LBL-17584
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE
DIVISION

Submitted to Energy and Buildings

PATTERNS OF INFILTRATION IN MULTIFAMILY BUILDINGS

H.E. Feustel and Th.P. Lenz

November 1984

**APPLIED SCIENCE
DIVISION**

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-17584
EEB-epb-84-8

Submitted to Energy and Buildings.

PATTERNS OF INFILTRATION IN MULTIFAMILY BUILDINGS

H. E. Feustel and Th. P. Lenz*

Energy Performance of Buildings Group
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

November 1984

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

* AVAL Gesellschaft fuer angewandte Computer- Hard- und Software mbH. Berlin, Federal Republic of Germany

PATTERNS OF INFILTRATION IN MULTIFAMILY BUILDINGS

Abstract

The amount of air infiltration in a building, for given weather data, depends on the leakage and its distribution on the building envelope. In our simulations of 17 designs of multiunit, multistorey buildings in Berlin, based on a typical meteorological year, we obtained a wide range of infiltration values, that varied according to the floor plan, the number and location of wall openings and cracks, and the flow resistance relationship between the inside and the exterior of the building. All structures investigated, although varying in age from 40 years old to newly constructed, and varying in height from 2 to 27 stories, had the following common features: all ground-floor flats showed the highest infiltration rates for the building, and infiltration rates for flats above the neutral pressure level have a minor height dependence. The overall ventilation rate for each of the buildings investigated is so low that infiltration alone is not sufficient to comply with ventilation requirements. Occupants control the ventilation in their flats by opening windows and doors, and, in this way they maintain satisfactory air quality but at far greater ventilation rates than necessary.

Introduction

With improved insulation of the building shell, heat loss due to ventilation --- whether controlled or by infiltration -- has become a significant fraction of the building's overall heat loss. The annual heat loss by infiltration, which is the random flow of outside air through unintentional openings driven by wind pressure and thermal buoyancy,[1] is, unlike the equivalent for conduction, not dependent only on the temperature difference between inside and outside the building, but also on wind speeds. High wind speeds often occur at higher outdoor temperatures than those used in design conditions and might drive higher infiltration rates than those calculated for design conditions (e.g. DIN 4701).[2] (Design conditions in DIN 4701 are characterized by minimum temperatures and the wind speeds which usually occur at these temperatures). Due to the smaller temperature differences in these cases, the infiltration heat loss itself need not exeed the calculated design value.

Whereas the annual energy consumption due to conduction can be calculated easily, the corresponding factor for ventilation poses some problems. Therefore, simulation programmes used to calculate annual heat consumption in a building usually use fixed ventilation rates for the whole year. Estimates of air exchange rates due to ventilation vary from 0.2 to 1.0 air changes per hour, depending on the programme's author. In other words, simulation programmes for residential buildings not only differ markedly in the algorithm each employs, but they all reflect lack of knowledge about a factor that is significant in assessing the amount of energy consumed annually.

The simulation work described here was carried out to satisfy the need for a model whose calculation of the annual heat consumption would take into account the heat loss due to conduction and the heat loss due to ventilation under design conditions.[3] This paper focusses on the distribution of the infiltration over the building height and the question of whether the infiltration that occurs provides sufficient ventilation for maintaining reasonable indoor air quality for the building's residents.

Computation Base

In order to establish a computational base, the annual heat consumption in multiunit residential buildings was simulated for seventeen different floor plans using an existing computer programme at the Hermann-Rietschel-Institut of the Technische Universitaet Berlin.[4,5] The simulations were based on an inland climate using a typical meteorological year (TMY) for Berlin, which was developed by Jahn.[6] The investigation period consisted of the days having a balance point temperature of 16°C as defined by VDI 2067.

To compare the results with those for a coastal climate, a second location in Germany was chosen. Because no hourly weather data were available for the coastal climate, the weather-data set was fitted to the monthly mean values for wind speed and temperatures for Hamburg-Fuhlsbuettel. Therefore, the mean temperature was reduced about 0.4 K and the amplitude of the daily temperature variation was reduced too. A comparison of average wind speeds show 1.3 (January) to 2.1 (May) times higher wind speeds for Hamburg. Accordingly, wind speeds for Hamburg were multiplied by these factors. These artificially obtained weather data for Hamburg represent an increase in degree days of 3% over the value given by VDI 2067.

This investigation covers multistorey buildings up to 27 floors. The buildings range in age from pre World War II through buildings still in design stage. The ceiling heights range from 2.5 m up to 4.0 m. All floor plans are shown in Reference #4. For staircases with outside walls, inside temperature was simulated at a value floating between 10 °C at design conditions (assuming an outdoor temperature of -14°C) and equilibrium between inside and outside (assuming outdoor temperature above 20°C). The temperature inside the flats was assumed to be a constant 20°C.

Compared to the static pressure associated with an undisturbed wind-velocity pattern, the pressure field around a building is generally characterized by regions of overpressure on the windward side and underpressure on the facades parallel to the air stream and on the leeward side of the building.

$$p_{wind} = 1/2 \rho (z,T) v^2(z) c_i(z) \qquad (1)$$

where:

p_{wind}	wind pressure [Pa]
ρ	density of air [kg/m^3]
v	wind speed [m/s]
c_i	pressure coefficient for wall i [-]

z height above ground [m]

T temperature [°K].

Excluding thermal stratification, the vertical profile of the mean wind speed in the atmospheric boundary layer depends primarily on the surface roughness and increases in velocity with increasing height above ground. The wind speed was calculated by the equation:

$$v(z) / v(z_o) = (z/z_o)^{1/m} \tag{2}$$

where:

v wind speed in height z [m/s]

v_o wind speed at reference height [m/s]

z height above ground [m]

z_o reference height [m], usually 10m above ground

$1/m$ exponent [-]; value depends on terrain roughness; for the following simulations 1/3 was used.

The wind-pressure coefficients and their distribution were calculated according to Krischer and Beck;[7] that is, the actual recorded wind direction from the weather-data set was converted into one of the eight directions on the compass.

Pressure gradients between the inside and outside of the building also arise from changes in air density resulting from temperature differences between outside air and inside air, called stack effect. The stack effect pressure gradient depends only on temperature difference, whereas the height of the neutral pressure level (NPL) is determined by the air leakage distribution. The neutral pressure level is defined as that height on the building facade where, under calm conditions, no pressure differences exist between inside and outside.

The permeability of the building envelope and the inside flow resistances were chosen from the flow coefficients listed in DIN 4701. The infiltration is described by the power law expression

$$Q = a\ l\ dp^{n} \qquad (3)$$

where:

Q infiltration [m^3/h]

a crack-flow coefficient [$m^3/m\ h\ Pa^n$]

l crack length [m]

dp pressure difference between inside and outside [Pa]

or:

$$Q = D\ dp^{n} \qquad (4)$$

where:

D air permeability [$m^3/h\ Pa^n$]

The crack length was measured from blueprints and considered to be constant for all simulation runs for a given floor plan. For simulation runs using the weather data for Berlin, the crack-flow coefficients noted in the building code were varied (see Table 1). To assure the highest possible flow rate, we assumed all doors inside the apartments to be open. In apartments, bathroom exhaust fans are almost all controlled by a timer or by the light switch; however, our calculations omitted all allowances for mechanical ventilation, even for bathrooms where no natural ventilation was indicated on the floor plan and the use of mechanical ventilation was highly probable.

For purpose of interpretation, we defined the outside permeability ratio (opr) as a characteristic factor for the cross-flow of air through a structure. That is,

$$\text{opr} = \frac{D_{\text{small}}}{D_{\text{total}}} \qquad (5)$$

The numerator of this quotient represents the sum of the permeabilities of the facades which gives the smaller value; the total permeability of the outside envelope of this chamber is used for the denominator. By using the permeabilities of the internal part of the chamber envelope for the numerator, equation 5 can also be used to calculate the inside permeability ratio (ipr).

The outside permeability ratio, combined with that used to describe staircase- and façade permeabilities, is responsible for the wind or stack dependency of the infiltration for a given flat. When outside permeability ratios for the façades are significantly different from one-half, the infiltration can be described as strongly stack dominated.

Results

When using the flow coefficients prescribed by building code DIN 4701 and the TMY for inland climate, the average infiltration rate for the entire heating season is between 0.04 and 0.22 air changes per hour (see Table 2). These calculated air-change rates correspond well with short-term measurements recorded at the Swiss Federal Laboratories for Material Testing and Research (EMPA).[8] Gertis,[9] NKB[10] and the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE),[11] however, recommend that air change rates in the range of 0.5 to 1.0 are necessary for preserving air quality

The infiltration rates we have described for buildings as a whole show a significant dependence on the building height.[4] It is known that thermal buoyancy is responsible for the high air-change rates at the groundlevel of a building and that wind pressure dominates the air changes on the upper storeys.[12] The relation of wind- and temperature-enforced air flow is dependent on the internal resistance to the vertical air flow and on the weather conditions. There are two extremes due to the building design: the shaft-type building with no vertical flow resistance, and the storey-type building with no vertical permeability at all.[13] Real buildings are in-between these two limits. The distribution of resistances can be significantly changed by the inhabitants. Even window openings of only a few centimeters show a tremendous impact on the ventilation rate of the area where the window is open and change the opening situation for the whole building.[14]

To learn about the distribution of infiltration in buildings, the average air change rates due to infiltration for the heating period were plotted for flats at different heights in the building for some selected buildings.

Figure 1 shows the floor plan of an eight-storey building (Brunsbuettler Damm 37) with three flats on each floor. The house was built in 1965. Whereas flat #1 and flat #3 are designed to have windows and doors on the west facade and the east facade, flat #2 has designed openings in one outside wall only. The outside permeability ratio (opr) for each flat is one-third for flat #1, zero for flat #2, and almost one-half for flat #3. Given these differences in permeability ratios for the three flats, infiltration behaviour can be expected to differ significantly as well.

Figure 2 (note the logarithmic y-axis) shows the progressive decrease in air-change rates due to infiltration from groundlevel to the seventh storey in flat #1. Parameter of the curves are the combinations of the crack flow coefficients listed in Table 1. Three sets of curves emerge, each one representing a different crack-flow coefficient for building components in the outside walls. In addition, each set itself contains three curves, each representing different permeability levels of the respective apartment doors. The shape of all curves indicates that the design of the flat tends slightly toward stack-oriented dependency.

The infiltration rates for flat #2 (see Figure 3) are totally stack-dominated. Its design permits little cross-ventilation, even when easterly winds are strong. Because of temperature differences between the outside air and the air in the stairshaft, the air pressure at the top of the staircase is high and does not allow outside air to flow through the flats above the neutral pressure level.[12] Even for a combination of loose building components (see #09), the average infiltration over the heating period is less than 0.01 air changes per hour, and very tight construction, as in cases #01 through 03, the infiltration value is ten times smaller.

Figure 4 shows the average infiltration rate for the same period of time for flat #3. Due to the equal distribution of permeabilities on two facades, not much stack dependency is present. Furthermore, because of the higher values for the permeability of the building envelope, the infiltration rate is almost independent of the storey the flat is located on.

For flats located above the neutral pressure level (NPL), when outside permeability ratios are much different from one, the infiltration rate decreases as crack-flow coefficients increase. The opposite is true for flats situated below NPL. For flat #2 the apartment door is the only exit for wind-driven ventilation. Therefore, the permeability of this door is a major factor in the increase in infiltration rate.

The findings in Buelowstrasse 96 were similar. This building, a row house completed in 1982, is seven storeys high. The ground floor and the top floor of the building each contain two flats; all other floors have three flats each. As the floor plan shows (see Figure 5), this house has a very high percentage of windows and, therefore, a high number of cracks. In two of the flats the windows are on two opposite facades; the flat in the middle (flat #2) has openings on the west facade only. The permeability ratio for the outside walls is one-third for flat #1, zero for flat #2 and one-quarter for flat #3.

Figure 6 shows the average infiltration rate for the heating season for all three flats under standard conditions (simulation #06). The curve for flat #2 is much steeper than those for the other two flats because of its lower outside permeability ratio. But even flats #1 and #3 are very much stack-influenced, which can be explained by the fact that their outside permeability ratios are so far from unity. Compared with similar cases depicted in Figures 2 through 4, the average infiltration rates here are all of the same magnitude. The whole house rates (see Table 2) are slightly lower than the comparable rates for Brunsbuettler Damm 37.

A third example, Buelowstrasse 61, represented in Figure 7, shows the infiltration distribution for an older building with ceilings up to 4 m. Each storey has two big flats (150 m^2 and 100 m^2) which represent a volume of 600 m^3 and 400 m^3, respectively. This large volume should be kept in mind when comparing these infiltration rates with those from the other houses, which have ceiling heights less than 3 m.

The permeability ratio for the two flats is 0.47 and 0.37, respectively. As expected, the curve for infiltration is less steep for flat #1. According to the different permeability ratio, the infiltration rate for flat #2 is more stack-dominated.

For the simulated coastal climate file, the infiltration rate of a house is less temperature-dependent than for comparable houses in inland climates. The wind effect is more significant in these regions. Figure 9 shows the average infiltration rate of the building shown in Figure 5, located in the coastal region. When the crack flow coefficients correspond to the German building standard (case #06), the simulation shows a significant increase in the infiltration for the whole house. The infiltration rate for flat #1, which has the highest opr-value of the three flats, increases tremendously under these conditions, reaching above NPL values of infiltration -- even higher than the values recorded at the ground-level.

Discussion

All curves depicting average infiltration rates over the heating period show a strong dependency on the outside permeability ratio. Flats with openings on only one facade are strongly stack-dominated, whereas flats with windows on at least two facades, are more balanced with respect to wind- and stack action. Thermal buoyancy is always a major factor in flats whose outside permeability ratio is much smaller than one-half. The relationship between the permeability ratios of the different flats on a single floor determine the slope of each curve. An inspection of Figure 8 and Figure 6 show these facts very clearly. In the buildings Brunsbuettler Damm 37 and Buelowstrasse 96 (Figures 1 and 5), there are two flats with high oprs and one flat with an opr of zero. The zero-opr flats absorb almost the whole stack effect, so that there is a smaller variation in infiltration rate with height for the other two flats. The infiltration for flats #1 and #3 is due to a cross-flow of air through the apartments. Because of the damping effect of the apartment doors in these units, the pressure distribution inside the staircase hardly disturbs the cross-flow of air through them. By contrast, in Buelowstrasse 61 (see Figure 7), both flats have high oprs, and in going from the ground floor to the fourth floor the air change rate is reduced by one half.

Of course, the outside permeability ratios do not tell us the amount of infiltration, which depends solely on the ratio and absolute magnitude of the permeabilities.

That infiltration in flats having an outside permeability ratio close to zero is height-dependent is illustrated by the dramatic decrease in the curves for these units -- on the order of three magnitudes (see Figure 3). To show the changes in infiltration above NPL, we had to use a logarithmic scale for the plots.

Conclusions

An important factor governing infiltration rates in multi-unit buildings with inside staircases is the height of the building. In such a building, flats with different oprs have quite remarkably different infiltration behaviour.

The infiltration rates for all buildings investigated in this study are lower than ventilation recommendations require. In flats situated above the neutral pressure level, average infiltration rates were often as much as three orders of magnitude under the guidelines set by building physicists. To prevent damage due to moisture and to supply adequate outside air for occupant comfort and safety in apartments with low permeability ratios, mechanical ventilation systems must be used. In addition, these flats should be equipped with very tight doors to protect them from the draft of upgoing air from the stairshaft. Not only does this draft cause complaints from tenants, it encourages them to open their windows excessively; a costly and unsatisfactory solution.

These three case studies clearly illustrate the relationship between infiltration and building design and climate in multistorey buildings. It is important that simulation programmes be improved and simplified so that in the future appropriate infiltration and ventilation parameters can be incorporated during the design stage of a building.

Acknowledgments

We gratefully acknowledge the support of the members of the Energy Performance of Buildings Group at Lawrence Berkeley Laboratory and the staff of the Hermann-Rietschel-Institut at the Technische Universitaet Berlin. The manuscript has benefitted from the comments of Laural Cook, Peter Cleary, David Grimsrud and Richard Diamond. In particular we appreciate the help with the drawings of Rosemarie Flinder.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

1. ASHRAE, Handbook of Fundamentals, Chapter 22, to be published in 1985.

2. DIN 4701; Regeln fuer die Berechnung des Waermebedarfs von Gebaeuden (1983). Beuth-Vertrieb, Berlin.

3. VDI 2067; Berechnung der Kosten von Waermeerzeugungsanlagen. Blatt 1: Betriebstechnische und wirtschaftliche Grundlagen (1977). Blatt 2: Raumheizung (1979). Beuth Vertrieb, Berlin.

4. Feustel, H. E.; Beitrag zur theoretischen Beschreibung der Druck- und Luftmassenstromverteilung in natuerlich und maschinell gelueфteten Gebaeuden. Fortschrittsberichte der VDI-Zeitschriften, Reihe 6, Nr. 151, (1984)

5. Lenz, Th.; Berechnung der Jahresheizarbeit fuer Lueftung in mehrgeschossigen Wohnhaeusern. Studienarbeit, Hermann-Rietschel-Institut, Technische Universitaet Berlin (1983), unpublished

6. Jahn A.; Das Test-Referenzjahr. Eine Sammlung stuendlicher Werte interessierender Wetterelemente. Teil 2: Ein Test-Referenzjahr fuer Berlin (TRY-Berlin). HLH 28 (1977), No. 7, pp. 257-265.

7. Krischer O. and H. Beck; Die Durchlueftung von Raeumen unter Wind-angriff und der Waermebedarf fuer die Lueftung. VDI-Berichte 18 (1957), pp. 29-56.

8. Luftwechselmessungen in nichtklimatisierten Raeumen unter dem Einfluss von Konstruktions-, Klima- und Benutzerparametern. EMPA-Bericht Nr. 36630, Bericht II, (1977)

9. Gertis K.: remarks at "Statusseminar Lueftung im Wohnungsbau", reported in: Sauer H. D.: Mechanische Lueftung bleibt umstritten. Clima Commerce International 18 (1984), No. 6, pp. 14-15

10. Indoor Climate, NKB Report no. 41 (1981)

11. ASHRAE, Standard 62-1981, Ventilation for Acceptable Indoor Air Quality

12. Zuercher Ch. and H. E. Feustel; Air Infiltration in High-Rise Buildings. In Proceedings of the 4th AIC-Conference on Air Infiltration Reduction in Existing Buildings, Elm, Switzerland (1983)

13. Feustel H. E.; Neufassung der DIN 4701 "Regeln fuer die Berechnung des Waermebedarfs von Gebaeuden". HLH 33 (1982), No. 9, pp. 329-333

14. Dickson D. J.: Ventilation with open windows. Electric Council Research, UK, ECRC/M1329 (1980)

Table 1: Crack-Flow Coefficients used in Calculating Infiltration

Number of Simulation	Windows	Crack-Flow Coefficient [$m^3/m\ h\ Pa^n$] Balcony Doors	Apartment Doors	Lobby Doors
01	0.15	0.50	1.00	2.00
02	0.15	0.50	2.00	2.00
03	0.15	0.50	3.00	2.00
04	0.30	1.00	1.00	2.00
05	0.30	1.00	2.00	2.00
06 *	0.30	1.00	3.00	2.00
07	0.60	2.00	1.00	2.00
08	0.60	2.00	2.00	2.00
09	0.60	2.00	3.00	2.00
16 *,**	0.30	1.00	3.00	2.00

Table 2: Average Infiltration Rates for the Heating Season (listed are the results for simulation #06)

House #***	Number of storeys	Average Infiltration Rate [$m^3/m^3\ h$]
ST 37	2	0.09
B 60	5	0.06
B 61	5	0.12
B 96	7	0.10
B 97	8	0.16
E 15	6	0.10
G 12	5	0.04
HH 15	15	0.11
HH 27	27	0.22
L 16	3	0.13
N 1	3	0.07
R 11	4	0.11
R 12	4	0.10
R 13	4	0.08
S 18	5	0.04
B 24	4	0.08
B 36	6	0.12
B 37	8	0.12

---

* Design conditions according to DIN 4701

** This version used a coastal climate

*** For house descriptions, see Reference 4)

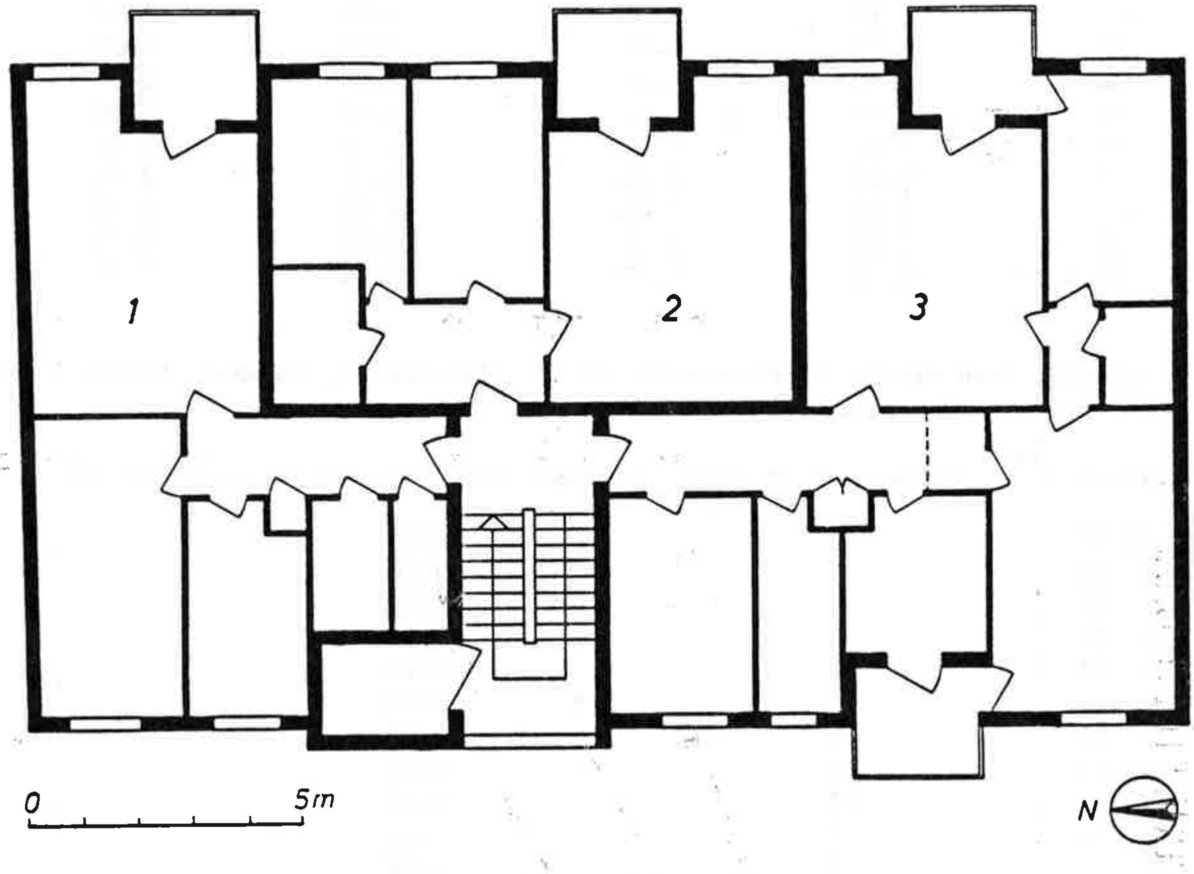


Figure 1: Floor Plan for Brunsbuettler Damm 37

Figure 2: AIR CHANGE RATES DUE TO INFILTRATION
BRUNSBUETTLER DAMM 37, FLAT #1

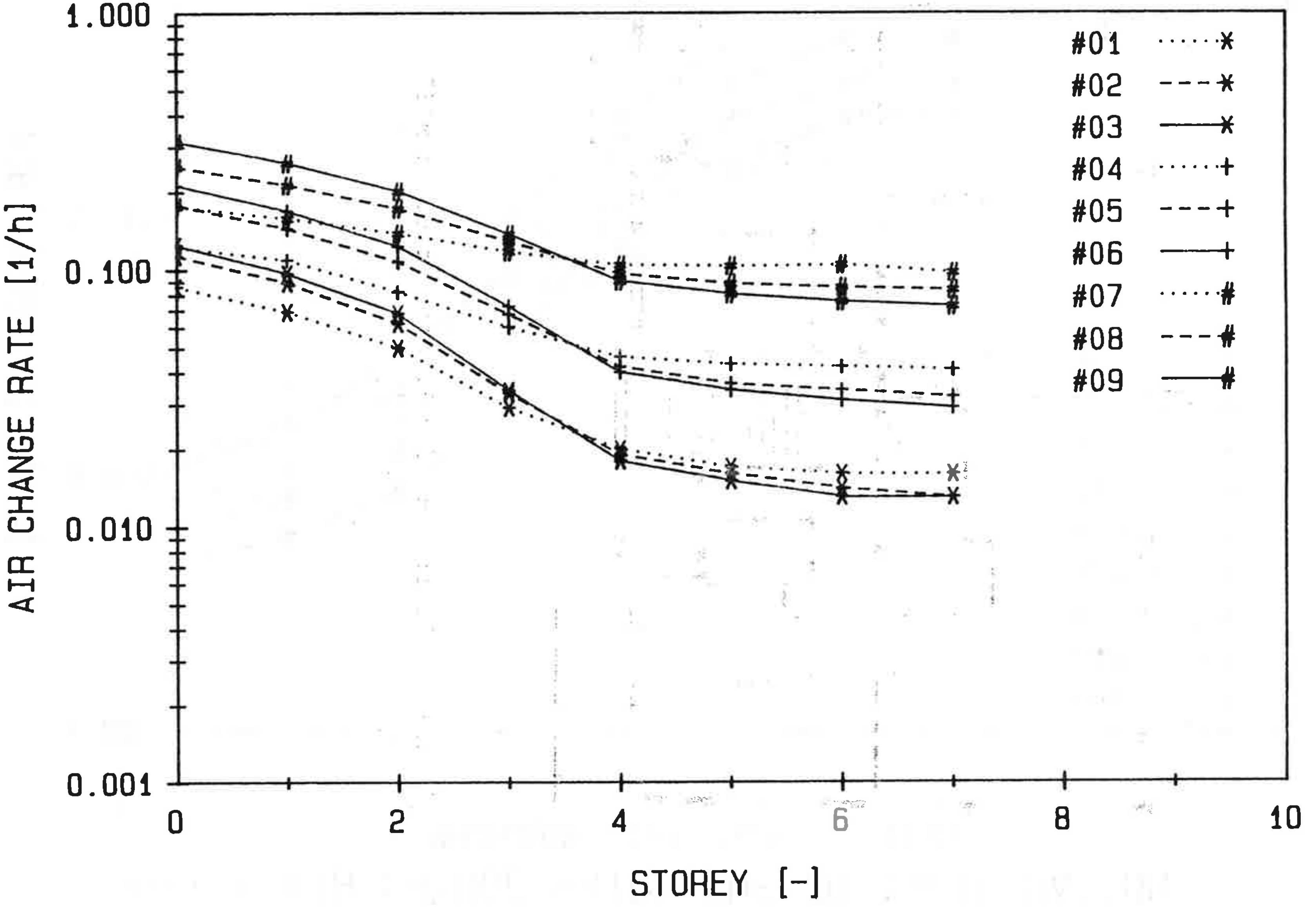


Figure 3: AIR CHANGE RATES DUE TO INFILTRATION

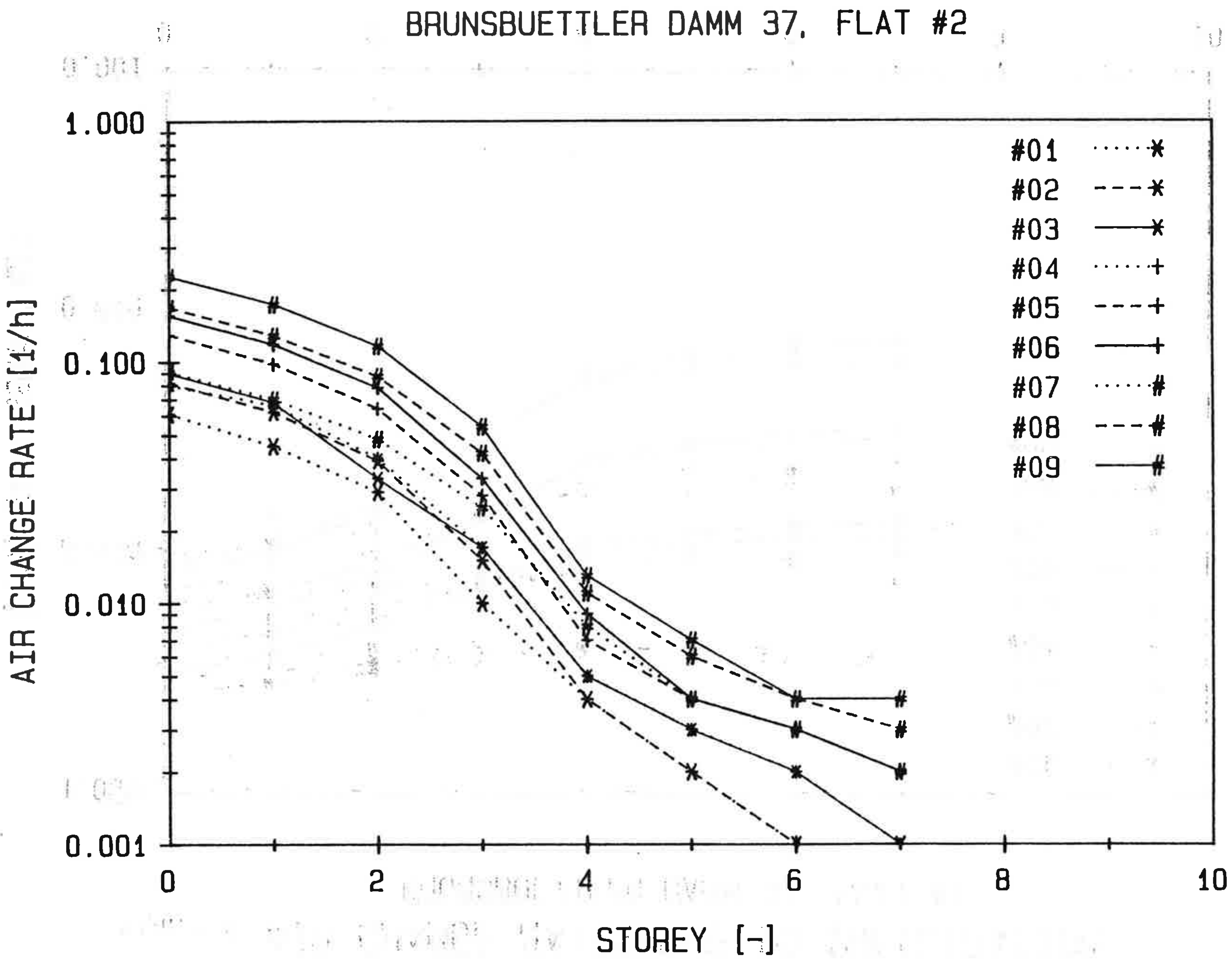
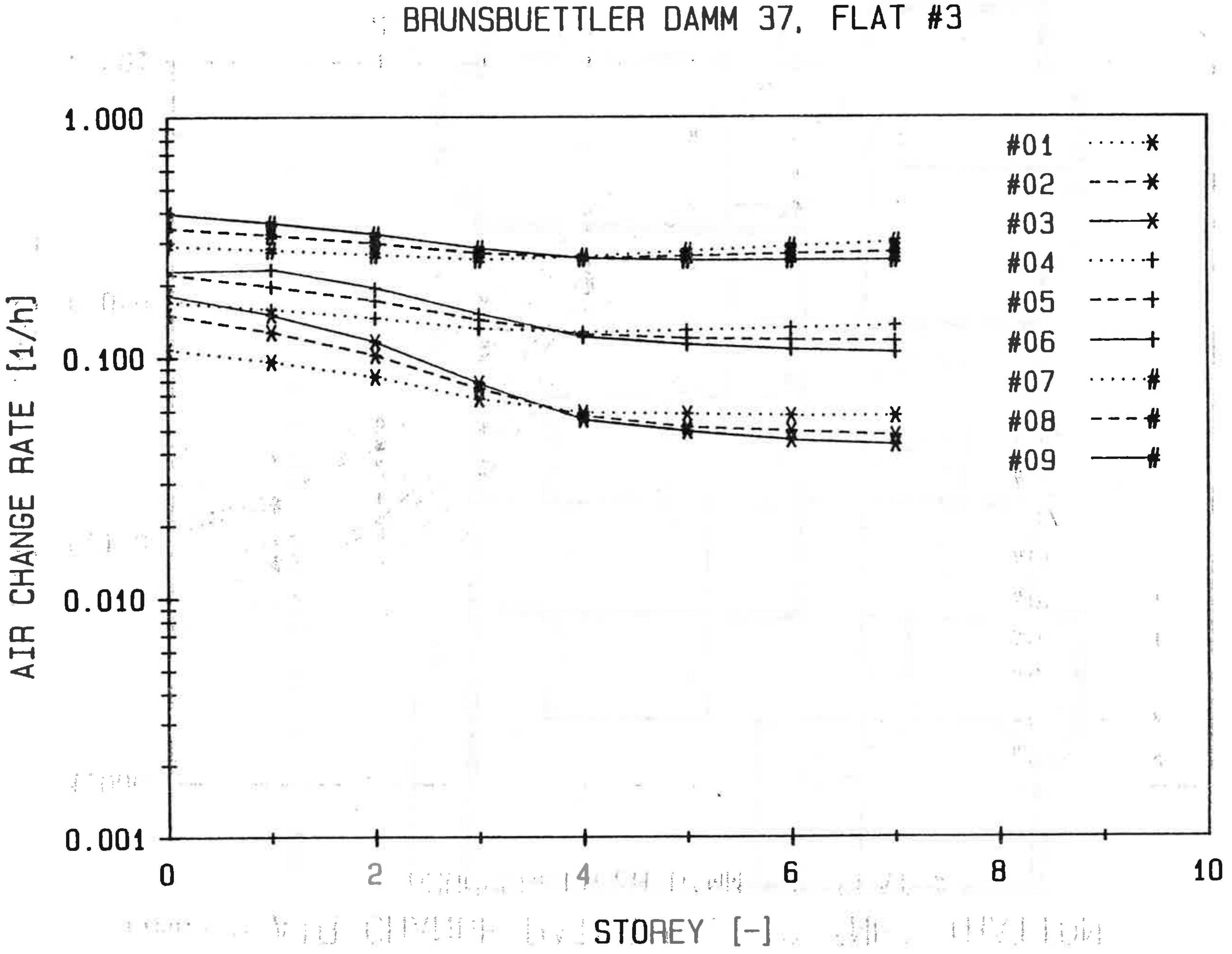


Figure 4: AIR CHANGE RATES DUE TO INFILTRATION



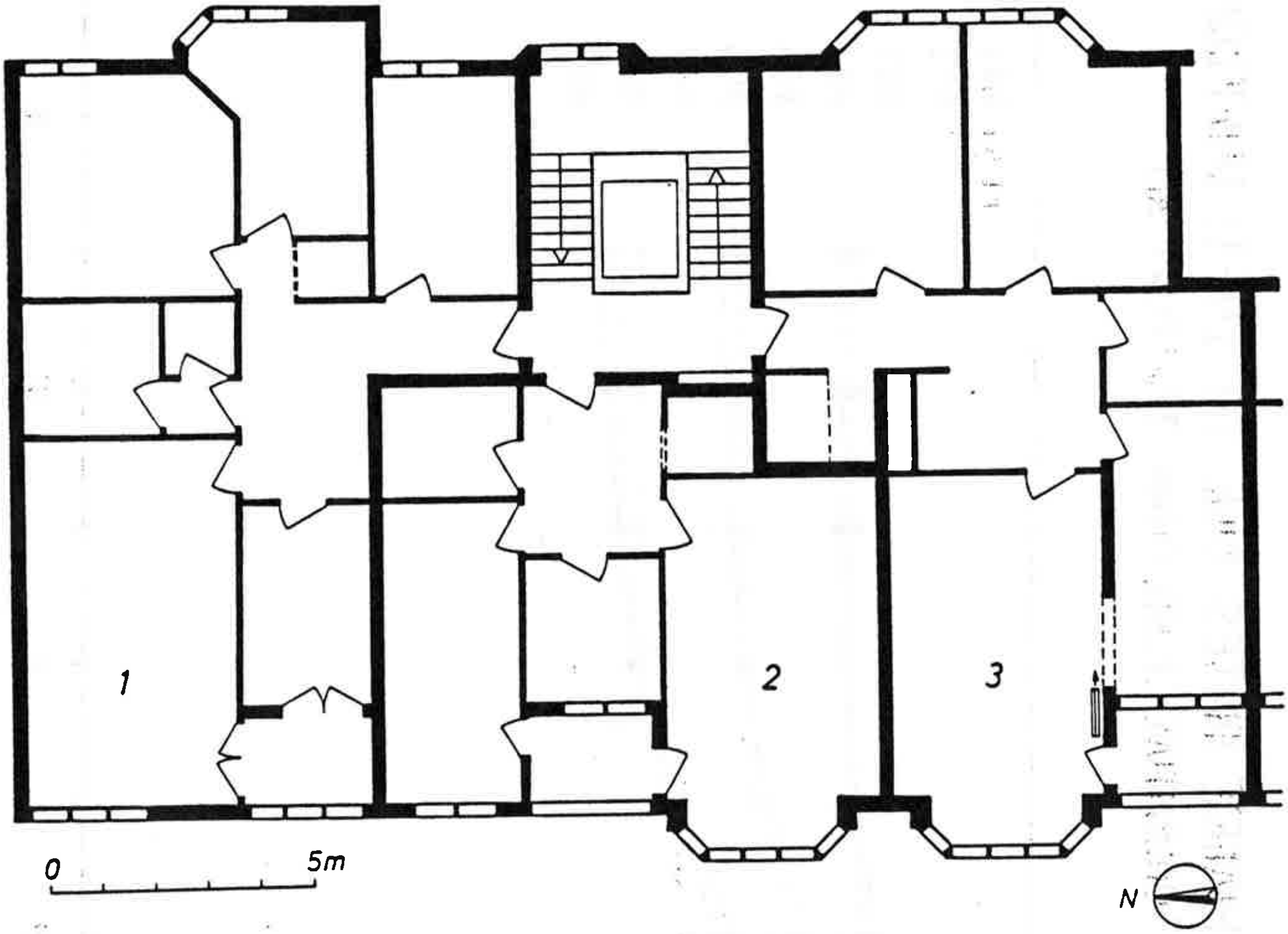


Figure 5: Floor Plan for Buelowstrasse 96

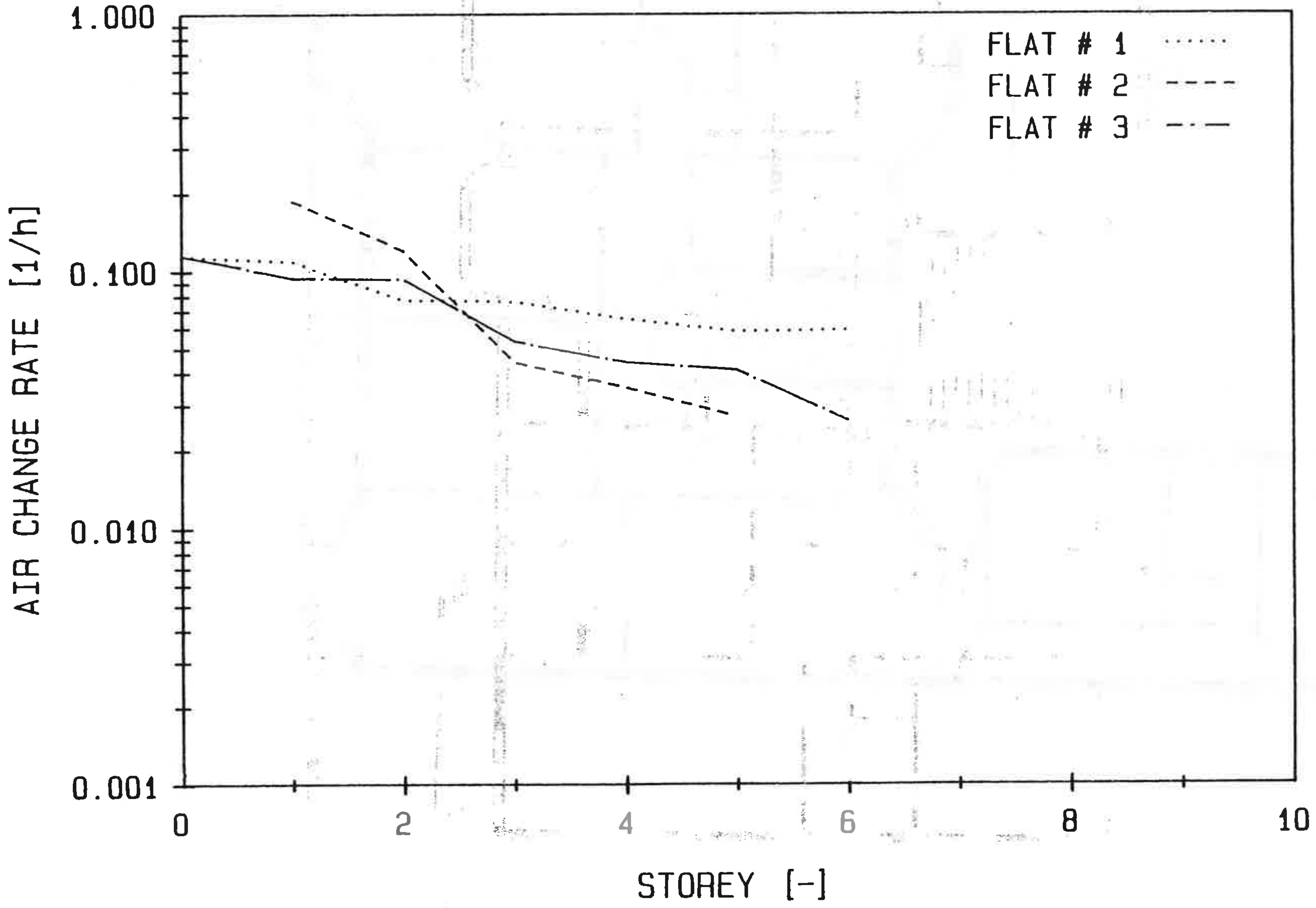


Figure 6: AIR CHANGE RATES DUE TO INFILTRATION
BUELOWSTRASSE 96, FLATS #1, #2 AND #3

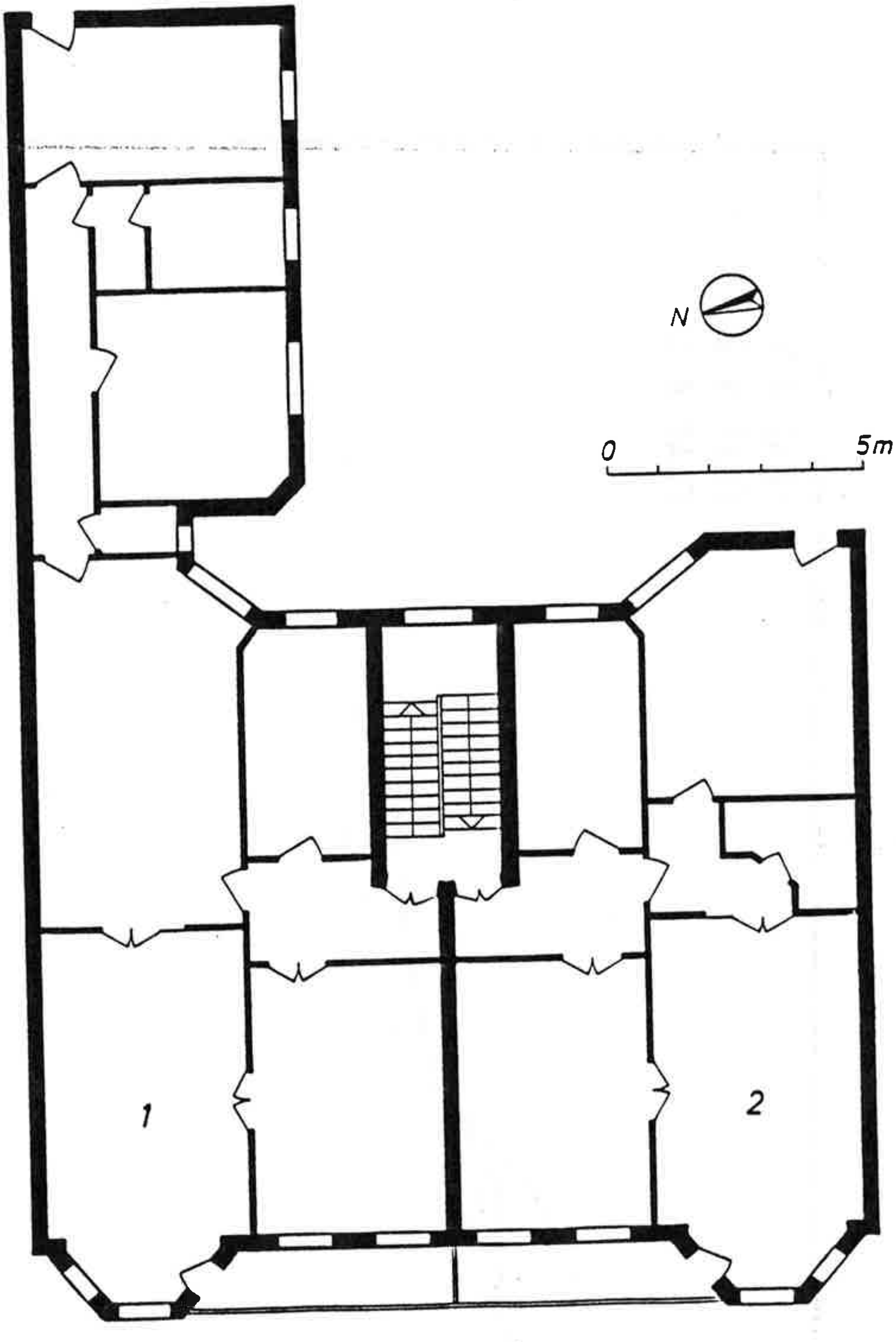


Figure 7: Floor Plan for Buelowstrasse 61

Figure 8: AIR CHANGE RATES DUE TO INFILTRATION
BUELOWSTRASSE 61, FLATS #1 AND #2

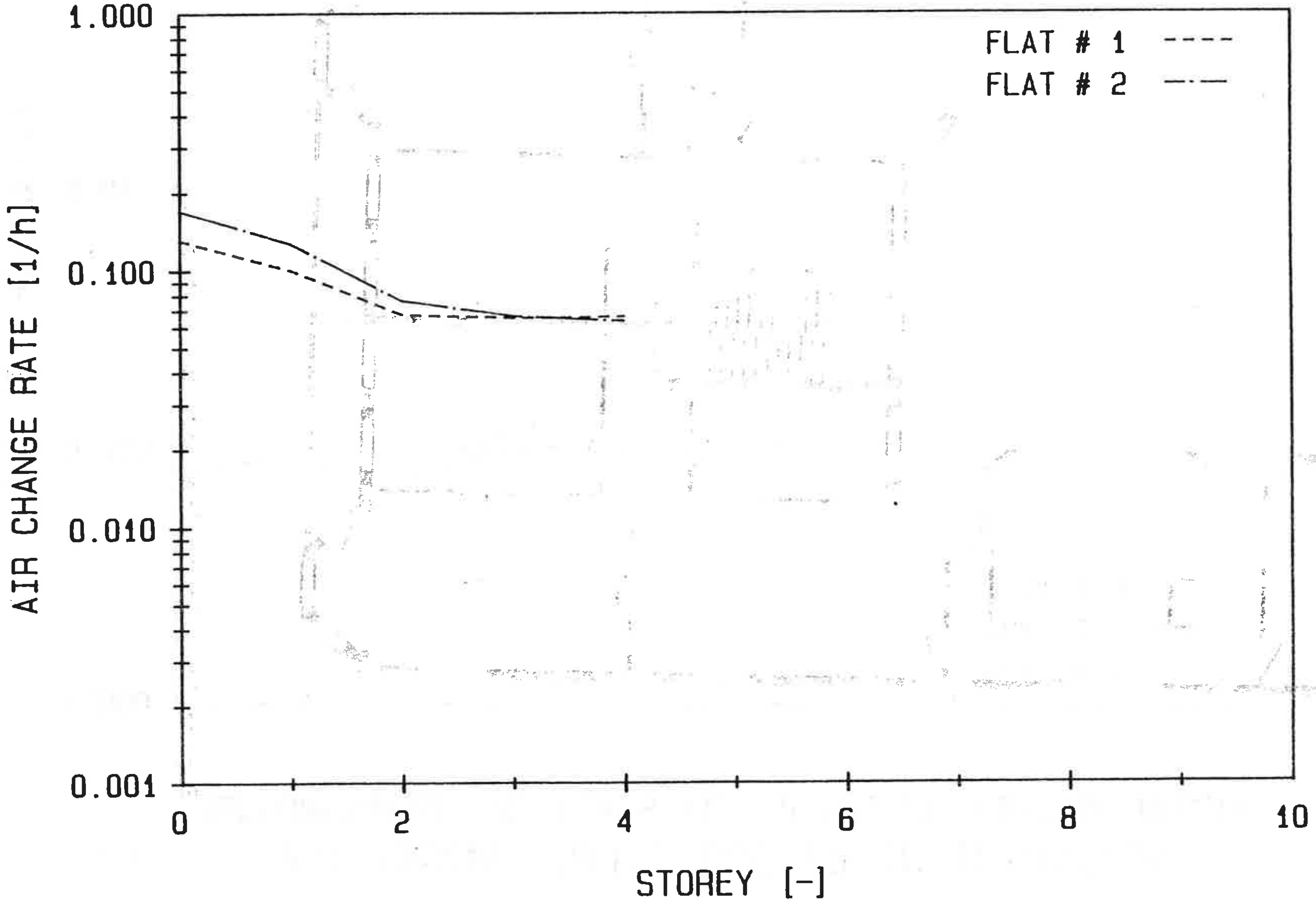
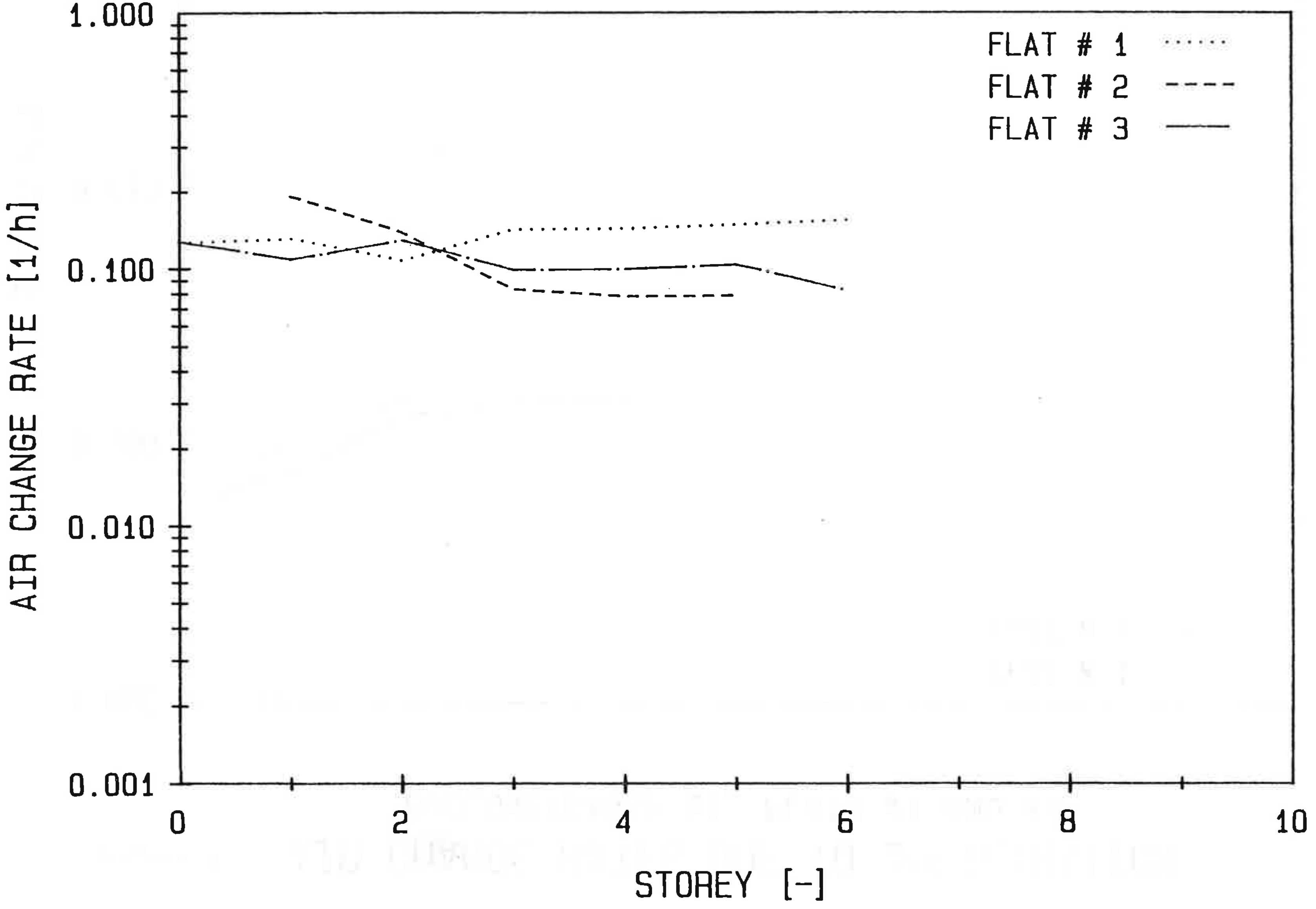


Figure 9: AIR CHANGE RATES DUE TO INFILTRATION
BUELOWSTRASSE 96, FLATS #1, #2 AND #3, COASTAL REGION



TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720