OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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VENTILATION AND OCCUPANT BEHAVIOUR IN TWO APARTMENT BUILDINGS

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SYNOPSIS

In this paper we approach the subject of ventilation and occupant behavior in multifamily buildings by asking three questions: 1) why and how do occupants interact with ventilation in an apartment building, 2) how does the physical environment (i.e., building characteristics and climate) affect the ventilation in an apartment, and 3) what methods can be used to answer the first two questions. To investigate these and other questions, two apartment buildings in Chicago were monitored during the 1985 - 1986 heating season. In addition to collecting data on energy consumption, outdoor temperature, wind speed, and indoor apartment temperatures, we conducted diagnostic measurements and occupant surveys in both buildings. The diagnostic tests measured leakage areas of the individual apartments, both through the exterior envelope and to other apartments. The measured leakage areas are used in conjunction with a multizone air flow model to simulate infiltration and internal air flows under different weather conditions. The occupants were questioned about their attitudes and behavior regarding the comfort, air quality, ventilation, and energy use of their apartments. This paper describes each of the research methods utilized, the results of these efforts, and conclusions that can be drawn about ventilation-occupant interactions in these apartment buildings. The major conclusion of this work is that a multidisciplinary approach is required to understand or predict occupant-ventilation interactions. Such an approach must take into account the physical characteristics of the building and the climate, as well as the preferences and available options of the occupants.

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1. INTRODUCTION

Unlike infiltration, the uncontrolled air flow through leaks in the building envelope, ventilation depends not only on climate and building characteristics, but also on the operation of mechanical systems and on the behavior of the building occupants. We find it interesting that only 35 of the 1858 entries in the Air Infiltration Centre's AIRBASE address the effect of occupancy on ventilation.[1] Work on the subject of occupant interaction with ventilation was being performed in Great Britain as early as 1950.[2,3] More recently, as part of the general interest in the topic of occupant effects on energy use, a number of studies of occupant-ventilation interactions have been made in the other European countries.[4-7] Our work focuses on occupant interactions with ventilation of multifamily buildings in the United States.

In this paper we approach the subject of ventilation and occupant behavior in multifamily buildings by asking three questions: 1) how does the physical environment (i.e., building characteristics and climate) affect the ventilation in an apartment, 2) why and how do occupants interact with ventilation in an apartment building, and 3) what methods can be used to answer the first two questions. To answer these questions we investigated ventilation and occupant behavior in two apartment buildings. Our approach is multidisciplinary, using research techniques from engineering, physics, and the social sciences. These case studies focus on both understanding each building, and evaluating the results obtainable with each of the research techniques.

2. BACKGROUND

The two buildings we are studying are in Chicago, Illinois, and are typical of much of the urban housing stock throughout the north-eastern and north-central United States. These buildings are part of a larger study of retrofit performance in multifamily buildings being conducted by Lawrence Berkeley Laboratory (LBL) and the Center for Neighborhood Technology (CNT), a Chicago based, not-for-profit organization working in energy conservation.

The climate in Chicago is predominately continental, ranging from relatively warm in summer to relatively cold in winter. While temperatures are moderated by the proximity of the Great Lakes, the average temperature in January is -5 °C. Annual degree days, base 18.5 °C, are 3600 for heating, and 370 for cooling. The average wind speed, 4.6 m/s, is somewhat higher than the national average. The normal air-conditioning season lasts from about mid-June to early September.[8]

We refer to the two buildings as Albany and Bosworth, after the streets on which they are located; both are in flat-terrain residential neighborhoods, amidst blocks of three-story apartment buildings. The buildings are very similar to each other, and are typical of early 20th-century construction in large U.S. cities. The buildings are three-story brick construction with a central fire wall, and were built in the 1920s. The arrangement of the apartments is similar, symmetrical floor plans with a common entry hall and central stair in front, and separate balconies and outside stairs in back (see Figures 1 and 2). As there are adjacent buildings on two sides, light and air is provided to interior rooms by air shafts, located between the buildings at Bosworth, and on the interior of the building at Albany. Albany is owned jointly by three of the households who rent out the other four apartments. Bosworth is owned by a not-for-profit housing organization, and is managed by two of the households; all of the residents at Bosworth are renters.

The building walls are uninsulated, and there is about 10 cm of insulation in the attic at Albany, and no insulation in the attic at Bosworth. Storm windows were recently installed in both buildings. Both buildings have basements half below grade which contain the boiler, domestic water heater, and laundry facilities. At Albany, half of the basement has been converted into an apartment.

Both buildings are heated by gas-fired steam boilers which are approximately twenty years old, and replace the original coal-fired systems. The distribution system is a single pipe run; the condensate falls by gravity down the same pipe that provides the steam. Because the distribution system relies on natural convection, has a large thermal mass, and does not have individual apartment control, control and balancing of such a system is difficult.[9] Poor system balance, the subject of a parallel study underway by CNT, means that some apartments will be overheated or underheated, depending on the location of the thermostat. (Thermostat relocation alone cannot solve the problem.) While ventilation (and infiltration) may contribute to the non-uniform heating load in the building, it is also one possible means for residents to control the temperature in their apartments, e.g., by opening windows in overheated apartments.

In buildings such as Albany and Bosworth, which have no central mechanical ventilation, the only options for residents to control ventilation are using small fans (especially to promote cooling in summer), and opening and closing doors and windows. Windows, however, provide several functions other than ventilation, and it is important to differentiate these reasons, as occupants may choose to open or close windows for reasons that have nothing to do with ventilation. People open windows for the following reasons (among others):

- to control the inside temperature due to broken or lack of control on heating system, excessive solar gain, poor heat distribution, etc.
- to control air quality, opening windows both on a routine basis, and at specific times, i.e., during cooking, cleaning, etc.
- to control excess humidity during showering, bathing, clothes washing, etc.
- to maintain contact with street: supervise children, talk with friends, listen to activities;
- to follow custom or tradition: windows open at night "because it's healthy", airing every morning for one hour, etc.

Some reasons for not opening windows include:

- windows are difficult or impossible to open (e.g., painted shut);
- security;
- to keep out dirt and insects (especially if they lack screens);
- to prevent heat loss;
- to maintain privacy or keep out unwanted noise.

Previous researchers have found strong correlations between the degree of window opening for airing and the external air temperature. Lyberg found, across several different study samples, a constant value for the product of the number of windows open and the temperature difference between inside and outside (Reference 5). Although these results would indicate that the controlling factor is the temperature of the outdoor air, we suspect that other variables also play an important role.

Many of the reasons for opening windows (and some of the reasons for keeping them closed) seem to relate to some form of occupant comfort. If the occupant is not comfortable with the prevailing indoor climate, he or she will try to modify it in the required direction.[10] However, measuring comfort to predict window opening is not a straightforward problem. Looking only at thermal comfort uncovers numerous physical and psychological factors. On the physical side are such factors as air temperature and movement, relative humidity, mean radiant temperature, activity level, and clothing. On the psychological side are such factors as temperature preference, tolerance, expectation and locus of control (an indication of how much control individuals feel they can exert over their environment). The question of comfort is further complicated by the variety of techniques occupants can use to maximize their comfort. In addition to opening windows to achieve comfort, occupants can change their clothing levels, use auxiliary heating, or complain to the management (or others) to provide more uniform heating.

3. METHODS

Given the complexity of understanding occupant interactions with ventilation, we used several methods to examine the problem. These methods represent different perspectives from which the problem can be approached, which in combination provide a more detailed picture. The methods chosen include 1) long-term monitoring of internal apartment temperatures, 2) short-term diagnostic measurements of air leakage, along with simulation of air flow within the building, and 3) detailed interviews with the occupants about their ventilation-related behavior. Other methods that were considered, but not undertaken because of budget limitations or practical considerations, were: monitoring window openings directly, photographing the buildings at frequent intervals, continuous tracer gas measuring of air flow, and having the occupants keep activity logs.

3.1 *Monitoring*

As mentioned previously, apartments experience different temperatures for a variety of reasons, which include peculiarities of the heating system (broken radiators, valves and vents), different orientation to sun and wind, location in the building with respect to height, buffering by other heated apartments, location of leaks, and modification by the occupants. We expected to see evidence of occupant behavior, such as window opening and the use of auxiliary heating by examining the temperature profiles of the individual apartments.

As part of CNT's research program, Albany and Bosworth were instrumented with data acquisition systems that collected six months of data on indoor apartment temperatures, outdoor temperature, wind conditions, and boiler energy consumption. All data points were stored every 10 minutes, allowing examination of the detailed temperature history of each apartment.

3.2 *Diagnostics and Simulation*

In addition to the monitoring of the apartment temperatures, we were interested in determining the air-flow patterns in the building due to infiltration. Air flow in apartment buildings is more complex than in a single-family structure because air is exchanged not only with the outside, but with the other apartments as well. The implications of inter-apartment flow are that under certain weather conditions, apartments may be exchanging more air with neighboring apartments than with outside, and the resulting stuffy conditions may prompt the residents to open windows to improve the air quality.

Air-flow patterns can be determined either by direct measurement, or by leakage measurements in combination with an air-flow simulation model. Because direct air-flow measurements are both expensive and depend on the building and the weather, we chose to make diagnostic leakage measurements. Blower-door testing of exterior-envelope and inter-apartment leakage was performed in both buildings. Previous measurements in similar construction had shown that as much as 60% of the air leakage is to adjacent apartments.[11]

Leakage measurements in multifamily buildings are relatively new, and as such, have seen little discussion in the literature.[12,13] We used two blower doors, running simultaneously, to make the measurements. The tests were similar to standard single-family blower door tests, except that each apartment's total leakage is measured with and without the adjacent apartments being pressurized. For each apartment test, all adjacent apartments were opened to outside to reduce series resistance effects. This is accomplished either by opening windows and doors, or through the blower-door fan opening in the other apartment. At each apartment/outside pressure difference, the flow was measured first without the second blower door operating, and then with the second blower door operating so as to make the pressure difference between the two apartments equal to zero. The leakage between two apartments is then computed by subtracting the leakage area with the second apartment pressurized from the total leakage area.

The air-leakage data obtained from the blower door tests are used in a multizone air infiltration model to calculate inter-zonal air flows and outside-air infiltration rates under different weather conditions.[14] The simulation model iteratively solves for the pressures and flows throughout the building, using a flow coefficient and exponent to characterize each leakage path.

3.3 *Household Interviews*

To understand how occupants modify apartment ventilation, as well as to examine the reasons why, we interviewed the residents from eleven of the thirteen households in the two buildings. Following ethnographic techniques, the questions were often open ended, allowing the respondents to describe their answers in detail. Many of the questions were based on previous exploratory studies of energy and behavior and were adapted for residents in apartments.[15-17] The interviews took between 30 and 60 minutes, and all but three were conducted in the resident's apartment; the remaining three interviews were conducted at the resident's work place.

The residents were asked about their comfort, clothing, temperature preference, window opening behavior and related activities, attitudes, etc. During the interviews we took notes, and immediately afterwards wrote out as much additional information as was remembered. Although this is more cumbersome than tape recording the interviews, the respondents seemed at ease and eager to participate in the survey. For the remainder of the text, quotation marks are used for those passages that were written down during the interview. Additional comments and notes written after the interviews are often paraphrased.

4. FINDINGS

4.1 *Monitoring Results*

Given the large quantity of data gathered (over six months of seventeen channels per building at ten-minute recording intervals), we examined daily average temperatures for each month, and then selected six to eight two-day periods from each building for more detailed analysis. The sample selection was based upon completeness of data, outside temperature, and day of the week. Four representative samples of the periods examined are shown in Figures 3 through 6. These figures contain plots of individual apartment temperatures versus time (10-minute data samples) in Bosworth and Albany, for two-day periods in February and April.

Figure 3 shows a two-day period for Bosworth in mid-February. The outside temperature averages for these two days are -10 and -9 ^{o}C. A quick examination of this figure shows that the coldest and warmest apartment temperatures differ by approximately 7 K. Looking at the legend, we see that both these apartments are on the first story, and the warm apartment is located directly above the boiler.

A closer examination of the plot provides a good indication of the operation of the building. Starting on the left side of the plot at midnight, the temperatures in all of the apartments decay due to the night setback of the boiler thermostat. The boiler fires again at around 6:00, after which it cycles to maintain relatively constant apartment temperatures until 22:00, when the night setback begins, a pattern which is repeated on the second day. All of the apartment temperatures behave similarly throughout this period, except for apartments 1b and 3a. Apartment 1b differs from the norm from 11:00 to 21:00 on the 10th and starting at 4:00 and 17:00 on the 11th. Apartment 3a behaves irregularly on the 11th.

The anomalous temperature patterns in these two apartments is our first indication that occupants are interacting with the temperature balance in the apartments. Window opening is a likely candidate for the cause of the anomalous temperature profiles. Looking first at apartment 1b, we can hypothesize that as the temperature rose in the morning it reached too high a level at around 11:00, at which point the occupant opened the windows, and then closed them at around 19:00. The temperature rises on the 11th could also be due to window closing. The profile for apartment 3a could also be explained by window opening: upon leaving the apartment at 8:30, the occupant opens some windows to air the apartment, which were closed upon returning at 18:30.

Although the window opening explanations for the temperature profiles seem plausible, the behavior in apartment 1b is puzzling. It is not clear how the windows were closed at 4:00 on the 11th, and then closed again at at 17:00 without any apparent openings in between. Figures 4 and 5 provide some additional evidence that may help explain the profile in Figure 3. Although the profile for apartment 1b in Figure 4 is similar to that in Figure 3, there is one significant difference. During the early hours of February 22, the temperature in 1b does not show the normal decay. This indicates that the occupant is likely to be using some form of auxiliary heating in the middle of the night, as the average outdoor temperature for the 22nd is -2 ^{o}C. The use of auxiliary heating in this apartment is confirmed in Figure 5, where the temperature rises dramatically in the middle of the night, and the boiler has not been on during this period. (The high temperature in 3a throughout this period could be due to continuous auxiliary heating, but we suspect the temperature sensor itself.)

Having confirmed the use of auxiliary heating in apartment 1b, we now question the window-opening explanation for its profile in Figure 3. The temperature rises attributed to closing windows is more likely to have been caused by the use of an auxiliary heater. We note that the initial slope of the temperature rise at 18:30 on February 10 is the same as that on April 20 (see Figure 5). Similarly, the temperature drops attributed to window opening could be caused by the auxiliary heater being turned off.

Figure 6 shows a two-day apartment temperature history for February at Albany. The temperature profiles are similar to those for Bosworth, again clearly showing the decays associated with the night setback of the boiler. The major differences between the two buildings are that the spread between apartment temperatures is smaller for Albany, whereas the boiler control at Bosworth provides smaller temperature oscillations. Figure 6 does not seem to show any window opening behavior, although it does show some auxiliary heating. Apartment 1a is significantly overheated on the night of February 10, and apartment 2b also shows a short temperature spike uncorrelated with boiler operation. The spike in 2b could possibly be from cooking, although there is an unexplained temperature spike in apartment 1b in the middle of the night.

4.2 Diagnostic and Simulation Results

The average leakage areas measured for each apartment were 2460 cm^2 for Bosworth, and 1880 cm^2 for Albany. The corresponding specific leakage areas (leakage area divided by floor area) of 19.0 and 18.8 cm^2/m^2 are surprisingly consistent, and significantly higher than the 13.3 cm^2/m^2 measured in a similar building in Minneapolis (Reference 10). We note that these are total leakage areas; in Bosworth approximately 60% of the leakage area was to other apartments, the remainder being in the exterior envelope. (Due to strong winds during the Albany tests, accurate measurements of inter-apartment leakage were not obtained.)

The leakage values used in the simulation of air flow in Bosworth are shown in Table 1. Taking into account the uncertainty in the measurements, average values were used for all similar flow paths (i.e., all diagonal inter-apartment leakage areas were assumed to be equal, all vertical inter-apartment leakage areas were assumed to be equal, and all horizontal inter-apartment leakage areas were assumed to be equal). As the simulation model uses both a flow coefficient and exponent to describe the leaks, the flow coefficients were determined from the leakage areas, and an average flow exponent of 0.65 was used.

In addition to the flow coefficients and exponents, the model also needs pressure coefficients as input. The pressure coefficients used for these simulations come from wind tunnel tests of a building with similar geometry. A plan of the site, presented in Figure 7, shows the shielding of the Bosworth building. (The wind tunnel site geometry was similar, although not identical, to the Bosworth site.)

Some significant simplifications in the simulation result from the shielding of the Bosworth site. Because the building is completely shielded on both sides, only wind from the front or back of the building will induce air flow through the building. Pressure coefficients are therefore required for only two wind directions, from the back of the building, and from the front of the building. The simulations presented are based on wind arriving from the front of the building (results of simulations for wind arriving from the back of the building differed by only 10%). Also, because wind from the front or back has the same effect in both apartments on the same story, and the stack effect does not create any horizontal pressure gradients, leakage between apartments on the same story does not play a role in the simulations.

The results of the simulations are presented in Figure 8, in which the outside air-flow rate into apartments on each story, and into the basement, are plotted as a function of wind speed. For all simulations, the indoor-outdoor temperature difference is 20 K, which is close to the average indoor-outdoor temperature difference during the heating season.

The results in Figure 8 are not surprising. As expected for a building with large internal leaks between zones, the upper stories do not receive any outdoor air at low wind speeds, all of the outdoor air being drawn into the basement and first story by the stack effect. The drop in outside air flow to the basement with increasing wind speed results from the lack of basement leakage at the front of the building. As the wind speed increases, the depressurization at the rear of the building competes with the stack effect by reducing the pressure difference across the exterior basement leakage sites. It should be noted that almost all the air entering the basement goes to the first-story apartments (a small fraction goes into the staircase). This implies even higher ventilation heat losses for those apartments, as the basement air temperature is somewhere between outdoor temperature and internal apartment temperature.

Figure 8 indicates that the overall air change rate of the building is not excessively high. At the average temperature difference of 20 K, and average Chicago wind speed of 4.6 m/s, the overall air change rate for the building is 0.6 air changes per hour (ach). It should be noted, however, that the average wind speed takes into account wind from all directions. Because only wind from the front or back of the building will induce the simulated flow rates, wind from other directions having even less effect on the ventilation of the building, the average air exchange rate will be even lower than 0.6 ach. In other words, the effective average wind speed will be lower than the 4.6 m/s all-direction average.

Because of this strong directional dependence of wind-induced air flow, the building will be in the stack-dominated region of Figure 8 for a significant fraction of the time. In this stack-dominated, and therefore non-uniform ventilation mode, the upper story apartments will receive little or no outside air, and should thus be stuffier than the first story apartments. Similarly, the first story apartments may seem draftier due to the higher influx of cold outside air. Depending on the UA-value of the building (i.e. conductivity of the building shell), these results also imply that the first story apartments should cool more quickly than the upper story apartments.

4.3 *Survey Results*

The average household size for the two buildings is 2.7 persons, with Bosworth having larger (3.3 persons) households than Albany (2.2 persons). The age distribution is 11 adults and 9 children at Bosworth with an average age of 19 years, and 12 adults and 1 child at Albany, with an average age of 32. The range in occupant ages for the two buildings is 1 - 61 years. Bosworth has three black and three white households; Albany has one black, one Hispanic, and five white households. While education levels are nearly the same for the household survey respondents in the two buildings (an average of 15 years of school for Bosworth, 16 years for Albany), household incomes were significantly different. Reported mean annual household income for six of the seven Albany households was $34,000; at Bosworth only three of the six households reported annual income, with a mean value of $22,000. The household patterns included couples, couples with children, 3-4 single men living together, single women alone, and single women with children. All of the residents had lived previously in apartments, many for a large part of their lives. Both Bosworth and Albany had three households where someone was home during the day.

The survey included a number of questions concerning when and why windows were opened in winter. The most consistent finding for our two buildings was that, in general, the occupants reported that they did not open the windows at all during the winter. The reasons for this were that the residents felt the apartments were already too drafty, that they wanted to keep the heat in, that it was too cold outside, and that it was too much trouble to unseal the plastic and rope caulk just to open the windows. The sealed windows were part of the routine the residents employed to reduce infiltration, which included installation of rope caulk every October, installation of plastic sheets over the inside of the windows (the houses already had exterior storm windows), and stuffing rags around the door frames. One resident kept one window unsealed for ventilation and as a fire escape, "I open it a little when I use that space heater [an unvented kerosene heater]."

Residents reported that in previous apartments they had had to open windows because of over heating in winter, but that this was not a problem for them now, "In other buildings with over-heating problems I have had the windows open all night. I don't feel too guilty opening windows, [but] I doubt if anyone in our buildings would open the windows [in winter]. I think the majority think it's on the cool side." A few residents would open the back door to air the house, for about fifteen minutes during the day, usually on a weekend. Only one resident reported that windows were opened in winter on a regular basis for relieving the stuffiness. In this case the windows were opened once a month, typically at night, just a crack, and for a few minutes. For the most part, the winter pattern of window opening is reflected by the resident who said, "I just wouldn't think when it's that cold to open them."

In contrast to the winter pattern of keeping all the windows sealed and shut, ventilation in summer was always dependent on opening windows and using fans for air movement. Residents relied on combinations of drawing shades, exhausting air, keeping the rooms closed during the day, wearing fewer clothes, drinking cold drinks, and other activities to stay cool. Only one household reported using an air conditioner. They had a window unit in the bedroom that they would use whenever the temperature would rise above 27 ^{o}C. Depending on wind and dirt, windows would be open a lesser degree. Residents of first floor apartments commented especially on dirt intrusion, "The city is dirty. If you keep the windows closed you keep the apartment clean." Others would leave windows open all the time, "morning, afternoon and night, except when it rains, and then only part way." Window fans are sometimes left running during the day when the residents are away so that the apartment won't be so hot when they return in the evening. "I have to leave the fan on [during the day] for him [the dog] because he can't stand the heat."

In addition to the window-opening behavior we were interested in other activities that residents were engaged in that might affect the ventilation or need for ventilation in their apartments. Most of the respondents changed their clothing levels to reflect the temperatures in their apartments. Taking off layers was a typical first response to apartment overheating. Putting on a sweater or flannel shirt was a typical response when it was too cold in the rooms.

On surprising finding was the widespread use of the gas stove as an auxiliary heat source for the apartment. Six of the eleven households reported using the gas stove or oven for auxiliary heating. Typical use was in the early evening in winter and in the early morning before the central system came on. The stove was also used for heating in the fall, before the heating season began. The usual pattern was to heat the kitchen, which was often the coldest and draftiest room. "In the evening when I come home it can be awfully drafty. I have it [the oven] on for 15 minutes. It's supposed to be self-cleaning, so I use that excuse." One resident also has an unvented space heater in the apartment, which is used for an hour or two in the evening.

To further understand related aspects of ventilation, residents were asked questions about drafts, stuffiness, cooking smells from other apartments, and the degree of acoustic isolation.

All residents commented that there were drafts in the apartments, especially around the doors—the back door in particular. The new storm windows had reduced drafts around the windows considerably. However, as mentioned earlier, the residents would still seal the windows in winter to stop drafts. Other reported drafts around the baseboard molding and the walls in the front room. The residents at Bosworth mentioned that the whole building was leaky, and needed tuck-pointing, i.e., the mortar in the exterior walls needs replacing. The enclosed (unheated) back porches at Bosworth were frequently mentioned as being drafty.

Few residents commented that it ever got too stuffy, "we have enough drafts," was a typical response. The kitchen was cited as the most common room to be too stuffy, particularly if the weather (in winter) warmed up. The interior rooms (bathroom and bedrooms) were also found to be stuffy at times. A few residents mentioned that they had condensation between the primary window and the storm window, but in general, moisture was not considered a serious problem. The only respondent that claimed to sometimes have moisture problems was the one that had a humidifier.

We also asked the residents questions about what they could hear from their neighbors, both above and below, as well as next door. We were interested in finding out whether there were direct connections between apartments which could transmit noise, thereby serving as indicators of possible air-flow paths. The residents were asked about what types of sounds they could hear: walking, music (both bass and treble) and conversation, and whether they could distinguish actual words. Our hypothesis was that if high frequency sounds (treble music or distinct words) were heard from a neighboring apartment, there was a greater possibility of direct paths between the units. Of course, whether a resident could hear their neighbor depends on how much noise the neighbor makes, in addition to the presence of any connections between apartments.

The general pattern was that residents were most aware of noises from above, less so from below, and almost not at all from the side. Specifically, upstairs noises included walking and running (especially kids), muffled music, mostly bass, and in one case, distinct conversation. Noises from below were music when it was turned up (mostly bass), and some talking, but not distinct words. Most residents commented that they could hear nothing from the apartment on the same story, "It's amazing how insulated we are crosswise compared to up and down." Residents mentioned that noise in general was not a problem, although it was more evident in summer when windows tended to be open.

5. DISCUSSION

Having examined the results of three different techniques for exploring ventilation and occupant behavior, we uncovered some surprising results and some apparent contradictions. The most surprising result is that, contrary to the results of previous studies, the survey responses indicate that these apartment occupants rarely, if ever, open their windows during the winter. This behavior seems to stem from the large inconvenience associated with window opening, due to sealing measures taken at the start of the winter season. Also, there may be less perceived need by the occupants for window opening as they find the apartments to be quite drafty. A third factor is the severity of the winter climate. The winter design temperature (99%) for Chicago is -22 °C, compared to -15 °C for

Stockholm and -4 °C for London.[18]

Because residents report no window opening activity, we had to re-evaluate the temperature profiles where we suspected window opening was taking place, to see if there were alternative explanations. Of course, survey respondents may not have reported accurately, whether through being unaware of other members of the household's activities, or through the desire to give a "correct answer." Nevertheless, we decided to see if explanations based on the survey results could be used to interpret the measured temperature data.

The survey responses indicate that auxiliary heating is used by the residents in Bosworth apartment 3a "all the time." Looking again at Figure 3, the dip in temperature could then be explained by the residents being out of the house during the middle of the day on February 11th, whereas on the 10th they are probably home and using auxiliary heating all day. This explanation is confirmed by further examination of the survey and monitoring results. The occupants explain that they are usually out on weekdays and home on weekends. This correlates well with the pattern of temperature dips on weekdays only and uniform temperatures on weekends, which was observed upon more detailed examination of the temperature data. Thus, by combining the monitoring and survey results, we have a clearer picture of building operation.

An interesting finding from the comparison of the survey data with the temperature profiles is the correlation between apartment temperatures and the reported temperature preferences of the occupants. People who reported liking colder temperatures live in colder apartments, and people who reported liking warmer temperatures generally live in warmer apartments. While this finding may not be altogether surprising, it does confirm that occupants are able to control—to some extent—the temperatures in their apartments to where they are comfortable.

A comparison of survey results with diagnostic/simulation results does not prove to be conclusive. The simulations indicate that the first story apartments get significantly more (cold) outside air, and are therefore likely to have more drafts. The upper-story apartments, which receive most of their air from the lower-story apartments might be expected to be stuffier than the first story apartments. The survey results do not confirm (nor do they disprove) any of these expected trends. The only correlation found is that the upper-story apartments at Bosworth appear to have somewhat less problems with drafts. The difficulty with such a comparison is the number of confounding effects that tend to mask the effects we expect to see. For example, two of the first story apartments have high temperature preferences, and use auxiliary heating to maintain their comfort. Auxiliary heating may completely mask the effects of outside air drafts.

A comparison of diagnostic/simulation results with measured temperature profiles does provide some interesting confirmations. According to the simulation, the first story apartments should have significantly higher heating loads due to infiltration. Depending on the ratio of infiltration heating load to conduction heating load, we would expect either the first or third story apartment temperatures to decay most quickly when the boiler turns off for night setback. Examination of the temperature profiles in Figures 3 through 5 confirms that the first story apartments cool off more quickly than the rest of the building. This effect is most obvious at Bosworth on the morning of February 22 (see Figure 3), and at Albany on the mornings of February 10 and 11 (see Figure 6). These results illustrate the importance of infiltration to the overall energy balance of these buildings.

6. CONCLUSIONS

The results of our investigations have provided us with a number of findings about ventilation and occupant behavior in these buildings, and about the suitability and applicability of the experimental methods tested. Our major finding is that the ventilation in these buildings cannot be explained by physical models alone, and that understanding behavioral interactions is key to understanding what is going on. While occupant behavior is often difficult to interpret, we have found the occupants' desire to improve comfort to be the driving force behind much of their behavior. Occupants will follow what is for them the path of least resistance to improve comfort, whether this is sealing windows with plastic, using the stove as an auxiliary heater, or complaining to the neighbors. It also became clear that these actions may not be optimal from an energy or economic view point.

We hesitate to generalize these findings to other buildings in different climates and cultures because we have found that our results are different from those published previously. We do feel, however, that an experimental approach that combines different methods provides additional insight into complex problems such as those found in looking at occupant interaction with ventilation systems. In particular, we stress the importance of understanding the specific characteristics of the building and heating system, the local climate, and the behavior of the occupants. In general, the combination of monitoring, diagnostic/simulation, and occupant surveys, seems to be a useful tool for understanding building operation, and for exploring building retrofits designed to reduce energy consumption or improve occupant comfort.

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Table 1. Leakage areas used in air flow simulation for Bosworth.

Location	Effective Leakage Areas [cm^2]
Apartment to Outside	
front	350
side	250
back	400
to roof	570
Apartment to Apartment	
horizontal	225
vertical	460
diagonal	220
Basement to Outside	
front	300
back	800
side	500
Basement to Apartment	700
Stairway to Outside	135/story
Stairway to Apartment	54

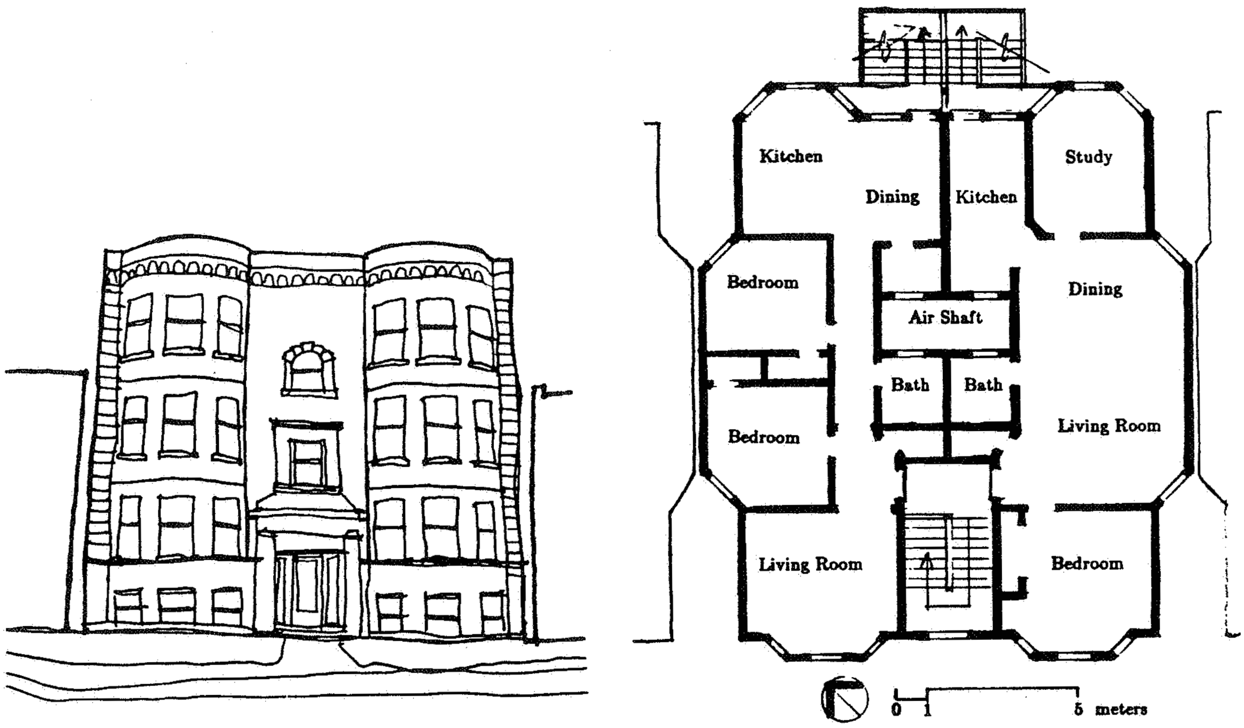

Figure 1. Plan and elevation for Albany, (Chicago, c. 1920).

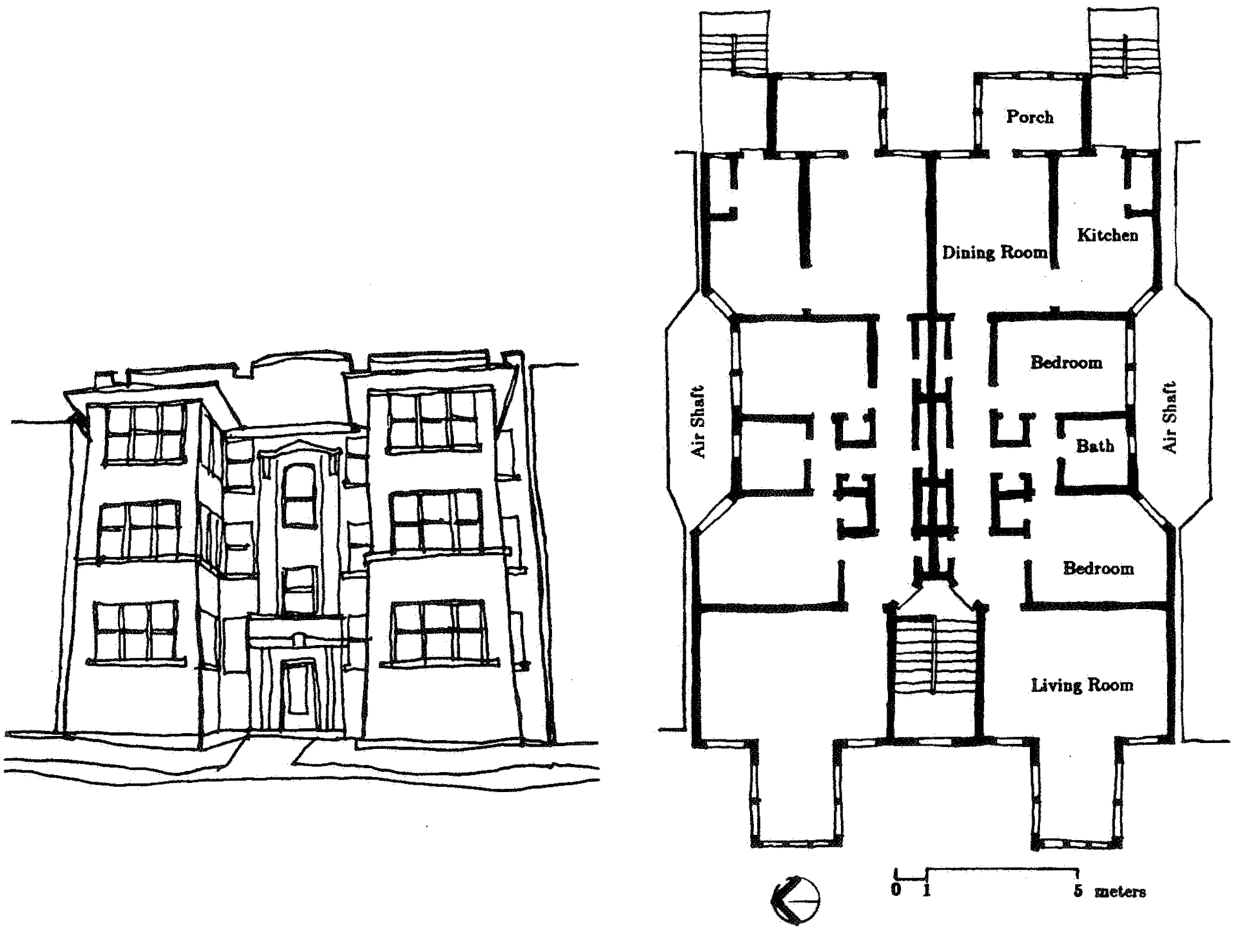

Figure 2. Plan and elevation for Bosworth, (Chicago c. 1920).

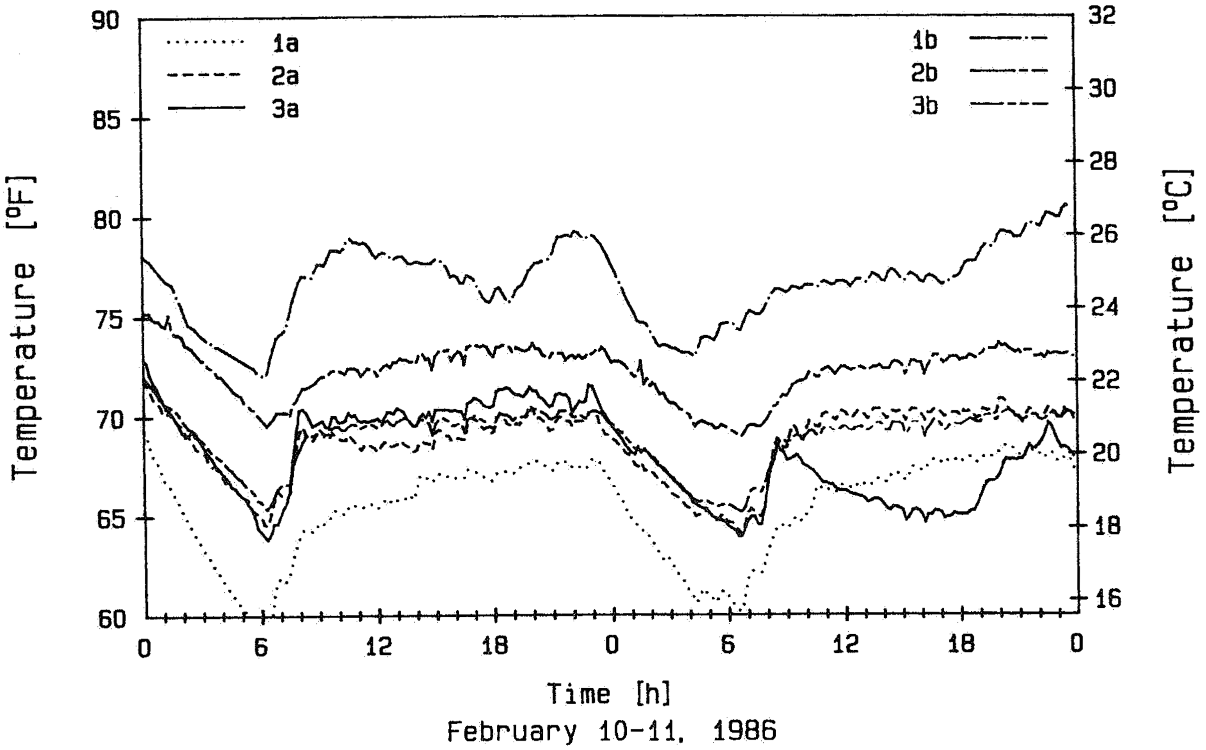

Figure 3. Apartment temperatures for Bosworth, February 10-11, 1986.

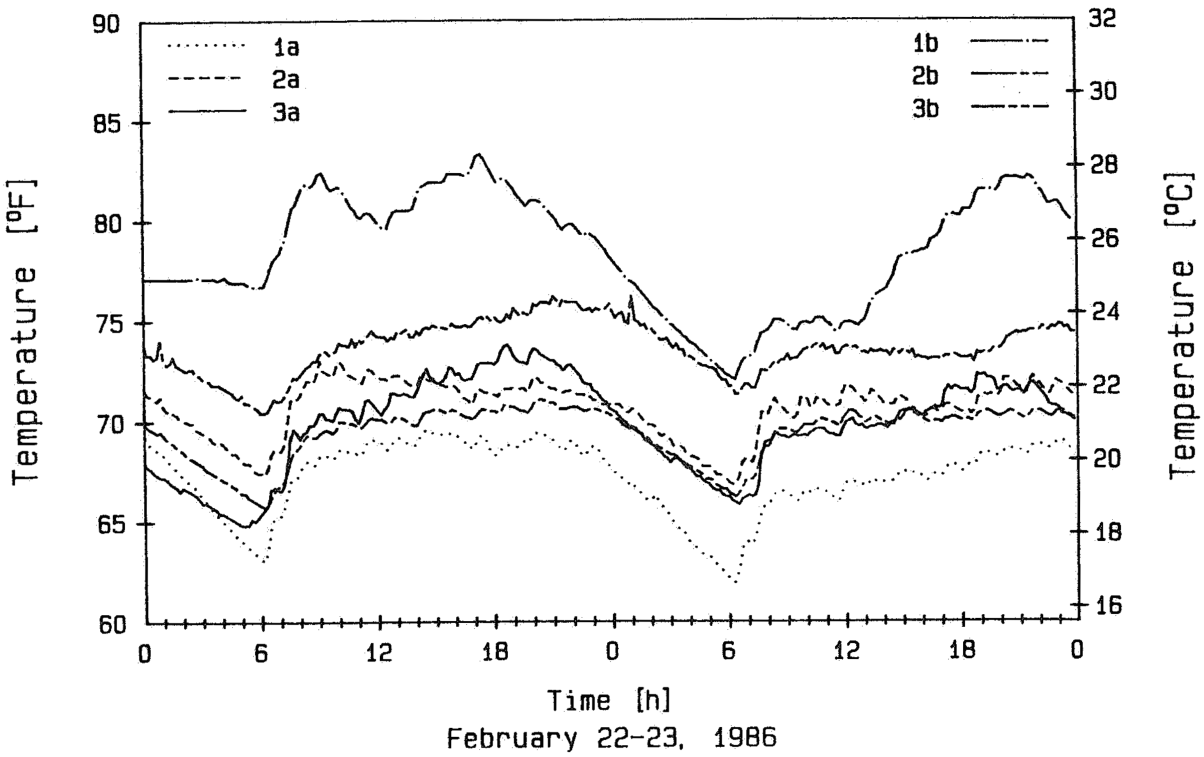

Figure 4. Apartment temperatures for Bosworth, February 22-23, 1986.

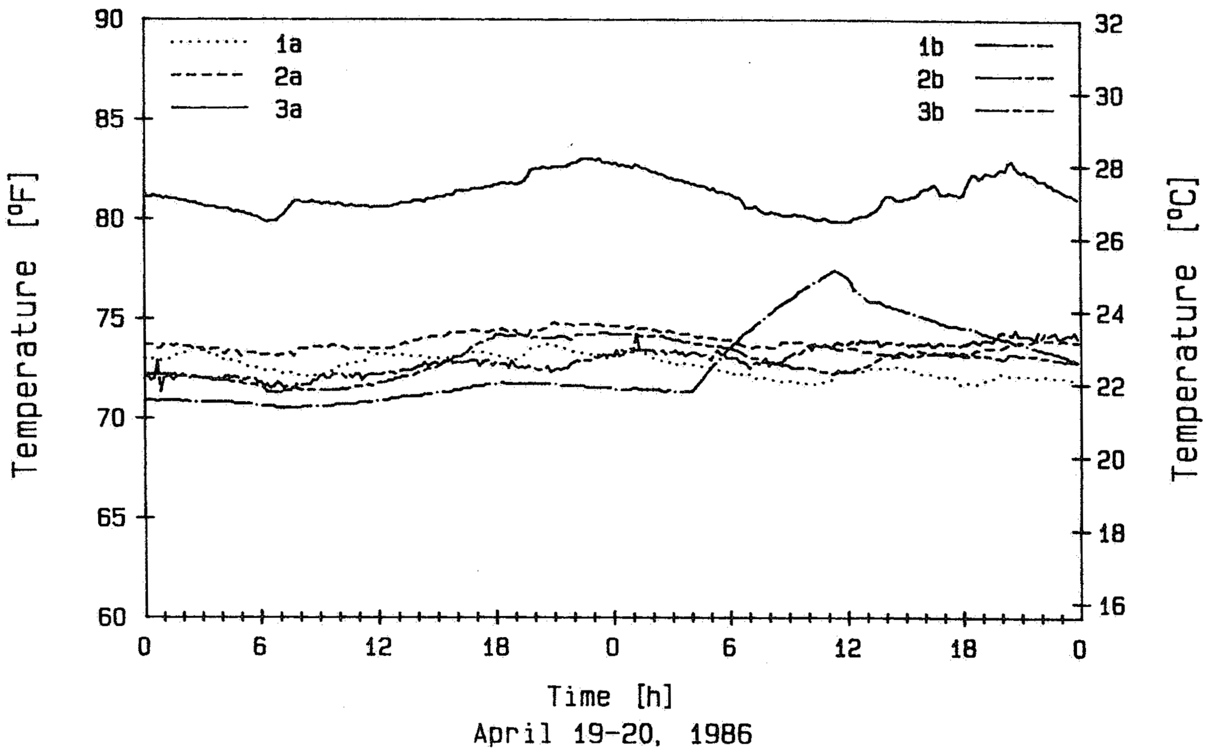

Figure 5. Apartment temperatures for Bosworth, April 19-20, 1986.

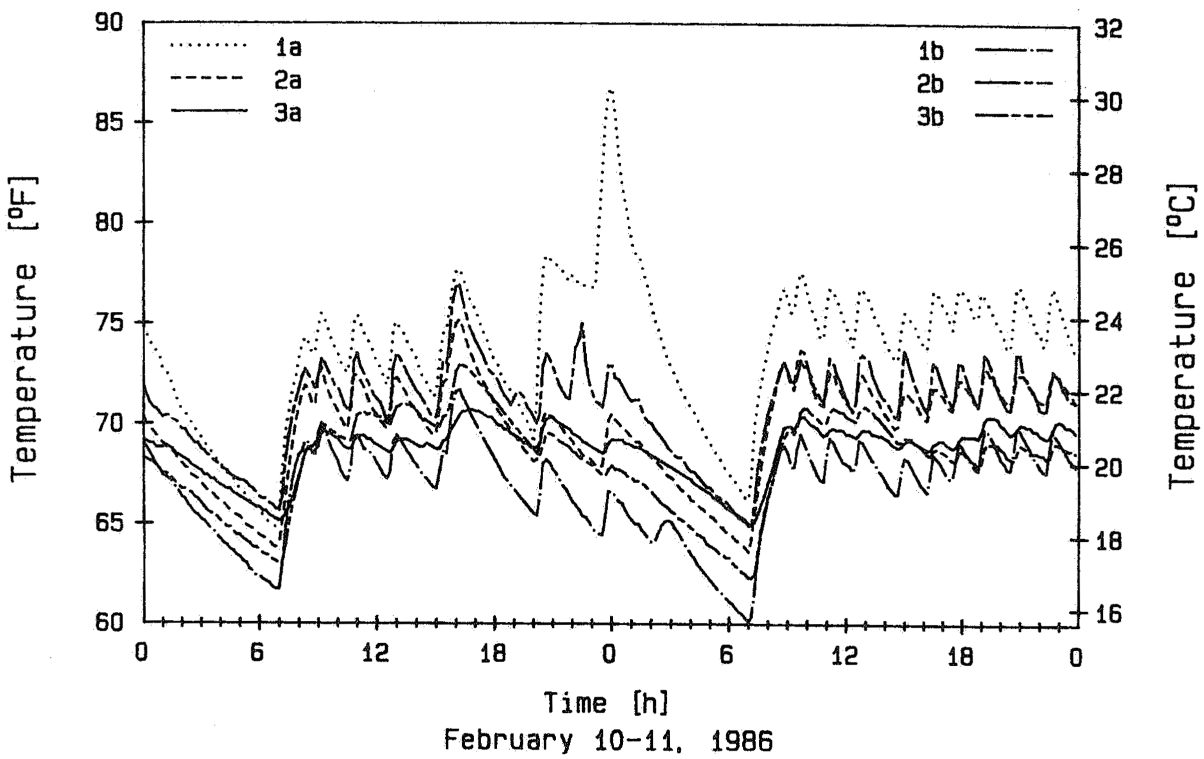

Figure 6. Apartment temperatures for Albany, February 10-11, 1986.

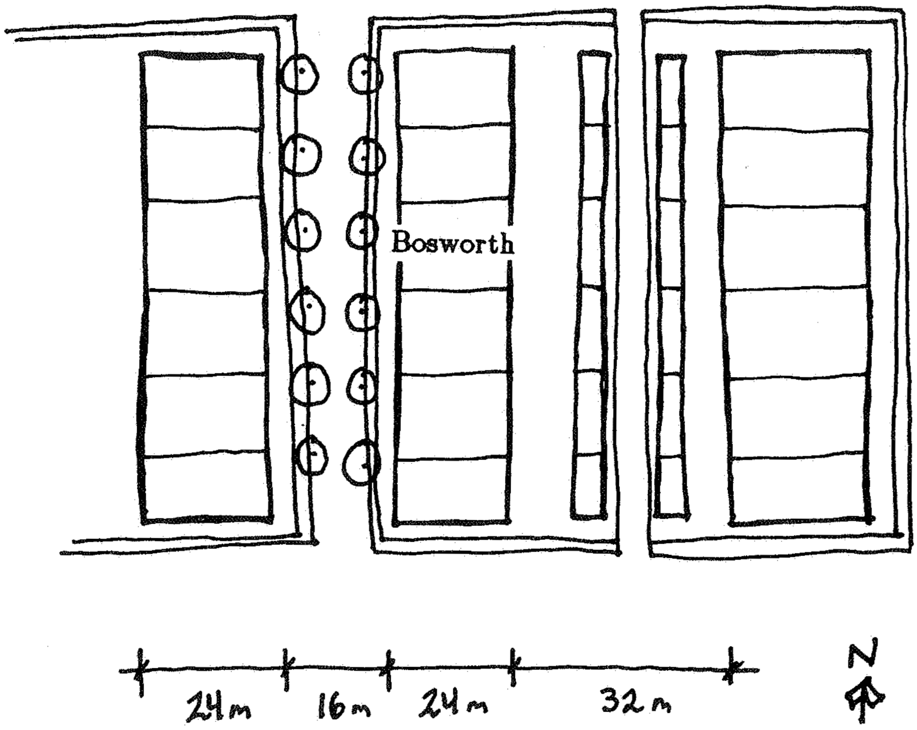

Figure 7. Site plan for Bosworth showing surrounding buildings.

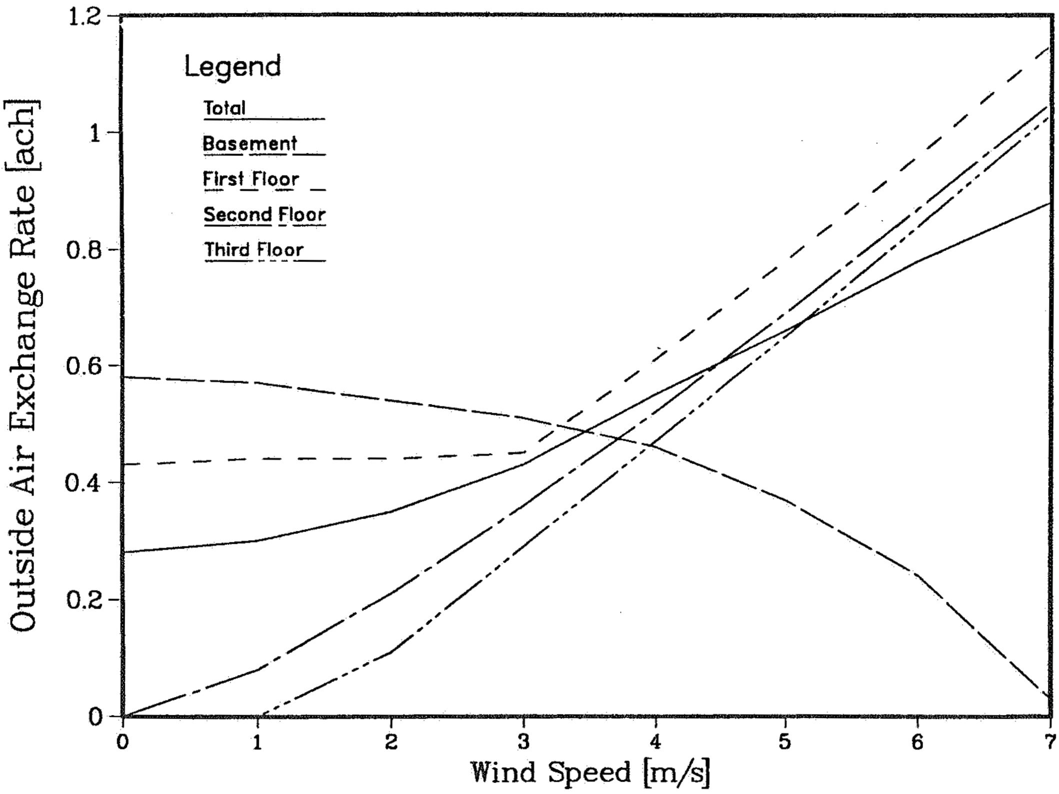

Figure 8. Outside airflow into each apartment at Bosworth as a function of windspeed for wind from the west.