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Do sunspaces work in Scotland? Lessons learnt from a CEC solar energy demonstration project in Glasgow

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SYNOPSIS

The paper examines the extent to which user's intervention may compromise the thermal performance of small sunspaces in the context of a Solar Energy Demonstration Project at Easthall in Glasgow (55°52'N), which was monitored from September 1992 to May 1994. Results indicate a tendency to close down windows etc. late in autumn and open them up early in spring relative to heat demand. In other words a user-driven energy load due to ventilation is higher in autumn and spring than in the central winter period. However, effective rate of ventilation, taking account of the preheat effect of the glazed spaces, is found to be more steady over an entire heating season. Thus, inclusion of glazed buffers has been shown to lessen the thermal burden of window opening in autumn and spring; while saving in winter due to preheated air for ventilation tends to be slightly higher than predicted. Results also indicate that amount and frequency of opening/ventilation relates to specific social and occupancy characteristics; and that some users were able to trim their energy load by better use of the controls at their disposal in the second season. As a by-product, the monitoring has shown that energy models which take a steady rate of ventilation over a heating season are unrealistic.

INTRODUCTION

The retrofit of 36 thermally sub-standard dwellings in Glasgow, monitored by the Mackintosh Environmental Architecture Research Unit at Glasgow School of Art under the auspices of the CEC Energy Demonstration Programme and Glasgow City Council, incorporates solar features as follows:

1 Unheated glazed spaces buffering part of both front and rear elevations, of varying orientation, to reduce losses due to thermal transmission and ventilation, and to provide additional space for utility/amenity purposes – see Figures 1a and 1b overleaf;
2 Roof-integrated air collectors and air-to-water heat exchangers to reduce water heating loads and raise air quality/temperature within common stairwells – this second aspect not being the subject of this paper.

The unheated glazed "buffer" space has been adopted as a passive solar technique to displace fuel for space heating in locations varying from north of the Arctic Circle to the Mediterranean. Application over this wide range of climatic conditions is in itself of some concern – to quote Page (1977) "We must seek an appropriate solar technology for each geographic location." Also where such spaces are large enough to function as a room, there is a risk that users will heat them

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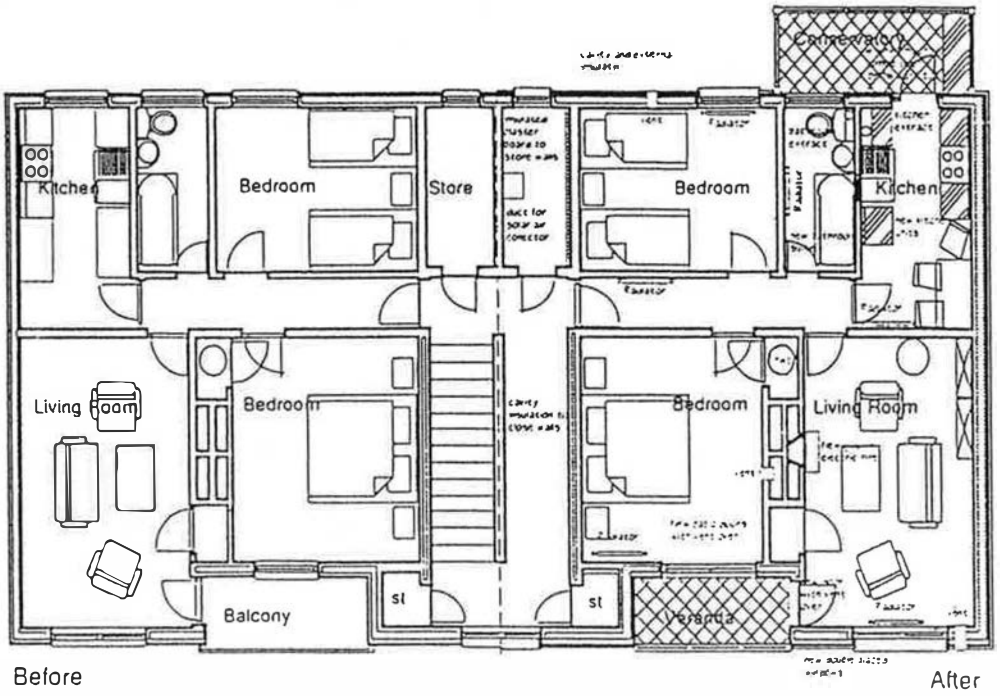
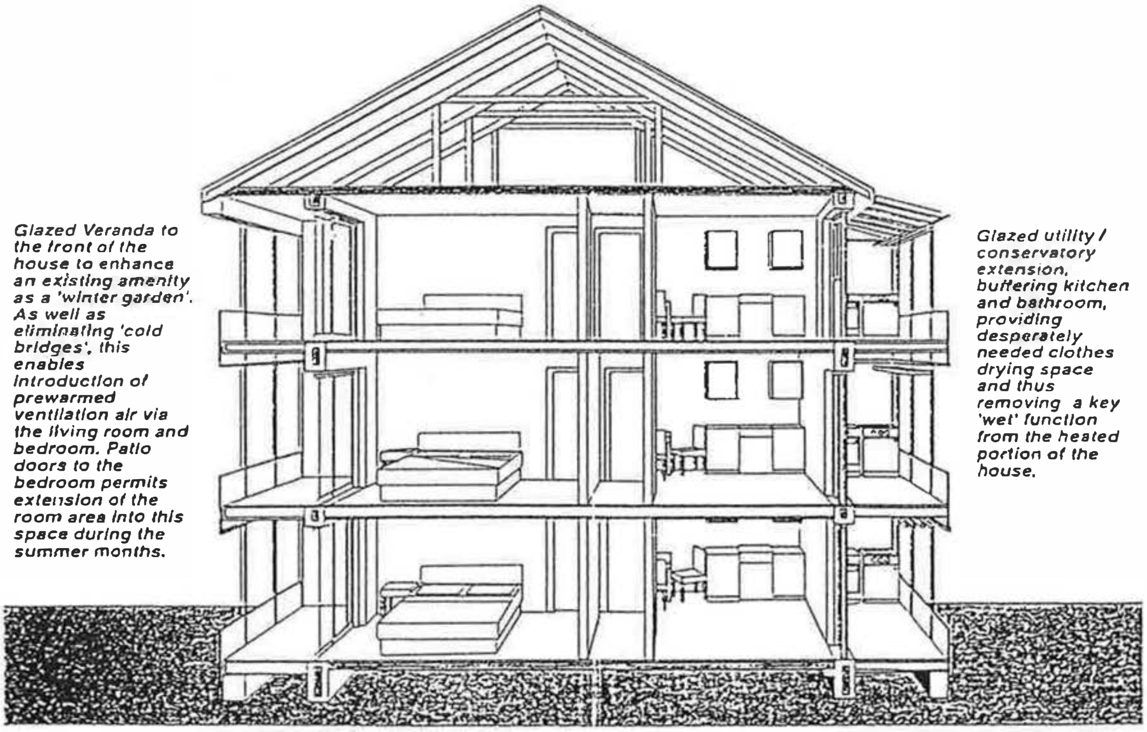


Figure 1a "Before" and "after" floor plan.


Glazed Veranda to the front of the house to enhance an existing amenity as a 'winter garden'. As well as eliminating 'cold bridges', this enables introduction of prewarmed ventilation air via the living room and bedroom. Patio doors to the bedroom permits extension of the room area into this space during the summer months.

Glazed utility / conservatory extension, buffering kitchen and bathroom, providing desperately needed clothes drying space and thus removing a key 'wet' function from the heated portion of the house.

Figure 1b Cross section through the glazed veranda and conservatory.

in winter; and in the case of small sunspaces, if they are opened up to adjacent heated spaces during winter, the system changes to one of direct solar gain with an extended heated volume.

For example, Bourdeau (1988) found that users in a newbuild sunspace project at 48.7°N near Nancy in N–E France seemed to open interconnecting windows too frequently in winter. In relation to the Easthall project, Ho and Porteous (1993, 1994) have reported the same tendency at interim stages of the project's evaluation. The aim of this paper is therefore to explore the users' interaction with the system in more depth, and in particular to assess the impact on performance of liberal autumn and spring opening of outer/inner windows/doors.

METHODOLOGY

The monitoring strategy was constrained by a relatively large sample and small budget. However, measurements of temperature in each space in every house, together with weekly fuel consumption for space heating (more accurately disaggregated in electric-heated houses than gas-heated), plus measured climatic data, enabled a fairly distinct picture to emerge with respect to the performance of the glazed spaces, and in particular the part played by the users in their operation of windows, doors, vents etc.

Using steady-state methodology (normal for housing), eqn. 1 yields an "equivalent" rate of air change, n^e, which acknowledges the thermal contribution of the sunspaces in the same way as would be the case for a mechanical ventilation system with a heat exchanger:

$$q^h + q^s + q^i = (\Sigma U.A + 0.33n^e.V)(t_i - t_o) \quad [W] \qquad (1)$$

where q^h is the net space heating load; $q^s + q^i$ is useful solar plus incidental gain to heated volume; $\Sigma U.A$ is the sum of fabric losses to outside, both directly and indirectly via buffer spaces; V is the heated volume; and t_i and t_o are respective inside and outside air temperatures; all averaged over 24 hours for a particular period, and all directly measured, calculated from direct measurement (e.g. q^s) or calculated from reliable data (e.g. U).

Ventilation rates between sunspace and outside, and sunspace and heated interior, are addressed in equation 2:

$$q^{ss} + q^{is} + q^{hs} = (\Sigma U^s.A + 0.33n^s.V^s)(t_s - t_o) \quad [W] \qquad (2)$$

where q^{ss} is the useful solar gain; q^{is} is the useful incidental gain; q^{hs} is the gain from the heated zones (all to the sunspace); $\Sigma U^s.A$ is the sum of fabric losses from sunspace to outside; n^s is the rate of air change between sunspace and outside; V^s is the sunspace volume; and t_s is the sunspace air temperature; all averaged over 24 hours for a particular period. Term q^{hs} is then expanded:

$$q^{hs} = (\Sigma U^b.A + 0.33n^b.V)(t_i - t_s) \quad [W] \qquad (2')$$

where $\Sigma U^b.A$ is the sum of fabric losses from heated zones to sunspace; and n^b is the rate of air change between sunspace and heated zones.

Abbreviating composite component $(\Sigma U^b.A + 0.33n^b.V)$ to H^b; and $(\Sigma U^s.A + 0.33n^s.V^s)$ in equation 2 to H^s, gives:

$$q^{ss} + q^{is} + H^b(t_i - t_s) = H^s(t_s - t_o) \quad [W] \qquad (2'')$$

Note that eqn. 2″ is only solvable for n^b and n^s if it can be assumed that all air which enters the sunspace from outside then passes to the interior. Since there are other possibilities, a third equation examines heat loss at each perimeter condition– i.e. fabric and ventilation losses are disaggregated for each bounding or ambient temperature with respect to heated zones:

$$q^h + q^s + q^i = \Sigma[(\Sigma U^p.A + 0.33n^p.V)(t_i^p - t_p)] \quad [W] \qquad (3)$$

where $\Sigma U^p.A$ is the sum of fabric losses for each perimeter condition, heated zone to sunspace, heated zone to outside etc.; n^p is the rate of air change between heated zone and each perimeter condition, including n^b, and $\Sigma n^p = n^r$, the real rate of air change to the heated volume; and $t_i^p - t_p$ is the temperature difference between respective parts of heated zones and ambient perimeter conditions.

Since n^p varies with each perimeter condition, the adoption of a "probable scenario" approach is necessary. From a pro-"ventilation-preheat" viewpoint, it would be ideal if all air change occurred via the buffers, and none directly, and vice versa. In reality neither extreme is possible. Rather than adopt a parametric approach with small incremental changes in the proportional distribution of n^p, a more broad-brush approach has been adopted, taking initially an upper and lower limit of probability, designated scenarios A and B.

Then, substituting relevant A and B values of n^p as n^b in equation. 2″, corresponding values for n^s are found. Scenario A's n^p may produce an unlikely, or inexplicable n^s value (e.g. negative), whereas B's may appear sensible. So by means of this fairly rudimentary cross-checking, a most likely scenario C for n^r may be found. Throughout this process, there is a tacit assumption that the house is not so opened up to the buffer spaces that the heated zone is simply extended to the outer glazing. The consequent change in the variables in the heat balance would then tend to give lower values for n^r relative to the larger volume. However since all variables in the heat balance other than ventilation are known, the method described is a valid expression of the purchased volume flow rate of fresh air relative to the intended heated volume.

Ventilation rates in dwellings are regulated by four influences: firstly what a closed building admits – too much if too air-leaky; secondly what an energy lobby wants in terms of fuel-efficiency; thirdly what occupants need in terms of health and environmental comfort; and fourthly what occupants like to do, or tend to do, in the way of operating controls. Having dealt with the first influence in terms of the energy-efficient retrofit in this project, the fourth may conflict with the second and third.

Fuel savings may be found by comparing the solar houses to a baseline reference model (REF–), heated and ventilated to the same level, and to a theoretical energy efficient reference (REF+), identical apart from omission of glazed spaces, and again heated and ventilated to the same standard. However, this rests on the assumption that the n^r profile is deemed reasonable, particularly with respect to the fourth influence. Therefore it is necessary to flesh out control by the occupants and place this in the context of previous surveys and analysis.

Use of controls, such as opening windows, is partly evident from examination of temperature profiles and comparing with n^r profiles. This is then supported by data from questionnaires, interviews, weekly diaries in a small number of cases, and observation by the monitoring team – abbreviated in this paper to *qido* data. The *qido* data not only builds up a strong picture with respect to use of windows, glazed doors and smaller fine-tuning devices such as hit-and-miss slot ventilators and louvres, but also enables this to be correlated to physical and social aspects of the households – e.g. location/fuel type, and family structure/habits respectively.

RESULTS

Users' influence compared with other variables

Table 1 summarises autumn, winter and spring n^e values for the SE/NW facing block (Wardie Rd.) and the E/W facing block (Glenburnie Pl.) over both heating years.

It may be noted that the sample size reduces in the second year due to less co-operation with weekly meter reading, that Glenburnie is consistently more ventilated compared with Wardie and that only Dec–Feb 1993–94 bucks the trend of lower values in the coldest quarter. There is not adequate detail here to begin to appraise the diversity of user-intervention with respect to ventilation, but elevational tables do enable a comparative oversight of results, with a key to location given in Figure 2.

Table 1 seasonal summary of n^e values [ac/h]

	Wardie	Glenburnie	sample
Sep–Nov 1992	1.05	1.32	17+17
Dec–Feb 1992–93	0.91	1.14	17+17
Mar–May 1993	1.15	1.25	17+17
Sep–Nov 1993	0.66	1.11	12+12
Dec–Feb 1993–94	0.59	1.29	11+11
Mar–May 1994	0.93	1.26	11+11

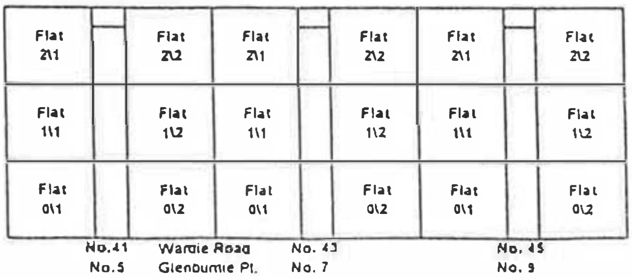


Figure 2 Key to elevational tables

Table 2 summarises n^e for 17 of 18 Wardie Rd. flats in 1992–93 (one household did not co-operate fully) together with temperatures, fuel type, household data, residents' comfort perception and monitoring agent's (MA's) perception with respect to air quality. The high ventilators (i.e. users) may thus be seen in context. For example, 45–0\2 is a gas heated house with young infants and adult smokers, perceived to be "very comfortable" by residents and "fresh" by the MA; whereas low ventilator 45–1\1 is a non-smoking pensioner, who also found her flat "very comfortable", but at a much lower temperature, and where air quality fell in perception to "tolerable"; and another non-smoking pensioner-household in 45–2\1, with similar temperatures but somewhat higher n^e than 45–1\1, was perceived to be "fresh".

Table 3 now summarises the mean n^e and n^r values for all solar houses in the first year together with heat inputs. In the case of n^r, there is a much bigger contrast between the fringes of winter and the coldest months compared with n^e. This gives respectively higher and lower loads compared with predictions which used a uniform n^r buffer/non-buffer split (Ho & Porteous, 1993).

Figure 3 effectively identifies low and high ventilators by expressing temperature as a function of space heating load. Individuals within this scatter may usefully be correlated to Tables 2 (Wardie, see above), 4, which lists the buffering effect for each house in Glenburnie, and 5 which ranks energy consumption, expressed in four ways, for both Wardie and GlenBurnie. A cluster of high and low consumers are located respectively to the right and left of Figure 3; while within each cluster, there is a significant range in terms of "warmth-value" relative to energy expenditure.

Table 2 Air temperatures (°C), and effective rates of air change (ac/h).

g	gas	I	home with infants.
e	electricity	O	home with old age pensioners only
p	pet	A	home with adults - no infants.
○	home with smokers	□	home with non-smokers
Z1	living room	all	all of house
Z2	rest of house	n°	effective rate of air change

(i)-(v) comfort on a scale where (i) is "very comfortable", (iii) is "comfortable" and (v) is "very uncomfortable".
a-c air quality scale (perception by MA) where a=fresh, b=tolerable, c=stuffy. (From 1992-93 questionnaire).

Wardie Road : September - November 1992 **Table 2a**

	No. 41				No. 43				No. 45			
Z1	23.75	g	22.45	g	22.82	g	20.66	g	19.95	g	21.39	g
Z2	20.84	I	20.77	O p	18.4	O p	17.91	A	16.73	O	19.42	I
all	21.64	○	21.23	○	19.61	○	18.66	○	17.61	□	19.96	□
n°	[1.04]	b	[0.81]	(i) b	[1.63]	a	[0.59]	b	[0.61]	a	[0.78]	b
Z1	22.2	g	23.75	e	21.29	e	22.62	g	19.48	g	21.96	e
Z2	19.63	I	20.42	O	17.08	O	19.93	I	16.29	O	19.14	O
all	20.33	□	21.33	○	18.23	○	20.67	○	17.16	□	19.91	○
n°	[0.89]	(iii) b	[0.41]	(i) c	[1.33]	(iii) a	[1.36]	a	[0.46]	(i) b	[0.86]	(i) b
Z1	23.33		▨ 23.44	e	22.51	e	22.39	g	▨ 25.53	e	▨ 21.12	g
Z2	18.78	□	21.11	A	18.38	O p	19.36	O	23.26	I p	18.29	I
all	20.02		21.75	○	19.51	○	20.19	○	23.88	○	19.07	○
n°		(iii) b	[0.64]	(iii) c	[0.89]	(iii) c	[2.55]	(i) a	[1.08]	(i) c	[1.85]	(i) a

Wardie Road : December - February 1992-93 **Table 2b**

	No. 41				No. 43				No. 45			
Z1	23.78	g	22.36	g	22.76	g	20.96	g	20.9	g	20.94	g
Z2	20.54	I	20.76	O p	8.06	O p	17.71	A	15.46	O	18.48	I
all	21.42	○	21.19	○	9.35	○	18.6	○	16.94	□	19.15	□
n°	[1.21]	b	[0.73]	(i) b	[1.38]	a	[0.33]	b	[0.41]	a	[0.72]	b
Z1	24.91	g	22.93	e	22.8	e	23.34	g	19.58	g	23.03	e
Z2	19.01	I	19.22	O	18.16	O	20.01	I	15.41	O	19.85	O
all	20.62	□	20.23	○	19.43	○	20.93	○	16.55	□	20.72	○
n°	[0.73]	(iii) b	[0.32]	(i) c	[1.01]	(iii) a	[1.73]	a	[0.38]	(i) b	[0.86]	(i) b
Z1	25.28		▨ 24.88	e	23.58	e	21.32	g	▨ 26.65	e	▨ 21.72	g
Z2	21.69	□	21.22	A	18.48	O p	18.58	O	23.35	I p	17.77	I
all	22.67		22.22	○	19.87	○	19.33	○	24.25	○	18.85	○
n°		(iii) b	[0.63]	(iii) c	[0.75]	(iii) c	[1.35]	(i) a	[1.05]	(i) c	[1.85]	(i) a

Wardie Road : March - May 1993 **Table 2c**

	No. 41				No. 43				No. 45			
Z1	23.64	g	22.43	g	22.89	g	21.05	g	20.57	g	21.09	g
Z2	20.96	I	21.13	O p	18.82	O p	18.96	A	17.08	O	19.43	I
all	21.69	○	21.48	○	19.93	○	19.53	○	18.04	□	19.88	□
n°	[1.46]	b	[0.79]	(i) b	[1.78]	a	[0.59]	b	[0.99]	a	[1.18]	b
Z1	24.47	g	24.43	e	22.87	e	23.16	g	19.35	g	22.27	e
Z2	19.84	I	20.78	O	19.39	O	20.38	I	17.15	O	19.35	O
all	21.1	□	21.78	○	20.34	○	21.14	○	17.75	□	20.15	○
n°	[1.11]	(iii) b	[0.39]	(i) c	[1.45]	(iii) a	[2.39]	a	[0.41]	(i) b	[0.89]	(i) b
Z1	24.66		▨ 24.69	e	23.32	e	21.13	g	▨ 25.56	e	▨ 22.12	g
Z2	21.92	□	20.87	A	19.51	O p	19.49	O	22.88	I p	19.24	I
all	22.67		21.92	○	20.55	○	19.94	○	23.61	○	20.03	○
n°		(iii) b	[1.05]	(iii) c	[0.88]	(iii) c	[0.91]	(i) a	[1.04]	(i) c	[2.3]	(i) a

□	8 best in terms of energy consumption	▨	8 worst in terms of energy consumption

Table 3 Effective and real air change rates, free gains and space heating loads: Mean solar demonstration house 1992–1993.

MONTH		n^e / n^r	q^s+q^i (W)	q^h (W)	$Q^{h\,Tot}$ (kWh)
Sep	Z1	1.4	182	192.4	291
	Z2	2.83	509	211.1	
Oct	Z1	1.1	194	308.7	557
	Z2	2.06	552	439.3	
Nov	Z1	1.06	164	379.3	652
	Z2	1.42	542	525.9	
Dec	Z1	1.02	148	459	946
	Z2	1.33	413	813.1	
Jan	Z1	1.03	139	444.6	893
	Z2	1.36	399	755.3	
Feb	Z1	1.03	151	395.8	708
	Z2	1.37	415	657.2	
Mar	Z1	1.18	188	379.3	750
	Z2	1.61	478	628.2	
Apr	Z1	1.22	189	304.2	546
	Z2	2.17	519	453.7	
May	Z1	1.22	216	199.1	286
	Z2	2.25	578	185.7	
Mean		1.14 1.82		Total : Measured :	5629 5629

Legend:

n^e effective air changes per hour, taking into account preheat affect of glazed spaces.

n^r real air changes per hour (approximate value within max – min range).

q^s useful solar gains.

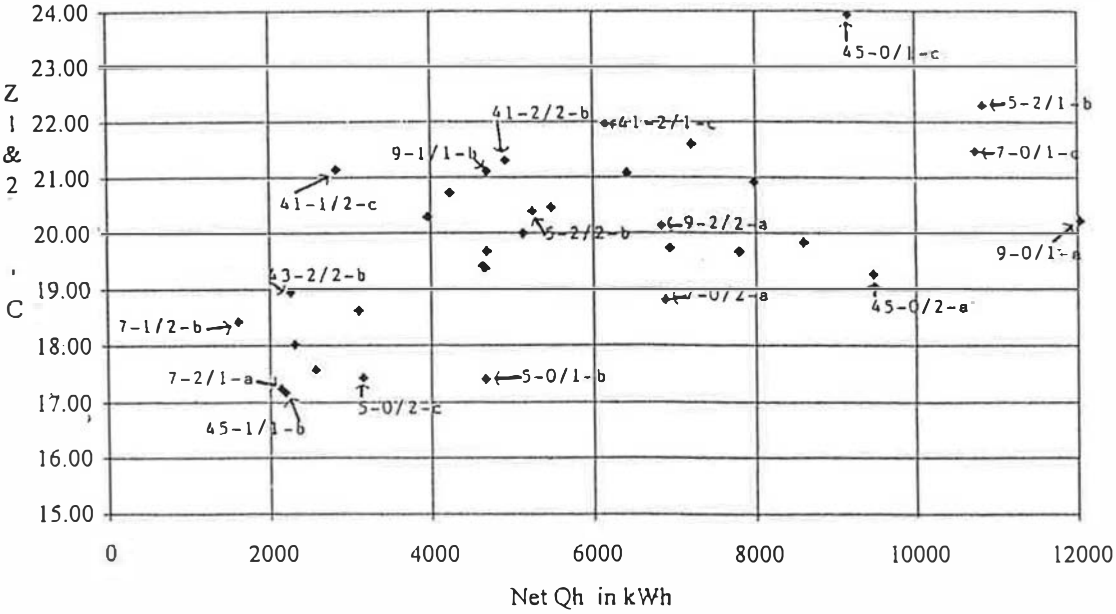
q^i useful incidental gains.

q^h and $Q^{h\,Tot}$ space heating load.

Note:

The mean monthly n^e values taken in conjunction with the mean transmission loss for all houses and the mean internal temperatures, will not necessarily correspond to the mean measured Q^h, since distribution of n^e relative to varying transmission loss is relevant.

Therefore, the n^e and n^r values have been weighted within each seasonal band, i.e. in Sept–Nov, Dec–Feb and Mar–May n^e corresponds to claculated means, but values for individual months vary. Similarly monthly Q^h totals are at slight variance with mean measured values, but the seasonal total corresponds to the mean for all 34 demonstration houses.



Legend: the first set of numbers (e.g. 5-2/2) denotes location of house, and the suffix letter denotes air quality as Table 2

Figure 3 Correlation between mean heated zone temperatures and net space heating load (Q^h).

Table 4 Temperature differences between buffer spaces, adjacent room and outside.

☐ flats that are best in terms of energy consumption
▨ flats that are worst in terms of energy consumption
☐ buffer spaces 'OK' - i.e. temp difference > 3K

actual temps	*temp difference*	
Temp in	BR1-V	Where : BR1 is temp in main bedroom
Veranda	V-To	K is temp in kitchen.
Temp in	K-C	To is outside temp.
Conserv	C-To	

Glenburnie Place : September - November 1992 **Table 4a**

15.55	6.62		13.66	5.8	15.02	2.47		15.17	5.62	12.26	5.06		14.94	3.37
V	9.28	▤	V	7.39	V	6.94	▤	V	7.09	V	5.99	▤	V	6.86
16.4	6.96	▤	12.48	8.79	13.91	4.17	▤	14.16	6.2	12.66	5.06	▤	15.11	3.5
C	10.13	▤	C	6.21	C	5.83	▤	C	6.08	C	6.39	▤	C	7.03
13.68	4.97		13.38	3.28	15.32	2.07		14.87	2.16	15.79	2.22		13.98	3.03
V	7.41	▤	V	7.11	V	7.24	▤	V	6.79	V	7.71	▤	V	5.9
10.78	10.14	▤	10.85	7.77	14.48	3.63	▤	15.5	1.5	14.64	6.38	▤	15.23	3.35
C	4.51	▤	C	4.58	C	6.4	▤	C	7.42	C	6.56	▤	C	7.15
11.06	3.9		11.4	4.3	15.95	3.84		15.7	2.74	13.84	5.93		15.49	2.04
V	4.79	▤	V	5.13	V	7.87	▤	V	7.62	V	5.76	▤	V	7.41
11.01	4.81	▤	9.17	7.78	13.83	7.9	▤	16.05	2.83	15.52	5.46	▤	13.37	6.27
C	4.74	▤	C	2.9	C	5.75	▤	C	7.97	C	7.44	▤	C	5.29
		No. 5					**No. 7**					**No. 9**		

C : 16/18 (87%) OK V : 12/18 (67%) OK

Glenburnie Place : December - February 1992-93 **Table 4b**

16.16	6.37		12.01	7.96	10.77	5.42		12.19	8.49	11.02	7.91		13.38	5.83
V	11.33	▤	V	7.18	V	5.94	▤	V	7.36	V	6.19	▤	V	8.55
16.82	6.31	▤	10.44	11.58	9.94	7	▤	11.39	8.85	12.61	7.16	▤	16.2	3.25
C	11.99	▤	C	5.61	C	5.11	▤	C	6.56	C	7.78	▤	C	11.37
14.29	4.31		12.11	3.5	13.69	4.74		12.18	6.25	12.88	6.9		11.45	4.15
V	9.46	▤	V	7.28	V	8.86	▤	V	7.35	V	8.05	▤	V	6.62
12.11	10.21	▤	8.59	9.21	12.57	6.38	▤	12.64	5.92	12.57	9.01	▤	12.48	5.08
C	7.28	▤	C	3.76	C	7.74	▤	C	7.81	C	7.74	▤	C	7.65
11.15	3.13		10.52	5.52	13.46	7.24		15.8	4.4	10.93	8.3		11.88	5.85
V	6.32	▤	V	5.69	V	8.63	▤	V	8.97	V	6.1	▤	V	7.05
10.77	5.15	▤	7.94	9.91	10.27	13.4	▤	15.56	3.44	14.26	6.37	▤	10.98	8.79
C	5.94	▤	C	3.11	C	5.44	▤	C	10.73	C	9.43	▤	C	6.15
		No. 5					**No. 7**					**No. 9**		

100% success (1 borderline No. 9 2/2)

Glenburnie Place : March - May 1992-93 **Table 4c**

18.9	3.3		16.58	4.07	15.89	2.62		16.3	3.9	15.49	5.39		16.81	1.87
V	10.44	▤	V	8.12	V	7.43	▤	V	7.84	V	7.03	▤	V	8.35
18	4.28	▤	14.34	6.08	14.5	3.08	▤	14.89	5.54	16.09	5.16	▤	16.48	2.77
C	9.55	▤	C	5.88	C	6.04	▤	C	6.43	C	7.63	▤	C	8.03
17.6	0.85		16.31	2.44	17.62	2.05		16.55	2.07	17.18	2.12		15.38	2.25
V	9.14	▤	V	7.85	V	9.22	▤	V	8.09	V	8.72	▤	V	6.29
15.87	4.73	▤	12.98	6.31	16.54	3.71	▤	16.24	2.34	14.75	5.55	▤	16.13	2.71
C	7.41	▤	C	4.52	C	8.14	▤	C	7.78	C	6.29	▤	C	7.67
16.02	3.23		14.85	2.39	18.25	3.48		16.5	2.12	14.84	4.59		16.65	2.04
V	7.56	▤	V	6.39	V	9.79	▤	V	8.04	V	6.38	▤	V	8.19
14.98	5.5	▤	11.95	6.39	14.45	8.33	▤	17.01	2.25	16.13	3.77	▤	14.41	5.07
C	6.52	▤	C	3.49	C	5.99	▤	C	8.55	C	7.67	▤	C	5.95
		No. 5					**No. 7**					**No. 9**		

C : 14/18 (78%) V : 6/18 (33%) usually Bedrooms too hot.

Table 4 (Continued) Temperature differences between buffer spaces, adjacent room and outside.

☐ flats that are best in terms of energy consumption
▨ flats that are worst in terms of energy consumption
☐ buffer spaces 'OK' - i.e. temp difference > 3-4K

actual temps	*temp difference*	
Temp in	BR1-V	Where : BR1 is temp in main bedroom
Veranda	V-To	K is temp in kitchen.
Temp in	K-C	To is outside temp.
Conserv	C-To	

Wardie Road : September - November 1992 **Table 4d**

18.31	2.82	17.95	4.05	15.66	2.3	15.9	3.03	12.69	4.24	14.75	5.33
V	10.23	V	9.87	V	7.58	V	7.82	V	4.61	V	6.67
13	8.31	12.75	9.23	12.02	7.17	11.92	6.41	9.2	7.45	12.81	6.8
C	4.29	C	4.67	C	3.94	C	3.84	C	1.12	C	4.73
18	2.55	20.14	0.93	14.2	2.2	19.73	0.34	14.99	1.98	17.74	1.36
V	9.92	V	12.06	V	6.12	V	11.65	V	6.91	V	9.66
12.17	7.77	13.54	7.46	12.15	6.46	13.44	6.7	10.74	6.61	14.42	5
C	4.09	C	5.46	C	4.07	C	5.36	C	2.66	C	6.34
16.38	3.27	16.14	5.16	14.16	3.74	17.89	2.41	15.34	6.84	13.9	4.91
V	8.3	V	8.07	V	6.08	V	9.81	V	7.25	V	5.82
15.79	3.95	14.53	6.76	10.41	8.99	14.48	6.82	13.45	11.36	13	5.39
C	7.71	C	6.45	C	2.33	C	6.4	C	5.37	C	4.92
No. 41				**No. 43**				**No. 45**			

V : 9/18 (50%) OK C : 15/18 (83%) OK - only 1 opened up too much to kitchen (41/01)

Wardie Road : December - February 1992-93 **Table 4e**

16.72	4.59	15.77	6.13	13.33	4.25	9.63	7.99	10.26	5.46	12	6.95
V	11.89	V	10.94	V	8.5	V	4.8	V	5.43	V	7.17
10.29	10.65	8.7	13.22	9.36	9.55	8.07	10.3	6.27	8.92	11.25	7.58
C	5.46	C	3.87	C	4.53	C	3.24	C	1.45	C	6.42
14.91	5.62	17.87	1.99	12.01	4.22	19.81	0.11	12.61	1.26	17.17	2.14
V	10.08	V	13.04	V	7.18	V	14.98	V	7.78	V	12.34
6.28	12.79	10.06	9.84	9.62	11.37	12.26	8.05	7.76	9.1	12.51	7.66
C	1.45	C	5.23	C	4.79	C	7.43	C	2.83	C	7.68
14.46	10.65	12.91	7.81	11.45	6.39	16.04	2.63	11.9	9.29	10.64	7.18
V	9.63	V	8.08	V	6.62	V	11.21	V	7.07	V	6.01
8.16	13.29	12.43	8.88	7.74	11.71	15.86	3.09	11.35	14.39	11.24	6.87
C	3.33	C	7.6	C	2.91	C	11.03	C	6.62	C	6.41
No. 41				**No. 43**				**No. 45**			

V : 13/18 (72%) OK C : 10/18 (56%) only 1 Conservatory opened up too much to kitchen (43/01)

Wardie Road : March - May 1992-93 **Table 4f**

19.11	2	17.6	4.67	16.54	1.68	15.86	3.1	12.71	4.46	14.38	5.3
V	10.65	V	9.14	V	8.09	V	7.4	V	4.25	V	5.92
14.83	6.54	14.21	7.99	14.53	5.13	14.05	5.5	10.89	6.18	14.76	5.14
C	6.37	C	5.75	C	6.07	C	5.59	C	2.63	C	6.3
18.68	2.33	19.53	1.69	14.55	3.28	lost		14.72	2.62	18.46	0.59
V	10.22	V	11.07	V	9.69		data	V	6.26	V	10
13.79	6.01	14.55	7.05	14.77	7.06	15.5	5.05	12.6	5.3	16.2	3.45
C	5.33	C	6.09	C	9.91	C	7.04	C	4.14	C	7.74
17.87	4.86	15.98	4.8	14.98	4.2	15.64	3.76	15.51	5.93	14.43	4.78
V	9.41	V	7.52	V	6.51	V	7.18	V	7.05	V	5.97
12.35	9.37	15.79	6.03	11.96	8.34	14.53	6.58	14.95	9.32	14.85	4.57
C	3.89	C	7.33	C	3.5	C	6.07	C	6.49	C	6.39
No. 41				**No. 43**				**No. 45**			

V : 11/18 (61%) OK - 2 verandas opened up to bedroom on a frequent basis (11%).
C : 14/18 (78%) OK - no conservatories opened up too much to kitchen.

Table 5 Energy consumption for space heating expressed and ranked in 4 ways (September 1992 – May 1993).

1 kWh/m^{3}K
2 £/K
3 kWh/m^3
4 £
[ ] Rank

Table 5a. Wardie Road

	No.41		No. 43		No. 45		
1	3.34 [23]	2.33 [13]	4.17 [29]	1.28 [2]	1.65 [7]	2.15 [14]	1
2	10.81 [15]	7.53 [10]	13.50 [22]	4.13 [1]	6.15 [6]	8.49 [13]	2
3	48.29 [26]	32.96 [16]	52.21 [27]	15.09 [4]	17.19 [7]	34.41 [17]	3
4	156.18 [19]	106.60 [13]	168.85 [20]	48.79 [2]	64.10 [5]	106.32 [12]	4
1	2.10 [11]	1.35 [3]	2.56 [16]	3.88 [27]	1.45 [6]	2.02 [9]	1
2	6.78 [7]	6.86 [8]	11.00 [16]	12.57 [19]	5.58 [4]	11.06 [17]	2
3	28.44 [11]	18.86 [6]	31.31 [14]	33.53 [28]	14.58 [3]	26.57 [10]	3
4	91.95 [9]	96.00 [10]	134.41 [15]	173.16 [21]	55.98 [4]	145.37 [16]	4
1		▨ 2.78 [20]	2.68 [18]	4.55 [30]	▨ 3.66 [26]	▨ 5.24 [33]	1
2		▨ 16.40 [28]	17.04 [31]	14.73 [24]	▨ 16.74 [29]	▨ 16.95 [30]	2
3		▨ 41.21 [21]	34.44 [18]	57.74 [29]	▨ 61.53 [30]	▨ 63.56 [31]	3
4		▨ 243.20 [30]	218.92 [27]	186.77 [23]	▨ 280.99 [34]	▨ 205.62 [26]	4

Table 5b. Glenburnie Place

	No.5		No. 7		No. 9		
1	▨ 4.79 [31]	2.66 [17]	1.42 [4]	2.76 [19]		▨ 3.53 [24]	1
2	▨ 15.51 [26]	11.69 [18]	4.60 [2]	8.92 [14]		▨ 20.58 [33]	2
3	▨ 72.64 [33]	35.14 [19]	14.36 [2]	36.67 [20]		▨ 45.78 [23]	3
4	▨ 234.98 [29]	154.64 [18]	46.66 [1]	118.59 [14]		▨ 267.15 [33]	4
1	3.09 [22]	1.81 [8]	2.54 [15]	0.96 [1]	2.25 [12]	1.42 [4]	1
2	14.61 [23]	5.86 [5]	8.21 [12]	4.91 [3]	12.83 [21]	7.25 [9]	2
3	43.05 [22]	20.77 [8]	31.11 [12]	10.88 [1]	31.44 [14]	15.39 [5]	3
4	203.77 [25]	62.21 [6]	100.60 [11]	55.39 [3]	178.94 [22]	78.75 [8]	4
1	▨ 3.04 [21]	2.05 [10]	▨ 5.02 [32]	3.96 [28]	▨ 6.17 [34]	3.68 [25]	1
2	▨ 23.97 [34]	7.56 [11]	▨ 16.25 [27]	12.79 [20]	▨ 19.97 [32]	15.33 [25]	2
3	▨ 31.25 [13]	21.08 [9]	▨ 71.93 [33]	46.16 [24]	▨ 80.62 [34]	46.39 [25]	3
4	▨ 246.16 [31]	77.82 [7]	▨ 232.65 [28]	149.30 [17]	▨ 260.79 [32]	193.01 [24]	4

☐ 8 all-round best in terms of energy consumption.
(37.5% electric).

▨ 8 all-round worst in terms of energy consumption.
(50% electric).

lowest cost - gas
lowest energy consumption - electric

highest cost - electric
highest energy consumption - gas

For example, in the "low" set 41–1\2 enjoys 4K more warmth compared with either 45–1\1 or 7–2\1, and only has to pay for about 285 kWh extra. On the other hand 43–2\2 has the same energy load as 45–1\1 and 7–2\1 and 2K more warmth, which, at a 19°C mean 24h whole-house temperature, should suffice in terms of comfort. Since there is not a big difference between any of the houses in terms of transmission loss, and all enjoy a degree of mutual thermal protection, the difference in performance must be mainly due to differing ventilation and/or heating regimes. But what drives such differences?

It has already been noted that Glenburnie flats have higher mean n^e values than their Wardie counterparts. This may be due in part to the former's main facade being more exposed to prevailing south-west winds. A tendency for the highest consumers/ventilators to be located on ground floor or 2nd floor gable positions may also be due in part to natural air-leakiness. However, it also relates to intervention on the part of the occupants. Flat 45–0\2 has a much higher air change rate compared to 45–0\1, although the gas heating in the former case and electric in the latter result in a reversal of ranking comparing the energy load expressed in kWh/m^{3}K with fuel cost. The ability to pay – 45–0\2 found the house "very easy" to heat compared with "easy" in the case of 45–0\1 – may be influential in indulging a certain lifestyle. This allows young children to use the glazed veranda as a play space, and take advantage of its direct access to the garden, as well as adopting a liberal airing regime all year round. The latter was well documented in 45–0\2's weekly diary, with the aim "to air the house". It is further relevant that 45–0\1 was perceived as stuffy, presumably due to the effect of high temperatures which are apparently enjoyed by the ocupants, rather than low rates of ventilation.

Having established that 45–0\2's high consumption of 5.24 kWh/m^{3}K is due to the user's airing regime, it is worth returning to flats 41–1\2 and 45–1\1, both low users but the former averaging 4K warmer than the latter. One might anticipate that 45–1\1 has the higher ventilation rate; but although its n^e is marginally greater than that of 41–1\2, the reverse is true for n^r – see Table 6 below.

Table 6 n^e cf. n^r for 41–1\2 & 45–1\1 [ac/h]

41–1\2	n^e	n^r A	n^r B	n^r C
Sep–Nov 1992	0.41	1.66	1.11	1.46
Dec–Feb 1992–93	0.32	0.94	0.69	0.81
Mar–May 1993	0.39	1.38	0.96	1.25
45–1\1	n^e	n^r A	n^r B	n^r C
Sep–Nov 1992	0.45	1.57	1.16	1.39
Dec–Feb 1992-93	0.38	0.77	0.62	0.65
Mar–May 1993	0.41	1.20	0.90	1.10

The higher n^r values in the case of 41–1\2 correspond to the *qido* data, while the respective occupants share the same tendency to open the patio door between bedroo... and glazed veranda, and are both away from home quite frequently. However 41–1\2 uses electric storage heating, while 45–1\1 intermittently operates a responsive gas system. Thus in this case it is the mode of heating, rather than ventilation, that must account for the 4K difference.

A further paradox is apparent taking 45–0\1 and 45–0\2 as two high consumers – one with high temperatures and average rates of air change, and the other with average temperatures but very high rates of air change – and 41–1\2 and 45–1\1 as low consumers. It may be seen from Table 4, that the buffering effect of the veranda appears better for the "high" set, suggesting that high rates of ventilation increase the space heating load, but do not negate the preheat effect. This is supported by comparison of n^e and n^r values for 43–1\1, known to keep the house well aired, and just below the median in terms of consumption-ranking and the mean when consumption is expressed as kWh/m^{3}K – see Table 7 below.

Table 7 n^e cf. n^r for 43–1\1 [ac/h]

43–1\1	n^e	n^r A	n^r B	n^r C
Sep–Nov 1992	1.33	3.01	2.15	2.38
Dec–Feb 1992–93	1.01	1.58	1.29	1.33
Mar–May 1993	1.45	2.77	2.14	2.22

Although both n^e and n^r are much higher than corresponding values for 45–1\1, the (n^r–n^e) differences for scenario C are of the same order in each case.

Before moving on to explore links between family structure and/or habits and ventilating regimes, it is worth noting that large devices such as windows are used more responsively in relation to seasonal changes than small devices such as adjustable slot ventilators. For example, Table 8a–c shows that 30% of respondents who acknowledged "often" opening the patio door between bedroom and veranda in winter doubles to over 60% from March to May. On the other hand, use of slot ventilators does not vary much between seasons in any category. Use of glass louvres between kitchen and utility-conservatory is more variable, again supporting the notion that the more visible or bigger the device, the more likely it is to be used. If this is the case, it questions the effectiveness of small manually operated fine-tuning devices.

With respect to windows/doors it is worth examining differences between high and low consumers. In the case of the bedroom's patio door being opened to the veranda from December to February, none of the low users listed "often" and 80% "hardly ever"; while 25% of the high users listed "often", 50% "sometimes" and 25% "hardly ever". On the other hand 80% of the low users professed to opening this door "often" in spring, while in autumn 60% stated "sometimes" and the remainder "hardly ever".

This suggests that either the sunnier spring weather relative to autumn provoked this response, or that there is a psychological "spring attitude" to ventilation after the long, relatively gloomy winter months, or a combination of such factors. The other interesting trait is that there is a similarity between high and low consumers' operation of windows and doors in spring, but not in either winter or autumn, when the former open up more frequently. For example, 25% of the "highs" open the outer conservatory window

Table 8 Occupant ventilation of glazed spaces and heated zones.

		Often		Sometimes		Hardly Ever	
Item	**Period**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
P	Sep-Nov	40%	21%	36%	12%	24%	67%
V	Sep-Nov	52%	55%	13%	5%	35%	40%
W	Sep-Nov	20%	4%	60%	13%	20%	83%
P	Dec-Feb	30%	18%	26%	15%	44%	67%
V	Dec-Feb	44%	44%	12%	8%	44%	48%
W	Dec-Feb	11%	4%	26%	4%	63%	92%
P	Mar-May	61%	36%	25%	14%	14%	50%
V	Mar-May	54%	50%	11%	8%	35%	42%
W	Mar-May	46%	7%	36%	11%	18%	82%

Legend :
P Patio door between BR1 and Veranda.
V Vent over patio door - between BR1 and Veranda.
W Outer windows to Veranda.

Table 8a
Main bedroom and veranda, opening patio doors, hit and miss vent and outer windows.

		Often		Sometimes		Hardly Ever	
Item	**Period**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
d	Sep-Nov	18%	0%	46%	23%	36%	77%
V	Sep-Nov	50%	50%	21%	8%	29%	42%
W	Sep-Nov	35%	9%	39%	22%	26%	69%
d	Dec-Feb	4%	4%	37%	11%	59%	85%
V	Dec-Feb	48%	48%	19%	7%	33%	45%
W	Dec-Feb	15%	4%	41%	15%	44%	81%
d	Mar-May	25%	18%	61%	22%	14%	60%
V	Mar-May	57%	57%	21%	7%	22%	36%
W	Mar-May	50%	14%	29%	21%	21%	65%

Legend :
d Glazed door between Living Room and Veranda.
V Vent over glazed door etc.
W Outer windows to Living Room.

Table 8b
Living room and veranda, opening glazed doors, hit and miss vent and living room windows.

		Often		Sometimes		Hardly Ever	
Item	**Period**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
d	Sep-Nov	52%	16%	40%	16%	8%	68%
l	Sep-Nov	33%	12%	50%	17%	17%	71%
W	Sep-Nov	29%	12%	46%	17%	25%	71%
d	Dec-Feb	44%	11%	37%	15%	19%	74%
l	Dec-Feb	31%	15%	50%	19%	19%	66%
W	Dec-Feb	19%	12%	39%	19%	42%	69%
d	Mar-May	64%	18%	32%	18%	4%	64%
l	Mar-May	52%	30%	33%	11%	15%	59%
W	Mar-May	57%	25%	29%	25%	14%	50%

Legend :
d Glazed door between Kitchen and Conservatory.
l Louvered panel between Kitchen and Conservatory.
W Outer windows to Conservatory.

Table 8c
Kitchen and conservatory, opening glazed doors, louvres and outer windows.

often in winter and 43% in autumn, compared with none of the "lows" in either season, whereas there is rough "high" and "low" parity for this window in spring.

The issue of family structure and habits is the most elusive relative to intervention. With a small statistical sample, apparent trends may deceive, and there are independent physical influences. For instance, houses heated by gas are expected to be more ventilated than their all-electric neighbours, as in Table 9a.

Table 9a n^e for gas and electric flats [ac/h]

1992-93	autumn	winter	spring	sample
gas	1.14	0.98	1.26	20
electric	0.87	0.77	0.95	14

But in the second year, there are exceptions to the rule in autumn and spring – see Table 9b.

Table 9b n^e for gas and electric flats [ac/h]

1993–94	autumn	winter	spring	sample
gas	0.61	0.64	0.89	12
electric	0.71	0.54	0.99	12

A second comparison of "smoking" and "non-smoking" households confirms a consistent trait. Table 10 indicates that, for the 2nd line in each year with the same small number of houses as the smoking ones (random neighbours), air change is significantly higher than the the whole sample in the first year, but somewhat lower in the second year. This then raises the issue of what the value for non-smokers might have been for a larger sample. Nevertheless it is a consistent and logical result.

Table 10 n^e for smoking condition [ac/h]

1992–93	autumn	winter	spring	sample
smoking	1.15	1.02	1.05	29
smoking	1.31	1.26	1.46	7
non-smoking	0.87	0.67	0.95	7
1993–94				
smoking	0.95	0.91	1.07	19
smoking	0.84	0.86	0.98	5
non-smoking	0.63	0.69	0.95	5

A third supposition to test is that families with infants under 10 years old invoke higher rates of ventilation. Table 11 again consistently supports this contention.

Other aspects such as ownership of pets are more difficult to pin down in terms of influence, but large pets add to the family metabolically and use of buffers as kennels may be linked to open windows. The prevalence of various types of net curtaining and Venetian blinds, even on outer buffer glazing is a consequence of "pride in home". This must have a negative effect on solar supply, but again it is hard to quantify. In any case, virtual universality renders it more a constant than a variable.

Table 11 n^e for "infant" condition [ac/h]

1992-93	autumn	winter	spring	sample
infant	1.36	1.31	1.65	9
non-infant	1.12	0.92	1.04	25
1993–94				
infant	1.26	1.40	1.72	4–5
non-infant	0.79	0.79	0.96	19

Half the households had lower fuel loads (kWh/m^{3}K) in the second year, and some of these made substantial savings – e.g. 43–0\1 and 43–0\2 down by about 50%, with lower temperatures and lower rates of air change.

Easthall's ventilation rates in a wider context

As stated under "methodology", having assessed user-impact on heating loads and performance of glazed buffer spaces, and before calculating savings compared with two reference models, it is of value to place trends with respect to ventilation in a wider context.

Dick and Thomas (1951) carried out two valuable field studies at Abbots Langley and Bucknall's Close. A linear increase in opening of "casements" and "hoppers", especially the latter, occurred over the temperature range to be expected in autumn and spring. Although this work is now over 40 years old, the type of window prevalent at that time gives more flexible control than is commonly the case today. Applying Easthall's mean autumn-spring temperature of 8.25°C to the findings at Abbots Langley yields 2.4 hoppers and 0.4 casements (approx. 0.4 m^2 opening) and an air change rate of just below 3.0 ac/h. The second study at Bucknall's Close indicated a sharp increase in air change above a wind velocity of 1.35 m/s when there were three vents open (say 0.1m^2 each) and above 2 m/s with no vents open. The mean autumn-spring wind speed in Glasgow of 4.5 m/s applied to these findings indicates an air change rate of 3.6 ac/h with three vents open and over 1.5 ac/h when closed up.

More recent work by Etheridge (1982) indicates that in wind-dominated conditions, 0.1 m^2 of open windows corresponds to about 1.0 ac/h, 0.3 m^2 to about 2.4 ac/h and 0.4 m^2

to over 3.0 ac/h; and the respective rates are about 0.5, 1.0 and 1.25 ac/h if buoyancy-dominated. These findings correspond to a regime within a house with all internal doors closed. If two internal doors are left ajar, one to the room with the open window, air change rates increase. A bedroom window with less than 0.1 m^2 opening corresponds to a 1.8 ac/h whole-house rate at 4.5 m/s wind speed compared with 1.0 ac/h when all doors are closed. Since parents are quite likely to leave their children's bedroom door open overnight, this survey helps to explain the values in Table 11.

Overall, such field studies support an expectation for the range of rates of air change experienced at Easthall in autumn and spring, and suggest that to model housing with one rate of ventilation over a heating season does not accord with people responding to their environment in a more intrinsically individualistic and complex way.

Energy "worth" relative to reference models

Therefore, accepting the n^r rates in Table 3 as a norm rather than an aberration, and inevitably large swings about a mean due to the characteristics and influences of the occupants, the energy "worth" of the project may be calculated. REF– is a real building, the same house type on the same site before renovation, but a theoretical model in that none of the occupants can afford to heat and ventilate to the same standard as the solar houses. It is relevant, nevertheless, to estimate how much energy would be required to to achieve the mean standard of the retrofitted houses. The space heating load for REF– in 1992–93 was estimated as 20,330 kWh. The solar houses' mean of 5,629 kWh (Table 3) is 72.3% or 14,701 kWh less, increasing slightly to nearly 75% in the second year.

REF+ is a theoretical model in every sense since all 36 houses in the demonstration had two glazed spaces. Calculating the energy "worth" of the buffered houses relative to REF+, as a competitor in terms of replication, is an important aspect of the project's evaluation. In this instance the difference is 2,550 kWh or 31.2%, more than the 28.4% predicted mean. This confirms that the buffer spaces do work in terms of preheating air for ventilation. The "utility" buffer is also needed extra space taking "wet" activities outwith the heated volume, and consequently condensation has been entirely eliminated.

CONCLUSIONS

1. The wide range in heating loads is mainly the result of differing demands with respect to warmth and ventilation.
2. Liberal ventilation does not tend to negate the preheat effect of buffers, and some frequent "patio door openers" were low consumers. So it appears to be a fairly robust technique, well suited to typical "airing-aspirations", and in this case its energy worth is about 2,500 kWh p.a.
3. The buffers reduce the impact of window opening in autumn and spring, with effective rates of air change steadier than real rates over a heating season. Modelling a single rate from September to May is not realistic.
4. Components such as windows and louvres are operated more responsively relative to seasons than small devices.
5. Indicators have emerged linking high fuel consumption to families with smokers and young children.

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