# Experimental Thermal Calibration of Houses

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## Abstract

A comprehensive thermal calibration procedure has been developed to measure the transmission and ventilation heat losses of unoccupied houses and their solar heat gain. It covers both whole house testing, and detailed measurements for surface temperature distribution and local heat flows through any component. Places where air leakage occur may also be identified.

## Introduction

The calibration procedure for unoccupied houses described in this paper covers whole house testing, individual component measurements for surface temperatures and heat flow, and tests for airtightness.

The period of testing depends on the information required. Airtightness tests can be carried out in a day or less, including setting up and removing the apparatus. Ventilation tests require a minimum of a few days and usually longer if a calibration is required in terms of wind speed, direction and temperature difference to cover a range of these variables.

Surface temperature measurements using an infra-red camera are instantaneous, although several hours or even a day may be needed for temperatures to stabilise when heating the house from cold. Using colour photography to record infra-red pictures of all surfaces takes a few days.

For whole house thermal calibration the shortest period is a week, preferably in mid-winter when solar heat gain is small because it has to be calculated. For greater accuracy, and to obtain solar heat gain experimentally from the same measurements as for transmission and ventilation heat losses, would require a period of 6 weeks in late autumn or early spring.

Testing outside the heating season would be less accurate. Solar heat gain would be high and lead to inaccuracies in the determination of the transmission heat loss. Internal temperatures would have to be higher than during the heating season to maintain a suitable temperature elevation above the outside, and this can have an effect on timber moisture content, its shrinkage and house airtightness.

Calibration equipment is installed for the period of tests only. It comprises heaters, thermostats, temperature recorders, tracer gas supply and sampling tubes and mixing fans in each major room for whole house tests. Additional equipment is required for detailed component measurements and for recording weather data.

Whole house calibration theory

The whole house calibration is based on the fact that under steady conditions the heat input to the house equals the heat lost by transmission and ventilation. With no occupancy and electric heating the only other heat input is from the sun, and the energy balance can then be expressed as:

electric heating (EEN) + solar heating (SEN)
= transmission heat loss (TEN) and ventilation heat loss (VEN) (1)

The balance strictly applies only when there is no change in heat stored in the structure and heat lost by evaporation. With steady internal temperatures, experience and simple calculations show that changes in external temperatures have negligible effects when measurements are averaged over periods of seven consecutive days.

It is convenient to work in terms of kWh/day averaged over these seven day periods. Electric heating (EEN) is measured directly. Ventilation heat loss is obtained from measurements of ventilation rates (V) and temperature elevation of the ventilation air:

$$VEN = V\Delta T \rho c \ 24 \ vol/3600 \qquad (2)$$

Ventilation rate V is in house volume air changes per hour and $\Delta T$ in K, $\rho$ is the air density ($kg/m^3$) c is the air specific heat (kJ/kg K) and vol the house volume ($m^3$). The 24/3600 is needed to give the value of VEN in kWh/day.

Substituting 1.2 $kJ/m^3K$ for $\rho c$ and simplifying gives:

$$VEN = V\Delta T \ vol/125 \quad kWh/day \qquad (3)$$

The theoretical transmission heat loss (TEN) is calculated from component areas (A), thermal transmittance values (U) and internal to external temperature differences ($\Delta T$):

$$TEN = \Sigma AU\Delta T \ 24/1000 \text{ or } 0.024\Sigma AU\Delta T \quad kWh/day \qquad (4)$$

Substituting equations (3) and (4) into equation (1), rearranging and dividing by $\Delta T$ gives:

$$\frac{EEN}{\Delta T} - \frac{V.vol}{125} = 0.024 \ \Sigma AU - \frac{SEN}{\Delta T} \qquad (5)$$

The left-hand side can be evaluated from measurements. The only unknown variable is then SEN, since 0.024 $\Sigma AU$ is constant and $\Delta T$ is measured. By plotting the left-hand side against known solar values representative of $SEN/\Delta T$ both 0.024 $\Sigma AU$ (the intercept) and $SEN/\Delta T$ can be obtained. Figure 1 shows this using the theoretical solar heat gain through the glazing (SENG) calculated in the way described later.

The value of the intercept and therefore 0.024 $\Sigma AU$ is around 2.58 kWh/day K, varying slightly with the three correlations given in the figure. Those with 18 data sets exclude the sunnier results, and there is

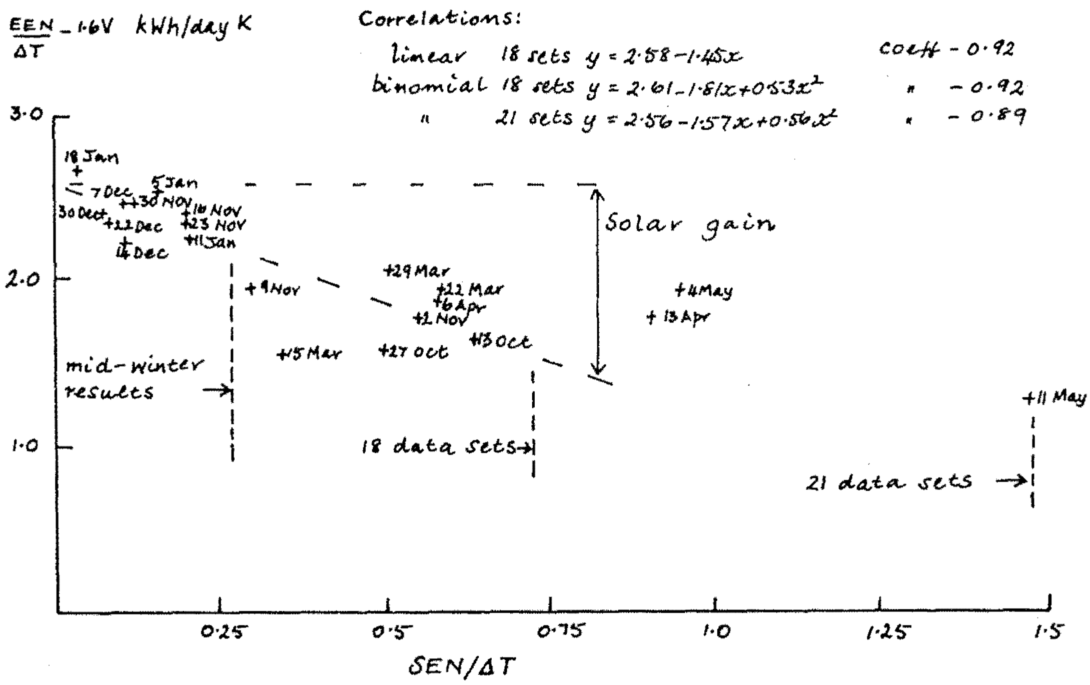



Figure 1. Graph for determining whole house experimental transmission heat loss and solar heat gain. Seven day periods are identified by the middle day date.

insignificant difference between linear or binomial correlation in either intercept or correlation coefficient. The value of the intercept can now be used in equation (5) with the experimental results to evaluate SEN.

Mid-winter results (16 November to 18 January in figure 1) cluster because the values of the weekly average insolation are similar. Six weeks of testing during this period would not produce a reliable intercept value. The minimum six-week test period needed to obtain a reliable intercept needs to include sunnier weather, for example, from 2 November to 7 December.

If tests are restricted to within the mid-winter period then it may be best to depend on a calculated value of SEN, to use in equation (5). A week of testing may be long enough. Fortunately, solar heating during mid-winter is small (∿5 kWh/day), ΔT is large (15 K or more) and relatively large errors (±20%) in calculating SEN will have little effect on the value of 0.024 ΣAU.

The first step in calculating SEN is to calculate the solar heat gain through the glazing (SENG) and then add to it the effective solar heating (SENS) through the non-glass area. The curves (1) in figure 2 can be used to obtain insolation on vertical surfaces from insolation measurements on the horizontal plane. Values of SENG are then calculated using the glass areas for each orientation, making allowances for shading and ground reflectance, and solar gain factors for example for plain glass of 0.76 for single glazing and 0.65 for double glazing (2).

For SENS test results (3,4) have shown that it varies as a percentage of SENG from about 33% for a well insulated house with double glazing ($\bar{U}$ elsewhere <0.5 W/m$^2$K) to 50% for a poorly insulated house with single glazing ($\tilde{U}$ elsewhere >1.5 $W/m^2K$). Put another way then this variation in SENS is 1% to 2% of the insolation on the whole of the exterior surface.

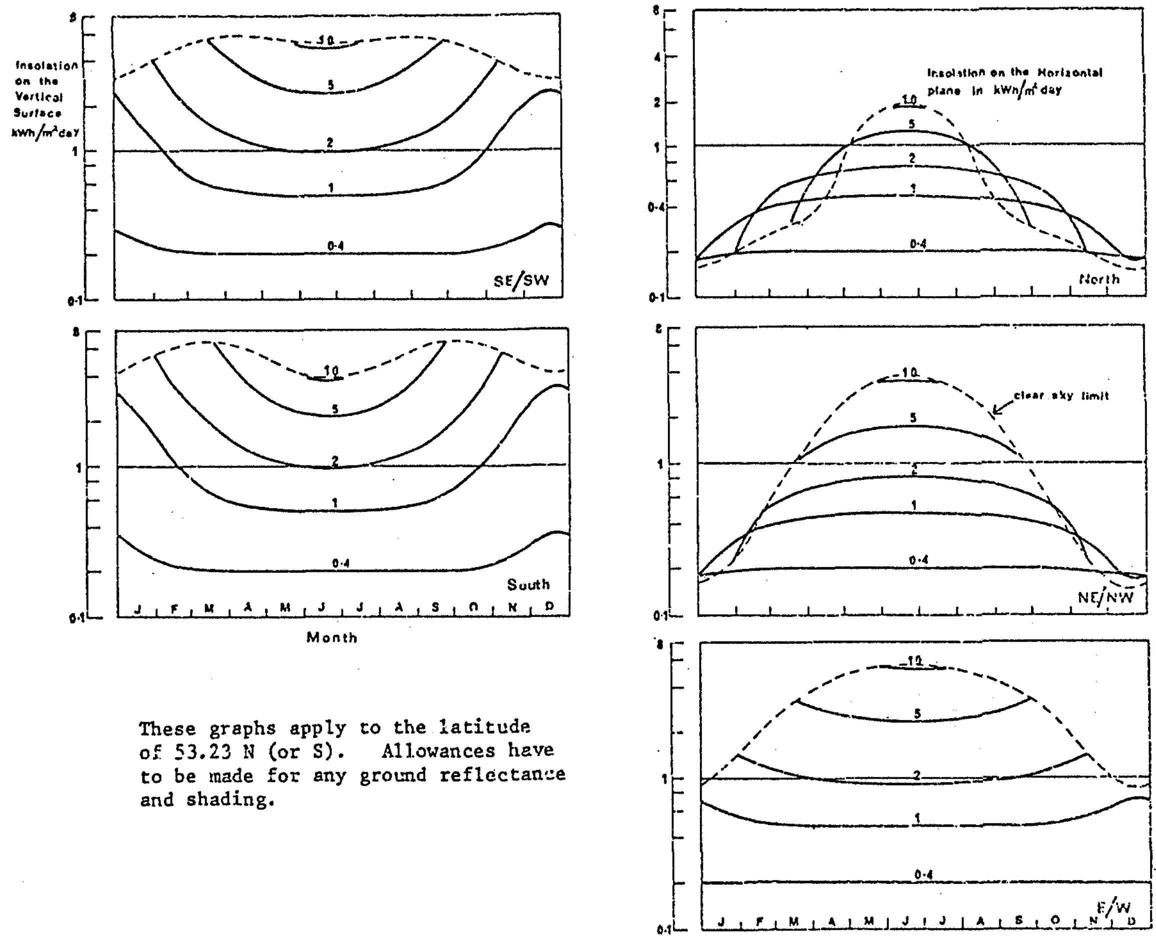


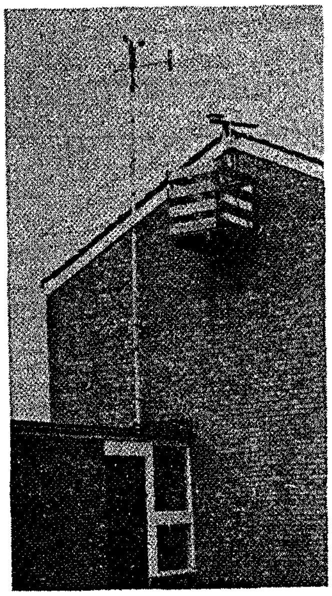

Figure 2. Graphs for obtaining insolation on vertical surfaces from measurements on the horizontal plane (1).

One way of obtaining SEN separately is to test with no heating other than the sun (EEN = 0) and use the theoretical value of $0.024\Sigma AU$ in equation (5). Difficulties arise from the small temperature elevation ($\sim$1 or 2 K) of the inside above the outside. Temperature variations around the house may be significant. Errors in measuring temperatures of $\pm$0.25 K may give an acceptable percentage error in $\Delta T$ when this exceeds 10 K, but not when $\Delta T$ = 1 K. There is also theoretical evidence (5) that with small temperature elevations the effect of radiation to the cold sky at night is to increase transmission heat losses by 50 to 100% in mid-winter which would mean SEN is underestimated.

## Whole house calibration instrumentation and equipment

The theory outlined above shows the measurements which have to be made. The house has to be heated and internal temperatures measured. Ventilation rates have to be measured and also external weather data. Ventilation rates are best measured continuously during the whole period of tests, then the weather data needed are external temperature and insolation on the horizontal plane. For a ventilation calibration, perhaps for later use, in terms of wind speed, wind direction and temperature difference then wind velocity is needed as well.

Checks on all instrumentation and test equipment should be carried out daily. Recorded data should be analysed daily for the first few days and then no more than a week in arrears. Unless this is done errors, omissions and malfunctions could make much of the data useless over a significant proportion of the few weeks allowed for the calibration.



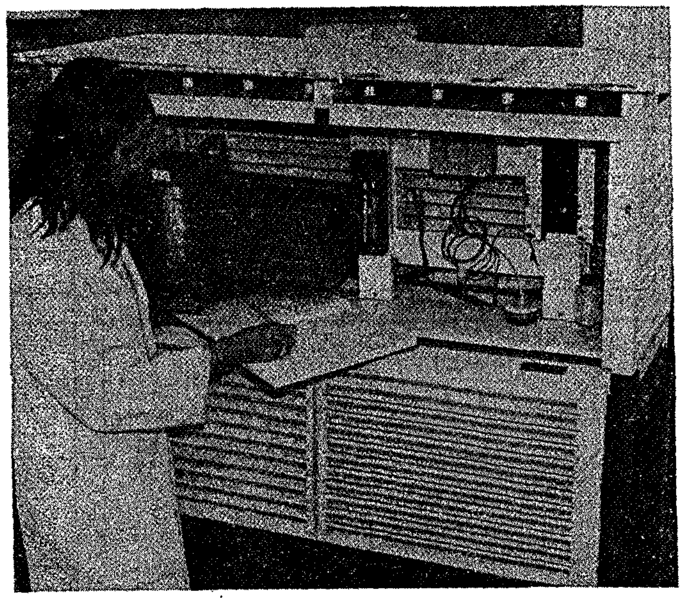


Figure 3. Weather station comprising anemometer, solarimeter and screen

Weather data can be recorded on site, figure 3, with a solarimeter mounted at ridge level, a Stevensen screen for temperature measurements, and an anemometer for wind velocity. The anemometer should be sited to obtain representative wind velocities on to the house by exposing them equally to the prevailing wind. The standard requirement for siting an anemometer, of open ground and 10m high may not be available locally, and may not be representative.

It is generally accepted that weather data recorded 10 km or even 15 km distant is sufficiently accurate when averaged over a week, although it is not known whether this has been checked. The main problem with distant weather stations is in having the data quickly enough, especially if the weather station is owned by others.

A typical set of equipment for one room is shown in figure 4. Each major room and the hall has a thermostatically controlled heater. Electricity measurements are made at each heater and for the whole house. Temperatures are recorded in each major room and the hall and landing. Analysis of results is made easier if the temperature in the house is uniform and constant to within say $\pm 0.5$ K, because then simple averaging measured temperatures gives a satisfactory whole house average. Internal doors are left open to help in this temperature requirement. To measure ventilation rates supply tubes for tracer gas are put in front of the mixing fans* which are in the doorways blowing into each major room. Tubes are also needed from each room to sample air to measure the tracer gas concentrations.

Inside temperature measurements may be made continuously using thermograph or thermocouple on to chart recorder, with some check on their accuracy using, for example, a calibrated mercury-in-glass thermometer. Data loggers using thermocouples would normally scan hourly and then record a near instantaneous temperature. The measurements are a mix of

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*In houses with ducted warm air heating or ventilation single point supply and sampling may suffice in the main supply and return ducts (6).

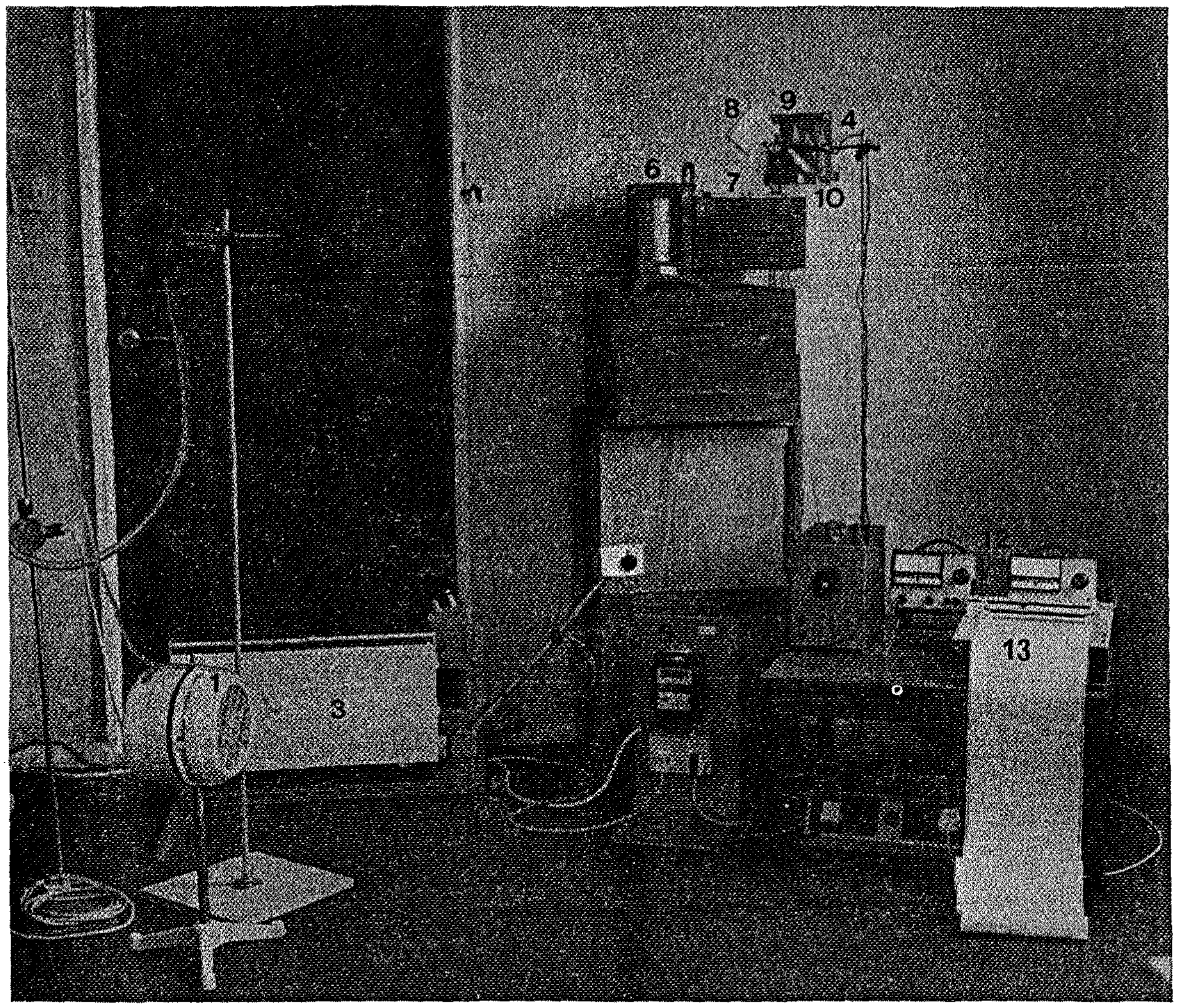


Figure 4. Experimental set up for one room (repositioned for the purpose of photograph)

(1) tracer gas supply + mixing fan, (2) tracer gas sampling, (3) electric heater, (4) heater control sensor, (5) electricity meter, (6) thermohygrograph, (7) calibrated thermometer, (8) surface mounted heat flow sensor, (9) embedded heat flow sensor, (10) differential thermocouple, (11) selector switch, (12) microvolt amplifiers, (13) chart recorder.

air (Ta) and mean radiant (Tr) temperatures. Transmission heat losses from a room are generally less influenced by Ta than Tr in the ratio Ta/Tr:0.33/0.67. People on average are about equally sensitive, i.e. Ta/Tr:0.5/0.5 (7). Instruments can be made to cover a wide range as the following list shows:

| | Ta/Tr |
|---|---|
| thermocouple (aspirated, radiation shielded) | 0.9/0.1 |
| freely exposed thermocouple (bead diameter of 1.5 mm) | 0.84/0.16 |
| mercury-in-glass thermometer | 0.67/0.33 |
| bimetallic thermograph | 0.67/0.33 |
| single black globe 30 mm diameter | 0.5/0.5 |
| single black globe 150 mm diameter | 0.4/0.6 |
| double black globe | 0.2/0.8 |

The globe instruments are particularly sensitive to air speeds (8).

In practice, errors arising from measuring the wrong mix of Ta/Tr can be made negligible, even with air heating, under steady temperature conditions The sensor should be placed in the centre of the room away from direct effects of the heating system, sun and radiation draughts from the windows Then it is easy to calculate that in a well insulated house (double glazing and Ū <0.5 W/$m^2$K) Ta would be less than 0.4 K higher than Tr for a temperature elevation of 15 K above the outside. The difference between the mix controlling heat loss (0.33 Ta/0.67 Tr) and that of a sensor (0.67 Ta/0.33 Tr) is then only 0.1 K, an error of less than 1% of $\Delta T$. Even in a poorly insulated house (single glazing, Ū of 1.5 W/$m^2$K) the error rises to only 3 to 4% with Ta 2 K higher than Tr. These small differences have been confirmed by measurements (9) in a poorly insulated house with air heating. Heating by hot water radiator eliminated the difference between Ta and Tr.

Ventilation measurements by continuous and decay methods have been used with carbon dioxide and nitrous oxide. The principles are simple (10). For the continuous method tracer gas is supplied at a measured rate continuously through each supply tube to be mixed by the fans. Each supply is adjusted separately (figure 5) so that the concentration is about uniform throughout the house as indicated by the continuous sampling from each room. Then the separate samplings can be mixed and a bulk concentration measured.

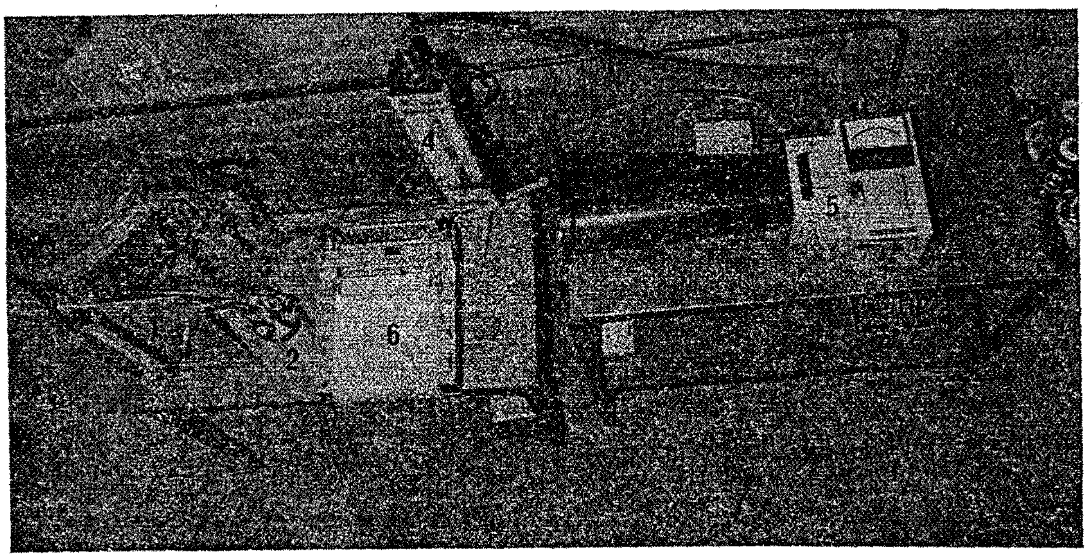

Figure 5. Apparatus for measuring ventilation rates.

(1) tracer gas flow meter, (2) tracer gas supply distribution box, (3) sampling control and mixing box, (4) sampling rate flow meter, (5) analyser, (6) chart recorder.

The ventilation rate is determined from the rate of supply of tracer gas divided by the measured bulk concentration for a gas not present in outside air. For a tracer gas such as carbon dioxide which is present in outside air the extra concentration is used as the divisor.

The tracer gas supply rate is governed by the concentration needed for analysis which itself is influenced by the ventilation rate. The relatively high concentration of $CO_2$ in outside air (∿0.033%) means that relatively large quantities of it are needed, typically 0.5 to 1.0 $m^3$/day to give a bulk concentration of around 0.06%. Far less $N_2O$ is needed, ∿0.1 to 0.15 $m^3$/day because a bulk concentration of 50 ppm is suitable.

A cylinder of $N_2O$ would therefore last weeks compared with days for a similar cylinder of $CO_2$.

A continuous recording of the bulk concentration gives a continuous record of ventilation rate. Hourly or 2-hourly averages with corresponding values of $\Delta T$ gives ventilation heat loss. To be exact, the value of $\Delta T$ should be calculated from the temperatures at which the air leaves and enters the house, but with steady and uniform temperatures the average of the room temperatures can be used, with the external screen temperature.

The decay method of measuring ventilation rates uses the same equipment. Tracer gas is introduced and mixed to give a uniform concentration. The supply of tracer gas is stopped and the bulk rate of decay of concentration measured. Thorough mixing makes the rate of decay the same in each room. For a tracer gas not present in outside air, ventilation rate is deduced from the relationship:

$$\text{concentration (time t)} = \text{concentration (time zero)}^{-Vt}$$

where V is the ventilation rate in house volumes per hour. A graph of ln concentration against ln t will have a slope of -V.

Changes in wind speed, direction and $\Delta T$ alter the routes of air infiltration and therefore the required rate of supply of tracer gas to each room to maintain near uniform concentration throughout the house. Adjustment to each supply rate is needed at times according to the measured concentrations from each sampling point. A correlation of ventilation in terms of wind speed, direction and $\Delta T$ is useful for use at other times but there is evidence of summer to winter variations in airtightness arising probably from expansion and contraction of timber due to changes in moisture content (6).

## Component measurements

Detailed measurements on the components separately may be required if the whole house calibration is unsatisfactory to show experimentally:

(a) the thermal performance of each component.
(b) local areas of high transmission heat loss, for example, due to thermal bridging, missing insulation, and at corners.
(c) places of air leakage.

The equipment needed is an infra red camera, preferably with a colour monitor and colour film camera, small contact heat flow sensors, and a smoke generator with pressurisation equipment. Some examples are given here where the equipment has been used.

The equipment used for measuring heat flow is shown in figure 6 in use on an insulated wall (11). The sensing head is shown held in place with adhesive tape with a thin layer of grease between the sensor and wall surface for good thermal contact. The sensor is very responsive and sensitive and it is best to record its output continuously, rather than depend on spot readings, as the record will show fluctuations. The paper screen is used to eliminate the effects of radiation onto the sensor from people running the tests. A human face 0.5m away increases the sensor output by around 25%, taking about a minute to reach the new output. The heating needs to be either at a constant input or very closely controlled, for example, using a thermistor. The normal bi-metallic thermostat controlling the fan heater gives an air temperature swing of ±2K and a heat

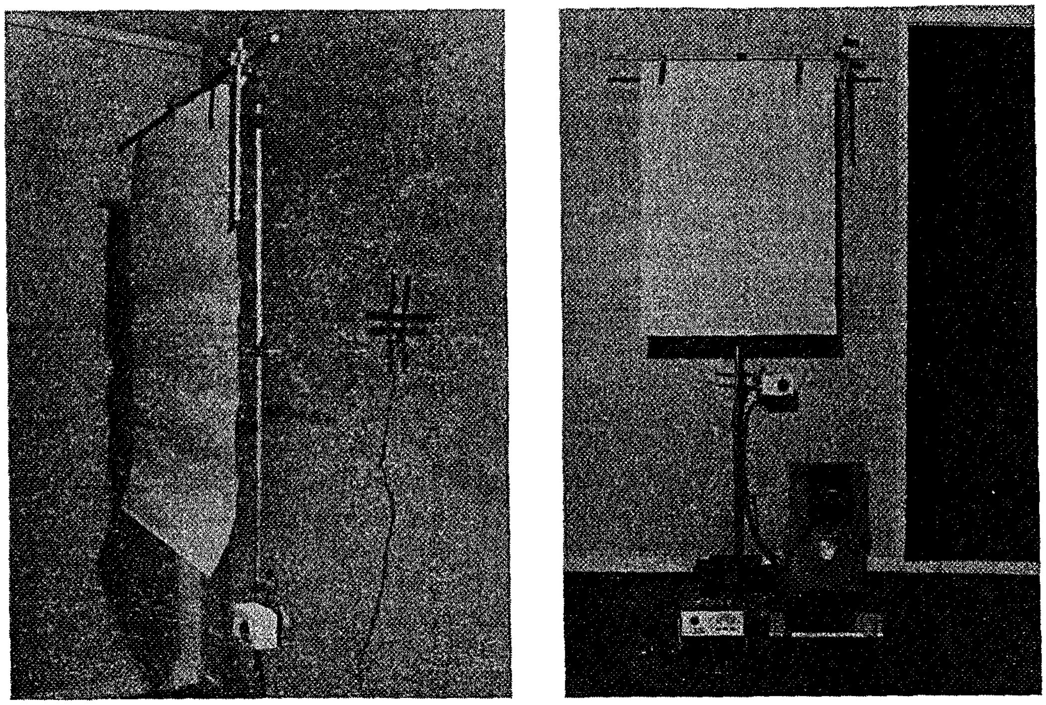

Figure 6. Apparatus for measuring heat flow showing the sensor on a wall screened from direct human radiation by a sheet of paper. The thermostat acts as a high temperature cut-out rather than control.

flow swing of ±70% (30% to 170%). Temperature stabilisation is also important. Room and wall temperatures have to be steady so the heating needs to be on for at least 6 hours before taking measurements. Fitting the sensor disturbs temperatures locally and readings should not be taken for at least an hour. This period should allow the temperature of the instrumentation to stabilise.

The effects of external changes in temperature and insolation on the outer surface on heat flow at the inner surface are delayed by several hours. Again a continuous recording of heat flow would be useful to see the changes and for making a 24 hour average.

Results of some measurements are shown in figure 7. An average heat flow rate of 9.8 $W/m^2$ was measured at the inner surface of the plasterboard and 7.9 $W/m^2$ on the inner surface of the insulating block. One explanation for this difference is that air flow in this cavity gives it a negative thermal resistance. The theoretical heat flow is 4.9 $W/m^2$, which means that there is an additional flow of 2.9 $W/m^2$. Measurements of temperatures through the wall show this to be because the foam insulation works far less well than predicted, corresponding to a k value of 0.08 W/mK rather than the value of 0.038 W/mK used in calculating the theoretical flow.

For measuring surface temperatures, the infra-red camera would be used. Insulated walls have warm surfaces internally and cold surfaces outside, provided of course the buildings are heated. A composite inside photograph is produced in figure 8. It is of the wall in figure 7. There are significant changes of 2 K over the wall. The outline of the insulated door to an outside porch is clearly visible and the threshold is very cold. The cold corner to the right of the picture is at the abutment to a timber-framed outside wall.

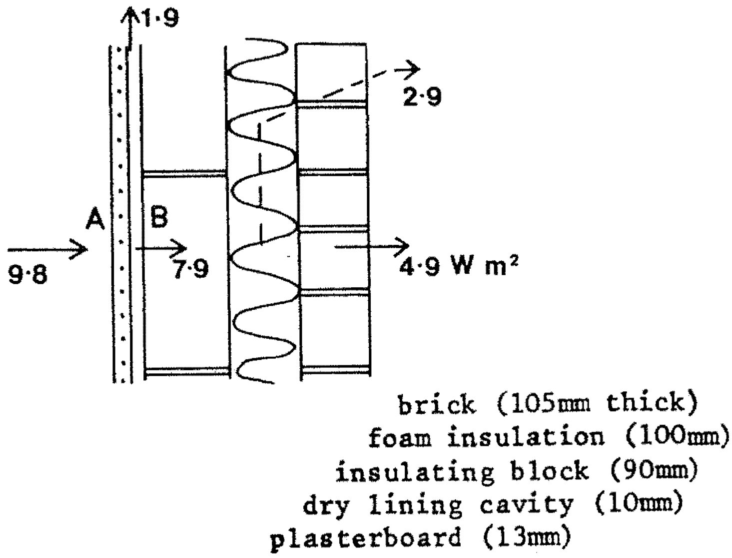


Figure 7. Thermal analysis of an external house wall based on heat flow measurements at surfaces A and B.

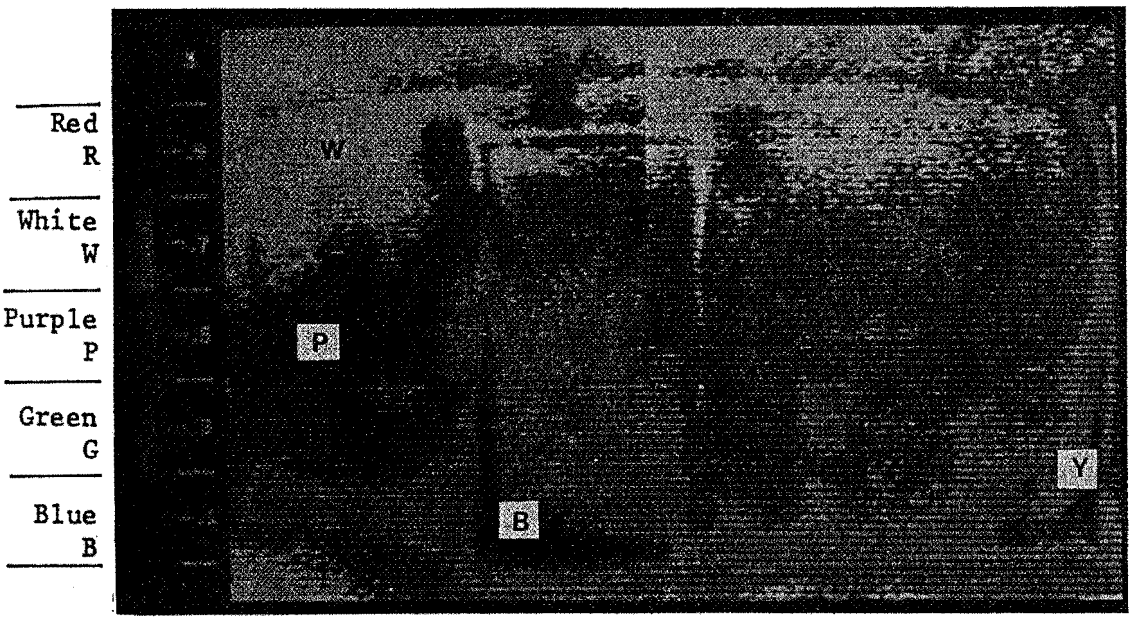


Figure 8. Infra-red composite photograph of an insulated wall. The original photograph was in colour as indicated, with each colour representing 1 K difference. Positions measuring representative (X) and local heat flows (Y) are shown.

Such a picture shows where to put heat flow sensors for both representative measurements (at X) and at cold spots (at Y). It is important to measure heat flow at cold spots because they may not be places where local heat flows are high, but where cold outside air is infiltrating which would reduce heat flow.

External surface temperatures may also be measured using the infra-red camera. Figure 9 shows this for a pair of houses, with a normal photograph included. The house on the left of the picture is well insulated

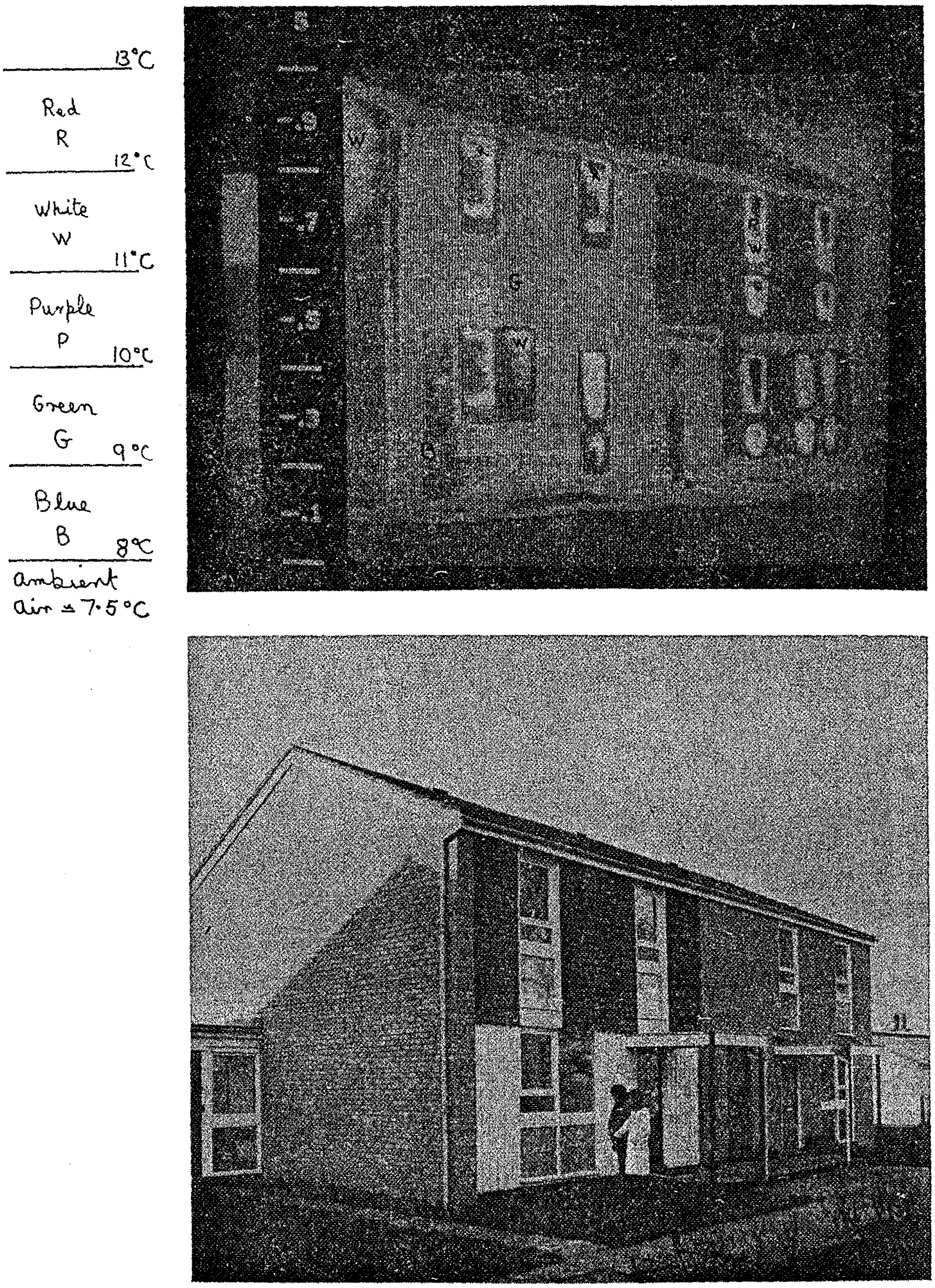


Figure 9. Infra-red and normal photographs of two heated houses. The one on the left is well insulated (wall $U < 0.5\ W/m^2K$) and the one on the right poorly insulated (wall $U \simeq 2.0\ W/m^2K$). The original infra-red photograph was in colour as indicated.

(U $\sim$0.3 to 0.5 W/m$^2$K, double glazed) and the one on the right poorly insulated (U $\sim$2.0 W/m$^2$K, single glazed) and the colder outer surfaces of the insulated house show this. The lower sections of the windows of the left hand house have been insulated internally, explaining why their surface appears at the same temperature as the rest of the front wall. The left-hand wooden cladding is the coldest part of the front wall, suggesting that it is better insulated than the rest, but it could be that cold outside air is getting behind the cladding.

The surface of most of the double glazing is in fact purple and white compared with white and red for single glazing, except for two red strips at the top of the openable upstairs windows. Here the explanation is warm air leaking from inside.

The gable wall is insulated, yet its colour, purple and white, suggests otherwise. The explanation is the residual effect of the sun. The IR photograph was taken about 4 hours after sunset on a sunny November day. The normal photograph was taken mid-afternoon.

The roof looks uniformly blue and cold, even though the loft insulation was 300 mm thick in the insulated house and 20 mm thick in the other. What is being seen is the reflection of the cold night-time sky.

Air leakage paths could be identified by slight pressurisation of the house or room, using a fan in a false door (10). Smoke generated in figure 10 shows clearly leakage around the window frame.

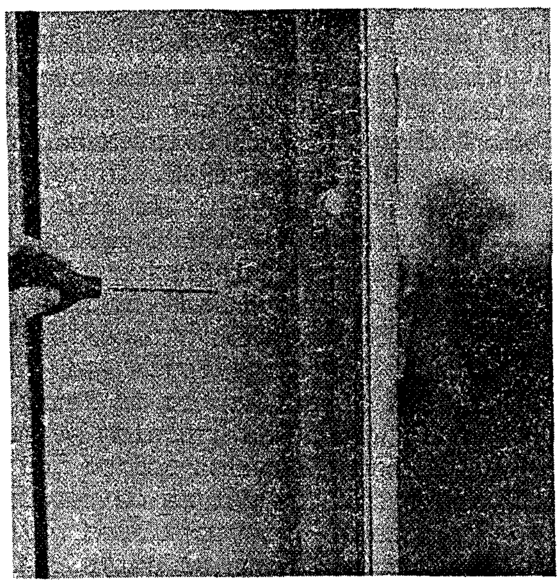

Figure 10. Pressurisation testing revealing air leakage between wall and window frame.

## Concluding remarks

The results obtained using the procedure presented in this paper depend very much on the skill of the people operating it and on their familiarity with the equipment. Setting up in a test house is essential to gain experience and check the equipment before on-site testing. The extent of testing must be defined clearly because in many cases not all the tests may be needed, afforded, or carried out in the time available.

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DISCUSSION

R. SONDEREGGER : Was the 1/3 of total air leakage you reported mean for the span between window sashes and frames or for the joints between window frames and the walls ?

J.B. SIVIOUR : For houses without any weatherstripping a reduction in the base infiltration (i.e with windows and doors closed)of one third on average would be achieved by weatherstripping the openable external doors and windows.

C.E. UGLOW : The effective solar gain in the test dwellings was estimated to be in the ratio of 2/3 through glazing and 1/3 through opaque fabric. Was this ratio the same in the well-insulated dwelling and the poorly-insulated solid wall dwelling ?
What percentage of the total external surface area comprised glazing ?

J.B. SIVIOUR : Yes, within the accuracy of the approximation. There is about a 15 % smaller solar gain through double glazing compared with single glazing.
The glazing area was about 10 m2.

J.E. WOODS : Two questions : 1) At £55 per fully calibrated houses, could you propose an alternative procedure ?
2) Using either procedure, what factors might be most important to consider if energy savings are to be maximized ?

J.B. SIVIOUR : As you suggest in your question, I have described a very comprehensive set of measurements for a detailed examination of the thermal performance of a house. Any of the techniques I describe could be used separately. I think it is best to do simple measurements first to check the performance of which you are most doubtful. As examples pressurization is a quick check on airtightness and can show air leakage routes, infra-red scans can quickly check insulation continuity. If fabric losses and ventilation rates are then shown to be as expected, further measurements may be unnecessary, but I think it is essential that both the fabric heat losses and ventilation characteristics are known otherwise occupants may be blamed for a greater energy loss than they actually incur.
On your second question, insulation is first to reduce fabric heat loss. Second is ventilation control (1) to remove moisture and odour close to their source (kitchen, bathroom, etc.) for better internal conditions (2), to reduce the need to open windows in winter, so saving an excess ventilation heating and (3) to incorporate ventilation heat recovery. Other energy saving techniques may become worthwhile when insulation is so thick that making it thicker still gives a negligible energy saving.

J.M. HAUGLUSTAINE : Is it possible to have the detailed price list of the different operations to make in a monitoring ? What cost your kind of monitoring ? (It is just to have a model of establishing of budget, taking into account cost of materials, time of man work...)

J.B. SIVIOUR : All test projects need to be costed individually and to do so the costs of monitoring may conveniently be divided as follows :
(a) consumable items which are installed and cannot be re-used, e.g. transducers, wiring.
(b) shared items, amongst a number of projects, e.g. data loggers and computing requirements.
(c) personnel for installation, testing, analysis and reporting. These costs may vary considerably especially depending on whether full overheads