ECRC/M1736

SPACE HEATING IN THE CAPENHURST LOW ENERGY HOUSES

by D. A. McIntyre

OCTOBER 1985

JOB NO. 4251

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SUMMARY

ECRC Capenhurst co-operated with two firms of builders to design, build and sell four low energy houses. The houses were insulated to a high standard and fitted with mechanical ventilation.

The average annual space heating energy consumption of the four houses was some 6000 kWh, 95% of which was provided at low tariff rate by storage heaters. The whole house average temperature over the heating season ranged from 17.6 to 20.3°C for the four houses. The owners maintained the living room at a constant comfortable level, while bedroom temperatures varied with the weather, with a slope of 0.4 K/degree change in outside temperature.

The heating system was based on two storage radiators: a fan storage radiator in the main lounge-dining room, and a thermostatic storage radiator in the hall. The combined storage capacity was 40 kWh. Additional heating was provided by a focal point heater in the lounge, and by an oil-filled panel radiator in each bedroom. The illuminated fuel effect of the focal point heater was used extensively, but very little use was made of the radiant elements to provide supplementary heat. While the bedroom heaters were not used very much, they were definitely needed if the bedrooms were to be used during cold evenings. Heated towel rails were fitted in both kitchen and bathroom.

The fan storage radiator was modified by the manufacturer to include superior insulation to reduce case emission. Two of the heaters were incorrectly assembled on site, and had inadequate heat emission; they were replaced by a newly available commercial fan storage radiator. The

radiant heater in the lounge was fitted with additional switching to allow a low heat setting of 400 W. This was found satisfactory by the owners. All other heating and control equipment was standard.

Output control of the fan storage radiator was by a clock thermostat operating the output fan. This operated satisfactorily. Input control of the hall storage radiator was by a Satellite room thermostat. This tended to undercharge in cold weather, but was otherwise satisfactory.

The owners' general level of satisfaction with the heating system was high. The hall and landing temperatures tended to droop in the evening; although this was only by 1 or 2 K, it was noticed and disliked.

The report suggests how future heating installations might be modified and improved. Some equipment could be simplified. The lounge storage fan heater was sufficient for all heating needs, and the radiant heater played little part as a provider of supplementary heat. Time clock control on the fan output could, with advantage, be replaced by a manually switched thermostat. An increase in capacity of the hall storage heater above the minimum design value would give increased owner satisfaction. Occasional bedroom heating is necessary; time clock control could be an advantage.

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OCTOBER 1985

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1. HOUSE DESIGN

1.1 Description of houses

ECRC Capenhurst co-operated with two firms of builders to design, build and sell four low energy houses. The houses were of two types, both standard designs of the builders, which were modified to incorporate extra insulation and mechanical ventilation. Both houses were three-bedroomed detached houses, of about 80 square metres floor area, and of conventional masonry construction. The houses were very well insulated, having walls with 100 mm wide insulated cavities, 150 mm of insulation in the loft and high performance windows fitted with double glazing. Particular attention was given to reducing adventitious ventilation, and the houses were fitted with a full supply and extract mechanical ventilation system, which incorporated heat recovery. The design heat loss was of the order of 3 kW. The design, construction and thermal performance of these houses is described in ECRC/R1760. This report is concerned with the all-electric heating system.

The houses were not research houses. The houses were built by ordinary builders, and were sold on the open market. While some subsidy was provided towards the extra cost of the improved insulation and ventilation equipment, the houses were sold at a premium price over gas heated houses of the same design, and the occupiers were in no way subsidised in the operation of the houses. House temperatures and energy use, together with the occupants' mode of use of equipment, was monitored for over a year. The design of the heating system was carried out according to principles which were agreed at the start of the project:

1. Over 90% of the energy supplied for space heating should be taken at the low rate tariff. At the time of building, the ratio between day and low rate tariffs was 3:1.
2. No experimental heating equipment should be installed. If any non-standard equipment was used, it should have only minor modifications which used standard parts.
3. Not more than two storage heaters should be used to provide the base heating. This was intended to emphasise the low energy nature of the house, as well as to keep capital costs down.
4. A focal point heater should be provided in the lounge. This was not strictly necessary from the point of view of system performance, but was an anticipation of the occupier's preference.

5. A fair degree of automatic operation should be provided.
6. All rooms should have a source of heat.

Floor plans and dimensions of the two types of house are shown in Figures 1.1 and 1.2. The appearance of the houses is virtually identical to similar buildings on the same estate. Two modifications were made to the layout of the Comben Madrid to accommodate the heating system. The division between lounge and dining room was removed, to allow heating of the downstairs living space with a single storage radiator, and the position of the lounge door was moved slightly to allow a storage heater to be placed behind it. In the Whelmar Oxford, the french windows were replaced with a normal window, to reduce the transmission loss and to eliminate a likely source of air leakage. Apart from these, all modifications to the houses were constructional, and did not affect the layout of the house.

Two houses were built by Whelmar to the Oxford design, at Cinnamon Brow, Warrington. They are identified in this report, and in the data analyses, by their coded addresses, 8GC and 9GC. The other two houses were built in Kippax, Leeds, by Comben Homes to the Madrid design; they are identified as 22AG and 31AG.

1.2 Heat loss estimates

The U-value of the modified construction elements was estimated from published figures of thermal conductivity.

Table 1.1 lists the building elements and their estimated U-values. Tables 1.2 and 1.3 list the building dimensions and estimated total heat loss coefficient. This is a relatively crude estimate, taking no account of the effect of corners, heat bridges, etc. A much more detailed treatment is given by Siviour (1983) which also includes the results of thermal measurements made in the houses. The simple treatment was sufficient for its purpose of sizing the heating system and providing a rough estimate of likely energy consumption. The Madrid has a slightly higher heat loss coefficient at 147 W/K than the Oxford's 140 W/K; this is primarily due to the larger floor area of the Madrid.

Table 1.1 Design U-values of building element

Element	Construction	U-value $Wm^{-2}K^{-1}$
External wall	Plaster/insulating block/100 mm mineral wool/brick	0.33
Ceiling	Conventional plasterboard and joists with 150 mm mineral wool	0.28
Windows	Double glazing in wooden frame	2.8
Floor (Madrid)	Suspended timber floor, with 75 mm insulation	0.33
Floor (Oxford)	Concrete raft, with 50 mm EP insulation	0.38
WC wall to garage, porch ceiling, bay window surround (Madrid)	Stud partition, with 100 mm mineral wool	0.45

Table 1.2 Heat loss summary (design stage). Comben Madrid

Building element	Area $A(m^2)$	U-value $U(Wm^{-2}K^{-1})$	Effective U U'	AU'
Windows				
to outside	13.3	2.8		37.2
to porch	0.9	2.8	1.8	1.6
Doors				
to outside	3.8	2.5		9.5
to porch	2.0	2.5	1.7	3.3
WC				
wall to garage	8.9	0.45	0.43	3.8
ceiling	2.7	0.28		0.8
Cavity walls				
to porch	4.8	0.33	0.22	1.2
to garage	3.6	0.33	0.31	1.1
to outside	101.1	0.33		33.4
Ceiling	42.1	0.28		11.8
Floor	42.8	0.33		14.1
Bed to porch	2.0	0.45	0.3	0.6
Hall to porch	1.9	0.45	0.3	0.6
Bay window surround	1.8	0.45		0.8
		Total transmission loss	=	119.7 W/K

Ventilation loss. House volume = 204 m^3
1 air change/hour, 60% heat recovery gives 27.2 W/K
Total heat loss coefficient = 147 W/K

Actual heat loss when built, estimated from measurements: (ECRC/N1652)

Transmission loss	=	136
Adventitious ventilation loss	=	24
Mechanical ventilation loss	=	8
Total	=	168 W/K

Table 1.3 Heat loss summary (design stage) Whelmar Oxford

Building element	Area $A(m^2)$	U-value $U(Wm^{-2}K^{-1})$	AU WK^{-1}	
Windows	16.7	2.8	46.8	
Doors	4.0	2.5	10.0	
Wall	100.3	0.33	33.1	
Ceiling	39.6	0.28	11.1	
Floor	39.6	0.38	15.1	
	Total transmission coefficient			116.0

Ventilation	Volume $V(m^3)$	Ventilation ac/h	Recovery %	
	182	1	60	
	Total ventilation coefficient			24.3
	Total loss coefficient			140.3

Heat loss when built, estimated from measurements: (ECRC/N1683)

Transmission	140
Adventitious ventilation	27
Mechanical ventilation	9
Total:	176 W/K

Table 1.4 Summary of energy predictions

Common assumptions:

Average whole house internal temperature	18°C
Average internal free heat prediction (excl. sun)	750 W
Ventilation fan heat contribution	65 W

Heating season: 212 days October-April

Weather: 20 year Heathrow average, less 1K correction for N. England.

Estimated space heating energy requirement:

Comben Madrid:	3500 kWh
Whelmar Oxford:	3010 kWh

Expected energy use for other purposes:

Mechanical ventilation	660 kWh
Water heating	3500 kWh
Cooking	1250 kWh
Miscellaneous	2250 kWh.

Table 1.5 The four houses

Location: Cinnamon Brow, Warrington
Builder: Whelmar
Design: Madrid

8GC	4 adults, 2 at work. Occupied 4th March, 1982
9GC	2 adults, 1 child. Both adults work, one on shifts. Occupied 19th March, 1982.

Location: Kippax, Leeds
Builder: Comben Homes
Design: Oxford.

22AG	2 adults, 2 children. 1 adult at work. Occupied 13th November, 1981
31AG	2 adults, 4 children. 1 adult at work. Occupied 26th February, 1982.

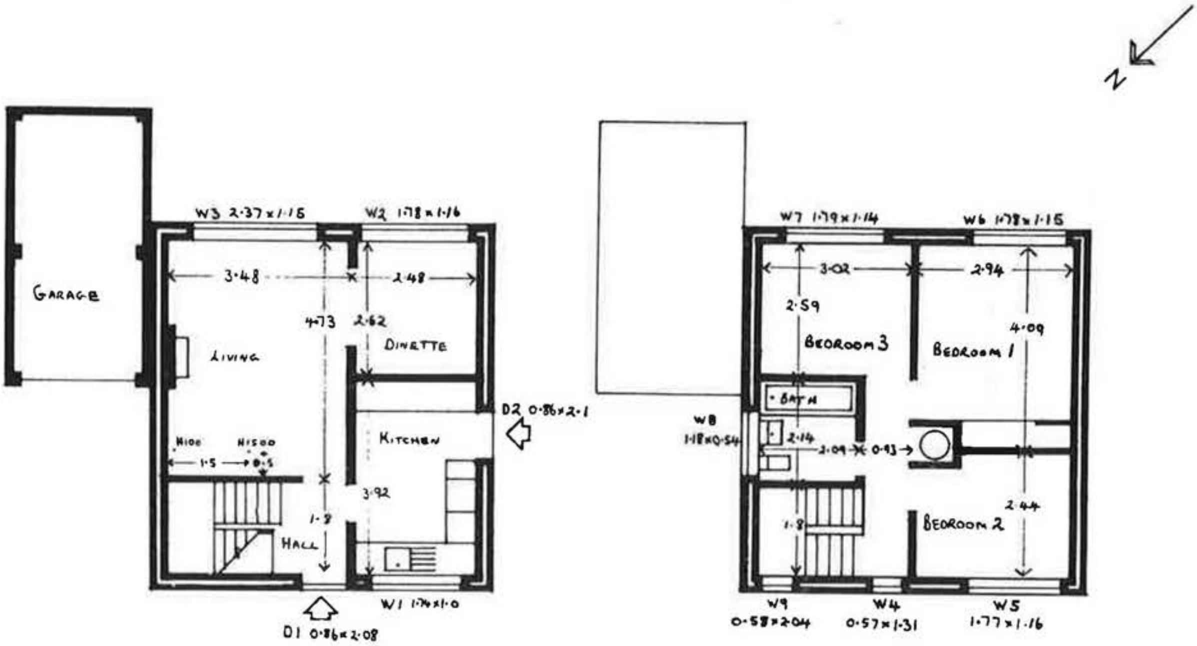


FIGURE 1.1 Whelmar Oxford design, at Gairloch Close, Warrington.

8GC 4 Adults, 2 at work. Occupied 4th March, 1982.
9GC 2 Adults, 1 child. Both adults at work, one on shifts. Occupied 19th March, 1982.

ECRC/M1736

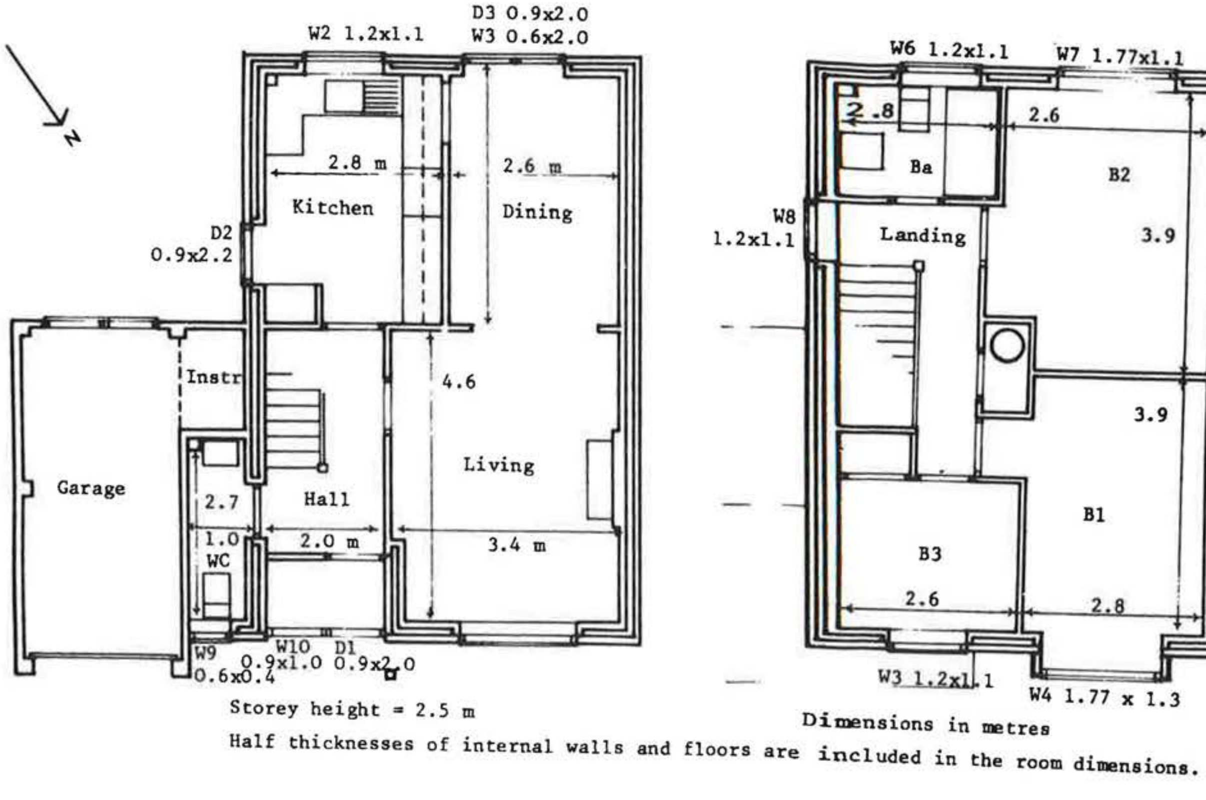


FIGURE 1.2 Comben Madrid design, at Ash Grove Croft, Leeds.

22AG 2 adults, 2 children. 1 adult at work.
Occupied 13th November, 1982.
31AG 2 adults, 4 children. 1 adult at work.
Occupied 26th February, 1982.

2. DESIGN OF HEATING SYSTEM

2.1 Sizing of storage heaters

The performance target of the storage heating system was that it should provide 95% of the net heating energy used over the heating season. This implies that the storage heaters need not be large enough in themselves to provide the full heat requirement on a design day. Some heat is provided by the free heat gains in the house, and the balance in cold weather is made up by direct acting heaters, using day rate electricity. Calculations from first principles of the necessary storage capacity therefore require assumptions about both the weather pattern over the year and the rate of free heat production. The gross design day heat requirement is

$$Q_{des} = 0.024H\,(T_{des} + 1) \quad \text{kWh}$$

where H (W/K) is the heat loss coefficient of the house, including both conduction and ventilation, T_{des} is the whole house internal design temperature, and the external design temperature is taken to be -1°C. The total storage heater capacity in the house is given by sQ_{des}, where s is the storage factor. The storage factor is estimated by means of two subsidiary factors:

$$s = yz$$

where y is the seasonal day percentage factor, and z is the so-called z factor. The seasonal day percentage factor can be simply estimated; if a fraction f of the energy over the season is to be taken at day rate, then $y = 1 - \sqrt{f}$. The z factor represents the effect of miscellaneous heat gains in the house. It may be calculated from first principles using published weather data and estimates of heat gains, or obtained from published tables, which incorporate the experience gained in Electricity Council field trials. The application of this procedure and typical values of y and z factors are set out in the Electricity Council publication DOM8.

The sizing procedure which was used for the heaters in the houses was compatible with DOM8, but set higher design targets. A target value of seasonal fraction of day units, f, of 2% was chosen, in the expectation that the vagaries of actual practice would increase the achieved percentage to around 5%. The z factor was taken from DOM8, but treats the whole house as if it were one large heated room; the normal DOM8 procedure discounts unheated rooms. This gives figures of $y = 0.86$ and $z = 0.67$, resulting in a storage factor of $s = 0.58$.

The original approach to heater sizing carried out at Capenhurst used an ab initio theoretical calculation, which gave a storage factor of $s = 0.6$. The above retrospective application of DOM8 shows the two approaches to be compatible, bearing in mind that the Capenhurst targets are higher than those in DOM8.

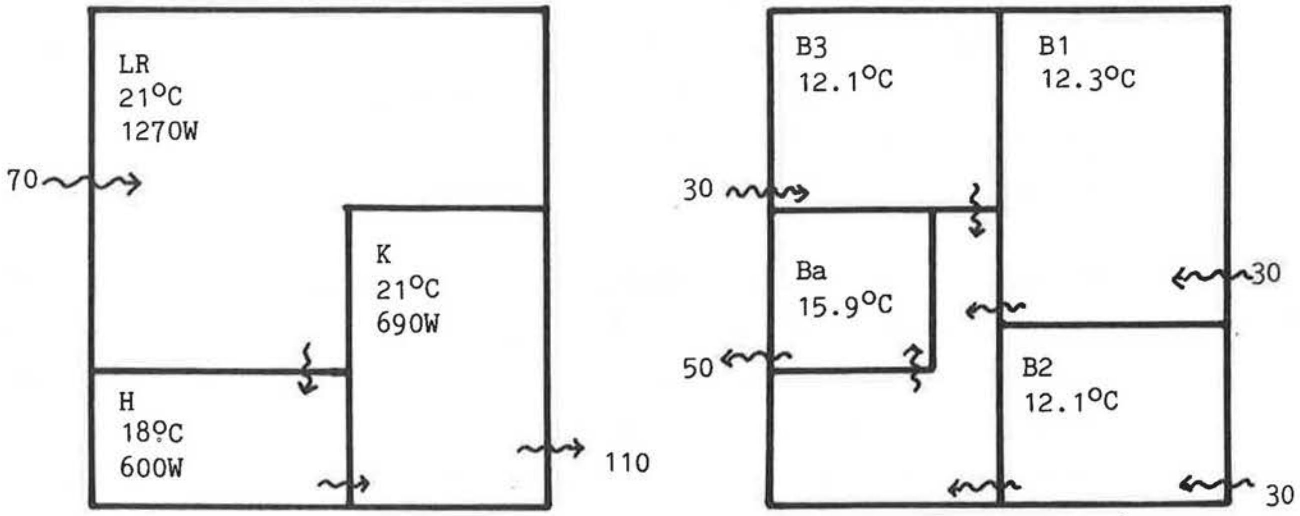
Using a design temperature of 18°C, and a heat loss coefficient $H = 147$ W/K, the required total storage capacity is estimated to be 40 kWh: see Table 2.1. The two designs of house are similar enough for the sizing results to be applied to both. Where detailed figures are given in this section, they apply to the Oxford. The total figure of 40 kWh storage capacity can be conveniently supplied by an 18 kWh capacity thermostatic storage radiator in the hall, and a 23 kWh storage fan radiator supplying heat to the living and dining rooms.

Table 2.1 Storage heater sizing

Internal average design temperature	T_{des}	18°C
House heat loss coefficient	H	147 W/K
Average free heat gain	F	815 W
Base temperature (T_{des} - F/H)	T_6	12.5°C
Storage factor (from Figure A2.1)	s	0.6
Storage capacity (T_{des} + 1) H x 0.024		40.2 kWh

2.2 Individual room temperatures

The low energy house is heated by two storage radiators, in living room and hall. An estimate was made at the design stage of the equilibrium bedroom temperatures in design weather. The expectation was that in such a well insulated house, the bedrooms would rarely, if ever, require heating. Figure 2.1 summarises the calculation and results. It was assumed that the living room is heated to 21°C, and the hall and landing to 18°C. The kitchen is also heated to 21°C, from incidental heat gains. Heat transfer within the house takes place by transmission through the



Ventilation rates shown in m^3h^{-1}

Fig. 2.1 Equilibrium temperatures were calculated at the design stage. Living room and kitchen are heated to 21°C, and hall and landing to 18°C. Outside temperature is -1°C, and the Bahco ventilation system delivers a total of 160 m^3h^{-1} at an inlet temperature of 10°C. Adventitious ventilation is ignored. The simplified floor plan shown above was used, and nominal U-values were used as listed below:

Outside walls	0.32
All internal partitions	1.7
Floor	0.38
Ceiling	0.3
Doors and windows	2.8

Equilibrium temperatures of the bedrooms were calculated by solving a set of simultaneous equations, and are shown in the diagram above. The average house temperature is 17.1°C, and the total power input 2650 W.

internal partitions and floors, and by circulation of air by the mechanical ventilation system. In this case, it was assumed that all the doors are shut, and that the only internal circulation is that provided by the mechanical ventilation system. The only heat supplied to the house is that required to maintain the design temperature levels in living room, kitchen and hall. The situation therefore represents the worst case for bedroom temperatures.

The results in Figure 2.1 predicts the bedroom temperatures on a design day to be about 12°C, and thus unacceptably low. Solar gain, heat gain from lights and occupants, and increased ventilation from the rest of the house from door opening will all act to increase the bedroom temperature, and so bedroom temperatures will rarely reach this low temperature in practice. Nevertheless, it does indicate that there will be a requirement for occasional supplementary heating in bedrooms. The bathroom temperature is maintained higher than the bedroom temperatures, since warm air is pulled into it by the ventilation system.

2.3 Supplementary heaters

The rating of a supplementary heater which is required to raise the temperature of a room is much larger than the calculated external heat loss. This is for two reasons: in a well insulated house, the heat transfer from the heated room to cooler rooms in the house will generally be larger than the heat loss to outside; further, when a room is heated to raise its temperature, heat must be supplied to raise the temperature of the structure. This increases the power required for a given rate of temperature rise; the effect is proportionally greater in well insulated houses when compared to ordinary ones.

The loading of a supplementary heater may be calculated using the admittance procedure, which is a means of estimating the effect of the thermal mass of the house during intermittent heating. The admittance procedure is set out fully in the CIBS Guide Section A5. To estimate the heater sizing for the low energy house, a simplified method was used, which was set out by McIntyre (1983). Table 2.2 sets out the calculation for one room of a house, and Table 2.3 summarises the results for each room in the house.

Table 2.2 Example of supplementary heater sizing. The calculation follows the method set out in ECRC/M1716.

OVERLOAD WORK SHEET

Room description: Living/Dining room. Whelmar Oxford. Date:

Internal design temperature T_{des} = 21

Steady temperature in rest of house T_h = 15

External design temperature T_o = -1

Room volume V = 55

Ventilation rate $N = 0.6$ ac/h. Ventilation loss $\frac{1}{3}NV = 11$ W/K

Preheat time $a = 2$ h. Total heating time per day, incl. preheat $n = 6$ h

Surface	Class	A m^2	U W/m^2K	AU W/K	ΔT K	AUΔT W	Y W/m^2K	AY W/K
External wall	A1	27.4	0.32	8.8	22	192.9	2.4	65.8
Window	A1	4.8	2.8	13.4	22	295.7	2.8	13.4
Int. partitions		19.7	1.7	33.5	6	260.9	1.9	37.4
Floor		23.1	0.38	8.8	22	193.1	2.6	60.1
Ceiling		23.1	1.7	39.3	6	235.6	1.9	43.9
Furniture	B	20					0.8	16.0
		ΣAU = 103.8 ΣAU_{ext} = 31			$\Sigma AU\Delta T$ = 1118.2		ΣAY = 236.6	

Steady state loss $Q_{des} = \Sigma AU\Delta T + \frac{1}{3}NV\Delta T$ = 1360 W

Room characteristic $P_o = (\Sigma AU + \frac{1}{3}NV)/(\Sigma AY + \frac{1}{3}NV) = 0.46$

Boost factor $B = 1.55 \exp(-0.11a) = 1.24$

Overload ratio $p = 24B/(24P_o + n(1-P_o) = 2.08$

(a) Room unheated during day
Installed capacity $Q_{max} = p\,Q_{des}$ 2830 W

(b) Room maintained at T_h during day
Steady background heat requirement $Q_h = ((\Sigma AU_{ext}) + \frac{1}{3}NV)(T_h - T_o) = 672$

Overload capacity $Q_x = p(T_{des} - T_h)(\Sigma AU + \frac{1}{3}NV) = 1430$

Total capacity $Q_{max} = Q_x + Q_h$ = 1800 W

Values of Boost factor B(a): (a) = 1, B = 1.40; a = 2, B = 1.24; a = 3, B = 1.

Table 2.3 Individual room thermal characteristics Whelmar Oxford

	Equilibrium temperature °C	External heat loss at 21°C	Total heat loss, at 21°C, T_h = 15°C	Incremental loss H W/K	External loss at 15°C	Overload capacity
Note	1	2	3	4	5	6
Room						
Living/Dining	21	920	1360	114	670	1460
Kitchen	21	610	870	73	440	810
Hall	18	480	-		345	
Bed 1	12.3	420	730	70	310	760
Bed 2	12.1	300	520	49	230	530
Bed 3	12.1	320	540	51	240	550
Bath	15.6	200	410	43	200	420

Notes:

1. Equilibrium temperatures calculated for upstairs rooms, when downstairs room at stated fixed temperature. External temperature -1°C
2. Loss to outside by transmission and ventilation
3. Heat input to room required to maintain steady 21°, with rest of house at 15°C
4. Incremental heat loss H (W/K) includes loss to rest of house
5. As 2.
6. Extra power input required to raise room temperature from 15°C to 21°C in 2 hours

Table 2.3 lists the steady state heat loss of each room to outside. If the temperature of one room is to be raised independently of the rest of the house, it will lose heat internally as well as externally. The table lists the incremental heat losses, which are large compared with the steady state external loss. For instance, the incremental heat loss of bedroom 1 was estimated to be 70 W/K, i.e., if all other room temperatures are held constant a heat input of 70 W will raise the room temperature by 1 K. This figure is at first sight very large, remembering that the whole house heat loss coefficient is less than 150 W/K, and reflects the large amount of internal heat transfer within the house. The consequence is that heaters designed for supplementary heating of individual rooms require an appreciable output, even in a very well insulated house.

The sizing of the supplementary heaters requires a number of arbitrary decisions. The sizing was based on the assumption that the heater was required to raise the temperature of a room from 15°C to 21°C in 2 hours, when the outside temperature was -1°C, and it was assumed that the room was heated for a total of 6 hours during 24. The rest of the house was assumed to be at a constant 15°C. In accordance with column 6 of Table 2.2, the living room radiant fire was fitted with 2 x 800 W elements, and each bedroom fitted with a 750 W panel radiator. Neither bathroom nor kitchen was fitted with a heater. It was expected that the gain from cooking would be more than enough to produce a comfortable temperature in the kitchen, and that gains from hot water would be enough to maintain the bathroom at a comfortable temperature. This was borne out in practice. Both kitchen and bathroom were fitted with a heated towel rail, but this does not make an important contribution to raising the room temperature.

3. HEATING EQUIPMENT

3.1 General description

The high degree of insulation of the Capenhurst house means that only a modest heating system is required. The greater part of the heat input is provided by two storage heaters: a controlled input thermostatic storage radiator (Creda TSR18) in the hall, and a controlled output storage fan heater (Creda Caribbean) in the living room. A focal point direct acting radiant heater in the living room provides top-up heat when needed. Each bedroom is fitted with an oil-filled thermostatic radiator. The system is sized so that some use of direct acting heaters will be required in cold weather.

The input to the hall storage radiator is automatically controlled by a room thermostat (Satellite controller) mounted in the hall. This controller was developed by the Environmental Engineering Section, and is described in ECRC/M1379. This regulates the charge input, and successfully maintains a constant temperature from day to day against fluctuations in outside temperature. The output from the living room storage radiator is controlled by a clock thermostat in the living room. This operates the output fan on the storage radiator if the living room temperature falls below the set point during the on period. The input control to the radiator, which controls core temperature, is manually set. Since half the output is under fan control, this setting is not very critical. All other heaters are manually operated. The siting of the heaters is shown in Figures 3.1 and 3.2. Figure 3.3 illustrates the installation in the Comben Madrid.

All the heating equipment in the houses is commercially available. Two heaters were modified before installation. The storage fan heater in the living room was fitted with improved insulation by the manufacturers, and the radiant heater in the living room was fitted with modified switching to give a low output setting of 400 W. New heaters have since appeared on the market, which make these modifications unnecessary. Table 3.1 summarises the heating and control equipment used. An attempt has been made to list prices, by showing the recommended retail price (RRP) excluding VAT. An electrical contractor would expect to obtain the equipment at a lower price.

H1	Modified Creda Caribbean 70111 storage fan radiator, input rating 3-7 kW
H2	Creda TSR 18 storage radiator
H3	Modified Belling 314 TR radiant heater in surround
H4	Towel rail, Dimplex TRC 90 mounted in tray recess.
H5	Dimplex oil filled radiator, B310
H6 H7	750 W with thermostat
H8	Towel rail, Dimplex TRC 130
T1	Satchwell TLC clock thermostat, controlling fan of H1
T2	Thermostat of Satellite controller, regulating charge input to H2.

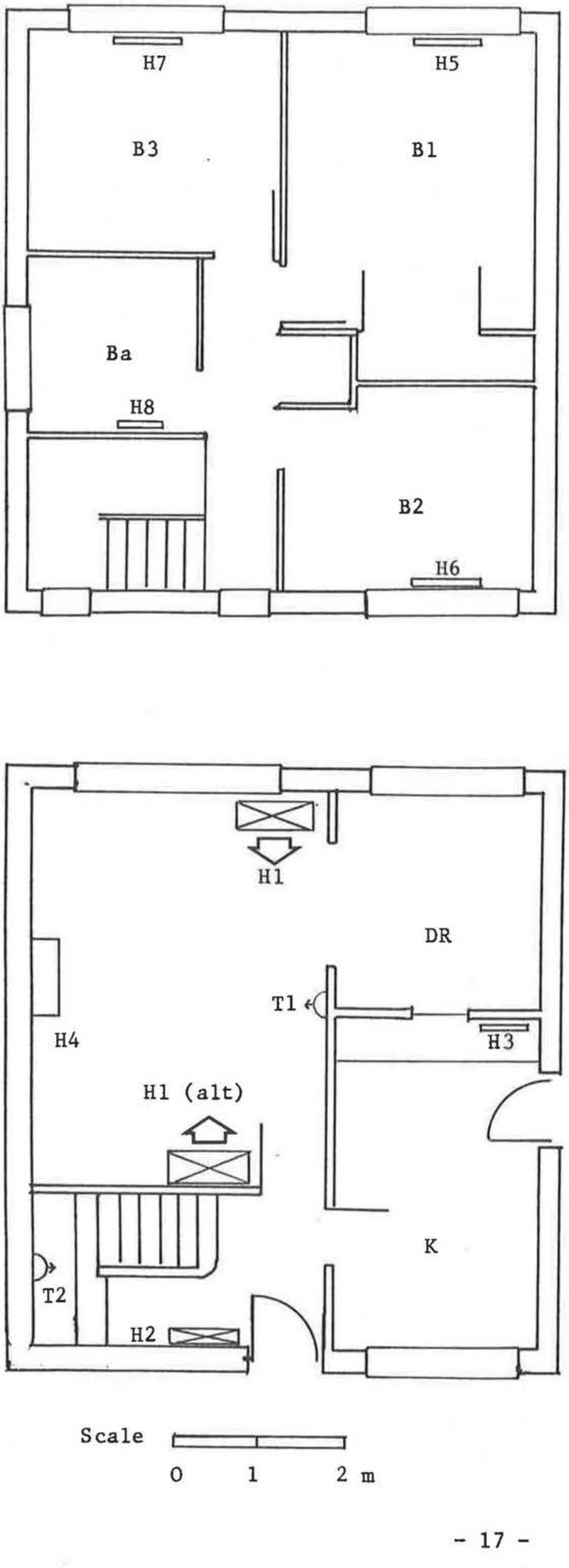
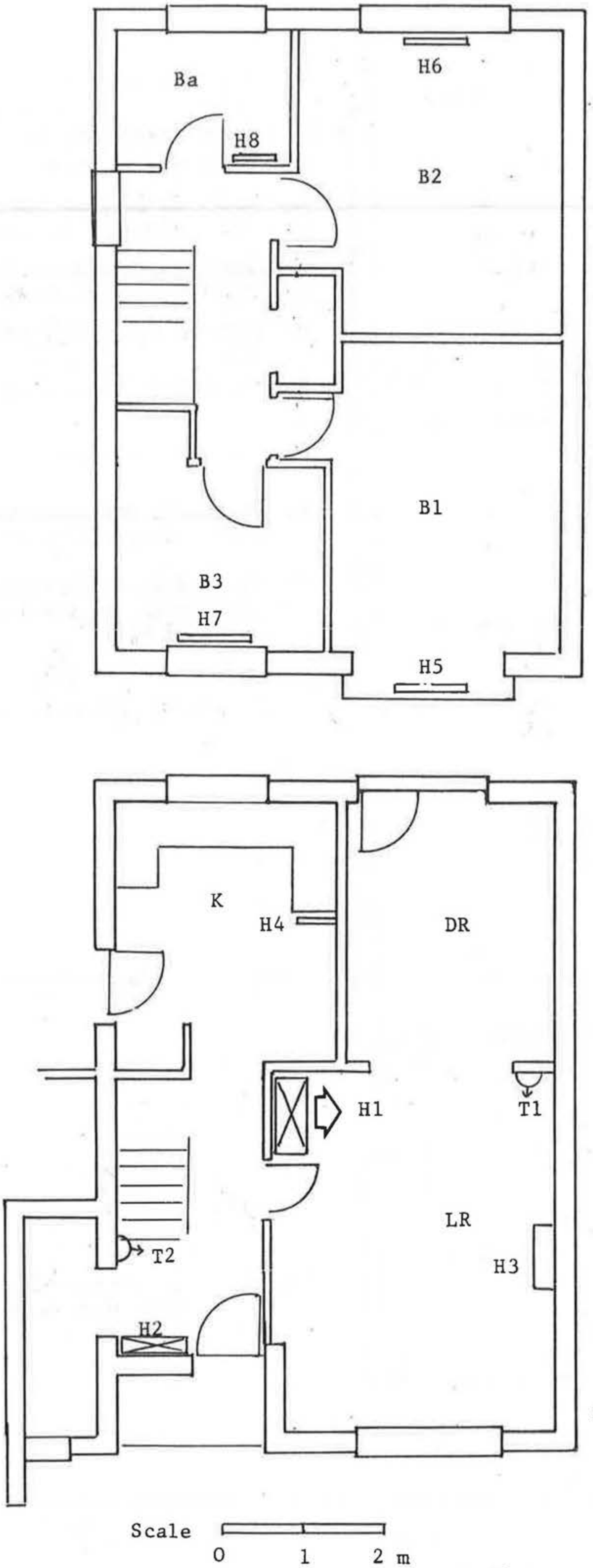


Fig. 3.1 Heater and control positions in Oxford



H1	Modified Creda Caribbean 70111 storage fan radiator, input rating 3-7 kW
H2	Creda TSR 18 storage radiator
H3	Modified Belling 314 TR radiant heater in surround
H4	Towel rail, Dimplex TRC 90 mounted in tray recess.
H5	Dimplex oil filled radiator, B310
H6 H7	750 W with thermostat
H8	Towel rail, Dimplex TRC 130
T1	Satchwell TLC clock thermostat, controlling fan of H1
T2	Thermostat of Satellite controller, regulating charge input to H2.

Fig. 3.2 Heater and control positions in Madrid

Lounge storage heater

Lounge radiant heater

Hall storage heater

Bedroom heater

Ventilation unit

Hot water cylinder

FIGURE 3.3 Internal views of one of the houses after occupation, showing the heating equipment.

Table 3.1 Heating Equipment

Room	Heater	Price	Remarks
Living room	H3 Focal point radiant heater. Belling 314 TK. 2 x 800 W elements.	£90	Modified at ECRC to allow 400 W low setting. 120 W fuel effect.
	H1 Storage fan radiator Creda Caribbean (70111). Input 3.8 kW.	£200	Improved insulation fitted by Creda.
	T1 Clock thermostat Satchwell TLC.	£25	
Hall	H2 Storage radiator Creda TSR18 (79001). Input 2.55 kW.	£95	
	T2 Thermostat Grawater Satellite.	£18	
Kitchen	H4 Towel rail Dimplex TRC 90 W.	£40	
All bedrooms	H5,6,7 Oil filled radiators Dimplex 3310.	£59	Built in thermostat.
Bathroom	H8 Towel rail Dimplex TRC 130 W.	£56	

Prices are retail, less VAT, 1982. Trade prices are lower.

3.2 Heater development

The low energy house was designed to be built with readily available materials and equipment. The heating equipment includes two items that have been modified from the standard version.

A direct acting focal point radiant heater is installed in the living room. This is intended for occasional use in mild weather, and for providing extra heat in very cold weather, when the storage system is not sized to provide full heating. Focal point radiant heaters are commonly fitted with 3 x 800 W quartz sheathed elements, which warm up rapidly. Direct acting heaters are normally used intermittently, and are required to provide rapid warm up of a room. While increased insulation reduces the steady state heat requirements of a building, it does not increase the speed of response of a room to heating; if the heater output is reduced to match the reduced heat loss, speed of response is made slower. The direct acting heater in the low energy house must therefore retain a reasonable maximum power output but requires a minimum setting lower than the 800 W available in existing heaters. From the user's point of view a simple dimmer would be ideal. However, British Standard 5046 restricts the use of dimmers for heater control. The allowed switching frequency is a reducing function of power. Unfortunately the permitted frequency allowed for switching a load of 800 W is so low that the variations in visible output from the radiant heater would be troublesome. The solution adopted was to modify a standard two bar heater to include series-parallel switching. This gives a low heat setting of 400 W. The heater is fitted with an illuminated fuel effect, lit by 2 x 60 W lamps.

Only one type of storage fan radiator was commercially available when the houses were built, i.e. the Creda Caribbean. This storage fan heater has rather less than 50% of the total charge input available as controlled output. It is desirable to reduce the case emission; this should lead to reduced energy consumption, fewer cases of overheating and better ability to cope with changeable weather. The Development Department at TI Creda agreed to supply Caribbean 70111 heaters with a slightly reduced input rating, and with the mineral fibre insulation replaced by opacified silica aerogel (Microtherm). A sample heater was supplied to ECRC for test. The measurements are summarised in Appendix A1. The modified heater performed better than the standard heater; however, the major fault in the standard heater was an incorrectly set charge controller, which allowed the core temperature, and hence case emission, to rise when the heater was operated with no output demand.

The use of Microtherm increased the proportion of output under control; at a charge setting of one half, the standard heater had a controlled output of 5 kWh, and a case emission of 7 kWh, while the modified heater had controlled output of 6 kWh and a case emission of 5 kWh. It is difficult to say if this improvement would be noticeable in practice.

While the heating and control system in the low energy house is not fully automatic, it has been designed to run with the minimum of user intervention. Once the thermostats and time clock have been set up, the only adjustment required is occasional resetting of the charge controller of the storage fan heater on changes in weather. This will only be required a few times each year. Inappropriate use or setting of the controls, however, will lead to the system behaving poorly, either producing too much or too little heat when needed, or resulting in the user taking too much energy at day rate. It was therefore considered important that the users should receive help in understanding the use of the controls. Each user was interviewed on moving into the house, and the function and use of the controls was explained. The thermostat and time clock was left set up at a suitable setting, and the user left with a set of instructions.

3.3 Heater installation

Figures 3.1 and 3.2 show the layout of the heating equipment in the Oxford and Madrid houses respectively.

The size of the fan storage heater, and the necessity to leave space in front of it for the warm air outlet, limits the placing of the heater and furniture. In the Madrid, the door to the living room from the hall was moved some 30 cm to allow the fan storage heater to be placed behind it, blowing directly into the room. The radiant heater was placed in the conventional position for the focal point fire. The TSR18 in the hall was placed adjacent to the front door. The original house design incorporated a floor to ceiling glass panel here; this was replaced with an insulated partition to prevent excessive heat transfer into the porch. The oil filled panel radiators were wall mounted under the windows in each of the three bedrooms. Placing the towel rail in the kitchen presented some problems, as there was no suitable position for it. The towel rail was mounted in a tray recess; this was not entirely satisfactory and the hanging space for towels was barely adequate.

The Oxford was wired to give alternative positions for the storage fan heater. One family preferred to use floor length curtain on the main living room window, thus ruling out this position for the heater. The other family started with the heater on the inner wall, but later moved the heater to beneath the window. As with the Madrid, positioning the towel rail in the kitchen was awkward. It was originally installed under the counter top. This position was not liked by the occupiers, and in both houses the rail was removed when equipment was positioned under the counter.

Both houses demonstrated that an 80 m^2 three bedroomed house is built to a very tight layout, and the positioning of heating equipment needs to be considered as early as possible during the design. Kitchens and bathrooms are extremely limited in space, and the positioning of even a towel rail presents difffculties.

3.4 Equipment performance and reliability

The performance of the heating system in terms of energy consumption and temperature control will be considered later. This sections deals with the equipment itself.

The two modified Caribbean storage fan heaters in the Madrid have worked satisfactorily, and no complaints have been received about their performance. The two Caribbeans in the Oxford proved to be unsatisfactory. The heaters were ordered directly from Creda by the electrical contractor, who initially assembled both heaters in one house. One heater was removed to the correct house, but after a few weeks complaints were received from the occupants of both houses of high case temperatures and low heat emission when the fan was operating. Investigation found the Microtherm insulation to be poorly installed and cracked. The heaters were badly assembled and the outlet air damper jammed. New Microtherm insulation was obtained, and the heaters rebuilt by ECRC. Nevertheless performance stayed consistently below expectation, in that the maximum recorded charge intake remained below design value. This problem was never fully explained, but was probably due to a malfunctioning outlet damper, which prevented air circulating properly through the core. The Caribbeans in the Madrid behaved satisfactorily. The occupants of 22AG used the fan sparingly, while those in No. 31 left the fan active under thermostat control 24 hours per day; there was thus some discharge of the core during the low rate period resulting in a high maximum charge intake. Table 3.2 shows typical full charge inputs for the storage heaters. The figures represent typical values during a spell of cold weather; higher figures were recorded when the heater was given full charge after a day of low charge. The TSR18 takes its full charge only if the output damper is fully opened during the evening; the difference in charge uptake between Oxford and Madrid is explicable in these terms.

Table 3.2 Recorded maximum storage heater charge

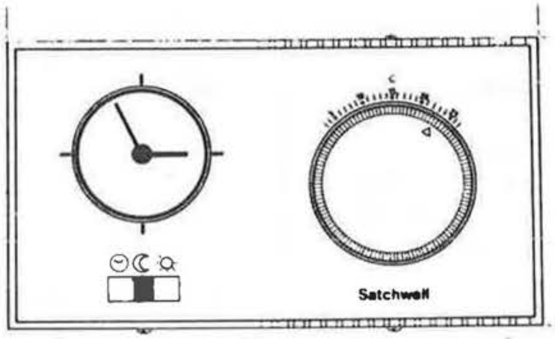
	Caribbean Fan Storage (kWh)	TSR18 (kWh)
8GC	15.0	18.0
9GC	16.5	17.5
22AG	20.5	16.5
31AG	27.0	16.5
Maximum (i.e. input x 7h)	26.6	17.8
Acceptance quoted by manufacturer.	23.0	18.0

The table shows the typical maximum charge input during cold weather, when maximum charge was required. In 31AG the fan operated during the low rate period, allowing a larger input.

As a result of the problems with the Caribbean storage fan heaters at Gairloch Close, the heaters were replaced by Creda TSF24 heaters during February 1983. This is a new design of storage fan heater, with both improved appearance and performance over the Caribbean.

No problems were experienced with the modified Belling radiant heater. The series parallel switching was satisfactory and there appeared to be no problems caused by the lack of visible glow at the low setting. Bedroom heaters operated satisfactorily, though were considered somewhat slow in response.

The output control of the fan storage heater is shown in Figure 3.4. The clock thermostat allows the occupants to select an ON period during which the output fan will operate under thermostat control to maintain the set temperature; the ON period was typically 1700 to 2200 hours. Outside this period, the time clock energises a setback heater in the thermostat housing, which causes the thermostat to operate about 6K below its nominal setting, e.g., if the thermostat is set at 20°C, during the setback period the fan will operate if the room temperature falls below 14°C. The thermostat operates in series with the fan selector switch on the storage heater, which selects low or high fan speed, and OFF. The room thermostat operated satisfactorily, but the users did not operate the system in accordance with our expectations. If fan operation is required during the setback period, the 'proper' procedure is to operate the selector switch on the thermostat housing, which de-energises the setback heater.



Selector switch: Timed/set back/on (continuous)

Figure 3.4 Storage fan heater output control.

The output from the Caribbean heater is controlled by a clock thermostat. The clock energises a set back heater, which reduces the controlled temperature by 6 K. There is no true off period.

However, this takes about 10 minutes to produce the desired result. It is quicker to turn up the thermostat setting by 6° to operate the fan, and this is what people did. This could lead to the thermostat setting being left at far too high a setting during the subsequent ON period. The absence of a direct ON/OFF switch for fan operation was a disadvantage.

4. RECORDED TEMPERATURE AND ENERGY

4.1 House temperatures

Temperatures in each room of the houses were logged every half hour, using thermocouple sensors mounted about 200 mm below ceiling height. Outdoor weather was measured on an adjacent site; insolation on a horizontal plane, wind speed and direction, and wet and dry bulb temperatures were recorded. The temperature sensors were mounted in a standard Stevenson screen; this is a white painted, ventilated enclosure, which allows shade air temperature to be measured with little or no effect of sunshine. Outdoor air temperature was also measured by a thermocouple mounted close to the external house wall; this temperature was consistently higher than the screen temperature. The screen temperature has been used in this analysis, as a standard measure of outside temperature. Data logging and analysis are described in ECRC/M1768 and ECRC/M1982.

Figure 4.1 shows the variation of weekly mean internal temperature as a function of mean screen temperature, for house 31AG for 45 weeks of the year April 1982 to April 1983. Six weeks of the summer were not recorded, and one week's data was lost through instrument malfunction. Whole house, living room and main bedroom temperatures are shown. It can be seen that there is a linear relation between inside and outside temperature. Figure 4.2 shows the regression lines for the four houses. In general, the occupants maintained the living room at a nearly constant mean temperature, which fell slightly as the outside temperature got colder. The greatest variation was found in house 22AG, where the living room temperature dropped by 2K between the warmest and coldest weekly outdoor temperatures. There was however a noticeable difference in average living room temperature between the houses. House 31AG kept their living room warm, with a seasonal average of 23°C. This is an average temperature, measured over the whole day and includes periods in which the occupants may have been absent. The coolest living room was that in 22AG, which was some 3K lower, with a seasonal average of just over 20°C.

All bedrooms were fitted with panel radiators, and could therefore be heated if required. In fact, these heaters were little used, and the bedrooms were primarily heated by heat transferred from the rest of the house. Bedroom temperatures varied strongly with outside temperature.

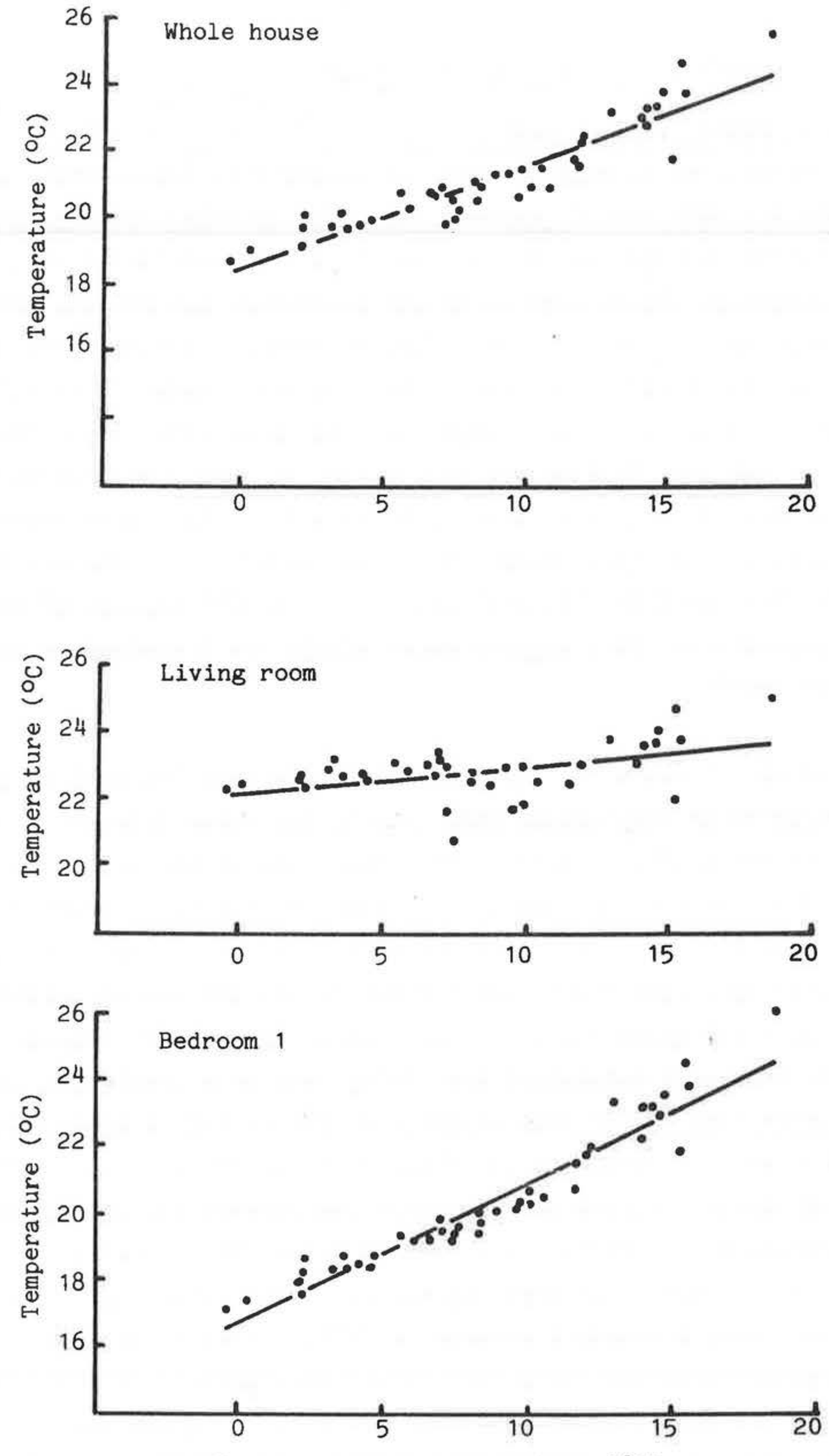


Fig. 4.1 Weekly mean internal temperatures of 31AG as a function of outside temperature. One year's data, less 6 summer weeks.

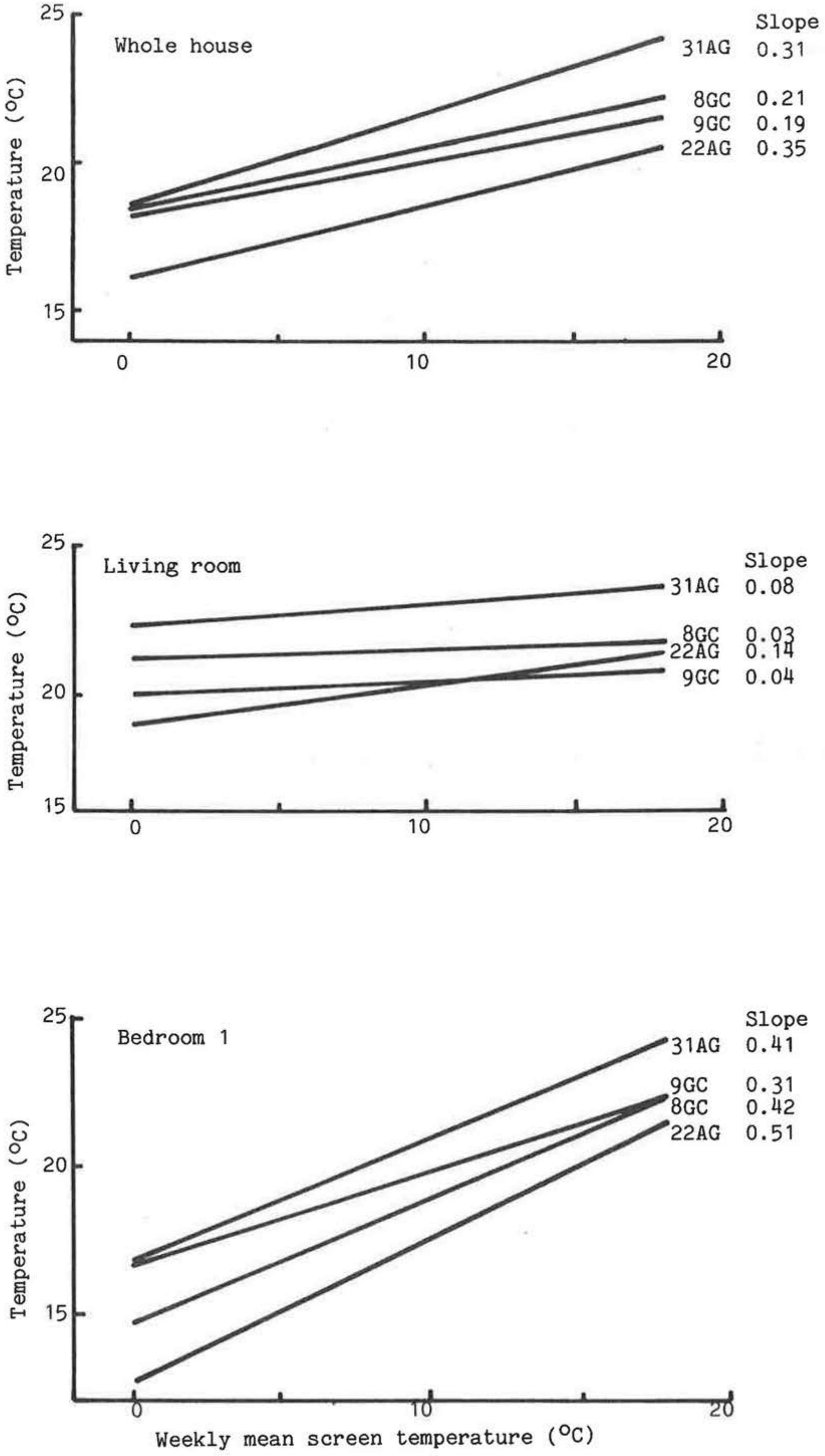


Fig. 4.2 Weekly average internal temperature as a function of outside temperature

Figure 4.2 shows the regression lines for bedroom 1 in each of the four houses; this room was chosen since it was occupied by adults in all houses, and neither empty nor used for daytime or evening activities. The slope is similar over the four houses, at about 0.4K bedroom temperature per degree change in outside weather. As with living room temperature, house 31AG maintained the highest temperature, nearly 4K above the bedroom temperature in 22AG. House 22AG had a mean bedroom temperature of 13°C over the week when the outside mean temperature was 0.5°C; again, this is an average temperature, so that the bedroom temperature would have been below 13°C on many occasions during the week. The order of houses 8GC and 9GC reverses for living and bedroom temperatures. 8GC has the higher living room temperature. The regression line of bedroom temperature versus screen temperature for house 9GC has a noticeably lower slope than that of the other houses; this is because the occupants routinely use the bedroom heater in cold weather.

The whole house average temperature again shows a marked variation with outside screen temperature. The two houses at Gairloch Close show very similar temperatures; the two houses at Ashgrove Crescent have regression lines with similar slopes, but with house 31AG consistently some three degrees warmer.

4.2 Total heating energy

Figure 4.3 shows the total space heating per day, averaged over a week, as a function of weekly mean screen temperature, for house 9GC. The points cannot be represented by a single linear regression line. Inspection of the figure shows three sections: in warm weather, above 12°C, the heating system is not used at all. Between 5 and 12°C there is a linear increase of heating energy as the outside temperature falls. Below 5°C, the slope of the curve flattens off. The cessation of heat input above 12°C is quite definite; the change in slope at 5°C does not really occur at a well defined temperature. The four houses show similar patterns. Linear regressions were performed on the middle part of the graph, and the results are shown in Figure 4.5. The houses show evidence of different manners of use: 31AG shows a linear variation of heating energy with outside temperature over the large range of 2-16°C. At the other extreme, house 9GC uses no heating above an outside temperature of 12°C, and then a very rapid increase in heating energy as the temperature falls below

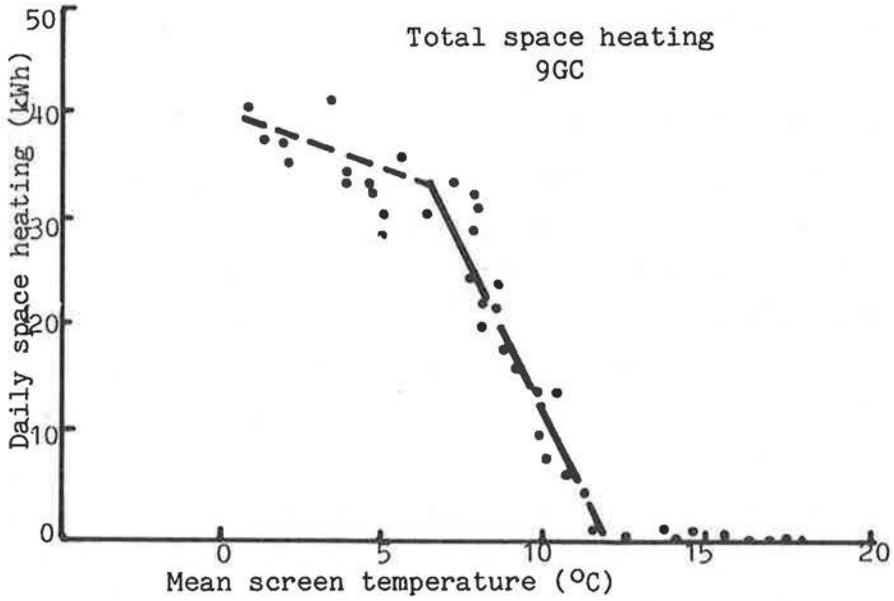


Fig. 4.3 Total weekly average daily space heating for 9GC. The regression line is fitted over the range 5 to 12°C screen temperature.

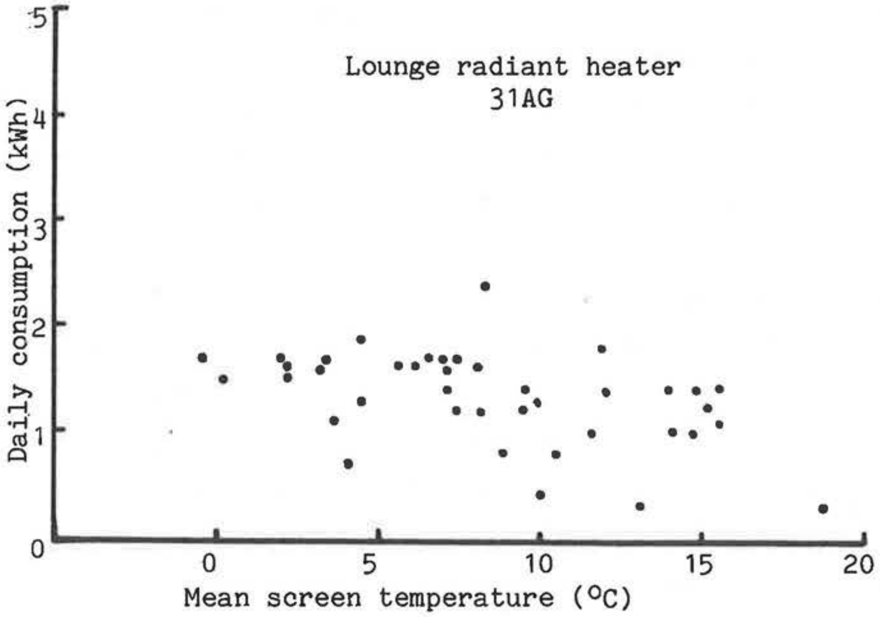


Fig. 4.4 Weekly average daily use of the lounge radiant heater. There is no relation between use and outside temperature. Use of the fuel effect for 12 h consumed 1.4 kWh.

12°C. The relative position of the lines in Figure 4.5 corresponds to the recorded temperatures shown in Figure 4.2. House 31AG uses consistently more energy than any other house, and this is reflected in the fact that it has the highest temperature.

The data becomes more consistent if we plot mean daily heating energy versus the difference between whole house average internal temperature and the outside screen temperature. Figure 4.6 shows linear regressions for the four houses; weeks where no heat input was recorded were excluded from the analysis. This approach brings the four curves close together, and they are linear over their range. If the lines are truly linear, then the intercept on the x axis is the temperature difference between inside and outside temperature where no heat input is supplied to the house. This temperature increment is produced by incidental heat gains within the house, together with heat gains produced by solar energy. Figure 4.6 shows the intercepts to be about 5K. The heat loss coefficients of the houses are about 150 W/K, so this implies a free heat gain equivalent to a constant 750 W. However, examination of the actual data points shows that the regression lines do not extend all the way down to the axis. There is a cut off temperature difference below which heating energy is not supplied to the house. This figure is 7K for three of the houses, and 6K for No. 22AG. This implies a rather higher free heat gain of some 1000W. These figures are in accord with our estimates. Preliminary energy analysis was based on a standard figure of 750 W internal free heat, excluding solar heat gains.

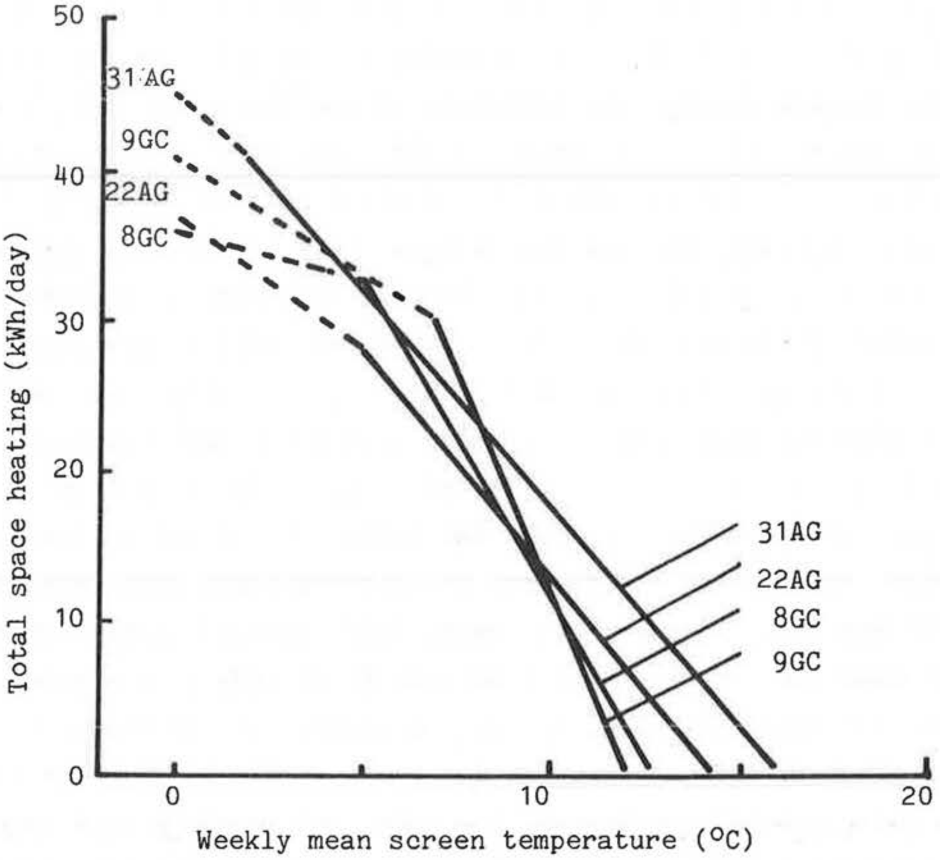
4.3 Individual heaters

Energy supplied to the storage heaters was logged every 20 minutes onto a single channel. During analysis, the energy was first examined to see if it corresponded to either heater or both together being fully on for the duration of the sampling period. If so, the energy was assigned accordingly. If not, the energy was partitioned between the two heaters in proportion to their rated input. This method introduces an error only for the sampling period during which the heaters switch on or off. Since this only happens twice per day, the error is not serious.

The first graph in Figure 4.7 shows the mean daily charge input of the storage fan heater versus mean weekly screen temperature. Three of the heaters show a linear increase of charge taken as the outside temperature falls, with a well defined flattening of the curve as the storage heater takes maximum input. The exception is the heater in 31AG, which continues to increase down to the lowest outside temperature. The rated input of the heaters is 3.7 kW, and so the maximum possible input is 7 x 3.7 = 26 kWh. However, the maximum charge intake is normally limited by core temperature, controlled by the charging thermostat. A maximum acceptance of about 22 kWh was expected. The heaters at Gairloch Close show a maximum charge intake well below this figure. This appeared to be caused by inadequate heat discharge. The problem was never satisfactorily resolved; it appeared to be caused by an outlet damper which prevented proper air circulation through the core. At the end of the recorded period, the storage fan heaters at Gairloch Close were replaced with Creda TSF24 heaters, a new design. House 31AG recorded charge intakes greater than expected. This occurred because their mode of operation was to leave the discharge fan under active control of the thermostat 24 hours a day. Thus in cold weather the fan would be discharging the core during the charge period, preventing the core from reaching full temperature, and so allowing a large charge to be taken. The fan storage heater in house 22AG shows a maximum weekly average of daily charge of 18 kWh; the individual daily charge rarely exceeded 20 kWh. There is no reason to suppose that the storage fan heater was physically different from that in 31AG, and the lower charge was caused by the occupants making much less use of fan discharge during the evenings. The core of the heater was therefore rarely, if ever, fully discharged at the start of the charge period.

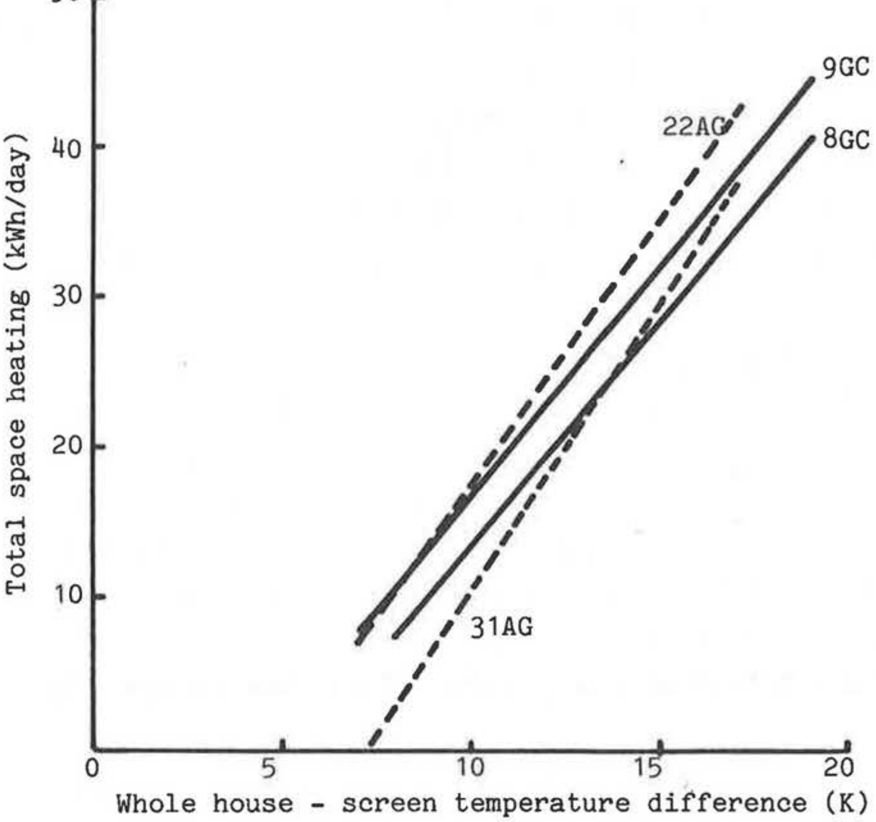
4.4 Hall storage radiator TSR18

The TSR18 storage radiator in the hall had its input automatically controlled by a Satellite controller. Limited output control is available on this type of radiator using the thermostatic damper, which can modify the total output by some 10%. Operation of this control was not monitored. Its operation was discussed with the occupants, and they were aware that the output setting had to be at maximum to achieve full rated output from the heater. Some of the householders operated the heater in "optimum" fashion, reducing the output setting late at night, and increasing it again the following evening. This ensures maximum output in the evening, and a reduction in the late evening temperature droop. It is not known how regularly this mode of operation was followed.



House	Linear regression a	 b	 r^2	 range (^{o}C)	Free heat increment (K)	Slope (W/K)
8GC	54.7	-4.31	0.84	4-12	8.4	180
9GC	72.1	-6.01	0.79	5-12	8.6	250
22AG	43.0	-3.0	0.79	5-14	6.2	126
31AG	45.6	-2.84	0.90	2-16	7.6	118

Fig. 4.5 Total space heating energy as a function of outside temperature. Linear regression analysis was performed over the range of data points that appeared linear by inspection. Free heat increment was obtained by comparing zero heat intercept with the equivalent whole house temperature.



Regression lines

	Slope (W/K)	Intercept (°C)	Actual cutoff (°C)
8GC	126	5.4	7
9GC	129	4.4	7
22AG	149	5.1	6
31AG	164	7.2	7

Fig. 4.6 Total space heating as a function of inside-outside temperature difference

Figure 4.7 summarises the charge taken by the TSR18 as a function of weekly screen temperature. The two houses at Gairloch Close show a very steep characteristic. The storage heaters take no charge above an ambient temperature of 11°C, and take full charge at ambient temperatures below 7°C. Both houses complained of inadequate heating on the landing, and it was their practice in cold weather to leave the Satellite thermostat at a very high setting (25°C) to ensure maximum charge input to the TSR. The two houses at Ashgrove Crescent show a much lower slope. The slopes are similar to each other, but displaced by some 3K, which reflects the difference in internal temperatures maintained in the two houses.

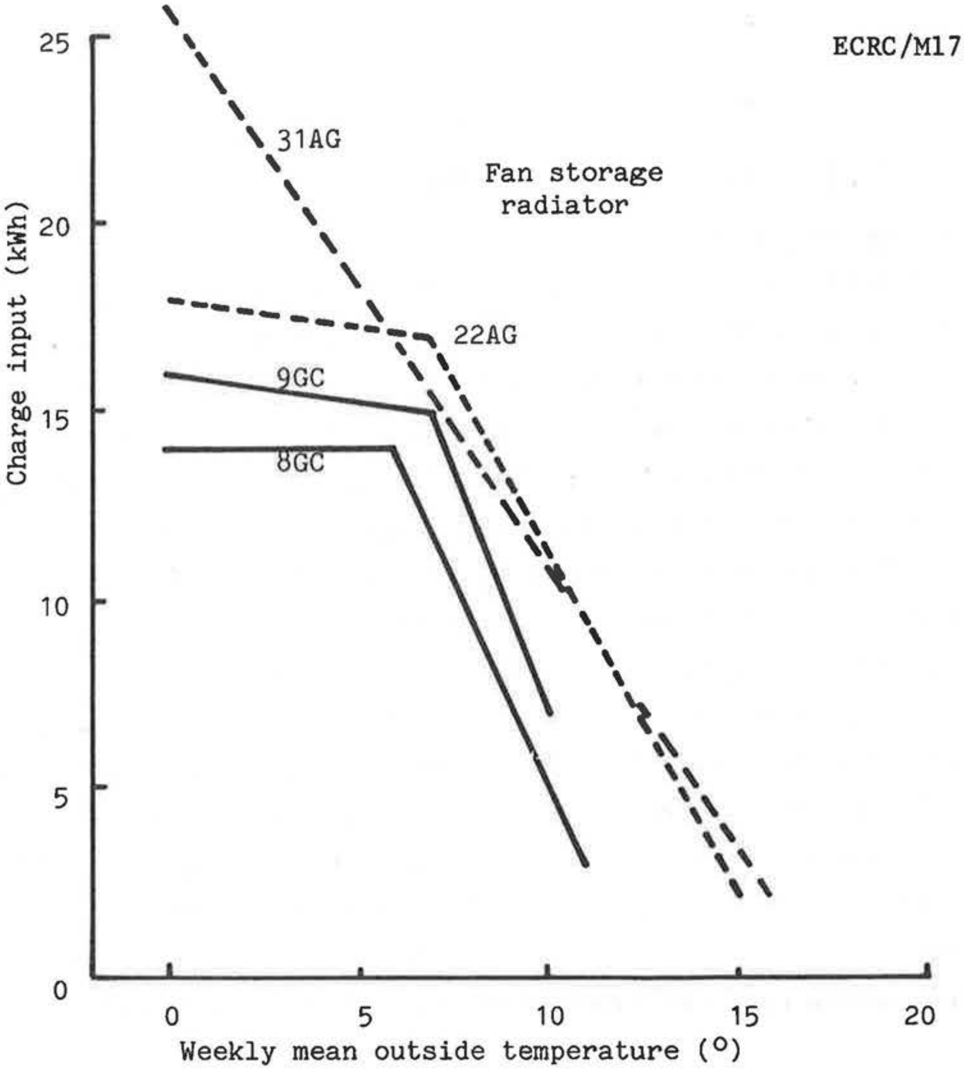
4.5 Radiant heater

Figure 4.4 shows the energy taken by the focal point radiant heater in the living room for 31AG. It is apparent that there is no important relation between outside ambient temperature and the use of the heater. Average use is about 1 kWh per day, corresponding to 2 hours use at the low setting of 400 watts. However, examination of the records show that the fuel effect lamps were switched on for 12 hours a day or more. This is equivalent to 1.4 kWh, and the fuel effect accounts for the major part of the radiant heater consumption. The other houses are similar, in that they show little or no variation of energy use with temperature. The sizing method adopted for the heating system of these houses, discussed in section 2 above, involves the expectation that direct acting supplementary heating would be necessary in cold weather, when the storage system is inadequately sized. These results show that this does not happen. Rather, the storage heater was adequate to maintain the living room temperature at a comfortable level, and the effect of under sizing is apparent as a fall in bedroom temperature, which was not compensated for by the use of the supplementary heaters in the bedroom.

Table 4.1 Average daily use of living room radiant heater, for weeks in which heating used

House	Energy (kWh/day)	Weeks
8GC	0.54	35
9GC	0.81	33
21AG	0.64	37
31AG	1.32	45

There was no important variation of heater use with weekly average outside temperature.



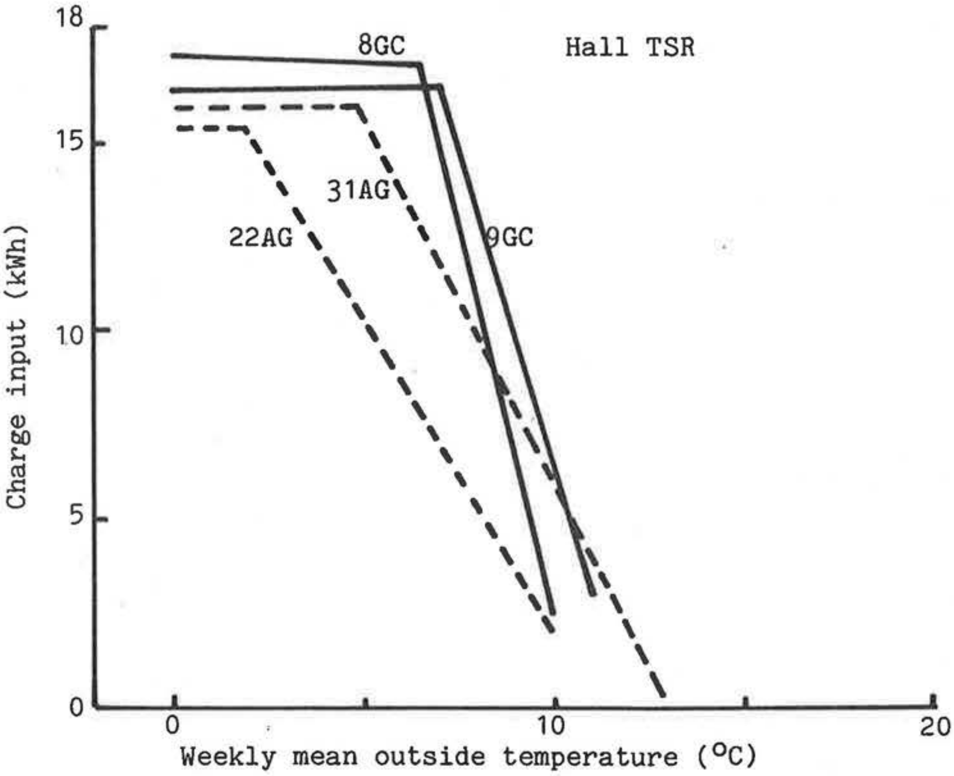


Fig. 4.7 Weekly average daily charge input of storage heaters
The GC fan storage radiators showed inadequate capacity and were later replaced.

5. CONTROLS AND THEIR MODE OF USE

5.1 Radiant heater

The radiant heater in the lounge was installed to provide additional direct acting heating, either to supplement the storage heating on a very cold day, or to provide warmth in mild weather, if, for instance, the storage heater had been undercharged. The heater also provides a focal point, and is fitted with a fuel effect, powered by 2 x 60 watt lamps. Section 4.5 showed that the weekly average consumption of the lounge radiant heater did not change appreciably as a function of outside air temperature, but remained fairly constant throughout the heating season. More detailed day-by-day examination of the records shows that use of the heater is largely confined to the fuel effect; the consumptions are summarised in Table 5.1. It can be seen that little use is made of the heating elements; what use there is is at the low, non-glowing, setting of 400 watts. Very little use was made of the 800 or 1600 watt settings. The fuel effect was used freely, particularly in 31AG, where the average daily use of the fuel effect exceeded 12 hours a day. Since all this energy is taken at day rate, it becomes a noticeable fraction of the total heating cost.

Table 5.1 Radiant heater use

		Hours of use			
		8GC	9GC	22AG	31AG
Lamp only	W	-	850	1160	2790
(120 W)	S	-	80	180	900
Low setting	W	110	70	30	6
(520 W)	S	50	20	10	-
One bar	W	30	8	-	14
(920 W)	S	5	3	-	4
Average usage	W	0.6	4.1	5.3	12.5
(h/day)	S	0.4	0.7	1.3	4
Total energy:	lamp	0	130	170	420
(kWh)	heating	130	60	20	20
Cost (total)	£	7.02	10.26	10.91	25.26

Notes: Winter (W) 3-9 May, 27 Sept. 82 - 5 May 83.
Summer (S) 10 May - 26 September 82.
Discrepancy between hours of use and total energy caused by lamp failure. All energy at day rate.

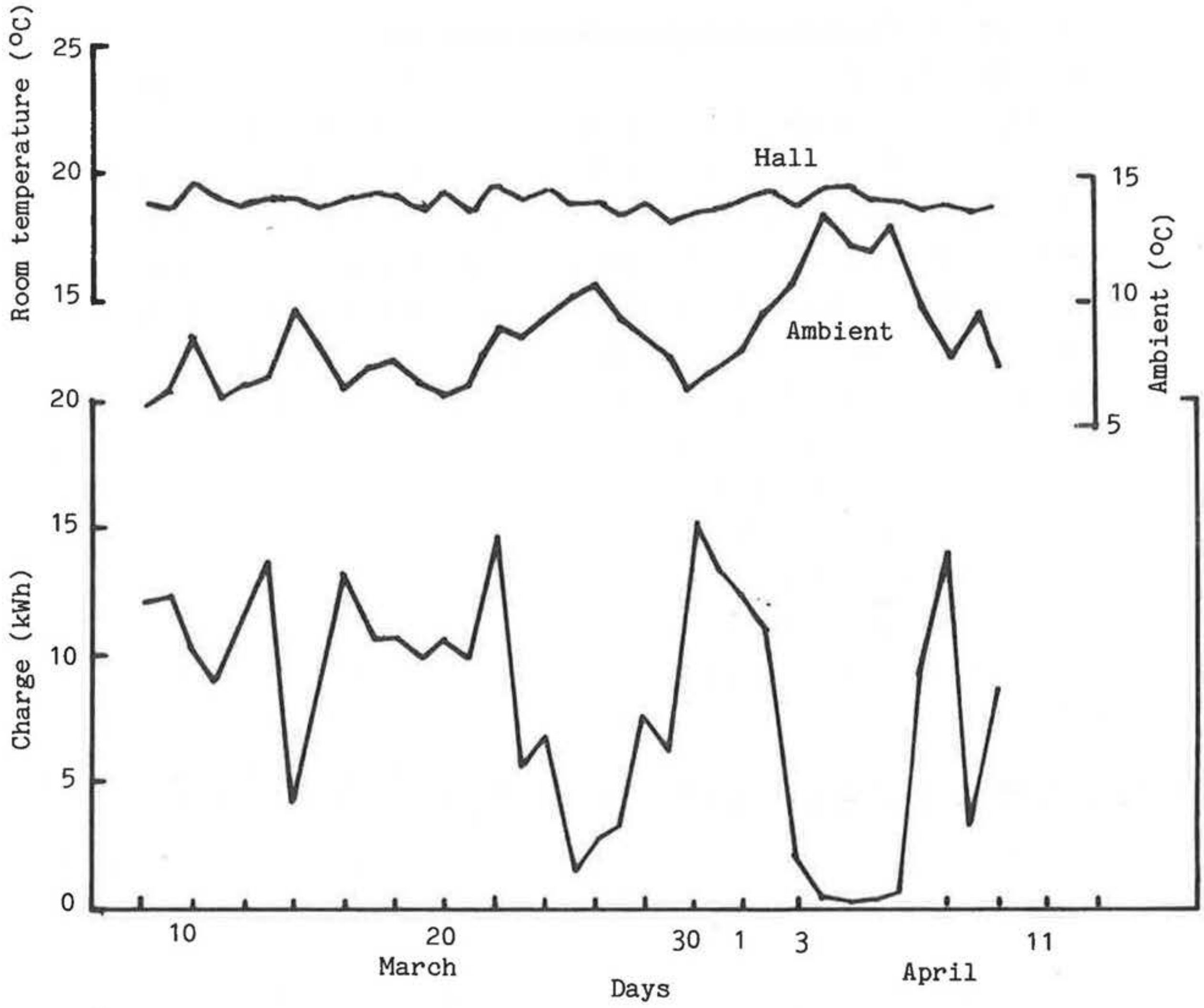


Fig. 5.1 Satellite controller operation

Charge input to the hall TSR is shown, together with outside ambient air temperature. Hall temperature shows little day to day variation, though the storage radiator charge input fluctuates considerably.

5.2 Hall storage radiator

The input to the hall storage radiator (TSR 18) was controlled automatically by a Satellite controller. In general the controller operated successfully to maintain a constant hall temperature against variations in weather. Figure 5.1 shows a record of hall temperature, charge input and outside temperature for 22AG. It can be seen that the controller operated actively to vary the charge input from day to day, and that the hall temperature was maintained virtually constant. It will be noticed, however, that there were large swings of input to the heater from day to day, ranging from full input to zero charge over a short period. This is typical behaviour for the Satellite controller, which tends to overcompensate for small variations in hall temperature. This often results in a two day cycle of operation, with the heater alternating between high and low charge. In a conventional house with reasonable thermal mass, these variations in charge input will have a relatively small effect on variation in house temperature; it can be seen in Figure 5.1 that the variations in charge input are not reflected in variations in temperature. Nevertheless this control behaviour is not liked by occupants, particularly when they find a cold heater on a day which clearly requires some heating energy. Although the air temperature may not be unacceptably low, the occupant clearly considers that the heater ought to be warm.

Another problem with the Satellite was in achieving full charge in cold weather. If the house is warm in the evening, it may not cool below the thermostat switch on temperature by the start of the low rate charge period at night; this problem is exacerbated in well insulated houses, since they cool very slowly. This problem was encountered by some of the occupants, who increased the Satellite thermostat setting to maximum to ensure full charge in cold weather. Thus it can be seen in Figure 4.7 that the hall TSR generally took full charge below an outside temperature of about 5°C.

The output control of the TSR is a damper valve activated by a bimetallic thermostat. The most effective mode of operation of the output control is manual; closing the damper at bedtime and opening it to maximum during the early evening gives the maximum delay in output to combat the evening temperature droop. If the damper is not opened fully during the discharge period, the heater is not fully discharged at the start of low rate period, resulting in a slight reduction in charge intake.

5.3 Fan storage radiator

The output fan of the storage fan radiator in the living room was controlled by a clock thermostat. See section 3 for a description of the equipment. The fan operation was recorded on an event recorder. Before the houses were handed over to the occupants, the clock thermostat was set to come on at 1600 hours, and return to the setback position at 2200 hours. Inspection of the event records showed that the occupants maintained this pattern of use for a few weeks after moving in, and then modified the pattern to suit themselves. By Autumn 1982, each household had established its own distinct pattern of use of the output control.

8GC

The typical use pattern is that the fan comes on during late afternoon at a variable time. It then remains on nearly continuously until 2200 hours. The regular switch off time suggests control by the time clock. This pattern of operation confirms the complaints of inadequate heat output from the storage radiator; if the heater had been delivering the full output, the room would have overheated, and the thermostat operated to turn off the fan. During the daytime the fan would sometimes be turned on manually to achieve an increase in room temperature; this was often done by turning up the thermostat (to overcome the daytime setback) rather than by operating the selector switch.

9GC

Both storage heaters at Gairloch Close had inadequate output. The occupants in 9GC rarely switched on the fan, since it produced little heat.

22AG

In conversation with the occupants, they stated that the fan was rarely used, and was left switched off at the heater. This is confirmed by the event records. For instance, in the period of 28 days from 17th November to 14th December 1982, there were no fan operations on 19 of the days and very little during the remainder.

31AG

The pattern of use here was quite different from the other houses. The clock thermostat was left active continuously, with no setback period at all. The fan could therefore come on under thermostat control at any time of the day or night. This produced a very steady lounge temperature, both over the day and from day to day. Fan operation during the night resulted in a reduction in core temperature, allowing the heater to take a greater charge than normal.

Figure 5.2 compares lounge heating for 22 and 31AG over a period of a fortnight in winter 1982. House 22AG shows a lounge temperature which stays between 18 and 19°C except for two days when the outside temperature rose to over 5°C. The output fan of the storage heater came on on only five days, and for under 2 hours on each day. Input to the storage radiator was fairly constant at around 18 kWh per day. Only the fuel effect of the radiant heater was used; at no time were either of the bars switched on. This can be contrasted with the record for 31AG. It can be noted that there is a considerable increase in fan duty, which is closely reflected in the charge intake to the heater. On the coldest days the charge intake rises to over 25 kWh, and the output fan is on for over twelve hours per day. The radiant heater fuel effect was on for up to 15 hours a day, but the heating elements were never switched on. The result is an average lounge temperature of 22.8°C, which may be compared with the average lounge temperature of 18.5°C in 22AG. However, the variation in lounge temperature from day to day is no greater in house 22AG than in 31AG, even though the latter uses the automatic control system to the full, and 22AG has virtually constant power input on every day.

5.4 Within day temperature profile

The hour by hour temperature variation in a house is subject to a large number of disturbing variables. While the heating system and its associated controls act to keep the temperature at a constant level, other factors, such as sunshine and changes in weather, act to produce changes in temperature. In addition the activities and demands of the occupants change from day to day. In order to get a general impression of the daily temperature profile, unaffected by these random factors, temperature profiles were produced for one house by averaging the temperature at each hour of the day over one week. Figure 5.3 shows the result for 22AG, for four different weeks chosen to represent different outside temperatures.

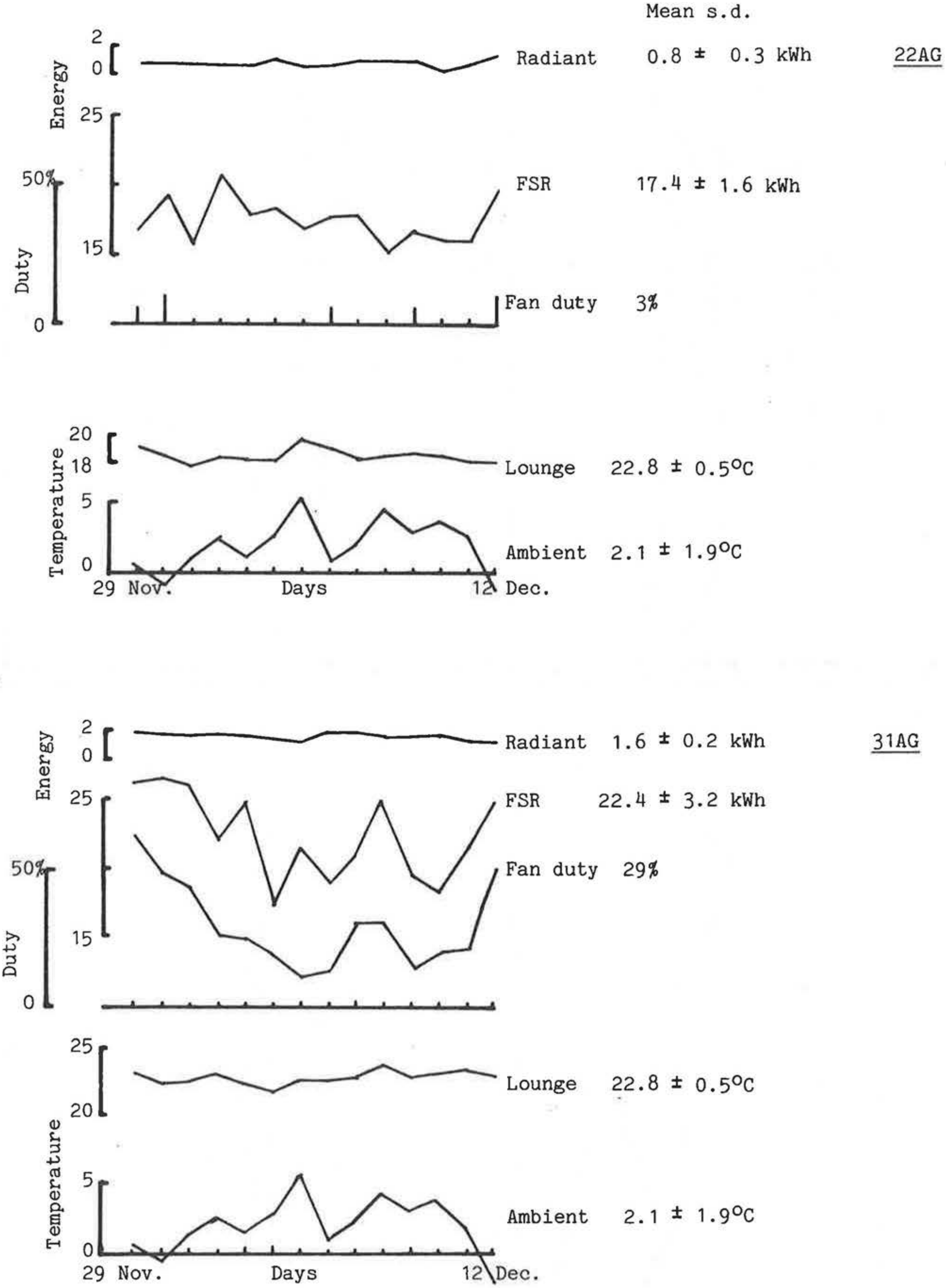


Fig. 5.2 Lounge temperature over a two week period. House 31AG has FSR under continuous thermostat control; fan duty and charge input follow outside temperature variation. House 22AG uses little output control, but between day temperature variation is small.

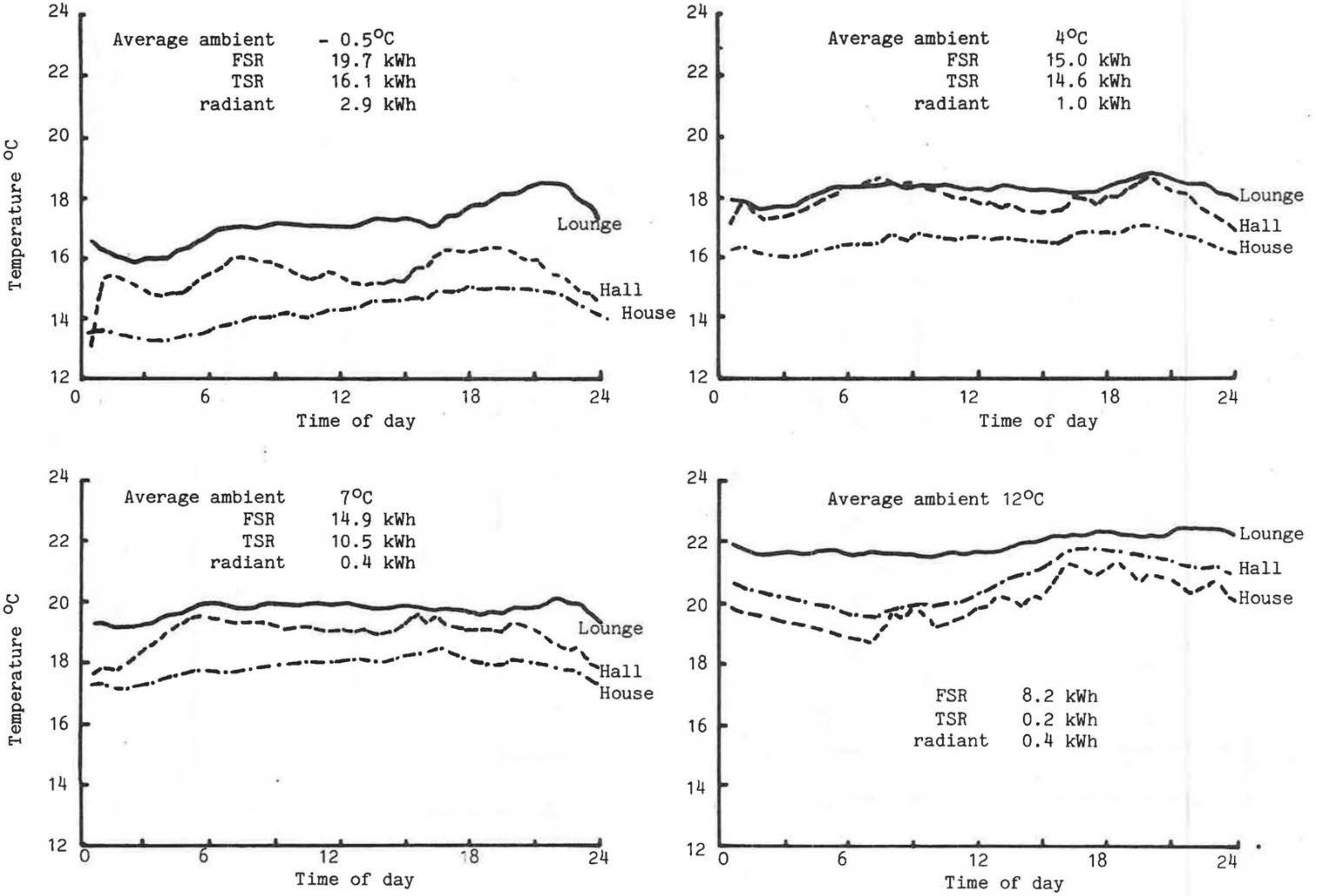


Fig. 5.3 Diurnal temperature profiles, averaged over one week, for 22AG

In cold weather, the house is at the low average temperature of 14°C. The lounge is brought up to 18°C in the evening by use of the storage fan heater and radiant heater. The hall profile shows the effect of the TSR. The initial steep temperature rise is presumably caused by a delay in the closing of the output damper, allowing warm air to escape during the initial hour of charge. Hall temperature reaches a first peak about 0800. A second temperature increase occurs at 1600 as the damper opens, and then the temperature falls after 2000 as the heater becomes exhausted. As the weather gets milder, the temperature curves flatten out; the lounge shows a virtually constant temperature over the whole day. The temperature profile for an outside temperature of 12°C shows the unheated house falling to a minimum temperature at about 0700 and rising during the day as solar gain takes effect. The small charge in the lounge storage heater acts to combat this, since maximum output coincides with the minimum house temperature; the result is a uniform lounge temperature over the whole day.

5.5 Upstairs heating

It was shown in section 4 above that the bedrooms can reach low temperatures in cold weather if there is no heat dissipation within them, and indeed bedroom temperatures down to 12°C were recorded in 22AG during the cold winter of 1982/83. All bedrooms were fitted with oil-filled, thermostatically controlled radiators of 750 watts rating. There was wide variation in usage between the houses - see Table 5.2. Both the Leeds houses (22AG and 31AG) used very little upstairs heating. In the case of 31AG, the high average temperatures maintained downstairs ensured reasonably warm bedrooms. 22AG had the lowest bedroom temperatures, but found them acceptable - see Figure 4.2. In house 8GC one bedroom was used as a study bedroom, and was in use for long periods; this is reflected in the bedroom heater usage. House 9GC used the bedroom heaters the most. After an initial reluctance to use the direct acting heaters, the occupants developed the custom of leaving the bedroom heaters on continuously on a low thermostat setting. They monitored the meter readings, and were satisfied with the energy consumption and cost.

The figures include bathroom towel rail consumption, which was not separately monitored. The rating of the towel rail was 130 watts, and all occupants stated that they did not use it for long periods; it seems unlikely that the towel rail accounts for any substantial proportion of upstairs heating consumption.

Table 5.2 Upstairs heating

	9GC	9GC	22AG	31AG
Low rate (kWh)	8	129	6	9
Normal rate (kWh)	194	233	33	11
Cost £	10.63	15.03	2.01	0.80

The construction of the oil-filled radiators produces a rather slow response. Tests in one of the ECRC test house bedrooms found that the heater operated under control of its inbuilt thermostat with a 80 minute cycle time, producing an air temperature swing of 0.6 K peak to peak, measured remote from the heater. A black table tennis ball mounted 1 metre from the centre of the radiator panel showed a peak to peak swing of 1.2 K. One occupant (9GC) found the direct radiation from the panel to his face noticeable when in bed.

6. USER REACTIONS

6.1 Close contact was maintained with the occupants of the four low energy houses. Before the houses were sold, prospective buyers were able to have the houses described to them by ECRC staff, and were given estimates of likely running costs. The performance of the houses was continuously monitored by ECRC from the date of occupation until May 1983. The monitoring necessitated a weekly visit by a member of ECRC staff to change the magnetic tapes in the data loggers. This meant that there was frequent and regular opportunity for informal communication; this was very helpful in giving early warning of any problems and maintaining good relations. In addition, some more extensive interviews were held with the occupants. These interviews were informal, though structured enough to ensure that all the major points were covered. No attempt was made to use any quantitative assessment scales on such a small sample.

The four families who bought the houses were self-selected; they chose to buy the low energy houses at a higher price than comparable houses on the same estate. None of them, however, was in any way committed to energy saving as a political or moral virtue. Their first concern was to get a well built house with low running costs. The satisfaction with the heating and comfort was closely bound up with satisfaction with the whole house. The two houses at Warrington suffered a number of early problems. The hall storage heaters were incorrectly wired; the lounge storage heaters were badly assembled, and had to be rebuilt and eventually replaced; the ventilation units were incorrectly installed, and delivered kitchen air to the bedrooms; the underfloor insulation warped. These problems were rectified, but of course the occupants were initially disappointed with their new house. There were no comparable problems at Leeds.

The interviews probed for dissatisfaction. Tables 6.1 to 6.4 summarise the user reactions; if the tables seem to concentrate on the dissatisfaction this must be seen in the context of general satisfaction. The occupants of the four houses are pleased with them, and consider their decision to buy low energy houses justified by the results. They would hesitate before buying an "ordinary" house.

An attempt has been made to summarise the results of the interviews under common headings in the tables. Although each house tended to establish its own separate pattern of use, many of the findings apply to all houses.

The storage fan radiator was capable of maintaining the lounge at a comfortable temperature, with little use of supplementary heating. The storage fan radiator was found acceptable; fan noise was not a problem. Positioning the storage fan radiator can be a problem. The Leeds houses provided a single, satisfactory, heater position. The Warrington houses provided alternative heater outlets, but neither was completely satisfactory. One family used full length curtains, preventing the heater being installed on the window wall. The heater requires a clear space in front for the fan outlet and since the radiant heater also requires space in front of it, there is a space restriction in a small room. The clock thermostat was not always used in the expected manner. The operation of the clock thermostat is to energise a heater in the thermostatic housing during the setback period so the thermostat mechanism sees a local temperature higher than the room temperature. If the fan output is required during the setback period, the occupant "should" use the selector switch, which will de-energise the setback heater. It will take about ten minutes for the thermostat to cool sufficiently to operate normally. An alternative is for the user to leave the setback heater on, but simply turn up the thermostat setting to compensate for the setback. Since this gives an immediate response, it was the preferred mode of use.

All four houses found the evening landing temperatures were cool. There was the feeling that the heaters had run out, and temperatures were falling; this was disliked. In absolute terms, the temperature would not be considered cold. However, the fact that it was below the lounge temperature, and was falling was disliked. In both the Warrington houses the hall heater was replaced by the larger TSR 24. This was welcomed, though it was too late in the heating season for it to be tested fully. The Satellite controller performed reasonably well. Its disadvantages were large input swings from day to day, though these were not reflected in large temperature swings, and inadequate charge input in cold weather. All occupants increased the thermostat setting in cold weather to ensure full charge. The damper output on the TSR was actively managed in one or two houses, by opening the damper in late afternoon and reclosing it at bedtime.

The kitchen was heated entirely by free heat from cooking, etc. One house found the kitchen to be cold in the early morning, otherwise there were no problems. The towel rails were rarely used.

The downstairs W.C. in the Leeds house has no source of heat gain other than air drawn in from the hall by the extract fan. The W.C. has only one internal wall in contact with the house, and can cool to low temperatures in Winter; 8°C was recorded at 31AG. These low temperatures did not seem to be actively disliked. As a comparison, the W.Cs in comparable gas heated houses on the same estate froze in the cold weather. 31AG are contemplating moving the kitchen towel rail into the cloakroom.

In all the houses the bedrooms were allowed to fall in temperature as the weather got colder. This was not considered a serious problem, except where the bedrooms were used during the evening. By the end of the first year, families had overcome their inhibitions about using the radiators, having found that bedroom temperatures could be raised at little cost. The response of the oil-filled radiators was slow. In some houses they were repositioned to suit furniture arrangements.

Table 6.1 Occupants' comments 8GC

Lounge	Radiant heater. This was used occasionally on the low (400W) setting. Fan storage radiator. There were justified complaints of low output; the heater was eventually replaced. The clock thermostat was used to activate the fan in the evening. If warmth was required in the day, the thermostat setting was turned up to override the setback. The low fan speed was used, and found quiet. The householder was sensitive to draughts; a slight downdraught was noticed in some positions, caused by air from the Bahco inlet coming down the wall.
Hall	The TSR18 was considered undersized. In cold weather, Satellite thermostat was set to 25°C to ensure full charge.
Kitchen	Was found chilly first thing in the morning, and a fan heater installed.
Bedrooms	Chilly in cold weather. One son uses bedroom extensively for hobbies. They were initially reluctant to use bedroom heaters, but now use them and find the cost acceptable.
Cost	Householder was initially worried that the costs would be substantially higher than predictions; after a full year's operation he is happy with the costs and the standard of comfort achieved.
General	The house suffered from several problems during the first months of occupation; these were corrected in Autumn 1982 and in Spring 1983 the hall TSR18 was replaced by a TSR24, and the lounge Caribbean fan storage heater was replaced by a Creda TSF24. In addition, a time clock was installed to control the upstairs heating circuit. These changes were welcomed by the occupants.

Table 6.2 Occupants' comments 9GC

Lounge	Radiant heater. Quite satisfactory, and the low 400W setting was adequate. Fan storage radiator. The output was found to be inadequate. As a result the clock thermostat and the output fan were rarely used.
Hall	The hall storage radiator was felt to be inadequate, with chilly stairs and landing. The Satellite thermostat was set at 25°C in Winter to ensure full charge.
Kitchen	No temperature problems. The towel rail position was unsatisfactory, and re-sited during kitchen decorations.
Bedrooms	Bedrooms are chilly in cold weather. During 1982-1983 Winter the panel radiators were left on continuously at a low setting (2-3). Occupants monitored the meter and found the cost acceptable. Mr. W. is disturbed by the click of the heater thermostat, and can feel direct radiation on his head while in bed. They would prefer to keep bedroom doors shut, but find they need to leave them open to increase heat distribution.
Bathroom	No problems.
Cost	The householder is concerned to keep energy costs low. He has installed a time clock to allow operation of washing machine overnight.
General	Initial building and installation problems caused dissatisfaction. These were resolved by the start of the 1982-1983 heating season. Hall and lounge storage radiators have been replaced, and a time clock fitted to the upstairs heating circuit.

Table 6.3 Occupants' comments 22AG

Lounge	Radiant heater. The fuel effect was used frrequently; the low 400W setting was used occasionally when heat was required. It was never necessary to have two bars on. Fan storage radiator. This worked satisfactorily. The input control was reset occasionally. The fan was under control of the clock thermostat for the first winter; the fan was switched off for most of the second winter.
Hall	The output damper of the hall TSR was opened each afternoon about 1600 and closed at bedtime. The landing cools off in the evening, which was disliked. The heater sometimes takes a low charge under Satellite control; the Satellite setting was normally 18°C, increased to 20°C in cold weather.
Downstairs W.C.	This can get very cold; however this was accepted, helped by the fact that similar conventional houses on the estate had problems with the W.C. freezing.
Kitchen	Adequately warm, towel rail not used.
Bedrooms	Bedrooms are cool in the evening. This is not felt to be a serious problem, but they expect to need supplementary heating once the children begin to use their rooms in the evening. The heater in the main bedroom is not used.
Bathroom	Satisfactorily warm; it is found to warm up rapidly when using bath or shower. Towel rail rarely used, as it is slow to warm up, and thought of as potentially expensive.
Cost	The bills are less than comparable gas houses on the same estate, and the occupants are very satisfied. This family run the house very economically, and as a result there was less free heat available to supplement the heating system than in the other houses.

Table 6.4 Occupants' comments 31AG

Lounge	Radiant heater. The fuel effect is switched on all day; the heating elements rarely, if ever, needed. Fan storage radiator. The clock thermostat is left on continuously, with the fan speed selector switch on high. The room thermostat is set at 22°C, and sometimes turned up in the evening. This mode of operation works well, and was found satisfactory by the occupants. They did not run out of heat in the evening. The storage heater was left on at a low charge setting well into mild weather.
Hall	The TSR is run under Satellite control, and not adjusted. The thermostat input set at 23°C, input at 6, "room temperature control" (damper) at 4.5. No problems were found with chilly hall or landing.
Kitchen	No heating problems; the towel rail was not used.
Bedrooms	Bedrooms were adequately warm, with little use of supplementary heating.
Bathroom	The bathroom was adequately warm, with little use of towel rail.
Cost	This household had the highest electricity consumption of the four houses. The occupants were aware of this, and considered their final bills entirely reasonable.
General	This household used the appliances and heating system freely and generously. The continuous heating and warm temperature of the living room ensured that the hall, landing and bedroom temperatures were warmer than those in the other houses. As a consequence, this house had no complaints about chilly bedrooms or landing.

7. DISCUSSION

The four houses used more space heating energy than was predicted at the design stage. Details of energy consumption are given in ECRC/R1760. The predicted energy consumption supposed a perfectly controlled and operated heating system. The actual manner of use of the heating system contributed towards the increased energy consumption in several ways.

Higher internal temperatures were maintained than the design values. An increase in internal temperature has a large effect on heat consumption. Over the season, the house runs about 12K above the average outside temperature of 6°C. This 12K lift is split about equally between free heat and the heating system. An increase of 1K in internal temperature will therefore require an increase of about 16% in heating energy.

Heating was maintained in mild weather. There was a felt need on the part of the occupiers to maintain a source of heat in mild weather, when no heating was required to maintain the design temperature. The main lounge heater was generally kept in operation in mild weather: it provided a source of heat for clothes airing, and insurance against an unexpected cold spell.

All families were satisfied with the size of their electricity bills, and when comparisons were made, found them lower than a conventional house with gas heating. It must be remembered that the families were not attempting to save energy as a primary goal. They made decisions on energy use according to their wishes and needs, modified to some extent by cost. In energy saving terms it is not "rational" to switch on the fuel effect of the radiant fire for over 12 hours per day. The decision is made on different grounds. Each house established a pattern of use, based on its own requirements, rather than a conscious decision to minimise energy consumption. For instance, 31AG were generous users of power for appliances as well as heating and hot water. They welcomed the low energy house, since it allowed them to have a very high standard of comfort without fear of excessive costs.

The storage fan radiator in the living room was adequate to provide sufficient heat in the living room, including temperature elevation in the evening. The Creda TSF24, which replaced the faulty Caribbean storage fan heaters in Warrington, is so designed that the main elements can also be used to provide warm air output on day energy. These new heaters were installed at the end of the monitoring period, too late for any information to be obtained on their usage. The provision of a focal point heater is therefore redundant for heating purposes. Reference to Table 5.1 shows that the heating use of the focal point heater is remarkably small; most of the energy consumption was for the fuel effect.

The clock thermostat output control was not entirely successful. It worked well and reliably, but did not meet the user's needs. The use of a time clock with a conventional heating system ensures that the heating comes on sufficiently early to ensure a comfortable house at the start of an occupied period. With a storage heating system, there is normally sufficient case emission to ensure that room temperature does not drop to uncomfortable levels. There is therefore little need for a time clock to bring on the output fan in advance of occupation, and it will normally be adequate to activate the fan manually when required. A disadvantage of the clock thermostat was the slow response of the manual selector switch; as a result, users largely ignored this and used the thermostat as an on/off switch. This has the disadvantage that settings are lost, and may not be properly restored for the next time period. A thermostat with built in on/off and speed selector switch would be a satisfactory replacement for the clock thermostat. There does not seem to be any strong need for automatic input control of the storage fan radiator. The hall and landing were cool in the cold weather. This was not seriously uncomfortable, but it must be remembered that these houses are sold at a price premium, and a high standard of heating is expected. A larger capacity of heater should have been provided; the original TSR18 was successfully replaced by a TSR24 in the two Warrington houses. The Satellite controller operated reasonably well, with two limitations. It tended to undercharge, by switching on late, in cold weather, and it produced large fluctuations in charge from day to day. Most occupants simply increased the thermostat setting to maximum to ensure full charge in cold weather. This might not be satisfactory with a larger heater. A storage fan radiator in the hall would give an improved temperature profile over the day, and reduce the necessity for automatic input control.

While one occupier found the kitchen chilly first thing in the morning, it seemed that in general heating was not required. The towel rail installation was not a success. The rail was rarely used, and finding a suitable location to install it proved a problem in both kitchens.

The bathroom had no heat source other than the rarely used towel rail, but this was found satisfactory by the families. Using the bath or shower rapidly increased the temperature. A delay switch, giving about four hours operation after switching on the towel rail might remove some of the inhibitions against its use.

All houses allowed the bedrooms to cool in cold weather. This was acceptable, except where bedrooms were required for evening use, where there was a definite requirement for heating. The oil filled radiators provided were reasonably satisfactory, though had a rather slow temperature response. Consideration should be given to the alternative of a convector panel heating with both faster response and closer temperature control. This would have the advantage that a range of heaters could be chosen which matched the storage heaters in appearance. Towards the end of the monitoring period time clocks were installed in all houses to control the upstairs heating circuit. This was welcomed by the occupants, though the work was carried out too late in the heating season for any conclusions to be drawn about how the occupants would use them.

8. CONCLUSIONS

(1) Temperature. The lounge temperatures were maintained at a comfortable level throughout the year. Bedroom temperatures were allowed to cool in cold weather, but without apparent discomfort.

(2) Heater sizing. The storage fan heater had adequate capacity for the lounge dining room. The hall heater was barely adequate, and could with advantage be increased from 18 to 24 kWh capacity. There was a reluctance on the part of the owners to use direct acting heating to supplement the storage system in cold weather.

(3) Heater performance. The lounge storage fan radiator was satisfactory. A new version with improved appearance and performance is now available. The thermostatic storage radiator in the hall performed satisfactorily. The modified focal point radiant heater with series parallel switching was satisfactory, and the low setting was acceptable to the users. However, the total usage of this heater was small, and the installation of a supplementary heater in the lounge is not strictly necessary, though the fuel effect was used extensively by some families. The bedroom heaters were not used a great deal, but all houses found them necessary on occasions. The oil-filled radiators could well be replaced by convector panels, to provide better appearance and more sensitive control. The towel rails were little used, and the difficulty of siting the kitchen towel rail outweighed any advantage. A preset delay timer might encourage use of the bathroom towel rail.

(4) Controls. The clock thermostat controlling the output of the lounge storage fan radiator was not used to full effect. A thermostat with a fan switch incorporated would be a satisfactory substitute. The Satellite controller, controlling input to the hall storage radiator, was reasonably satisfactory in maintaining a constant temperature from day to day, but produced swings in charge input, and some undercharging in cold weather.

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