

ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING  
ACCEPTABLE INDOOR AIR QUALITY

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PAPER 3

VARIATIONS IN HOUSEHOLDERS' WINDOW OPENING PATTERNS.

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## SYNOPSIS.

The window opening survey was concerned with identifying the objective correlates of window opening. Preliminary analysis indicated that the number of openable windows in a dwelling was an important explanatory variable. Results showed that there were smaller differences in window opening levels between house types when the percentage of open windows was taken as the relative measure than when the absolute number of open windows was considered. It was found that the variation between households in terms of their total daily window opening was greater than that within households. It was suggested that householders adopted consistent window opening patterns, an hypothesis which received support from the finding of a strong positive relationship between window opening in different room types.

A potential model of window opening was proposed. On the basis of findings from the analysis of observed relationships between window opening in certain room types and selected weather parameters, it was hypothesised that although window opening was primarily a function of external air temperature, relative humidity and windspeed were influential at high values. It was further hypothesised that all households follow a similar curve of window opening against increases in temperature but that the threshold temperature marking the foot of the curve varies from household to another.

Analysis showed that the frequency distribution of the average percentage of open window observations in each household was skewed to the right. Thus, in order to test the model, households were divided into three groups (high, medium and low) on the basis of their window opening. Results showed that the relationship between temperature and the three groups was as predicted.

## THE STUDY.

The theoretical significance of ventilation increases as insulation standards improve. It is consequently important that householders' window opening patterns should be understood. The present window opening survey was therefore concerned with identifying the objective correlates of window opening as well as the subjective motivations for the opening and closing of windows. Householders were also asked about the effects of specified weather conditions in three room types in winter and summer. However, only the results of the observed data will be discussed in this paper.

## 1. METHODOLOGY.

### 1.1 The Sample.

The sample consisted of 113 households on two local authority estates in Middlesex (at Cowley N = 78, at Mezen N = 35). The houses were of similar physical construction but were of eight design types with different elevations and varying window arrangements. They all had partial gas central heating to Parker-Morris standards.

### 1.2 Data Sources.

The study made use of three main data sources; a series of systematic window observations, mean hourly meteorological data and a postal questionnaire.

#### 1.2.1 Window Observations.

All 113 households were surveyed on one day. This was repeated 100 times during the period from October 1979 to April 1980. The days and times were chosen in such a way that each house was surveyed twice at each hour between 9a.m. and 6p.m.. It is important to note however that the hours recorded as the hours of visit were not necessarily the exact times at which the observations were made. For example, an observation recorded as having been made at 3p.m. would actually have been made sometime between 3p.m. and 4p.m.. This was because on average it took twenty minutes to make a round of observations. A window was recorded as open if the bottom frame of the window was judged to be more than 1" away from the frame. A window was otherwise recorded as closed. When the 100 observations had been completed, the data were summarised to facilitate the analysis of window opening patterns in individual rooms. A count was made of (a) the total number of open windows and of (b) the number of open (i) sitting-room, (ii) kitchen and (iii) main bedroom, windows in each house on each day. The individual figures from each house were then summed to give the number of windows (total, sitting-room, kitchen or main bedroom) open on the estate for each of the 100 days.

#### 1.2.2 Mean hourly meteorological data.

Meteorological readings for five weather parameters - external air temperature ( $^{\circ}\text{C}$ ), relative humidity (%),

windspeed (knots), rainfall (mm), and sunshine duration (1/10 hour) - were obtained from the meteorological station at Heathrow Airport. The mean values recorded were for the sixty minutes immediately following the stated hour of observation.

## 2. ANALYSIS AND RESULTS OF THE OBSERVED DATA.

### 2.1 Basic Statistics.

#### 2.1.1 Household consistency.

The average daily number of total open windows,  
$$\frac{\sum_{\text{day } 1}^{100} (\text{TOTAL})}{100}$$

and the standard deviation about that mean, was calculated for each house. The number of total open windows for the observation period for the two estates combined has a mean of 1.27 (N = 113 households) and a standard deviation of 1.5 window observations. This figure is larger than the standard deviation of total daily window opening for most of the individual households (figure 1) indicating that the variability between households (in terms of their total daily window opening) was greater than that within households. This essentially means that while some householders did fluctuate in their window opening from day to day, they were still fairly consistent over the 100 days - some householders consistently opened only a few windows whilst others consistently opened several windows.

#### 2.1.2 The number of windows observed to be open in relation to the number of openable windows.

Figure 2 is a scattergram of the relationship between the number of openable windows in a dwelling and the total number of windows observed to be open in each house over the 100 days. The results of a Wilson Chi Square Test show a positive relationship between the number of openable windows in a house and the total number recorded as open ( $\chi^2 = 25.19$ ,  $df = 5$ ,  $p < .01$ ). This finding is taken to indicate that the number of openable windows in a house is a potentially important explanatory variable. It was therefore decided that results would henceforth be expressed as percentages. However, it must be noted that when the proportion of open windows in each house is used in a second chi square test, the results are still significant, though this time only at the 5% level.

### 2.1.3 Window opening in specified room types.

Table 1 gives the mean percentage of total open window observations on the two estates ( N = 100 days in each case). The mean percentage of open window observations in the three room types is also given. The table shows that on both estates the windows in the main bedroom were open more frequently than those in either the sitting-room or the kitchen. The sitting-room windows were seldom observed to be open.

### 2.1.4 Inter-relationships between window opening in different room types.

Householders have been shown to be fairly consistent in terms of their daily window opening (figure 1). Scattergrams showing the relationships between window opening in different room types were drawn - each diagram had 100 points marking the percentage of open windows in one particular room type against the percentage observed to be open in another room type on that day ( N = 100 days). Analysis of these diagrams indicates that householders' consistency extends across room types; that is, there is a strong positive relationship between window opening in different rooms. High and significant correlation coefficients were obtained for each scattergram confirming the hypothesis that householders adopt general window opening levels. However, it is important to note that these correlations do not necessarily indicate that windows in different room types are open simultaneously, though this may well be the case.

### 2.2 Relationship Between Window Opening and Weather Parameters.

Table 2 shows the correlation coefficients obtained between open window observations and weather parameter values at the hour of observation. The correlations between open window observations and external air temperature are highly significant and take high values for all room types on both estates ( 1 tailed test,  $df = 98$ ,  $p < .01$ ). The results for other weather parameters differ according to estate and room type. All the correlations for relative humidity are negative. Under a null hypothesis that relative humidity had no effect, this represents a probability of 1 in 256. Also, four of the correlations are highly significant. Similarly, the correlations for windspeed are all negative, though only one is highly significant. Seven of the sunshine duration correlations are positive, four are highly significant. However, there is no apparent relationship between rainfall and open

window observations on either state.

Third order polynomial fits of the open window observations for each room type against each of the five weather parameters were drawn. Examination of the curves for temperature ( figures 3 and 4) confirm that there is a strong positive relationship between window opening and external air temperature. Relative humidity rarely fell below 60%. Thus, the left-hand extremities of figures 5 and 6 cannot be relied upon. However, the suggestion of an upturn at the right-hand extremes are supported by examination of the original scattergrams (not given). Most of the recorded windspeed values were between 3 and 15 knots. Inspection of the curves in figure 7 within that range suggest a slight negative gradient for Cowley data only, and no relationship for the Mezen data. The original scattergrams (not given) show a wide range of open window percentages with a tendency for the points to converge at high windspeeds. The curves for sunshine duration at Cowley (not given) suggest a slight increase in window opening with sunshine duration, though no such increase is apparent at Mezen. Inspection of the polynomial curves for rainfall (not given) support the hypothesis that there is no apparent relationship between rainfall and window opening.

### 2.3 A Tentative Model of Window Opening.

Based on the analysis discussion of the previous section (2.2), a model of window opening is proposed. It is hypothesised that window opening is primarily a function of external air temperature and that relative humidity and windspeed are influential only at high values. Also, that for any individual household the temperatures occurring at the times when windows are opened are approximately normally distributed with the same standard deviations for all households but with means varying from one household to another ( figure 9). The model predicts that the percentage of open windows at given temperatures follows the cumulative normal distribution. It is a feature of the model that at extremely low temperatures all households will have no windows open, and similarly that at extremely high temperatures all households will have all windows open.

Window observations were restricted to a six month winter period. On the one hand the winter itself was mild and low air temperatures were rarely reached, with the result that some households had a few windows open on almost every observation day. On the other hand the omission of summer observations meant that few high temperatures were included in the data and window opening saturation was never reached. It is suggested that the observation period covers only the central portions of the curves as indicated in figure 10.

Figure 11 shows a frequency distribution of the average percentage of open window observations (over the 100 days) in each household (  $N = 113$ ). The distribution is skewed and covers almost the entire percentage range. In order to test the proposed model households were divided into three groups:

- a) a "low" group who tend to open a small proportion of their windows
  - b) a "medium" group of householders who on average open a moderate proportion of their windows, and
  - c) a "high" group who tend to open most of their windows.
- These three groups together comprise "all" households (  $N = 78$  and  $N = 35$  for Cowley and Mezen respectively).

As previously mentioned the 113 households fall into eight house types. The total number of windows opened (over the 100 days) by householders within a particular house type, were listed in descending order and divided accordingly into three groups, i.e the top, middle and bottom third. The high window openers from each house type were then collectively referred to as the "high" group, and similarly for the "medium" and "low" groups. Thus, each house type was represented as equally as possible in the three groups.

The curves generated by third order polynomial fits (figures 12 - 35) provide a test of the model.

Figures 12 - 19 provide tentative confirmation of the model outlined in figures 9 and 10. At the lower temperatures the curves for the low groups have the smallest gradients, those for the medium groups have a small positive gradient, whilst those for the high groups have a larger positive gradient. This is as predicted from the theoretical curves in figure 9. Indeed figure 12 suggests that at the lowest observed temperatures the high group will already have a proportion of windows open, followed respectively by the medium and low groups. This feature is confirmed by figures 15 and 19. All eight diagrams provide evidence of a strong positive association between window opening and external air temperature. There is one slight exception however - the downturn of curves in figure 17. These are due to only two data points drawn for days 1 and 99. The negative portions of the curve are therefore unreliable.

Figures 20 - 27 show the relationship between window opening and relative humidity in different room types for the high, medium and low groups. The polynomial curves for the three groups are approximately parallel. The three groups are composed of different individual householders and it is therefore unlikely that important factors other than weather parameters or factors correlating with weather parameters, produce similar window opening patterns. Thus the form of the three curves is taken as evidence for the reliability of a particular trend in window opening patterns.

S - shaped relationships between window opening and relative humidity are strongly present at Cowley, and to a



lesser degree in the three Mezen groups. The agreement in terms of curve shape between the room types for each estate could be explained by other factors - such as householders adopting general window opening patterns, with the decision to open one window increasing the likelihood of further window opening. However, it is difficult to explain the similarity shown by four out of the six graphs for separate groups except in terms of common influences, namely perceived changes in the weather. No explanation can be provided for the initial maximum point in these four sets of curves, although it must be noted that this maximum occurs between 40 - 60% relative humidity, and relies on a small number of points ( 10 and 9 points respectively for Cowley and Mezen). Nevertheless, the right-hand extremes of these curves are based on substantial numbers of data points. The upturn between 80 - 100% relative humidity may be attributable to the emergence of an awareness of relative humidity in this range, possibly associated in some cases with rain. The convergence of data points on the polynomial curve of the original scattergrams ( not shown) supports this suggestion of an increasing sensitivity to relative humidity with increases in relative humidity. The portions of these curves with a negative slope may reflect the association of relative humidity with temperature.

Figures 28 - 35 for windspeed show a peak followed by a decline in four out of six cases for the separate rooms. In all cases the curves include a substantial portion of negative gradient as windspeed increases. The one exception is for the Cowley high group where the upturn is based on one data point. No explanation can be offered for the existence of the maximum points. However, the negative gradient is consistent with the hypothesis that people close windows when windspeeds are sufficient to cause draughts or damage. In this connection a tendency for the data points to converge upon the polynomial curve of the original scattergrams ( not shown) suggests that the relative importance of windspeed increases with windspeed itself.

When considering sunshine duration and rainfall, the division of householders into three groups, reveals no common pattern and adds nothing to the earlier discussion.

TABLE 1      Mean percentage of open window observations at  
Cowley and Mezen

Estate	Mean percentage of open window observations			
	SIT	KIT	B1	TOTAL
Cowley	12.6	28.4	36.9	25.8
Mezen	10.0	21.7	23.8	18.1

TABLE 2      Correlation coefficients obtained between window opening  
in specified room types and weather parameter values at  
the hour of observation

Weather parameter	Estate	Room type			TOTAL
		SIT	KIT	B1	
Temperature	Cowley	.76**	.73**	.66**	.74**
	Mezen	.57**	.53**	.62**	.73**
Relative humidity	Cowley	-.20*	-.13	-.22*	-.23**
	Mezen	-.24**	-.07	-.31**	-.32**
Windspeed	Cowley	-.13*	-.23**	-.08	-.15
	Mezen	-.17*	-.12	-.09	-.17*
Sunshine duration	Cowley	.32**	.19*	.35**	.36**
	Mezen	.26**	-.13	.15	.12
Rainfall	Cowley	.17*	.15	.14	.14
	Mezen	-.08	.02	-.10	-.06

\*\* p < .01

\* p < .05

FIGURE 1  
Standard deviations of total open window observations  
for 113 households

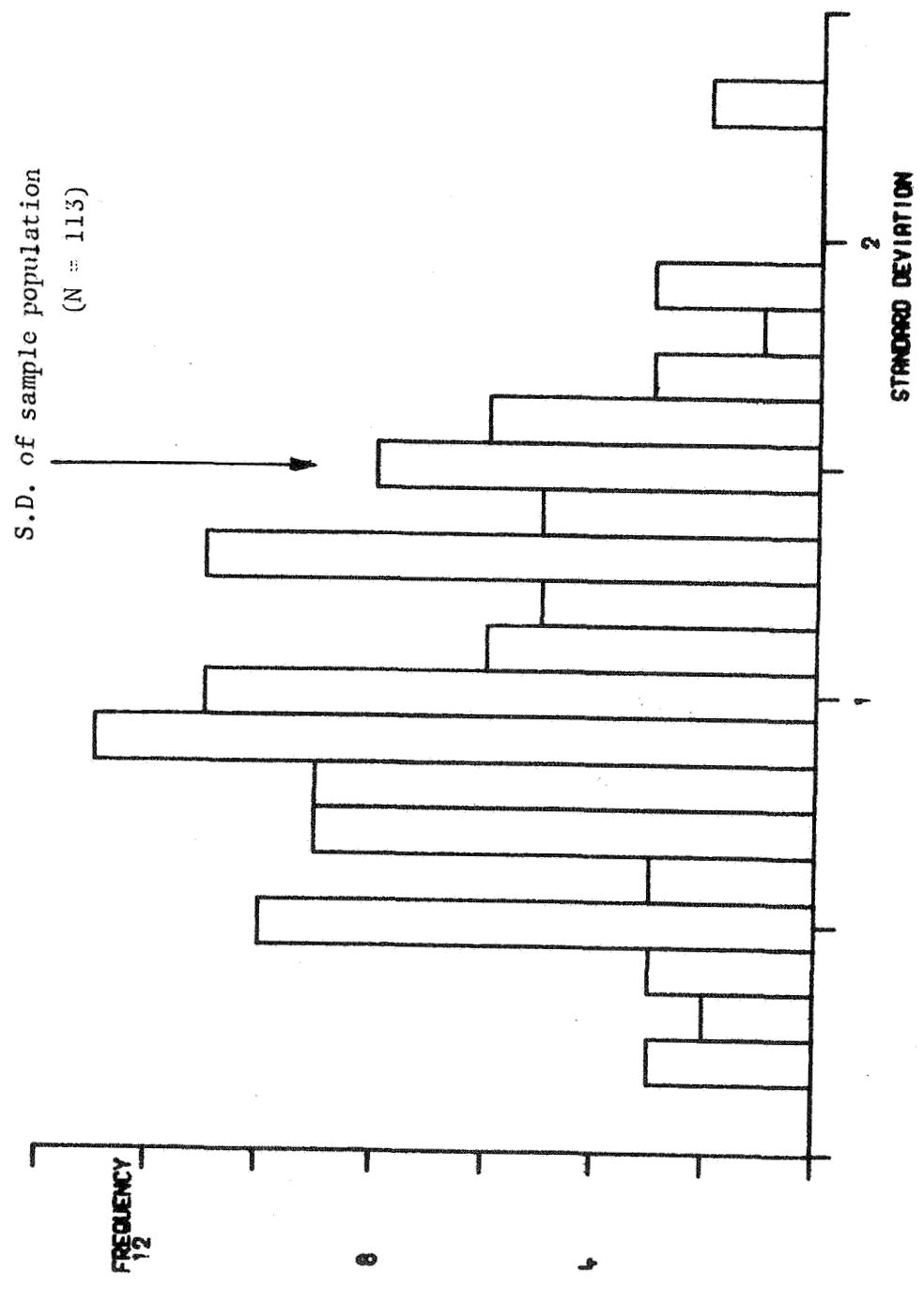
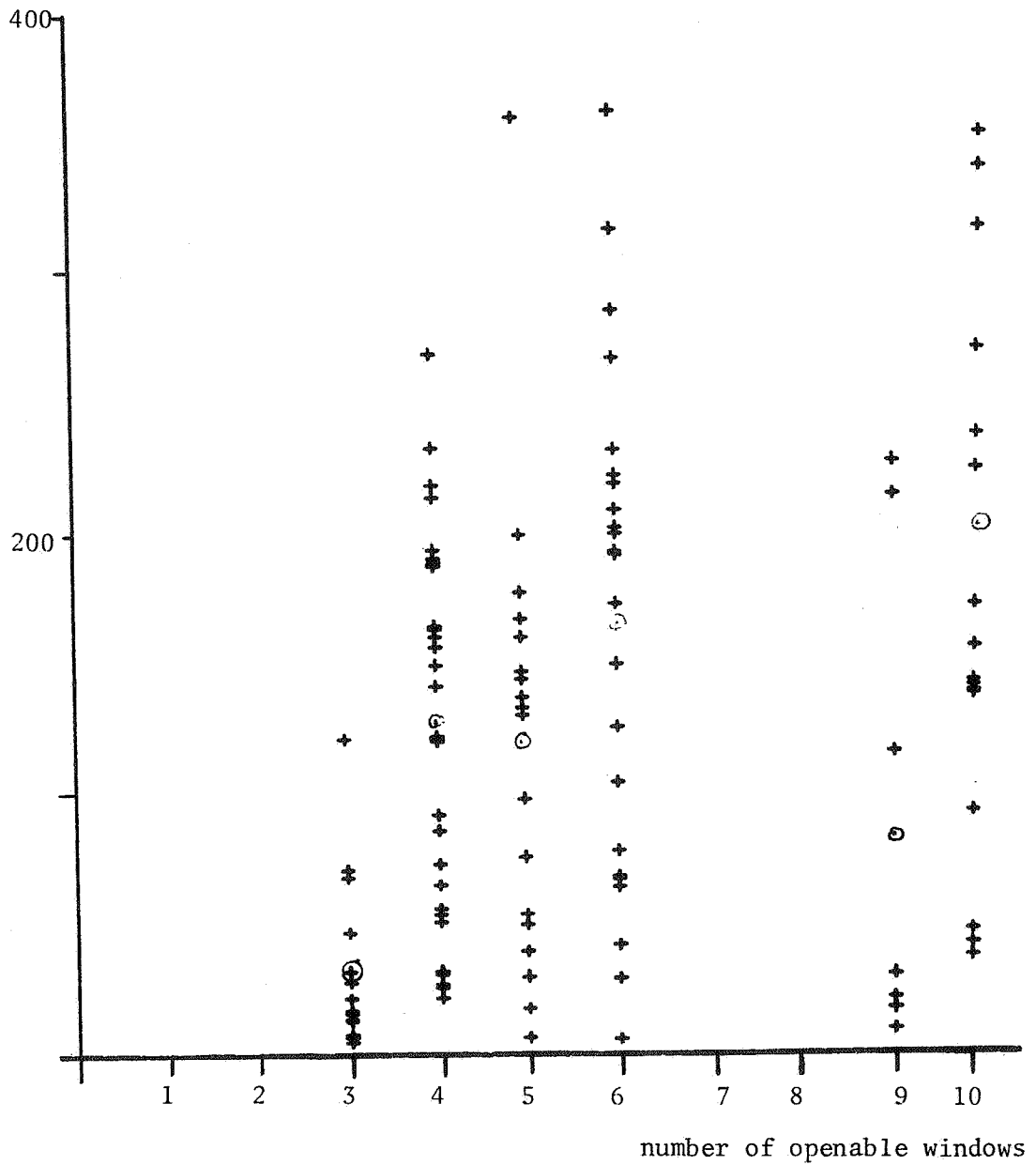


FIGURE 2

Relationship between number of openable windows and the  
number of total open window observations

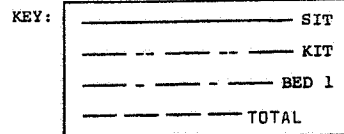
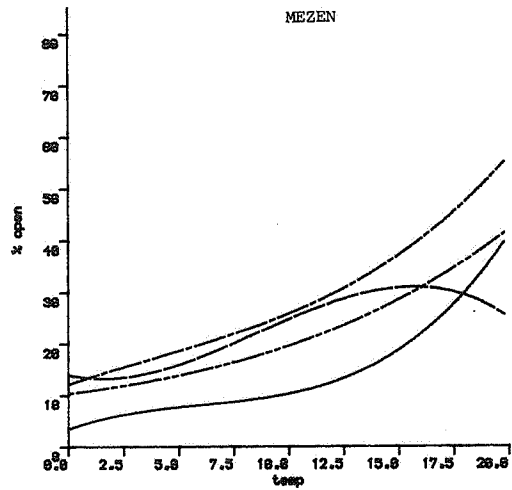
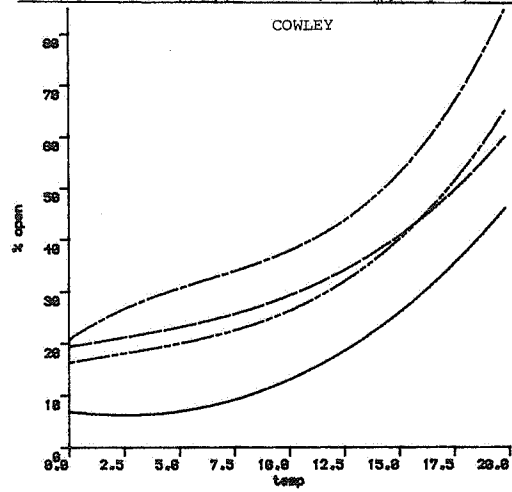
Total number of  
open windows over  
100 days



⊙ = mean of each group

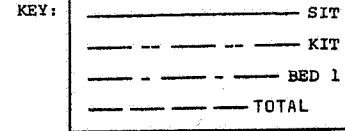
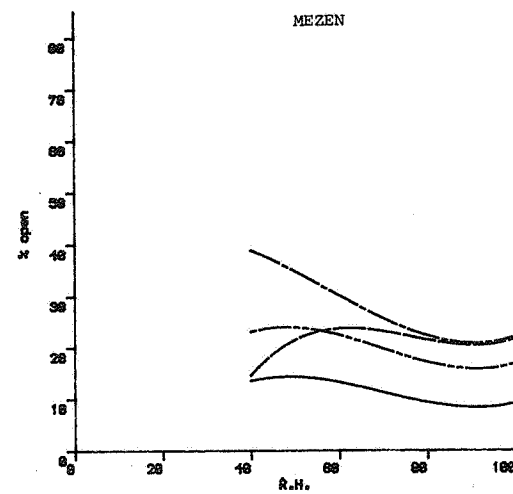
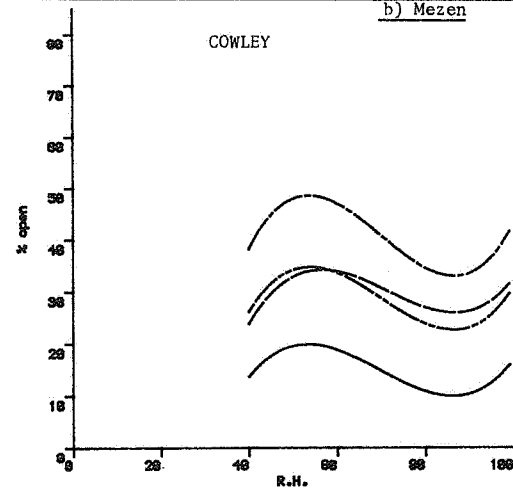
FIGURES 3 and 4

Relationship between temperature and window opening in specified room types at a) Cowley and b) Mezen



FIGURES 5 and 6

Relationship between relative humidity and window opening in specified room types at a) Cowley and b) Mezen



FIGURES 7 and 8

Relationship between windspeed and window opening in specified room types at a) Cowley and b) Mezen

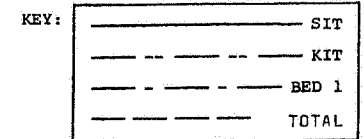
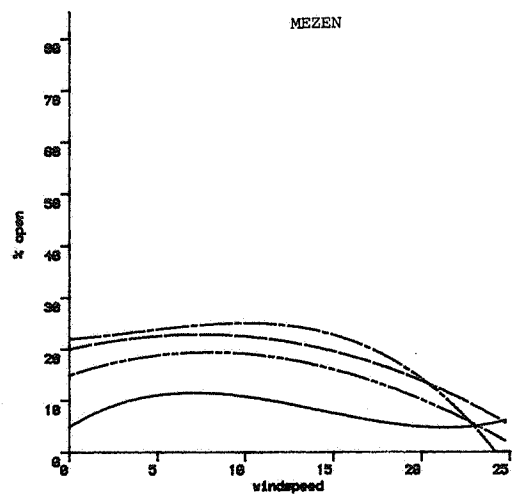
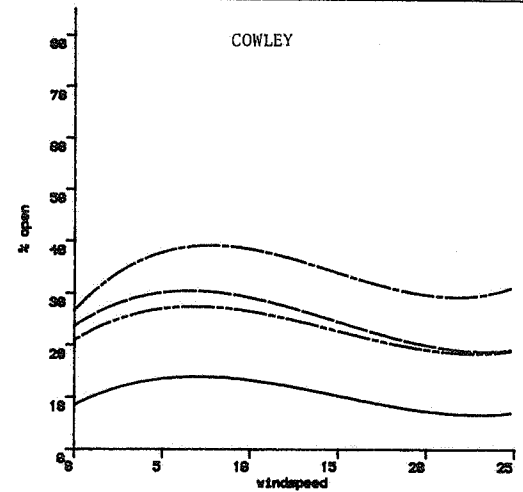


FIGURE 9      Illustrative normal distribution curves for two households

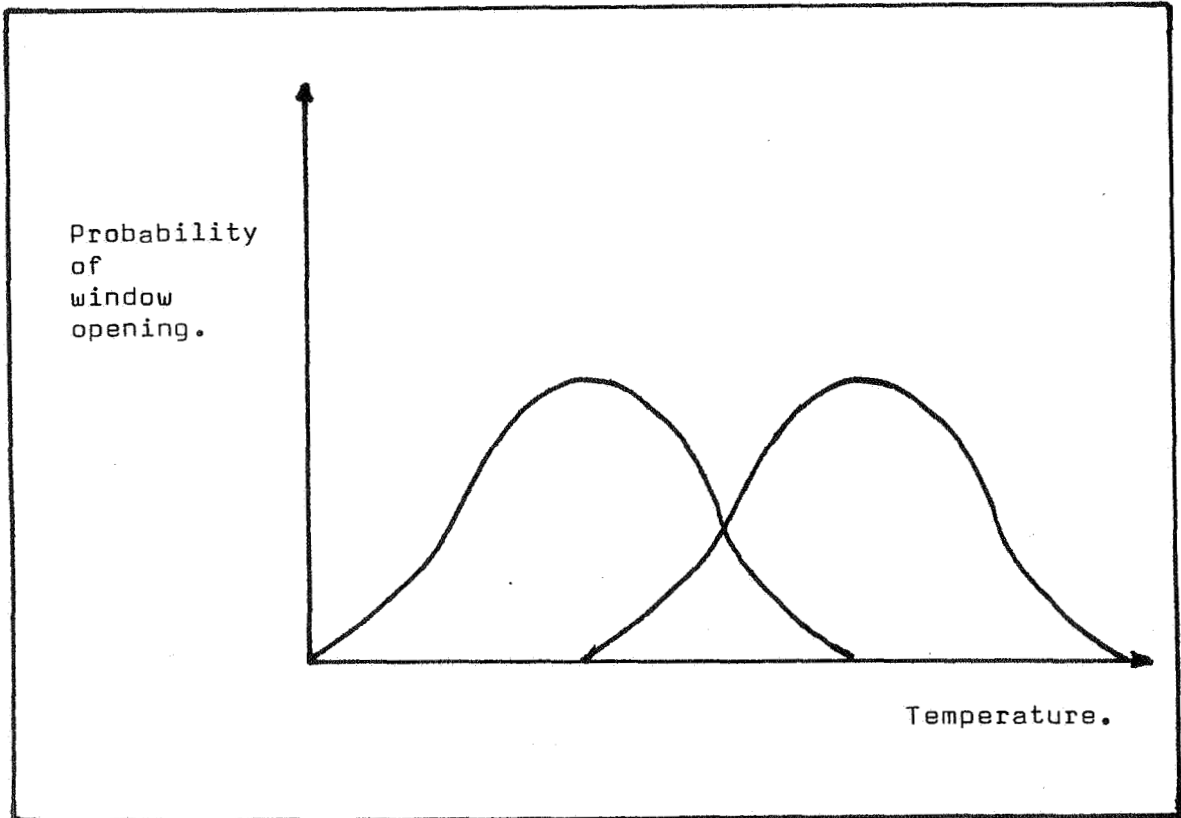


FIGURE 10      Hypothesised cumulative distribution curves for sample extremes

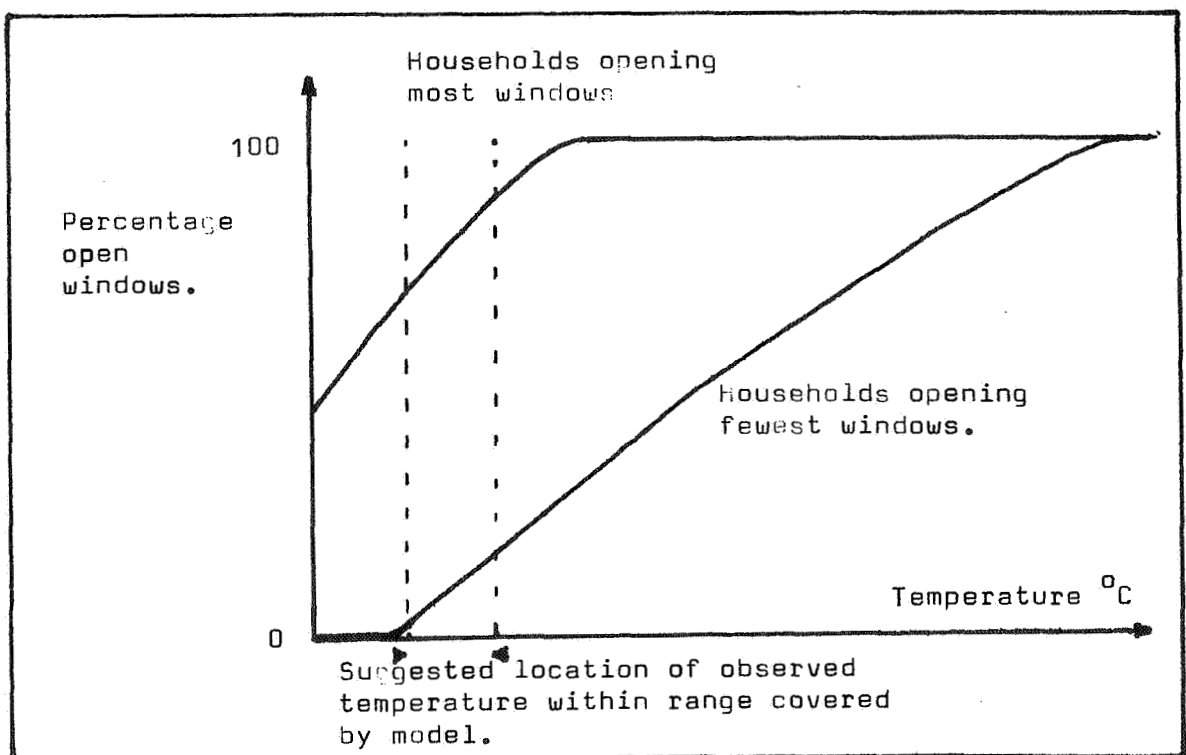
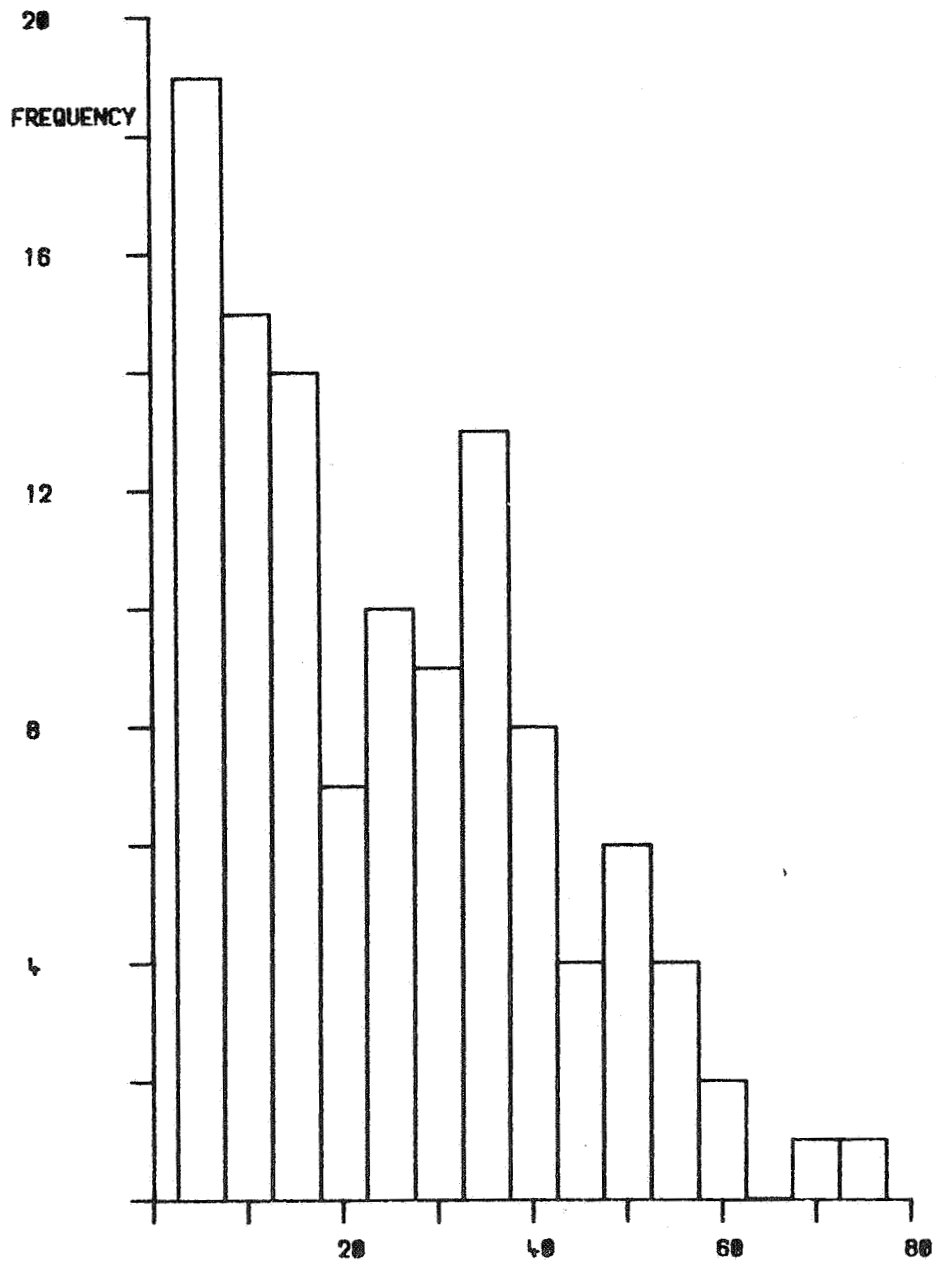


FIGURE 11

Frequency distribution of the average percentage of total open window observations in 113 households.

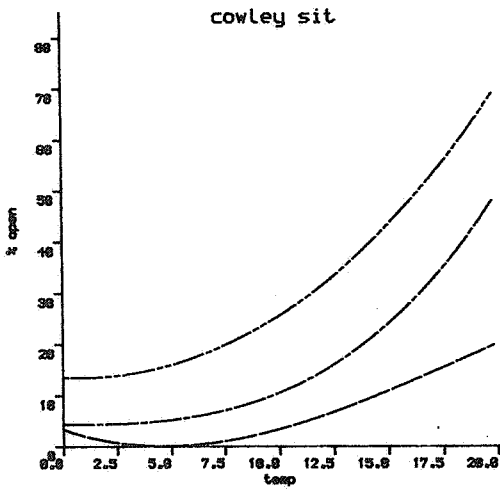
Number of households



Percentage of total open window observations

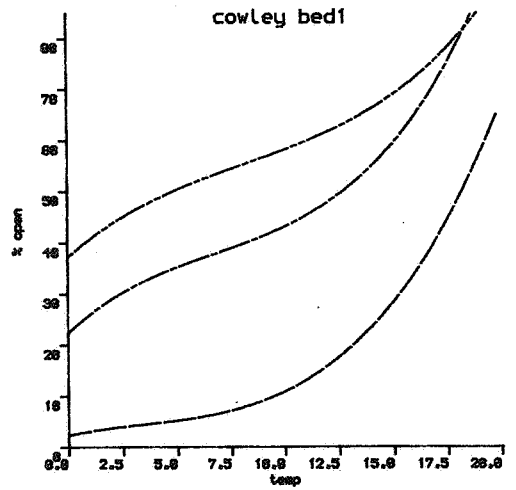
FIGURES 12 and 13

Relationship between temperature and window opening in three groups at Cowley

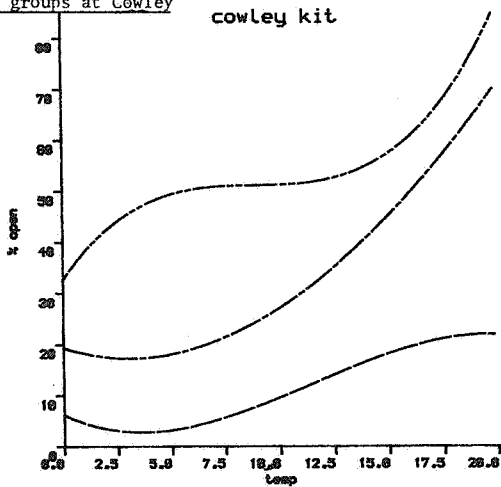


FIGURES 14 and 15

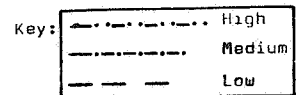
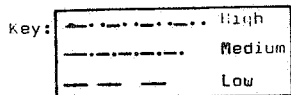
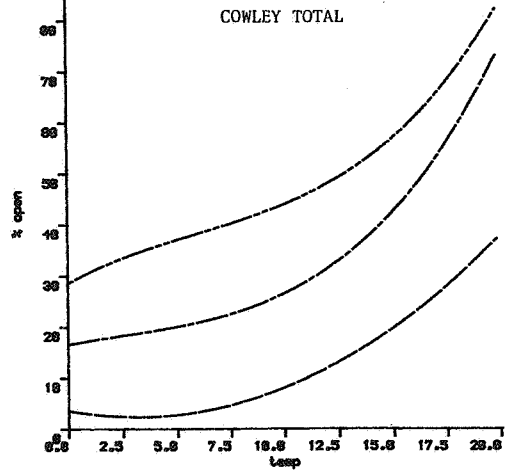
Relationship between temperature and main bedroom window opening in three groups at Cowley



Relationship between temperature and kitchen window opening in three groups at Cowley



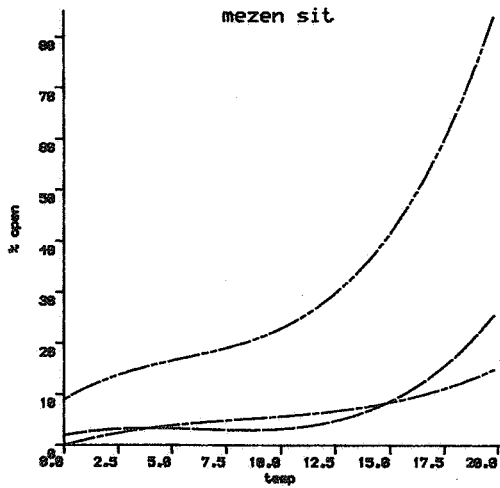
Relationship between temperature and total window opening in three groups at Cowley





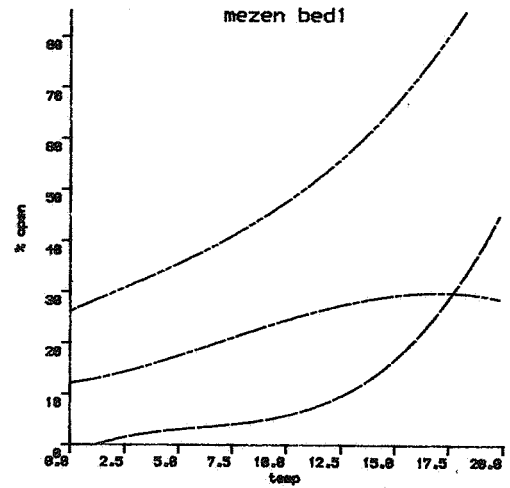
FIGURES 16 and 17

Relationship between temperature and sittingroom window opening in three groups at Mezen

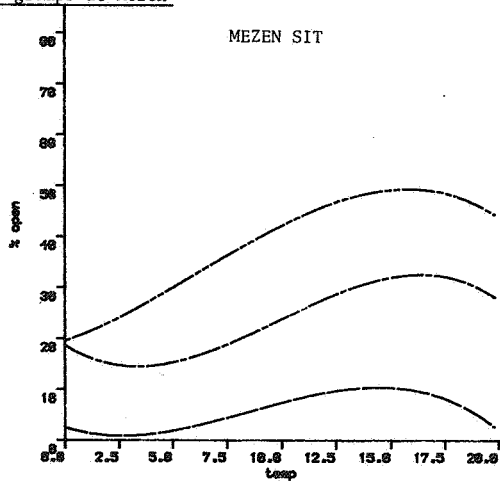


FIGURES 18 and 19

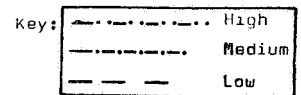
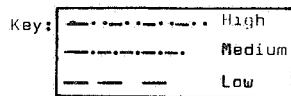
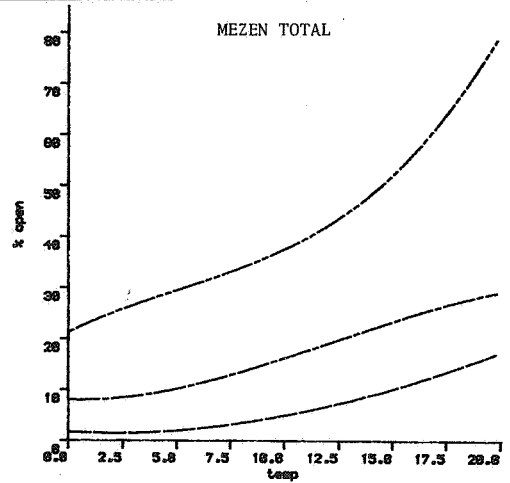
Relationship between temperature and main bedroom window opening in three groups at Mezen



Relationship between temperature and kitchen window opening in three groups at Mezen

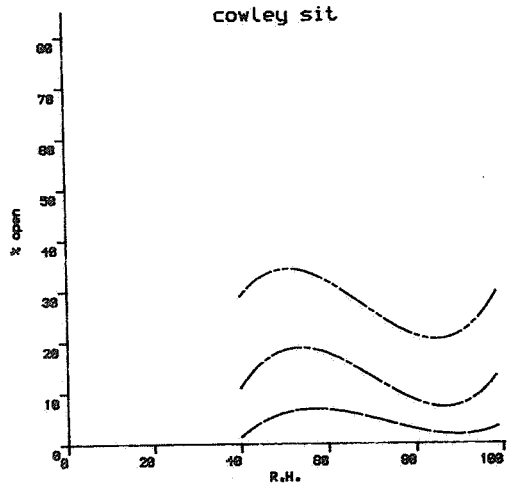


Relationship between temperature and total window opening in three groups at Mezen

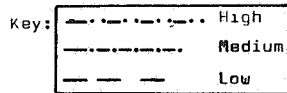
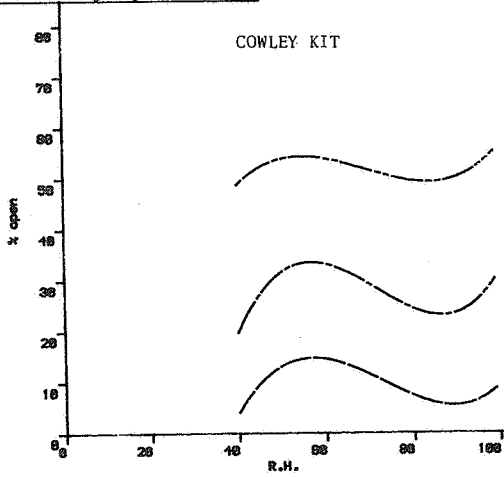


FIGURES 20 and 21

Relationship between relative humidity and sittingroom window opening in three groups at Cowley

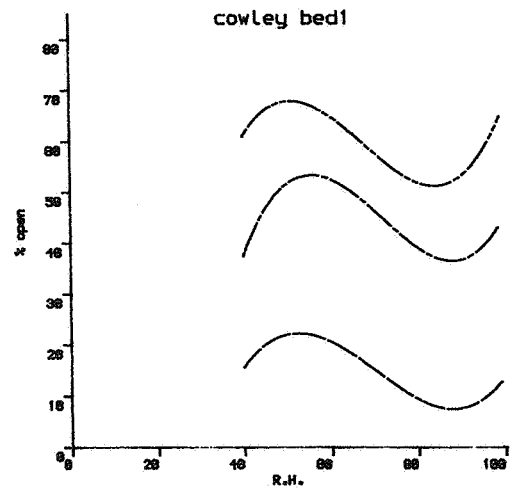


Relationship between relative humidity and kitchen window opening in three groups at Cowley

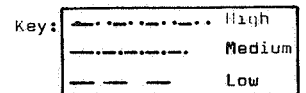
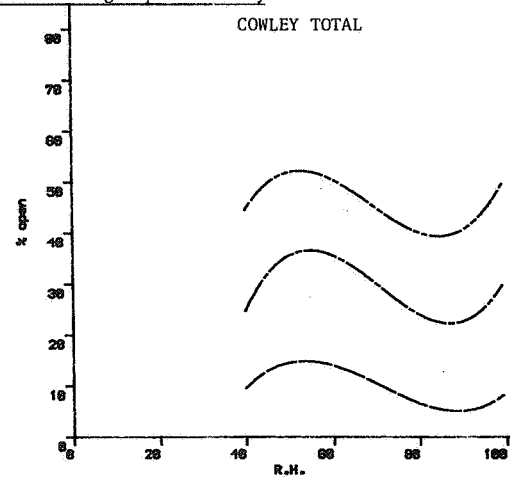


FIGURES 22 and 23

Relationship between relative humidity and main bedroom window opening in three groups at Cowley

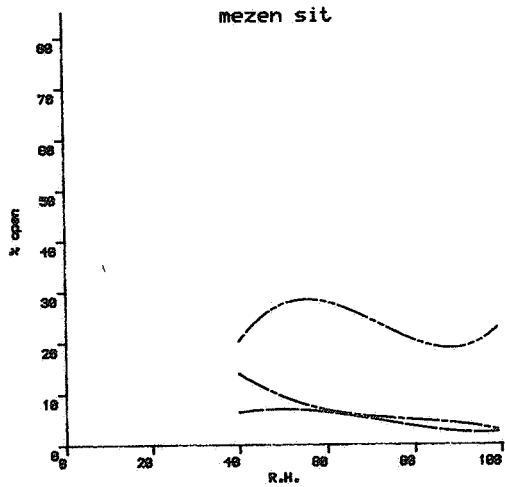


Relationship between relative humidity and total window opening in three groups at Cowley

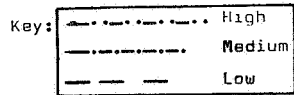
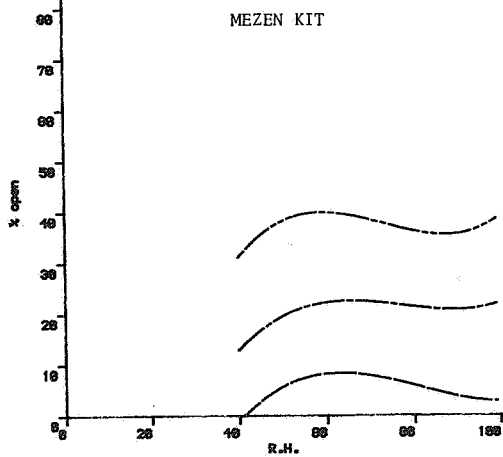


FIGURES 24 and 25

Relationship between relative humidity and sittingroom window opening in three groups at Mezen

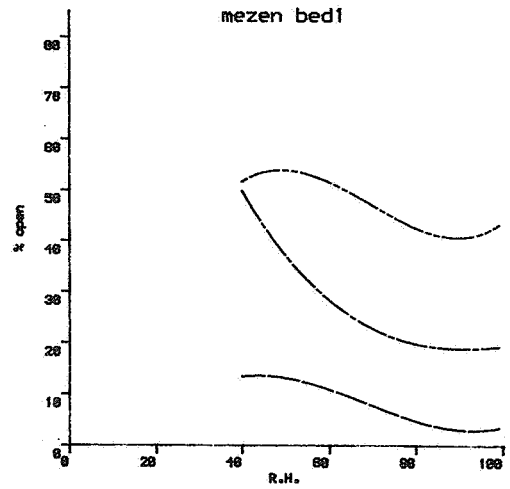


Relationship between relative humidity and kitchen window opening in three groups at Mezen

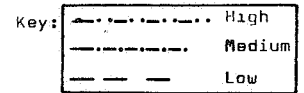
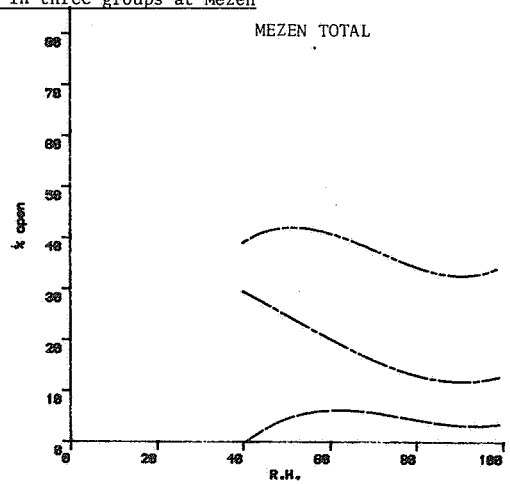


FIGURES 26 and 27

Relationship between relative humidity and main bedroom window opening in three groups at Mezen

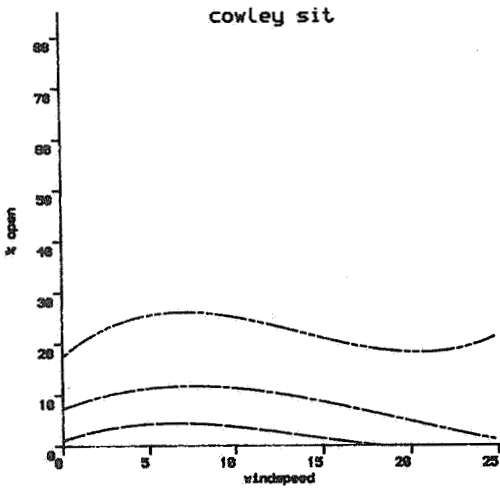


Relationship between relative humidity and total window opening in three groups at Mezen

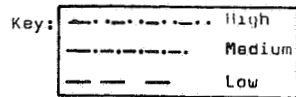
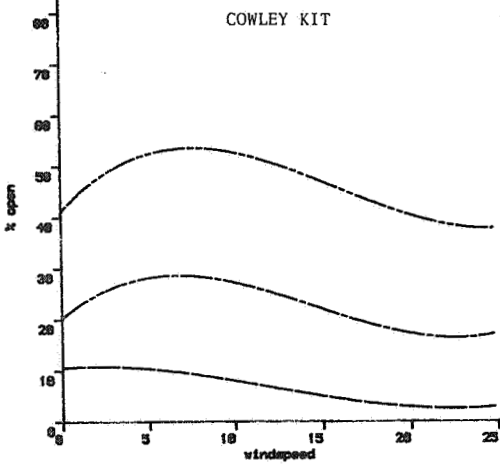


FIGURES 28 and 29

Relationship between windspeed and sittingroom window opening in three groups at Cowley

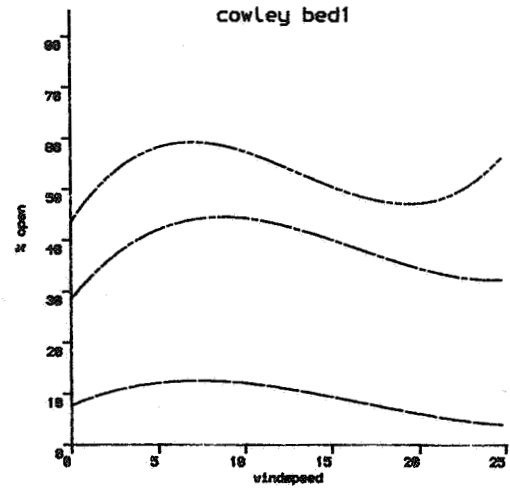


Relationship between windspeed and kitchen window opening in three groups at Cowley.

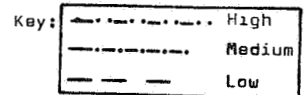
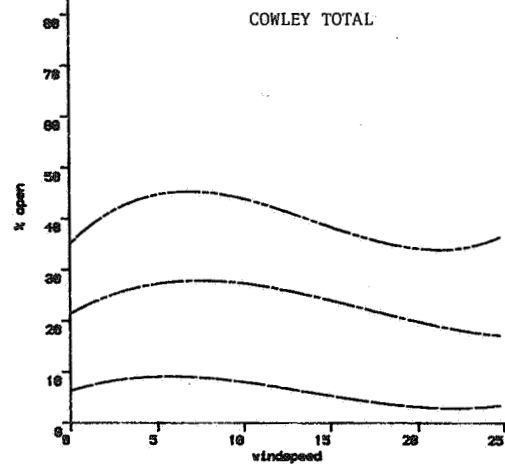


FIGURES 30 and 31

Relationship between windspeed and main bedroom window opening in three groups at Cowley

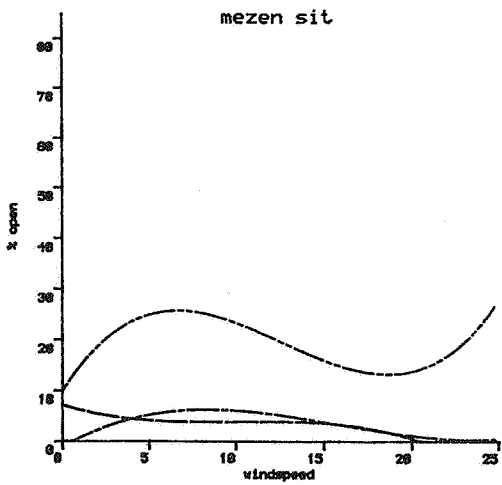


Relationship between windspeed and total window opening in three groups at Cowley

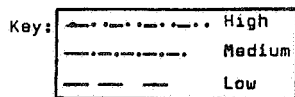
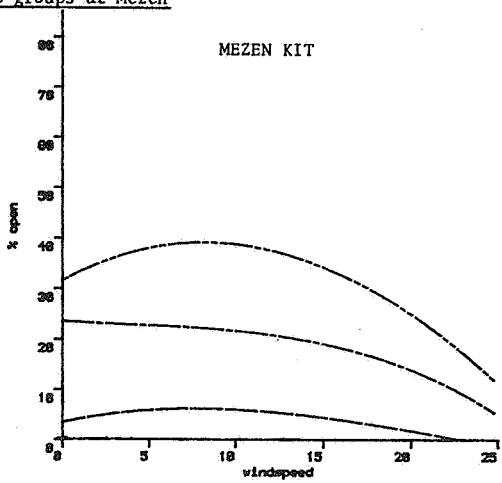


FIGURES 32 and 33

Relationship between windspeed and sittingroom window opening in three groups at Mezen

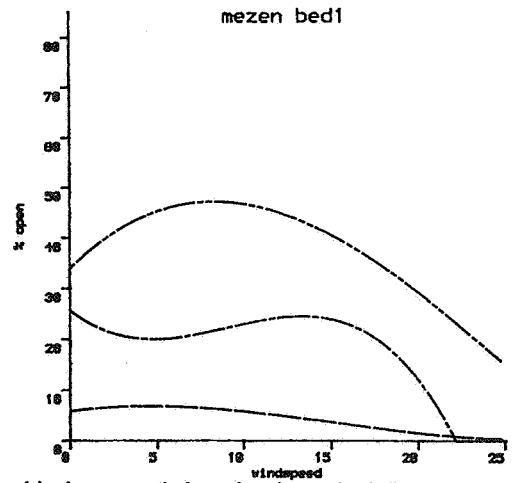


Relationship between windspeed and kitchen window opening in three groups at Mezen



FIGURES 34 and 35

Relationship between windspeed and main bedroom window opening in three groups at Mezen



Relationship between windspeed and total window opening in three groups at Mezen

