canada Report 16898. (May 1977). pp. 121-31.

15. R.D. Lipschutz, J.R. Girman, J.B. Dickinson, J.R. Allen, and G.W. Traynor. Infiltration and Indoor Air Quality in Energy Efficient Houses in Eugene, Oregon. Lawrence Berkeley Laboratory Report 12924. (August 1981).

16. If one looks at the distribution of energy use for projects in which the climate is progressively more severe, one finds it to get smaller as climate gets colder. Hedlin and Bantelle, for example (ref. 14) found little evidence for behavioral effects in energy use and little variation in the overall range of energy use in a very cold climate (approximately 10000 degree days). Sonderegger (ref 10), working in New Jersey (5000 degree days), found a factor of two to one. Burnett (ref 11), found a range of roughly 10 to one in Portland houses (4500 degree days). This study has found a range of 20 to 1 for gross electricity consumption in a climate even milder than that of Portland (2800 degree days). This suggests that temperature preference becomes increasingly important as climate becomes milder.

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