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Movers and Stayers: The Resident's Contribution to Variation across Houses in Energy Consumption for Space Heating*

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A general method is proposed that identifies the contribution of resident-dependent effects to the observed variability of energy consumption in similar houses. The method presumes that in addition to records of energy consumption over time, one has access to information about the date of change of occupants. For Twin Rivers data, the role of resident-dependent effects is seen to dominate the role of effects that depend on structural variations over which the resident has no effective control.

INTRODUCTION

One of the questions central to the Twin Rivers program is why there is so much variation in energy consumption across identical houses. The highest users of energy typically use at least twice as much energy as the lowest users, whether one looks at winter gas consumption (nearly entirely space heating) or summer electric consumption (about one-half air conditioning).

Looking at energy consumption data alone, one cannot distinguish between two alternative hypotheses concerning the observed variation in energy consumption: (1) variation is due to occupant behavior, and (2) variation is due to differences in nominally identical structures over which the occupant has no control. In the first category one would place interior temperature setting, opening of windows, deployment of drapes, and level of use of appliances. In the second category one would place missing panels of insulation, cracks in the structure, and defects in appliances.

Should one of the two hypotheses be strongly verified and the other strongly rejected, the significance for public policy is clear. If occupant behavior is dominant, one concentrates attention on the residents, clarifying by research and subsequent publicity the kinds of actions that have energy penalties and savings and their magnitudes. If nominally identical units are structurally far from identical, however, one concentrates one's attention on quality control at the time of construction (on energy performance standards), and on periodic on-site inspections of building performance.

Our data tend to confirm the first hypothesis at Twin Rivers — the resident rather than the structure creates most of the observed variation in consumption. There is little reason to believe that this result generalizes to other communities however, without considerable further testing. What we put forward here is a *method* to distinguish the contribution of resident and of structure, one that can be applied whenever one has, in addition to data on energy consumption, data about where and when there has been a change of occupant (typically a sale or change of tenant, often coded directly in utility records).

The general strategy is to examine the changes in energy consumption of a sample of houses for which a change in ownership occurs. Such houses play a role similar to

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identical twins in heredity–environment studies. In practice, this means choosing two winters between which the occupants of a sizeable number of houses have changed. If the energy uses of this sample, the "movers", correlates well from one winter to another, one would have evidence pointing to the likely role of construction quality in creating variability in energy consumption. However, if the movers' consumption in the first winter does not correlate at all with the consumption in the second winter, all variation in energy use would be attributed to the differences among occupants.

Also analyzed in the same way is another sample of houses without change in ownership (the "stayers"), a control group of sorts. Correlations performed on this sample show that time-dependent effects play a noticeable role in the variation in energy consumption between houses, and we have tried to model these effects.

It is useful to elaborate on the fundamental idea behind this analysis of movers and stayers, before the description of the actual data manipulation. Consider the energy consumption of nominally identical houses (same floor plans) in two winters with perfectly identical weather conditions. If the energy-related behavior of the occupants in each house were equally identical from one winter to the other (but not to each other), we would expect each stayer house to use the exact same amount of heating energy in both winters. The only differences in consumption would occur among houses, not between the two winters.

In the case of the movers, the occupants of each house have changed from one winter to the other and energy related behavior is likely to be different. If, nonetheless, each mover house used the same amount of heating in both winters, like the stayers, we would conclude that occupant behavior is not a relevant factor influencing energy consumption. Any variation in energy use among houses would have to be attributed to hidden structural differences between the nominally identical units. If, in turn, high users in the first winter became randomly low, middle or high users in the winter following the move, with no apparent correlation, we would attribute the cause to the change in occupants and deduce that differences in occupant behavior, not hidden structural differences, are responsible for the observed variation in energy use among nominally identical houses.

The actual data, as can be expected, are more complex than either of these extreme cases. The weather conditions in the two winters under consideration are not identical and neither are the houses. To complicate matters further, the 1973 oil embargo occurred between the two winters. Even when the data are corrected for these effects, the movers' consumption patterns do not fit precisely either of the two extreme scenarios sketched above. They do, however, resemble more closely the scenario of random change in consumption levels after a move, rather than that of constant consumption levels. This leads to the conclusion of this paper that the variation among occupant behavior is the chief cause for the observed variation in gas consumption among houses. An interesting deviation from the ideal case described earlier is displayed by the stayers: their individual consumption levels do not remain exactly constant, in other words, some "crossover" between houses occurs, indicating that consumption patterns change in time even if both house and occupants remain the same.

The quantitative derivation and subsequent discussion of the above effects, the methods to correct for unequal weather in the two winters and for houses of more than one type: these are the topics treated in this paper.

The energy consumption data of movers and stayers were previously studied by Lawrence Mayer and Jeffrey Robinson, following the suggestion of Robert Socolow. Mayer and Robinson showed that a significant difference exists between movers and stayers, when comparing the change in individual consumption from one winter to another, in a non-parametric statistical investigation [1]. In this article, a parametric approach will be formulated and quantitative results derived that assign the causes of the variation in energy consumption between "identical" houses.

DESCRIPTION OF THE DATA

Meter readings of gas and electricity consumption from public utility records have

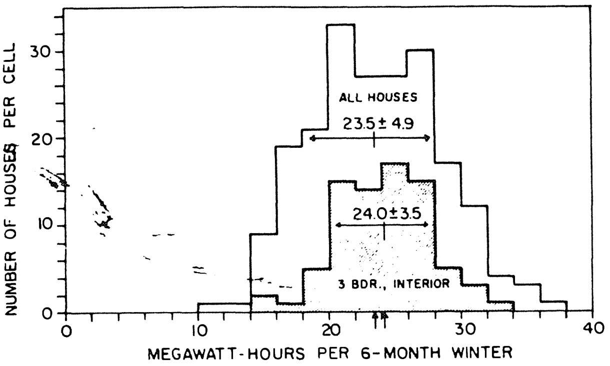

Fig. 1. Histogram of 1971/1972 gas consumption.

been collected over a period of several years for most houses in the four quads of Twin Rivers. For this analysis the 248 townhouses located in quad 2 have been selected. They are arranged in blocks of up to ten units facing each of the four compass directions. As only the furnace runs on natural gas in these houses, the monthly gas consumption readings* directly indicate the energy used for space heating. The distribution of gas consumption in the 6-month winter season (November–April) of 1971/72 is shown in Fig. 1 for a sample of 205 townhouses selected for this study. The consumption of highest and lowest users are more than a factor three apart. The standard deviation is 22% of the mean. A sizable portion of this variation can be ascribed to the different physical features of the house. Aside from the number of bedrooms, by physical features we intend such "obvious" design differences as double pane *versus* single pane windows and an extra end wall (for end units). Among all physical features tested, these have been shown to be the only statistically significant factors [1].

The first two rows of Table 1 display the main statistics of the gas consumption of the full sample of 205 houses and of three subsamples of two, three, or four-bedroom, interior units with all-insulated glass. The means of the distributions decrease with diminishing number of bedrooms and decrease in the second winter, compared to the first, a consequence of 12% conservation and 5% milder weather [1]. Conservation and dependence on weather, though interesting topics by themselves, are not the subject of this paper. To eliminate the effect of these factors, the gas consumption in the second winter is adjusted "across the board" by multiplying all 1973/74 data with the ratio of the means of both winters, 1.182; the results are shown in the bottom row of Table 1, in the units implicit to the rest of this paper: "constant 1971/72 MWh per 6-month winter".

Implied in this correction is the assumption that the variation in gas consumption is proportional to the level of consumption, *i.e.*, that the standard deviation is proportional to

*The original readings are in units of hundreds of cubic feet of natural gas, corresponding to 102,500 Btu or 30.04 kWh or 108.2 MJ. The unit chosen in this article is MWh (1 MWh = 3.6 GJ).

TABLE 1

Gas consumption (MWh per 6-month winter) statistics in two winters of the full sample and of subsamples with two, three and four-bedroom interior units with insulated glass

		Full sample (N = 205)	X-bedroom interior units with insulated glass		
			X = 2 (N = 32)	X = 3 (N = 45)	X = 4 (N = 16)
1971/72	Mean	23.46	17.69	23.77	25.49
	Standard Dev.	4.89	2.44	3.84	3.99
	Coeff. of Var.	0.209	0.138	0.161	0.156
1973/74	Mean	19.85	14.00	20.31	22.56
	Standard Dev.	4.60	2.13	3.29	2.74
	Coeff. of Var.	0.232	0.152	0.162	0.122
1973/74 adjusted*	Mean	23.46	16.55	24.01	26.67
	Standard Dev.	5.44	2.52	3.89	3.25
	Coeff. of Var.	0.232	0.152	0.162	0.122

*1973/74 values multiplied by the ratio of the means 23.46/19.85 = 1.182.

the mean. The same assumption will be used in a future section, when correcting for variations caused by differing house features. The proportionality of individual gas consumption to degree-days tends to support this assumption: as the weather gets colder, the variation in consumption caused by hidden structural differences among houses (manifest in their individual proportionality constants) increases proportionately. At the same time, larger houses (with larger proportionality constants) have more window frames and wall surfaces to cause variation in consumption than smaller houses. Variations among the occupants (*e.g.* differences in the thermostat setting or in the frequency of window openings) cause similar variations, in gas consumption, though one can argue that they be less than proportional to the level of consumption. The data presented in Table 1 lend enough support to the assumption of proportionality of standard deviation to level of consumption to justify its adoption throughout this paper; the coefficients of variation (standard deviation divided by the mean), though not constant, show no obvious correlation with the corresponding means. As one would expect, the coefficients of variation of the full sample, which includes houses of all sizes, are larger than those of the three more narrowly defined subsamples. The standard deviation of the full sample shrinks somewhat less than proportionately to the mean from one winter to the other, a disturbing but not dramatic deviation from our hypothesis.

The assumption of invariance of the coefficient of variation makes the following analyses easier and is more plausible on theoretical grounds than, say, assuming that the *standard deviation* is an invariant. However, it is not essential to the conclusions of this paper; the following analyses would have similar results, if the data were treated in a fashion consistent with the assumption of a standard deviation invariant with consumption.

VARIATION IN ENERGY CONSUMPTION CAUSED BY DESIGN FEATURES OF THE HOUSES

In this section we will eliminate the "obvious" variation due to design features, such as number of bedrooms, by using regression techniques. We have also carried out parallel studies of a more nearly identical set of houses composed of three-bedroom, interior units. Very few movers (21) are among these houses and the results, therefore, have reduced statistical significance, but they are consistent with what we obtain when including all types of houses.

The relative importance of design features can be assessed from the data through ordinary least squares regressions of the gas consumption of the 205 houses. Regressions performed for the two winters yielded the following estimates of the coefficients:

1971/72:

$$\begin{array}{llllll} GC = 25.14 & -\,5.98\mathrm{BR2} & +\,3.03\mathrm{BR4} & +\,3.26\mathrm{END} & -\,0.95\mathrm{INS} \\ R^2 = 0.523 & (0.56) & (0.75) & (0.59) & (0.35) \end{array} \tag{1a}$$

1973/74:

$$\begin{array}{llllll} GC = 25.88 & -\,7.06\mathrm{BR2} & +\,4.28\mathrm{BR4} & +\,2.90\mathrm{END} & -\,1.39\mathrm{INS} \\ R^2 = 0.565 & (0.60) & (0.79) & (0.62) & (0.37) \end{array} \tag{1b}$$

where

GC	is the gas consumption in MWh per 6-month winter;
BR2 & BR4	are variables taking the value of 1 if the unit has two or four bedrooms, respectively, and 0 if otherwise;
END	takes the value of 1 for end units, 0 for interior units;
INS	is the area of double glass in houses where such an option was exercised, in tens of square meters (mean (INS) = 1.21).

The numbers in parentheses indicate the standard errors of the estimated coefficients.

These regressions essentially repeat the analyses done by Mayer and Robinson [1] and, before them, by Fox [2]. A detailed discussion of the meaning of each term is given in ref. 3. Of main interest to us is that about 54% of the total variance* in the gas use of the 205 houses can be attributed to "obvious" design features, represented by the variables BR2, BR4, END and INS. The

*The variance is estimated by the *square* of the standard deviation. The figure of 54% is an average of the two R^2 values in eqns. (1).

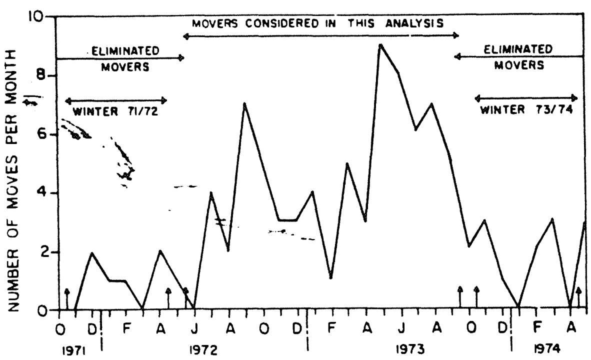

Fig. 2. Plot of moves occurring during a 32-month period.

main purpose of this article is to find the sources of the remaining 46%.

In selecting the sample of 205 houses from the full set of 248 townhouses, all units for which data were missing in either of the two winters were excluded. Moreover, all houses with a change in ownership in either winter were eliminated, including those with a move in October or May (houses with a move during these extra two months "bracketing" the 6-month heating seasons were excluded in order to avoid any interim effects caused by an imminent or a recent move).

Figure 2 displays the frequency of moves from the beginning of the first winter to the end of the second. Out of the 205 units, 52 houses were found to have different owners in the two winters (1971/72 and 1973/74). Choosing the winters two years apart, rather than one, was necessary to obtain a reasonable size of this subsample.

NORMALIZING THE GAS CONSUMPTION

The next step is to eliminate the variation caused by the "obvious" physical features from the 205 houses. To this purpose, the gas consumption of each house is normalized by the amount it "should" have used, given its physical features, according to the regression eqns. (1a) or (1b):

$$GN_i = \frac{G_i}{GC_i} \times 100 \qquad (2)$$

where

G_i is the measured gas consumption per 6-month winter of the ith house;

GC_i is the gas consumption of the ith house estimated by the regression eqns. (1a) or (1b);

GN_i is the normalized gas consumption (100 = "right on target").

TABLE 2

Normalized gas consumption statistics for stayers and movers compared to raw gas consumption of 3-bedroom interior units

		Stayers			Movers[1]		
		Full sample (N = 153)		3-Bed int. (N = 57)	Full sample (N = 52)		3-Bed int. (N = 21)
1971/72	Mean	100.8 ± 1.1[2]		24.5[3]	97.7 ± 2.0[2]		22.7[3]
	S.D.	14.1 ± 0.8[4]		3.6	14.2 ± 1.39		3.0
	C.V.[5]	0.140 ± 0.008		0.149	0.145 ± 0.015		0.132
	F value		1.13			1.21	
1973/74	Mean	100.3 ± 1.2		20.6	99.2 ± 2.29		19.7
	S.D.	15.0 ± 0.9		3.0	16.5 ± 1.62		3.2
	C.V.	0.150 ± 0.009		0.143	0.167 ± 0.017		0.164
	F value		1.10			1.04	

[1] A change in ownership occurred in these houses between the two winters.
[2] Units: Dimensionless; 100 = estimate by eqns. (1a) or (1b).
[3] Units: MWh per 6-month winter.
[4] All distributions here assumed to be Gaussian. Thus, the error of the standard deviation (S.D.) was estimated by $\sigma_{S.D.}$ = S.D./$\sqrt{2N}$, the error of the mean (M) by σ_M = S.D./$\sqrt{N}$. The error (σ_c) of the coefficient of variation was estimated by $\sigma_c = \sigma_{S.D.}/M$.
[5] Coefficient of variation.

An alternate and more familiar way to eliminate the variation explained by "obvious" physical features would have been to take the residuals, $G_i - GC_i$, as a measure of relatively high or low consumption. Normalized gas consumptions, GN_i, were preferred on the grounds that the residuals are observed to increase with increasing gas consumption levels, G_i. It is easier for a large house to be 2 MWh "off target" than a small house, while it is roughly equally likely for both to be 10% "off target."

Table 2 displays the relevant statistics in both winters for both movers and stayers. The first and third columns refer to the normalized consumption, GN_i, of all houses; the second and fourth columns refer to the raw consumption, G_i, of a subsample of three-bedroom, interior units. If we have been successful in making all houses "identical" by normalizing their gas consumption, their distribution should be the same as for physically identical houses. Specifically, we are interested in comparing the widths of the distributions. Because of the different units (dimensionless and MWh per 6-month winter), the coefficients of variation (C.V.) should be compared. The F values for movers and stayers in both winters are obtained by dividing the square of the larger C.V. by the square of the smaller C.V. None of the F values are significant at a 2 × 5% (two-sided) level of confidence, which is equivalent to saying that the distributions are likely to represent the same variable.

EVIDENCE FOR DISCRIMINATING BETWEEN MOVERS AND STAYERS

As we have just seen, the distributions of gas consumption for both movers and stayers, in both winters, are statistically equivalent. The difference between movers and stayers becomes apparent only when we ask how well the consumption level of each individual house is reproduced from one winter to another. A suitable measure of this reproducibility is the "relative consumption":

$$RC_{ii} = \frac{GN_i(t_3)}{GN_i(t_1)} \tag{3}$$

where

RC_{ii} is the relative consumption of the ith house;

t_1 & t_3 indicate the winters 1971/72 and 1973/74, respectively.

A value of $RC_{ii} = 1$ means that the ith house has used the same amount of gas in the second winter as it used in the first, after allowing for what a house of its size uses "on average."

Anticipating later usefulness, the statistics have been calculated for the natural logarithm of relative consumption, $LRC_{ii} = \ln(RC_{ii})$ and are shown in Table 3.

Since the relative consumption varies relatively little around its mean equal to unity, we have $\ln(RC_{ii}) \cong RC_{ii} - 1$, and the variance of LRC is not much different from the variance of RC. Figure 3 compares the relative consumptions of movers and stayers.

The small difference in the means is not significant*. On the other hand, the difference in the variances is highly significant†. A

*A t-test of the difference between the means yields a value of $t = 0.614$; more than 40, but less than 50 out of a 100 pairs of random samples of the same variable could be expected to produce the same difference between their means.

†The ratio of the variances gives an F-value of 3.11. There is only a 0.1% chance for a random F-value higher than 1.81.

TABLE 3

Statistics on the natural logarithm of relative consumption, LRC

Statistics	Stayers (N = 153)		Movers (N = 52)	
Mean	−0.0059	± 0.0087	0.0112	± 0.0262
Standard Deviation	0.107	± 0.006	0.189	± 0.019
Variance (S.D.^{2})	0.01148	± 0.00004	0.03576	± 0.00034

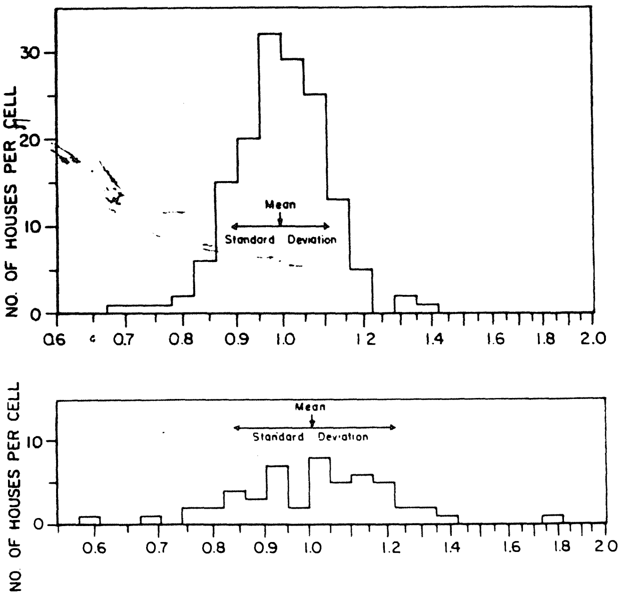

Fig. 3. (a) Relative consumption of 153 stayers. (b) Relative consumption of 52 movers.

change in ownership greatly disrupts the "traditional" consumption level of an individual house; averaged over a large number of houses, however, disruptions of opposite sign tend to compensate each other.

It is interesting to observe that, if we define relative consumption as the ratio of the *raw* (instead of normalized) gas consumptions:

$$RCR_{ii} = \frac{G_i(t_3)}{G_i(t_1)} \qquad (4)$$

the means and the variances for both winters and for both movers and stayers are very close to the corresponding statistics for *RC*, as seen in Table 4. So why work with normalized gas data rather than with straight raw gas data, when apparently the physical features are "divided out" anyhow by taking relative consumptions? The reason is that we need to compare the variance of the movers' relative consumption to the maximum possible variance. If the consumption level of each house in the second winter were totally unrelated to its own level in the first winter, we would compute a maximum variance for the relative consumption of 0.05011 ± 0.00048. To obtain this result, we add the variances of the logarithms[‡] of the movers' normalized gas consumptions in both winters,

$$\sigma^2[LGN(t_1)] + \sigma^2[LGN(t_3)] =$$

$$(0.145)^2 + (0.171)^2 = 0.05011 \qquad (5)$$

according to the laws of propagation of variance of uncorrelated factors.

Had we used raw gas data, the result in eqn. (5) would have been more than twice as large, because it would have included the variation due to the "obvious" physical features as well.

The difference between the movers' relative consumption, 0.0358, and the maximum possible variance of 0.0501 that we derived, suggests that there exists a weak link between the consumption of movers' houses before and after the change in ownership. An *F*-test, however, predicts a better than 5% chance that two random samples (of only 52 units) of the same variable would have produced the same ratio of the variances.

[‡] Though not explicitly shown in any table, the variances of the logarithms are nearly identical to the square of the coefficients of variation listed in Table 2.

TABLE 4

Natural logarithm of relative consumption from raw gas data, *LRCR** and from normalized gas data, LRC**

Statistics	Stayers (N = 153)		Movers (N = 52)	
	LRCR	*LRC*	*LRCR*	*LRC*
Mean	−0.0112 ± 0.0090	−0.0059 ± 0.0087	0.0116 ± 0.0269	0.0112 ± 0.0262
Standard Deviation	0.111 ± 0.006	0.107 ± 0.006	0.194 ± 0.019	0.189 ± 0.019
Variance (S.D.^{2})	0.01238 ± 0.00004	0.01148 ± 0.00004	0.03767 ± 0.00036	0.03576 ± 0.00034

*As defined in text, eqn. (4). Numerical values identical to Table 3.
**As defined in text, eqn. (3).

Thus, over the two year period, the movers' houses "forgot" much of their previous consumption levels, while the stayers "remember" much better, though less than perfectly. The following section is devoted to a quantitative interpretation of these qualitative effects.

A THREE-FACTOR MULTIPLICATIVE MODEL FOR THE HOUSES' GAS CONSUMPTIONS

The facts of central importance to the following discussion are the differences between the variances of the relative consumptions, RC — differences in variances for stayers, movers and for houses where the consumption level changes at random from year to year.

A three-factor model is proposed to interpret the meaning of these differences both qualitatively and quantitatively. The three factors that appear to play a role are: (1) non-persistent consumption patterns of residents and/or house: "change", responsible for the broadening of the relative consumption distribution as time goes by; (2) persistent behavior of the occupants: "lifestyle", manifested in the abrupt change across a move; (3) "quality," establishing a weak link between the consumption patterns of a house before and after a move.

The distinction between persistent and non-persistent effects, first formulated by Socolow [personal communication], is made necessary by observing that the stayers do not reproduce their consumption rankings from year to year perfectly. This observation is the primary evidence of the factor "change".

By "change" we intend (a) changes occurring in the occupants' lives over time: children are born, spouses trade domestic life for a job, incomes change, etc.; (b) changes imposed on the house: the addition of storm windows and storm doors, the paneling of walls and basement, the purchase of humidifiers and other appliances, etc.; (c) aging of the house; the compression of attic and wall insulation by moisture, cracked wall joints, new leaks around window frames. Experience with these houses suggests that parts (a) and (b), changes involving the occupants, are predominant (but our method of analysis cannot tell this).

By "lifestyle" we intend that part of the occupant-related behavior assumed to be persistent in time, including thermal preference, the operation of south facing drapes and thermostat setbacks.

"Quality" encompasses any built-in invisible differences, persistent in time, between apparently identical houses, possibly caused by variable diligence of different construction crews building the town or by wind exposure, color, etc.

Admittedly some of the distinctions between the three factors may be arbitrary. Compare, for instance, the "persistent" yearly treck to Florida of one family to the "once-in-a-lifetime" voyage to Europe of another family. Interactions between the different factors cannot be ruled out either. The assumptions made in the model proposed below will be spelled out in detail shortly. The multiplicative model is represented by the following equation:

$$GN_i(t) = 100 \cdot C_i(t) \cdot L_i \cdot Q_i \tag{6}$$

where

- t represents time (t_1 in the first winter of 1971/72, t_2 in the second (1972/73), t_3 in the third (1973/74);
- $GN_i(t)$ is the normalized gas consumption of the ith house, as defined by eqn. (2), in the tth 6-month winter;
- $C_i(t)$ is the time-dependent variable, "change", for the ith house;
- L_i is the "lifestyle" for the occupant of the ith house, independent of time;
- Q_i is the "quality" of the ith house, also time-independent.

The means of the three variables, C, L, Q, are assumed to be close to unity. The variance of each variable determines the extent to which that variable contributes to the total variation of the normalized gas consumption, GN, among identical houses.

The relative consumption, defined in eqn. (3), of stayers, movers and random pairs*, "divides out" two, one or none of the factors of the model:

$$\textit{Definition:} \qquad RC_{ii} = \frac{GN_i(t_3)}{GN_i(t_1)} \tag{4}$$

*Please see opposite page for footnote.

$$\textit{Stayers: } RC_{ii}^{S} = \frac{C_i(t_3)}{C_i(t_1)} \tag{7a}$$

$$\textit{Movers: } RC_{ii}^{M} = \frac{C_i^{\mathrm{new}}(t_3)}{C_i^{\mathrm{old}}(t_1)} \cdot \frac{L_i^{\mathrm{new}}(t_3)}{L_i^{\mathrm{old}}(t_1)} \tag{7b}$$

Random pairs of movers:

$$RC_{ij}^{RM} = \frac{C_j^{\mathrm{new}}(t_3)}{C_i^{\mathrm{old}}(t_1)} \cdot \frac{L_j^{\mathrm{new}}(t_1)}{L_i^{\mathrm{old}}(t_1)} \cdot \frac{Q_j(t_3)}{Q_i(t_1)} \tag{7c}$$

The superscript "new" refers to the new wners in the second winter; the subscript "j" efers to the jth house in the second winter, andomly paired with the ith house in the irst winter.

From the data we know the variances of he (logarithms of the) left hand sides of the hree eqns. (7). We can derive the variances of each of the three factors on the right hand ide if the following three assumptions hold: 1) the three factors, C, L, Q, are uncorrelated with each other; (2) the variance of each actor does not change between the two winters; (3) the variables representing the new owners, $C^{\mathrm{new}}(t_3)$ and $L^{\mathrm{new}}(t_3)$, and the variables representing the old owners, $C^{\mathrm{old}}(t_1)$ and $L^{\mathrm{old}}(t_1)$, are uncorrelated and of identical variances. While the lack of correlation between old and new owners in assumption (3) seems reasonable, the variation between individual lifestyles of the new occupants may need some time to "settle" to that of the old occupants. In fact, Table 2 shows that the movers' normalized gas consumption in the second winter is of slightly wider distribution than that of the stayers and that of the movers in the first winter, but an F-test on the variances is not significant at the 5% confidence level. Assumption (2) is made plausible by the constancy of the standard deviation of the stayers' normalized gas consumption across three winters: 14.1, 14.4 and 15.0 in 1971/72, 1972/73 and 1973/74, respectively. The slight increase over three years cannot be regarded as significant. Assumption (1) is the hardest to confirm: it implies, for instance, that there is no interaction between occupants and their houses (*e.g.* a "tight" house encouraging some occupants to save energy or, conversely, decreasing their alertness to energy conservation), a claim questioned by many social scientists. Though no evidence could be found supporting or refuting this assumption and no direct test could be devised, this author is confident that interactions between the three factors, if they exist, would not be so large as to seriously alter the quantitative results derived below.

With these assumptions, the propagation of variance can be written as:

Stayers: $\sigma^2[LRC^S] = 0.01148 \pm 0.00004 = 2\sigma^2[LC]\ (1 - \rho[LC(t_1), LC(t_3)])$ (8a)

Movers: $\sigma^2[LRC^M] = 0.03576 \pm 0.00034 = 2\sigma^2[LC] + 2\sigma^2[LL]$ (8b)

Random pairs of movers: $\sigma^2[LRC^{RM}] = 0.05011 \pm 0.00048 = 2\sigma^2[LC] + 2\sigma^2[LL] + 2\sigma^2[LQ]$ (8c)

where $LRC^S = \ln(RC^S)$, etc., $\rho[LC(t_1), LC(t_3)]$ is the correlation coefficient between these variables in the two winters (see below).

Working with the logarithms of the variables was necessary in order to stay within the conventional linear framework of the analysis of variance (ANOVA). The following results involve the movers only (eqns. 8b and 8c):

"Quality": $\sigma^2[LQ] = 0.00718 \pm 0.00029$ (9a)

"Change" and "lifestyle": $\sigma^2[LC] + \sigma^2[LL] = 0.01788 \pm 0.00017$ (9b)

*We refer to the reasoning that led to eqn. (5). Conceptually, totally uncorrelated consumptions between two winters can be thought of as the consumptions of random pairs of houses: house 17 in the first winter and house 28 in the second, etc. We symbolize this by the "randomly paired" relative consumption RC_{ij}, where i, j label random pairs of houses. Though in this analysis we use random pairs of movers, it can be shown that random pairs of stayers have an almost identical distribution of relative consumption.

How can we separate the individual contributions of LC and LL to the total variance in eqn. (9b)? The stayers (eqn. 8a) do not yield enough information to distill "change", C, from "lifestyle", L; The correlation coefficient $\rho[LC(t_1), LC(t_3)] = \rho_{LC2}$ expresses the degree to which the stayers reproduce their consumption level over two years. Since $\rho_{LC2} \geq 0$, we can state merely that $\sigma^2[LC] \geq 0.00574$. The limited amount of data (too few houses, too few winters) does not warrant an exact evaluation of ρ_{LC2}, although more information is available and will be discussed in the next section. Thus, the certain quantitative results so far are expressed by eqns. (9).

Summing up what we have learned until now, we can state that "the observed variation in gas consumption among identical houses ($\sigma^2[LGN] = (0.158)^2 = 0.02505 \pm 0.00024$) is caused to 71.4% by different occupant-related consumption patterns ($\sigma^2[LC] + \sigma^2[LL] = (0.134)^2 = 0.01788 \pm 0.00017$), and to 28.6% by different house-related characteristics ($\sigma^2[LQ] = (0.085)^2 = 0.00718 \pm 0.00029$)." Translated into physical units, the observed standard variation among identical houses is an average of 3.71 MWh per 6-month winter, at an average consumption of 23.46 MWh per 6-month winter. Occupant-related consumption patterns alone would cause a standard deviation of 3.14 MWh per 6-month winter, while persistent quality differences between houses alone would cause a standard deviation of 1.99 MWh per 6-month winter.

TIME-DEPENDENT CHANGES IN CONSUMPTION PATTERNS

Concerning the variation in consumption among our nominally identical houses in *one* particular heating season, the occupants are responsible for 71% of the observed variation, the houses for 29%. However, the stayers sample provides more information related to the partition between persistent and non-persistent consumption patterns.

"Change," the non-persistent factor, can be thought of as the result of a continuous series of random decisions by the occupants affecting energy consumption. The factor "change" is represented by the variable $C(t)$. The "decision status" of the ith family at time t determines *its* value, $C_i(t)$, of the variable $C(t)$. A histogram of the values $C_i(t)$ of all families (or houses) at a given time, t, yields the distribution of the variable $C(t)$ for that time*. The limited number of possible decisions, the workings of peer pressure and other "stabilizing influences" prevent the distribution of consumption over many houses from broadening indefinitely: no statistically significant broadening in gas consumption distribution has been observed in Twin Rivers over the years. Thus we can visualize the non-persistent *consumption* pattern of an individual family as a "random walk" within a finite range $\pm\sigma[LC]$; the "speed" at which an individual family randomly "walks" can be observed in the widening of the stayers' *relative consumption* distributions over one, two or more years up to a maximum of $\pm\sqrt{2}\sigma[LC]$. The *relative consumption* of the movers, in turn, shows no widening. Since the move totally separates the identities of the families before and after the move (separating $C_i^{old}(t_1)$ from $C_i^{new}(t_3)$), the *relative consumption* already has the full width $\pm\sqrt{2}\sigma[LC]$.

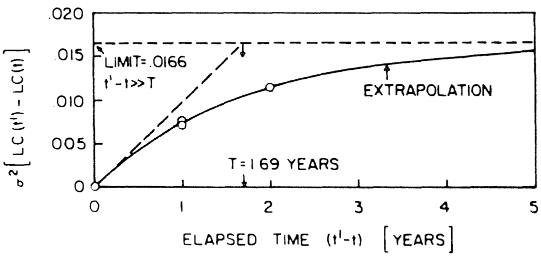

Fig. 4. Variance of stayers' relative consumption as a function of time.

Figure 4 shows the logarithmic variances of the relative consumption of the stayers among the three winters 1971/72, 1972/73 and 1973/74. The variances are 0.0077, 0.0071 and 0.0115, respectively. The relative consumption distribution over two years is clearly wider than the two relative consumption distributions over one year. For short periods of time or for a very large maximum range of the "random walk" one can apply the law of diffusion, whereby the variance is proportional to elapsed time:

*One can show that the resulting mean and the standard deviation are practically the same for movers and stayers.

$$\sigma^2[LC(t') - LC(t)] = 2\sigma^2[LC](1 - \rho[LC(t), LC(t')]) \propto (t' - t) \qquad t' - t \geq 0 \tag{10}$$

For large periods of time or for a small maximum range, one would expect the dependence on elapsed time to level off, since the variance of the random walk (l.h.s. of eqn. 10) cannot exceed $2\sigma^2[LC]$. In a rather speculative manner, one could postulate the correlation coefficient in eqn. (10) to "decay" exponentially, with increasing elapsed time:

$$\rho[LC(t), LC(t')] = \exp[-(t' - t)]/T \qquad t' - t \geq 0 \tag{11}$$

where T is a time constant associated with changes in consumption patterns of the occupants.

From the data in Fig. 4, averaging the two relative consumptions for $t' - t = 1$ year, we obtain $T = 1.69$ years and $\sigma^2[LC] = 0.00830 = (0.091)^2$. In other words, the variation in normalized gas consumption over the years, of the same family in the same house, is likely to stay within ±9.1% of their average consumption. Though the set of decisions affecting this variation in gas consumption is assumed to be continuously under review, it is not likely to change drastically in less than a year or so. Over two or more years, however, the family progressively resembles itself no more or less than any other family, concerning energy behavior that is susceptible to change.

These results fit well into the previous analyses: now one could state that "the observed variation in gas consumptions among identical houses is caused: 33% by non-persistent changes in consumption patterns, 38% by persistent occupant-related patterns and 29% by persistent house-related quality differences." However, given the scant amount of winters for which consumption data are available at this point, such a conclusion is speculative and awaits confirmation by further research.

CONCLUSION

The variation in a 6-month winter's gas consumption among a sample of 205 townhouses has been explained to about 54% by "obvious" physical features, like the number of bedrooms, the area of insulated glass, if any, and whether the house is an end unit. The main thrust of this article was to determine the factors responsible for the remaining 46% variation that cannot be explained by conventional factors.

The strategy was to observe the changes in consumption levels of the houses in three different samples: (1) "stayers", where houses and occupants remain the same in every winter; (2) "movers", where the houses remain the same, but the occupants change; (3) "random pairs", where both houses and occupants change. The measure for the change over time in consumption is defined as "relative consumption" between two winters: the ratio of the consumption in the second winter divided by the consumption in the first. The data allow three different factors to be discerned: (1) non-persistent consumption patterns of occupants and/or house, "change"; (2) persistent behavior patterns of the occupants, "lifestyle"; (3) persistent consumption patterns of the house, "quality". Assuming that these factors are uncorrelated and that their variances remain constant for different winters and for different sets of occupants (concerning "movers"), we can state that 71% of the variation unexplained by conventional factors is caused by occupant-related consumption patterns, a combination of the first two factors above, and 29% by persistent house-related quality differences. Close scrutiny of the stayers' sample consumptions across one and two years suggests, somewhat speculatively, that the 71% are the sum of 33% non-persistent patterns ("change") and of 38% persistent, occupant-related patterns ("lifestyle").

We have proved experimentally that (so far) unpredictable behavior patterns of the occupants introduce a large source of uncertainty in the computation of residential space heating energy requirements. The lesson to be learned is two-fold: (i) there is little practical usefulness in pushing too far the detail of any deterministic model for the prediction of heating load requirements; (ii) the effect of retrofits, weather or other factors physically influencing the heat load of a house should be tested on many houses occupied by real people. These conclusions may be the strongest *a posteriori* justification for the approach of the Twin Rivers project. That approach placed special emphasis on the monitoring of a large number of populated houses, to be modeled in relatively simple fashion, instead of testing a sophisticated model under laboratory conditions.

The paper by Seligman *et al.* [4] describes how questionnaires have identified the importance of considerations of health and comfort in determining level of summer use of air conditioning. Another way in which our group addressed variability was through on-site inspection of identical houses. This work uncovered numerous structural problems that merited attention, but for the most part it failed to disclose a pattern of structural problems across houses that correlated with level of energy use. Yet another study involved direct monitoring of interior temperatures across houses. This revealed a rough correlation of higher interior temperatures with higher consumption of natural gas. Thus, our various attempts to clarify the variability in energy consumption across houses are broadly consistent, all pointing to the significant role of the resident. It follows, we believe, that constructs of the problem of achieving energy conservation in housing that exclude the resident are seriously incomplete.

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APPENDIX

Data acquisition

The data presented in this chapter were gathered from the monthly readings of the Public Service Electric and Gas utility, Twin Rivers' natural gas supplier. The utility records list four-digit readings (in units of 100 ft^3, corresponding to 0.03004 MWh) and special flags for missing or estimated readings. All meters are read at the end of the month, within three to four days. Even if the reading order were not the same each month, the error introduced by the uncertainty in the exact reading date cannot be large, when compared to the 6 months of the entire heating season. Moreover, any such error would occur in the mild months of November or April, that contribute little to the total 6-month gas consumption.

There are 248 townhouses in quad 2, upon which we concentrated our efforts. In a first elimination process, all houses with missing or estimated readings that influence the computation of the 6-months (November–April) consumptions were eliminated. The monthly electric consumption records of the Jersey Central Power and Light utility for the same houses were consulted to establish when and where a change in ownership occurred: when the billing address of a customer changes, a special code number is increased by one. All houses for which a move occurred during any of the eight winter months October–May, in either 1971/72 or 1973/74, were also eliminated. Subletting a house to another family was considered a "*de facto*" move. Such occurrences could be detected from the change in the resident's name in the utility records, although the billing address remained unchanged. The electric utility records proved very useful in detecting a prolonged absence by the owners: under such circumstances the electric consumption, a good measure for the "activity" inside the house, would drop to very low levels, while a sizeable gas consumption would remain even if the thermostat were set back to 12 °C (55 °F), the minimum possible setting on the thermostats employed in these houses. Such absences over several months were also excluded.

As a result of these successive eliminations, the original 248 townhouse sample was reduced to a "clean" sample of 205 townhouses. This sample, in turn, was split into "movers" and "stayers", according to whether a change in ownership occurred between the heating seasons under consideration.

Cavity barriers and ventilation in flat and low-pitched roofs

Cavity barriers restrict the spread of smoke and flame; they are required by Building Regulations in certain types and sizes of new building and have been installed in some existing buildings. In flat and low-pitched roofs with a continuous weather-proof layer problems do not normally arise if cavity barriers are used in warm roof deck designs, but in cold roof deck designs care must be taken to ensure that there is adequate ventilation of the roof cavities. A total clear opening area of not less than 0.3 per cent of the plan area of the cavity should be used.

The practical problems of choosing appropriate materials and methods of fabrication and erection of cavity barriers and fire stops are discussed in Digests 214 and 215. This digest assesses the implications for ventilation of using cavity barriers and examines, where necessary, how adequate air movement can be provided in both new and existing flat roof voids, designed with or having installed cavity barriers.

This digest does not purport to be an authoritative interpretation of the legal requirements of the Building Regulations but has been produced as an aid to understanding their technical intention.

Voids often occur in flat and low pitched roof construction, particularly those with suspended or separate ceilings. Their presence has many advantages such as providing a space to contain pipework and other services. Ceilings can be constructed to resist the passage of fire but inadequacy of design and construction, the presence of openings or failure in fire are liable to allow smoke and hot gas to enter the void and spread rapidly through the horizontal plane. Following a number of fire incidents and fatalities particularly in institutional types of building, the Building Regulations, 1976, introduced requirements for the provision of cavity barriers and for fire stopping to restrict the unseen spread of fire and smoke.

The requirements to restrict the spread of smoke and flame, however, do not negate the need for providing ventilation in the cavities of certain forms of roof construction and particularly those with a continuous waterproof layer. The installation of cavity barriers and fire stopping without appreciating the implications for ventilation could seriously impair the efficiency of air movement. This could lead to a build up of moisture within the roof construction which can cause deterioration of many building materials resulting in the possibility of structural collapse.

Cavity barriers

A cavity barrier is defined in the 1976 Building Regulations (Part E, Safety in Fire, Regulation E14) as a construction to restrict movement of smoke or flame within a cavity, including a construction provided for another purpose if it conforms with the criteria required of a cavity barrier. The requirement for the installation of cavity barriers and the maximum permitted distance between cavity barriers are related to the Purpose Group of the building and are set out in the table to Regulation E14(4), the relevant part of which is given below.

Table 1 Maximum distance between cavity barriers in a roof void.
Based on the table to Regulation E14(4) of the Building Regulations 1976 and irrespective of the class of exposed surface within the cavity (excluding pipes, cables or conduit).

Purpose group of building or compartment	Maximum distance
I and flats or maisonettes within III	No limit (Cavity barriers not required)
II and III except flats and maisonettes	15 m with area limited to 100 m²
Any other	20 m

Purpose group I covers private dwelling houses, PG II institutional and PG III other residential buildings. Purpose groups IV, V and VI cover offices, shops and factories, respectively, VII embraces other places of assembly and finally, VIII is for storage and other general buildings.

It should be noted that cavity barriers are not required by E14(4) to subdivide roof voids in purpose group I buildings or for flats and maisonettes in purpose group III, although some barriers in and at the perimeter of voids may nonetheless be required by E14(2) and (3). In all other purpose groups, cavity barriers may be required in roof voids by E14(4) as well as by E14(2) and (3).

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Digests 214 and 215 examine in detail appropriate materials and methods of fabricating suitable cavity barriers. Building Regulations and the Digests seek to achieve, in the materials and constructions they describe, a close fit of the barrier in the cavity and at the joint between the barrier and any through-going services. Thus the passage of air is restricted and any requirements for ventilation must be met within the permitted maximum distances and areas that result from the sub-division of roof space by the cavity barriers.

Flat roof design

The detail and construction of flat roofs varies greatly but currently it is common practice to classify them according to the location of the insulation in relation to the deck as being of warm or of cold roof deck design, see Digest 180.

Warm roof deck

In warm roof deck design the insulation is placed immediately below the waterproof layer with a vapour barrier beneath the insulation and on the upper side of the roof deck. The ceiling may be independently suspended at a lower level providing a cavity between the ceiling and the roof which is not ventilated with outside air. The roof deck is consequently warm and the insulation is protected from reaching dew point conditions by the vapour barrier on its warm side.

Since any cavity formed between the roof deck and the ceiling does not require ventilating this method of construction is not affected by the installation of cavity barriers. However, a warm roof deck design does not necessarily provide the best design solution for buildings requiring cavity barriers, particularly as other problems must be considered, for example the movement of the thermal insulation and its effect on the integrity of the water-proof layer and the costs incurred in the future for the replacement of the water-proof layer.

Cold roof deck

In cold roof deck design the insulation is placed immediately above the ceiling, usually with a vapour barrier interposed. A cold void is thus created between the insulation and the roof-deck, which supports directly the water-proof layer. Outside air is allowed to pass through this cavity helping to clear any build-up of moisture which could result from the percolation of interior air from beneath the ceiling (see Fig. 1). In addition, as the waterproof layer and supporting upper deck approach the outside temperature, the ventilation minimises the risk of condensation occurring on the deck. It is possible, however, by the use or installation of cavity barriers to interrupt or impair the efficiency of the ventilation, and it is this form of roof deck design, or variations of it, that are mostly affected by the use of cavity barriers in both new and existing buildings.

Existing roof decks

In view of recent experiences and legislation it may be considered necessary to install cavity barriers in certain existing buildings. In such cases the roof structure should be carefully examined and classified either as warm or as cold roof deck design. If warm, no problems should arise; if cold, then the implications for ventilation must be considered. If for some reason cavity barriers have already been installed in an existing cold roof without considering the implications for ventilation then the roof structure should be examined immediately and the necessary provision made for ventilation.

It is clearly possible to provide the ventilation needed between cavity barriers by roof cowl ventilators. However, it would be an advantage to have the additional facility of being able to use eaves or perimeter ventilation. At present it is necessary to obtain a relaxation of Regulation E14(2)(a) for this purpose; however, there are proposals to amend the regulation in order to permit generally in external walls the use of eaves ventilation openings to the adjacent sub-divided roof cavities. An additional advantage of providing roof ventilation is to assist with the clearance of smoke which may enter the void. However, the size of ventilation openings normally provided may be inadequate for complete smoke clearance.

If an existing building has little thermal insulation then the question of upgrading may occur at the same time as the installation of cavity barriers. Great care must be exercised in this situation. A complex solution combining cold and warm roof deck design should be avoided as should any possible duplication of vapour barriers, as experience has shown that these types of solution are often unsatisfactory.

Methods of ventilation

In most cases ventilation in flat and low-pitched roofs relies on intermittent winds of varying direction and intensity. For the ingress and exhaustion of air it is, therefore, necessary to arrange ventilators at least at both ends of a cavity avoiding the occurrence of any dead pockets of static air. Openings at one end of a cavity will not provide sufficient movement of air. A flow of air may be induced thermally where a deep roof zone is available by providing ingress at the lower eaves and escape at the high point of the roof or ridge. Apertures may be arranged in the form of cowls through the weatherproof layer or, in cases where the local authority agrees to relaxation of E14(2)(a), of openings either on the facade of the building within the roof zone, or at the underside of any roof overhang. In some forms of construction it is possible to provide ventilation at the base of a flush fascia detail, but care must be taken not to infringe the integrity of any required cavity barrier or to impede the flow of air by other construction materials such as insulation or rendering (Fig 1). In order to provide adequate ventilation within the voids between cavity barriers, it may be necessary to combine alternative types of aperture, particularly with large complex roof areas (Fig. 2).

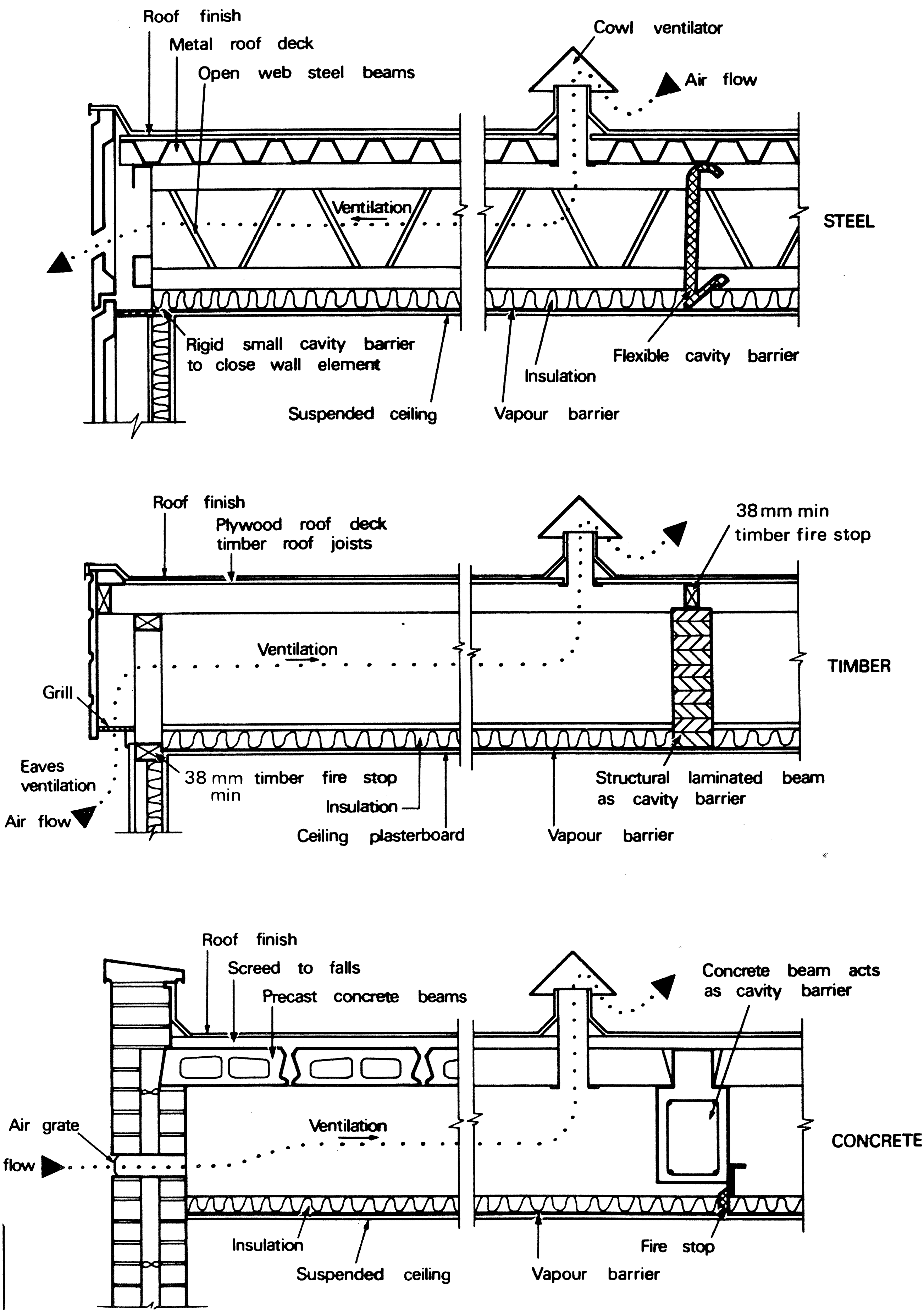

Fig. 1 Typical cold roof deck construction showing ventilation detail

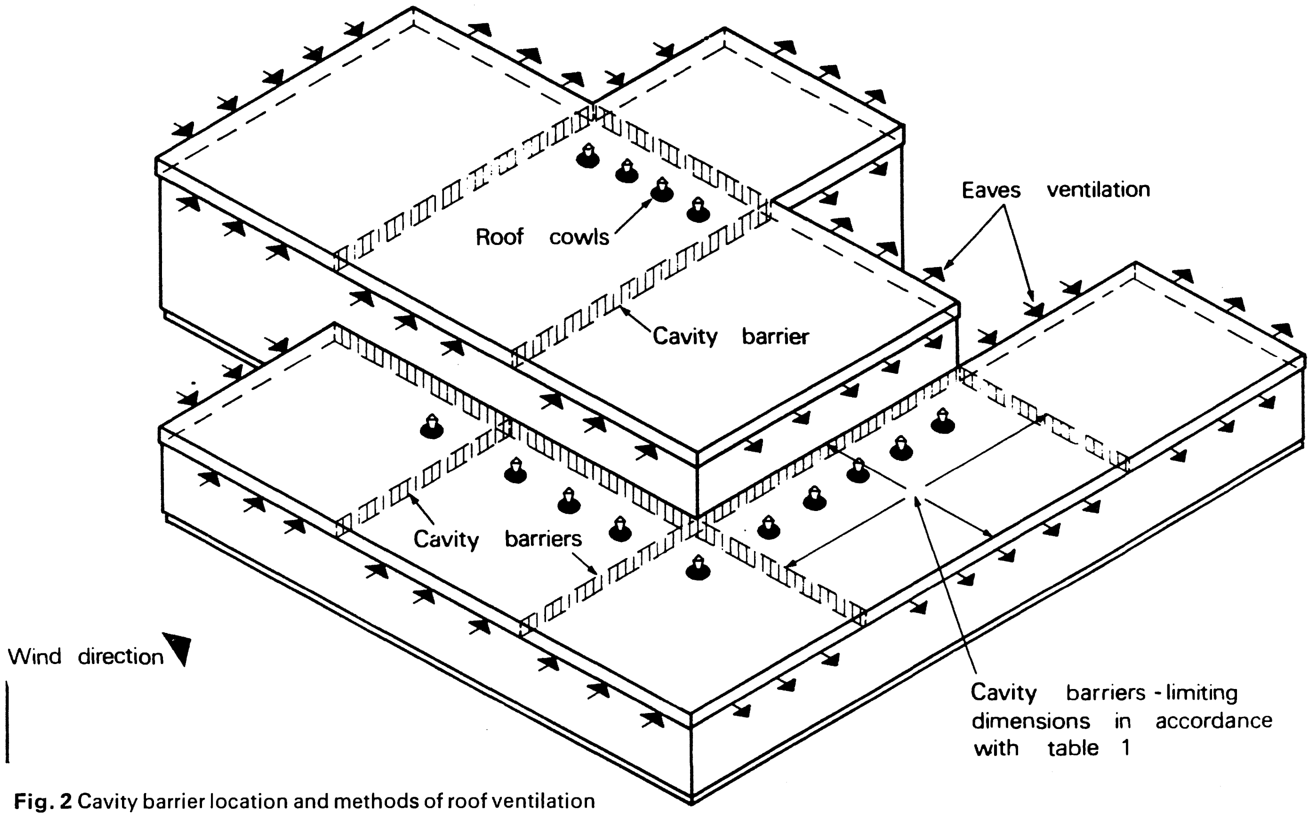

Fig. 2 Cavity barrier location and methods of roof ventilation

The amount of clear aperture area required to give adequate ventilation will vary according to location, and the efficiency of the air movement. Since, however, material degradation does not occur, and performance of cold roof construction is not affected by an excess of ventilation it would seem appropriate to use a minimum distributed clear aperture opening area of not less than 0.3 per cent of the total plan area of the cavity, increasing this figure extensively wherever possible and especially when achieving satisfactory distribution within the cavity becomes difficult because of plan configuration. Thus a roof with a span of 30 m and with a cavity barrier at mid-span will require an aperture area of 0.023 m^2 for each metre of width and at each end of the two cavities formed. This could be met by a continuous 23 mm wide slot or by air grates or ventilators each having a clear aperture of 0.023 m^2 and spaced at 1 metre intervals.

Unusually-high relative humidities may occur in certain buildings such as those associated with swimming pools, service kitchens and some industrial processes. In these cases special arrangements should be made to exhaust the wet air from the building using fans and in the case of cold roof deck design a similar approach should be taken with the roof voids. Attention also needs to be paid to the selection and location of the materials used in the roof construction to ensure that any damp conditions that may arise do not cause deterioration.

Ventilator design

Many types of ventilators, including louvres and cowls, both directional and non-directional are available and some are designed to ventilate the cavities in cold roof deck design. In some cases the ventilation can be incorporated as part of the construction detail. Where ventilators penetrate the waterproof layer care must be taken in detailing to ensure that there is no possibility of water ingress *around* the ventilating device into the roof space. Ventilators should be selected and sited to achieve the following:

induce maximum air flow throughout the full length of a cavity without infringing cavity barrier requirements;

be of sufficient clear opening area to provide the required ventilation rate;

prevent the ingress of snow, rain, insects, birds and leaves;

be sited to facilitate inspection;

be located so that there is no danger of obstruction in the void by loose materials, such as insulation;

be of maintenance-free materials and constructed to avoid the occurrence of condensation within the ventilator.

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