DETR Framework Project Report :

Field investigations of the thermal performance of construction elements as built

Prepared for :

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Safety and Health Business Plan

Field investigations of the thermal performance of construction elements as built

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Final Report

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Executive Summary

This report describes the results of in-situ measurements carried out to determine the as-built thermal transmittances (U-values) of building elements and how these test results compare with predicted performance, as calculated using the methods described in the relevant Standards. It has been prepared for dissemination to designers, builders, other researchers in the field, construction training and education establishments and relevant British Standards committees.

The elements (29 in total) comprise mainly of a mixture of cavity walls and timber frame walls and are generally typical of those in new dwellings in Great Britain complying with the 1995 Edition of Approved Document L (England and Wales) or the 1997 Amendment to the Technical Standards Part J (Scotland). The measurements reported here were carried out between December 1998 and March 1999 and between November 1999 and March 2000. For each construction, a comparison is made between the measured U-value and the U-value calculated using the method in BS EN ISO 6946, showing that in a number of cases the measured U-values are greater (i.e. worse) than the U-values obtained by calculation.

The results of the present project, together with those of past projects by Ward, indicate that existing calculation procedures such as BS EN ISO 6946:1997, as used for regulatory purposes, may often underestimate true heat losses for walls, in some cases by more than 30%.

The U-value measurements involved the use of (thermopile-based) heat flux meters, typically 100 mm in diameter and approximately 3 mm thick, which were pressure-fixed against the element being tested throughout the period of monitoring, a monitoring period being typically about 2 weeks. For each case, hourly heat flows together with internal and external temperatures were recorded continuously over the period of measurement.

A comparative test was carried out in collaboration with another organisation, Alba Building Sciences, in order to compare the measurement techniques used. The results of the tests indicated that, at least in the case of the wall for which the comparison was made, there was good agreement between the measurement results obtained by BRE and those obtained by Alba Building Sciences, thereby lending greater credibility to the measurement techniques used by the two organisations.

It is notable that the difference between calculated U-values and measured U-values correlates with construction type with some constructions giving

significantly greater differences than others. For example, partially filled cavity walls typically showed a greater difference between calculated and measured U-values than did timber frame walls. This would appear to indicate that, for at least some types of construction, the method given in BS EN ISO 6946 does not account for all the factors that can influence a U-value and generally underestimates it, although part of this discrepancy was found to be attributable to construction defects.

Future Building Regulations could address this through the application of increments or incremental factors to U-values in situations where thermal performance is likely to be affected. The present project provides an indication of the magnitude of the adjustments which would need to be applied. It is recommended that in a future revision of the Regulations for the Conservation of Fuel and Power, a way of determining the appropriate increments to allow for insulation defects and workmanship factors be incorporated, possibly drawing from the methodology and knowledge base in countries where such increments, known as "Delta-U" terms, are already in use. The observed differences obtained from the present work could assist in the development of suitable "Delta-U" terms.

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Introduction

In order to predict the fuel consumption, CO_2 emission, cooling load or running cost of a proposed building, the thermal transmittances, or U-values, of the building's elements need first to be determined. A SAP calculation, or a Carbon Index Calculation, for instance, requires information about the U-values of all the elements of the dwelling.

U-values are used in the prediction of fuel consumption for the building stock as a whole and regulations are laid down concerning the U-values for new building works. It is therefore important to examine the reliability of existing methods of calculating U-values.

The 1995 Edition of Approved Document L (England & Wales) and the Amendment to Part J in Scotland in 1997 introduced double glazing as standard for compliance via the Elemental Method. The result of this was to reduce the options for trading off wall U-values against window U-values, leading to walls in new constructions having generally lower U-values and being more likely to contain an insulation material within the cavity.

As a result, walls of new buildings often contain insulants with conductivities of 0.04 W/m·K or less and are generally designed to have thermal transmittances typically of around 0.60 - 0.45 W/m²K. Sloping ceilings for new dwellings invariably have insulation and generally have U-values in the region of 0.35 W/m²K or better[1]. These reductions to U-values, provided that they lead to corresponding improvements in actual thermal performance, will lead to a substantial improvement in the energy efficiency of new housing. At the time of writing this report the Regulations for the Conservation of Fuel and Power are under review and this is likely to lead to yet further reductions in U-values.

Figure 1 shows the distribution of wall types from two surveys carried out in 1998, one carried out by Ceram Building Technology[2] and the other by BRE[3]. It is based[4] on the results of these surveys and shows that cavity walls are used in a large majority of new dwellings and that timber framed and internally insulated

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[1] S M Doran, M C Phillipson and B R Anderson "Review of the operation of the 1995 edition of the Regulations for the Conservation of Fuel and Power (England and Wales)" BRE CR 304/98

[2] House Wall Construction Project, HC368, CERAM, April 1998 (PiT)

[3] *ibid*

[4] The Ceram survey suggested that approximately half of their data corresponded to small builders and half to large builders and so the BRE data has been weighted to reflect the same mix of small and large builders enabling better comparison with the Ceram distribution

walls together account for only about one tenth of new dwellings. Notwithstanding this, timber framed dwellings are becoming more popular and may become more common in the future.

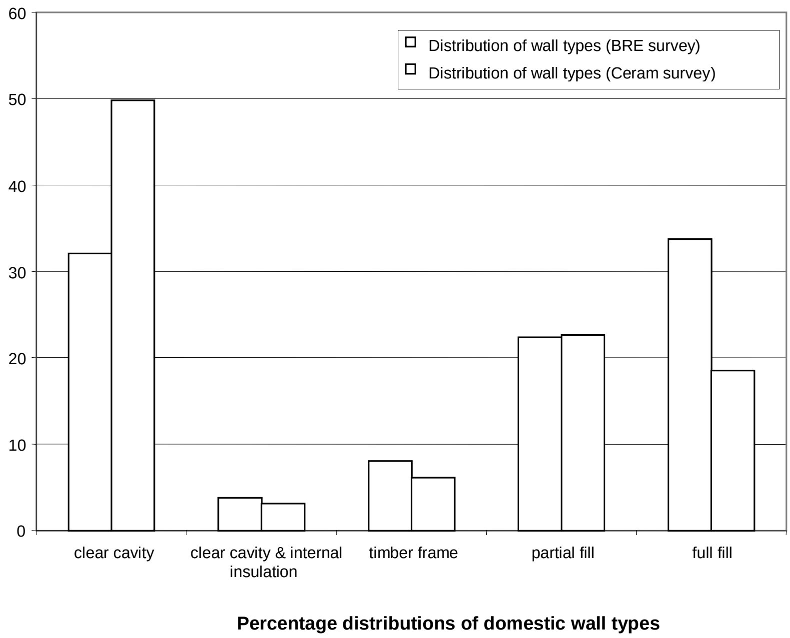

Figure 1 : Distribution of wall types for new dwellings

For regulatory purposes the U-value of an opaque building element (excluding metal cladding) can be calculated using the Proportional Area Method, described in Approved Document L (1995 edition) or by using the Combined Method[5]. Both of these methods of calculating U-values make use of information about the thermal conductivities of the materials and their respective thicknesses, as well as information about repeating thermal bridging within the construction.

The calculation procedure described in BS EN ISO 6946 is largely based on "ideal" constructions, although limited provision is made for imperfections in the structure, such as small air gaps around the insulation. The standard also allows for the thermal conductivities of construction materials, geometrical effects and air voids, but does not deal with ageing of materials, moisture related phenomena, adventitious air movement or with factors that may be influenced by workmanship. Furthermore, certain types of construction are more vulnerable to these processes than others, and there are a number of factors, such as cavity

[5] BS EN ISO 6946:1997

width, robustness of insulation materials, the use of air/vapour barriers, and the use of rendering or moisture control layers which could potentially affect the U-value of a building element over time.

Some work has been carried out by CEN/TC 88[6] to assess the influence of ageing processes on properties of materials. The results suggest a rise in conductivity for unfaced rigid polyurethane insulants of several percent over the lifetime of a building, which may arise largely due to loss of blowing agent. In practice manufacturers may apply techniques (e.g. impervious linings) in order to inhibit the gradual loss of blowing agent and slow down the ageing process.

Some research[7] has also been carried out by IEA Annex 32 on the impact of building techniques which has shown that certain construction defects carry a risk not only of causing higher U-values but also of the onset of major problems such as fungal defacement, rain penetration, reduction in comfort and interstitial condensation. Further studies[8] on the impacts of quality-related problems have shown that U-values can in some cases be raised considerably and ways of addressing these problems at the construction stage have been explored.

CEN/TC 89, the committee responsible for EN ISO 6946, is aware that there are shortcomings in the Standard and has requested research to develop it. Hitherto the necessary work has not been done and as a result questions remain about the accuracy of the Standard in practice.

The general reduction in U-values for new buildings which has occurred over recent years has led to reductions in the projected energy requirements for new buildings. Boiler sizing, which is based on expected heat losses under design conditions, will tolerate a certain increase in fabric heat loss due to ageing, weathering or workmanship, but it is possible that boiler sizing or sizing tolerances could still be underestimated in some cases. It is intended that the present work will provide indications of the actual reduction in heat loss resulting from more stringent Building Regulations and provide some useful pointers to assist in the appropriate sizing of heating systems in new buildings taking account of the U-values which are likely to be encountered in practice. The development of a more accurate method of calculating U-values, possibly through an adjustment to the U-value to account for factors not covered in BS EN ISO 6946, could also lead to more reliable determination of the level of CO_2 emission and the life-cycle financial and environmental costing of buildings.

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[6] CEN/TC 88 N 970 E “Thermal insulation products for buildings – Factory made rigid polyurethane foam (PUR) products - Specification

[7] H Hens & A Janssens “Risk Analysis: Filled Cavity Walls” Report STA-B-98/2

[8] Hens, Janssens & Depraetere "Cavity walls with high insulation Quality: Performance prediction using calculation procedures and field testing" STB-B-99/R1

Description of the project

In total, 29 building elements were tested between December 1998 and March 1999 and between November 1999 and March 2000. The data refer to constructions that are consistent with new housing built to 1995 standards. The building elements which were included in this study are summarised in the following table.

Table 1 : Constructions for which U-values were measured

No.	Type of building	Type
1	End-terraced house	Internal insulation on cavity wall
2	2nd floor flat	cavity wall (partially filled with EPS)
3	End-terraced house	timber frame wall
4	Single-storey school	cavity wall (partially filled with PI)
5	Sheltered flats	cavity wall (partially filled)
6	Ground floor flat	cavity wall (partially filled with EPS)
7,24	Day room, sheltered housing	internal insulation on cavity wall
8	Single-storey school	cavity wall (partially filled with PI)
9	1st floor flat	cavity wall (partially filled with EPS)
10	Bungalow	cavity wall (partially filled)
11	Semi-detached house	sloping ceiling (insulation/pbd laminate)
12	1st floor flat	timber frame wall
13	Detached house	clear cavity wall
14	Semi-detached house	steel frame wall
15	Semi-detached house	room in roof
16	Flat	room in roof
17	Flat	partially filled cavity wall
18	Commercial building	cladding wall
19	Educational building	cladding wall
20	End-terraced house	fully filled cavity wall
21	Mid-terraced house	fully filled cavity wall
22	Mid-terraced house	fully filled cavity wall
23	End-terraced house	fully filled cavity wall
25	Health education building	cladding wall
26	Semi-detached house	room in roof with foam insulant
27	Mid-terraced house	timber frame wall
28	Semi-detached house	timber frame wall
29	Semi-detached house	clear cavity wall (comparative test)
30	Semi-detached house	timber frame wall

For most cases in the above table measurements were carried out on two different locations of the element in order to assess the repeatability of the measurement and to provide a safeguard against equipment failure.

U-values were determined by measuring the heat flow through the element and the temperature difference across it. In an ideal situation the internal and external temperatures would be constant, giving a steady and accurately determined U-value. In practice steady state conditions do not occur, however, and consideration has to be given to the variations in temperatures and heat flows before the U-value can be determined reliably. Since most building structures have a significant thermal mass, variations in internal or external temperatures lead to large fluctuations in the heat flow either into or out of the element. In the present work this latter effect was particulary marked in the case of some of the well-insulated cavity wall constructions where reversals to the normal direction of heat flow were found to persist, in some cases, for up to 24 hours. Instantaneous measurements of the U-value, therefore, would not be practicable for this work and it is necessary to measure the heat flows and temperatures over several days in order to arrive at a reliable result.

For each U-value measurement temperatures and heat flows were monitored over several days. The U-value was then derived from the sum of the heat flow readings (expressed in W/m^2), with corrections for thermal storage effects, divided by the sum of the temperature difference readings (expressed in K) over the period of the test. The duration of the measurement period, which depended upon the type of construction, had to be sufficient that the change in the energy stored in the structure between the beginning and the end of the measurement period was relatively small in comparison with the energy that has flowed through the structure during that time. A measurement period of 14 days in winter conditions was generally found to be adequate for the wall and roof constructions which were studied.

Figure 2 shows two examples of the in-situ measurement apparatus installed in a school and in a house. In each instance the picture shows two heat flux meters pressure fixed via a pulley system and retort stands. Wires connecting the meters to a logging device at the base of the stands are also visible.

Figure 2 : In-situ measurement apparatus installed in a school caretaker's office - January 1999 (left), and in a house - February 2000 (right).

The constructions which were tested are summarised in Appendix A of this report. That appendix also presents results from the measurements, derived using the techniques described in ISO 9869, and it provides direct comparisons between the measured U-values and the U-values calculated using the methodology in BS EN ISO 6946.

Appendix B provides information about how the data were analysed to obtain a U-value, making appropriate corrections for thermal storage. Appendix C contains a commentary on the effects of thermal mass and length of measurement period on the precision of the measured U-values obtained. Appendix D contains a description of calibration runs carried out on the heat flux meters using a thermal conductivity apparatus. A description of the instrumentation used to measure the appropriate temperatures and heat losses is given in Appendix E, while Appendix F describes some comparisons carried out on some of the heat flux meters, as an additional check on their relative calibrations. Finally, Appendix G contains some retrospective comments about how the project was carried out.

Findings

The in-situ measurements were carried out on a variety of constructions, and the correlation of the difference between measured and calculated U-values (using BS EN ISO 6946) with construction type is studied in the subsequent analysis.

Thermal mass effects generally complicated the analysis of the data and corrections for this had to be applied in order to improve the precision of the U-value which could be obtained. The following two graphs illustrate the difference in the precision with which the U-value could be determined for instances of widely differing thermal mass. Figure 3 was taken from data from a timber frame wall (case no. 12) and Figure 4 was taken from data from a cavity wall with a concrete blockwork inner leaf (case no. 5).

Figure 3, derived from data in case no. 12, shows how the heat flow and U-value were influenced by variations in temperature for a lightweight construction, in this case a timber frame wall. The U-value derived from the preceding 5 days of data (hereafter called the 5-day U-value) is plotted against hourly internal and external temperature (in °C) and measured heat flow. It is notable that enhanced heat flows (indicated by elevated crosses in the graph) tended to occur in periods when the internal temperature was rising whereas lower heat flows (indicated by lower crosses in the graph) generally occurred at times when the internal temperature was low or decreasing. The heat flux (q) in this lightweight case was seldom negative, however.

Figure 4, derived from the data in case no. 5A, shows an example of how the heat flow and U-value behaved with respect to varying temperatures in the case of a heavy wall construction where the internal temperature was fairly constant. The 5-day U-value is plotted along with internal and external temperatures together with the heat flow signal from one of the heat flux meters. In this case the internal temperature was fairly steady but the external temperature varied quite considerably. Although thermal storage corrections were applied to the U-value, the U-value was still observed to vary to some extent, particularly towards the end of the monitoring period when the external temperature dropped suddenly.

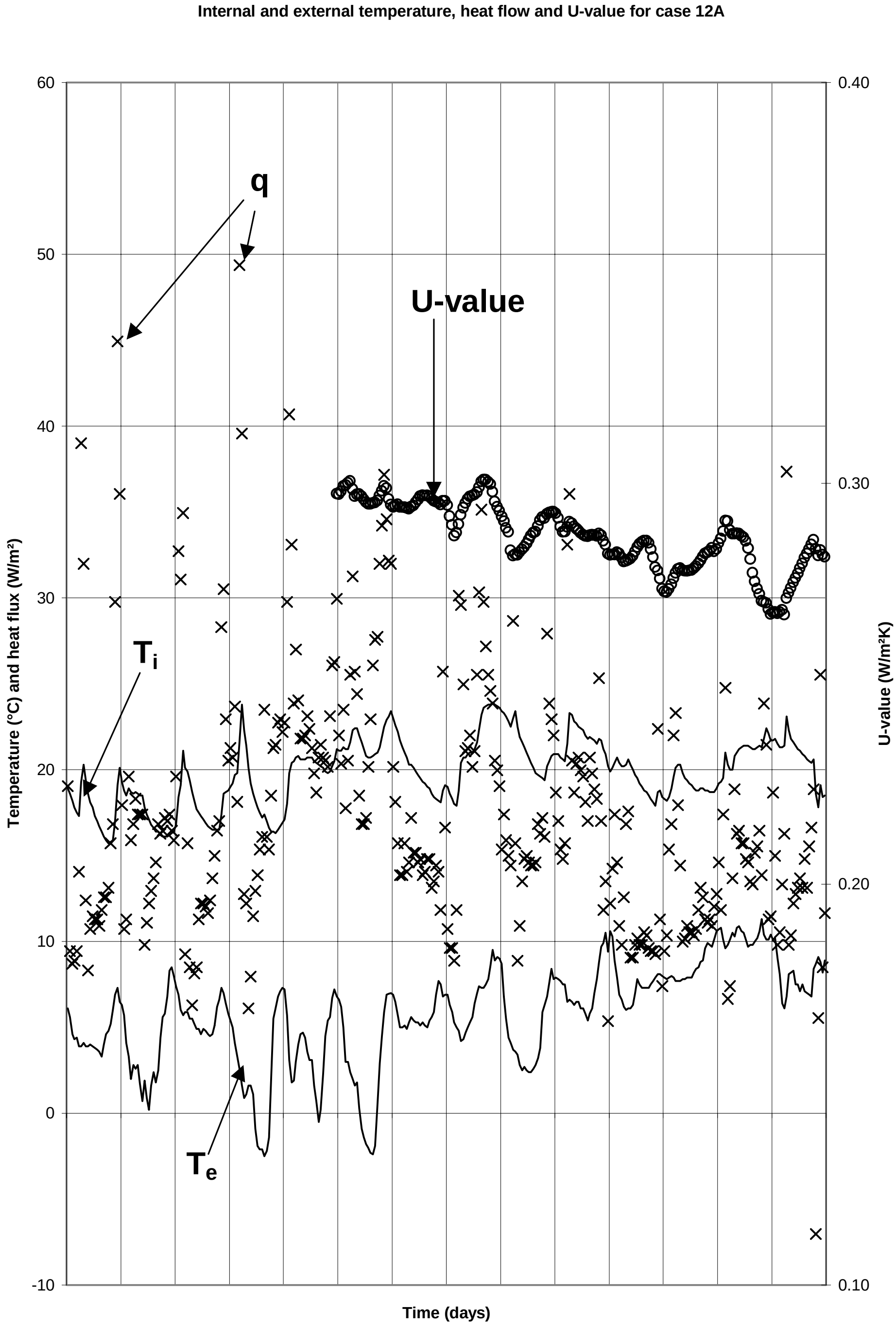


Figure 3 : A graph of temperatures, heat flow and U-value against time for a timber frame construction. The internal and external air temperatures (T_i and T_e) are shown as solid lines, the heat fluxes (q) are shown as crosses and the measured U-value is shown as circles.

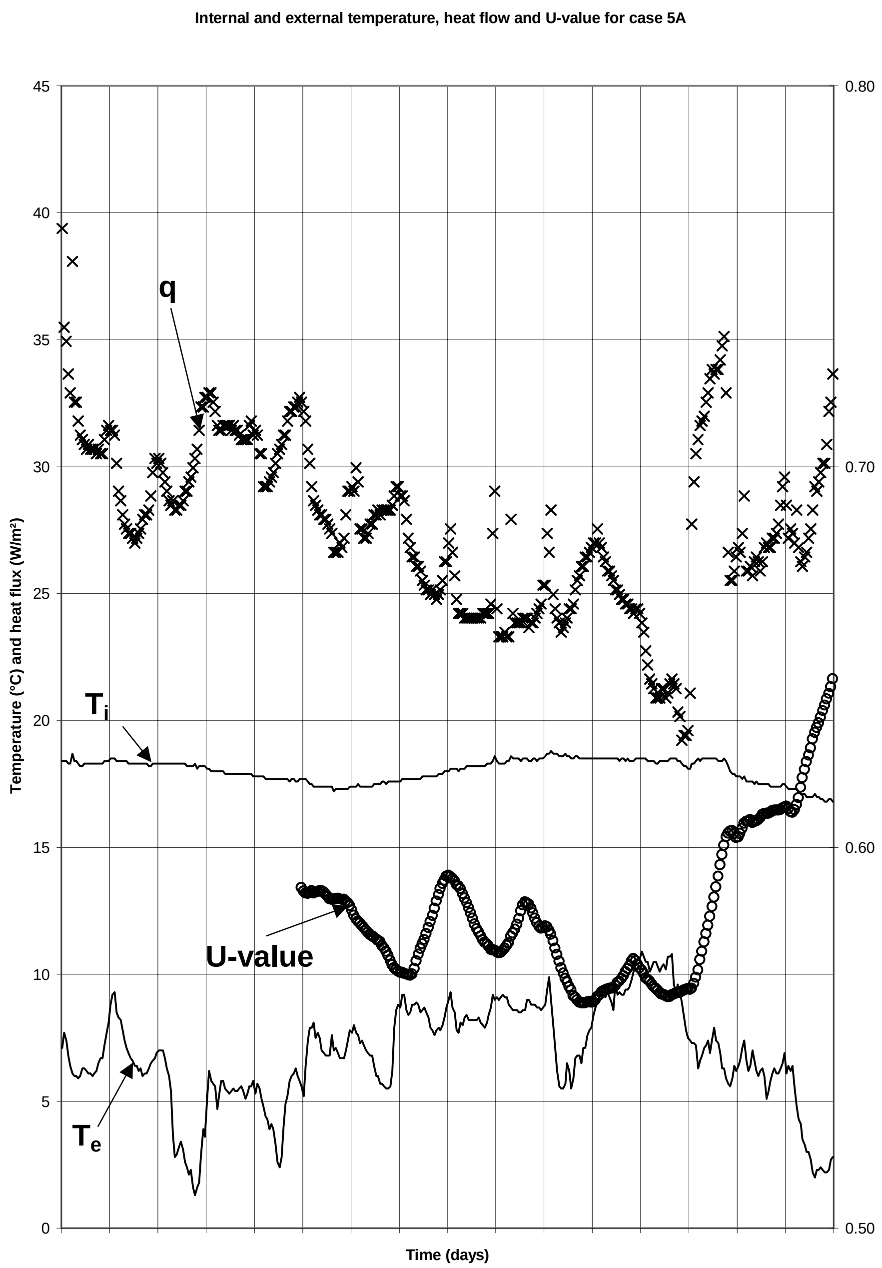


Figure 4 : A graph of temperatures, heat flow and U-value against time for a cavity wall construction where indoor temperatures were relatively steady. The crosses represent observed heat flows, the upper solid line represents indoor air temperatures, the lower solid line represents outdoor air temperatures and the circles represent the 5-day U-value (including thermal storage corrections)

The sensitivity of the U-value to the internal and external temperature was generally higher for heavy wall constructions such as in case 5A than it was in lighter constructions such as timber frame walls or sloping ceilings where the influence of thermal mass was much less. As a result of the relatively steady indoor temperatures the heat flux did not vary as much as in other examples and in this instance the heat flux was never negative.

Figure 5 illustrates how large the effect of thermal mass can be in extreme cases, such as in case 4B where the wall was of a heavy construction and both the internal and external temperatures varied considerably. In this case the heat flux showed reversals (i.e. negative values) for several hours at a time. The heat flux reversed during overnight periods when the heating was switched off and the heat flux readings (shown as crosses in the graph) were negative. The instances for which the heat flux was negative corresponded to a situation where heat stored in the wall was released back into the room and where the temperature of the air inside the building fell below the temperature of the inner layers of the wall.

Conversely, the highest levels of heat flux occurred in the mornings when the heating system was switched on, and it appears that a considerable amount of the heat in the building was absorbed by the wall during this time.

It is interesting to note that in this case, despite the low U-value of the wall, and despite its high thermal capacity, the room temperature dropped considerably during the overnight period (i.e. from 21°C to about 14°C). Although the present work, by its very nature, could not establish why this was the case it was noted that the windows occupied a large proportion of the external wall and it would seem plausible to suppose that most of the overnight heat losses were due to the windows.

Figure 6 illustrates the variation in the calculated U-value for the same case 4B, where each point on the U-value curve was calculated from the 5 days of data immediately before the point. The uncorrected 5-day U-value (U) is shown as a thin line and the 5-day U-value with thermal storage corrections (U') is shown as a broad line. The standard deviation of the uncorrected 5-day U-value was large in this case, and was calculated to be 0.08 W/m²K. When thermal storage corrections were applied (shown by the broad line) the standard deviation fell to 0.05 W/m²K thus giving a 30% improvement to the precision of the U-value.

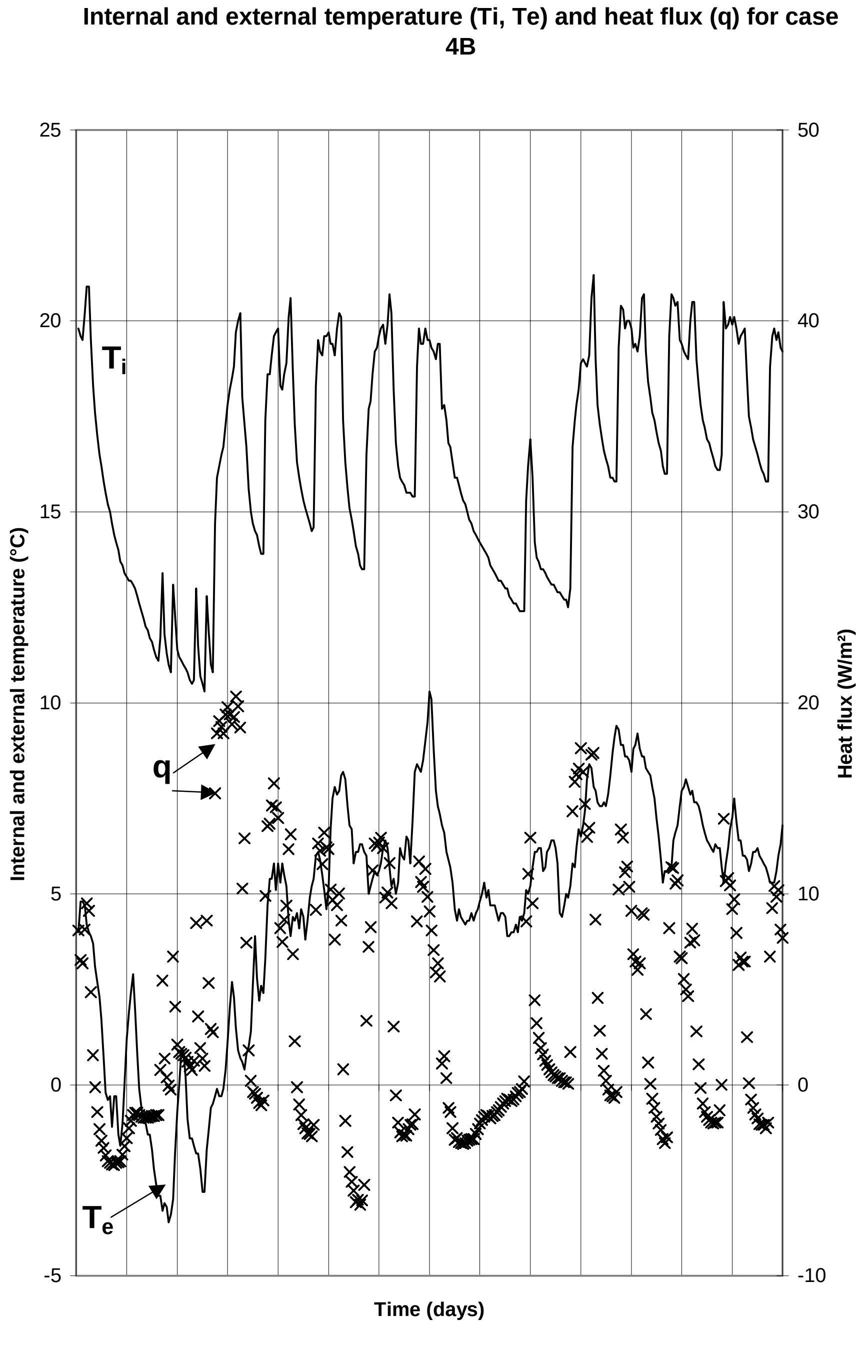


Figure 5 : A graph of temperatures and heat flow against time for a cavity wall construction where indoor temperatures varied considerably. The upper solid line (T_i) represents internal temperature, the lower solid line (T_e) represents external temperature and the crosses represent the heat flux readings (q).

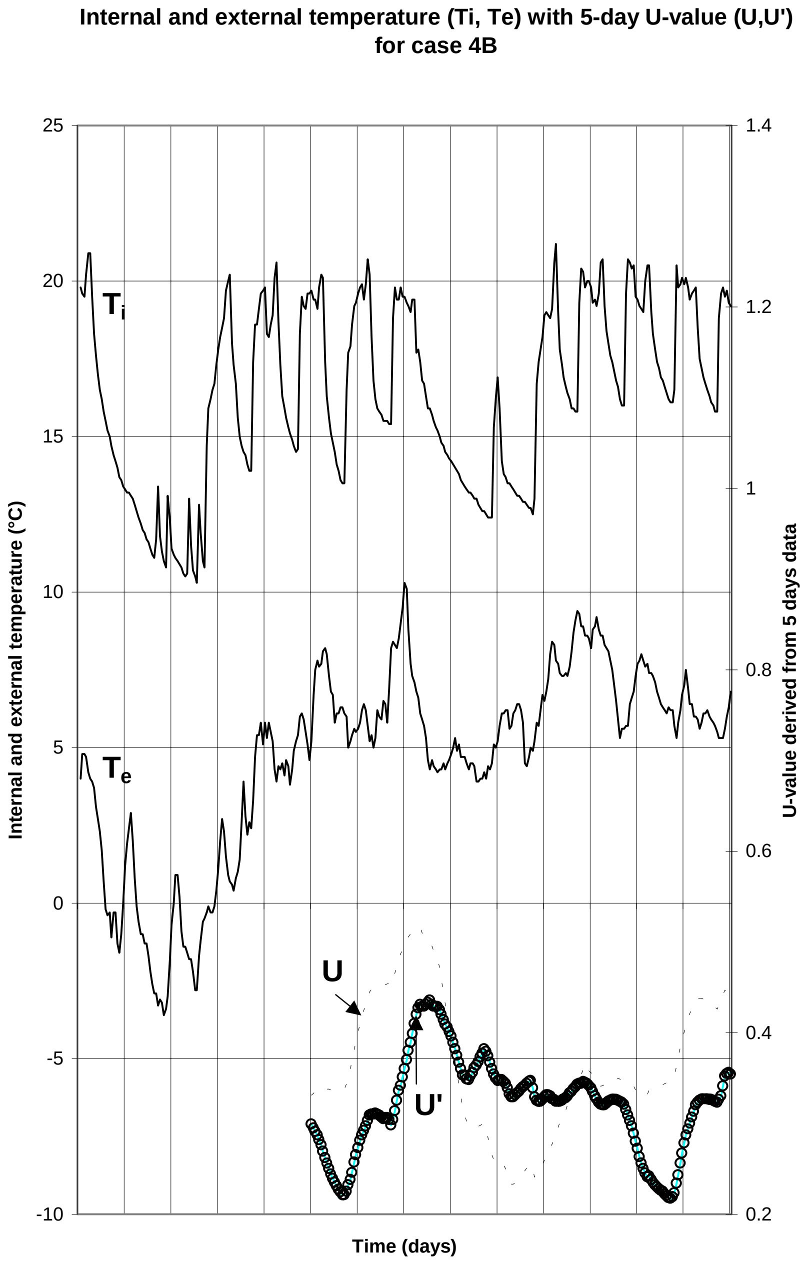


Figure 6 : A graph of temperatures, heat flow and U-value against time for a cavity wall construction where indoor temperatures varied considerably. The uppermost line (T_i) represents internal temperature, the second line (T_e) represents external temperature and the two lowest lines represent the U-values with (U', shown as circles) and without (U, shown as a line) thermal storage corrections.

These results, together with other results obtained in this work, provide some pointers as to the amount of time necessary in order to obtain a reliable U-value and this is discussed briefly in Appendix C. Constructions where there is a large thermal mass on the inner side of the insulation require a longer measurement time than lightweight constructions and for some constructions, such as timber frame, measurement periods of significantly less than two weeks may still provide reliable results. Being able to reduce the time required to measure the U-value would be a considerable advantage as it would free equipment sooner and enable a larger number of measurements to be carried out in a given time.

Results for some of the measured U-values, without corrections, are shown in the following graph and table.

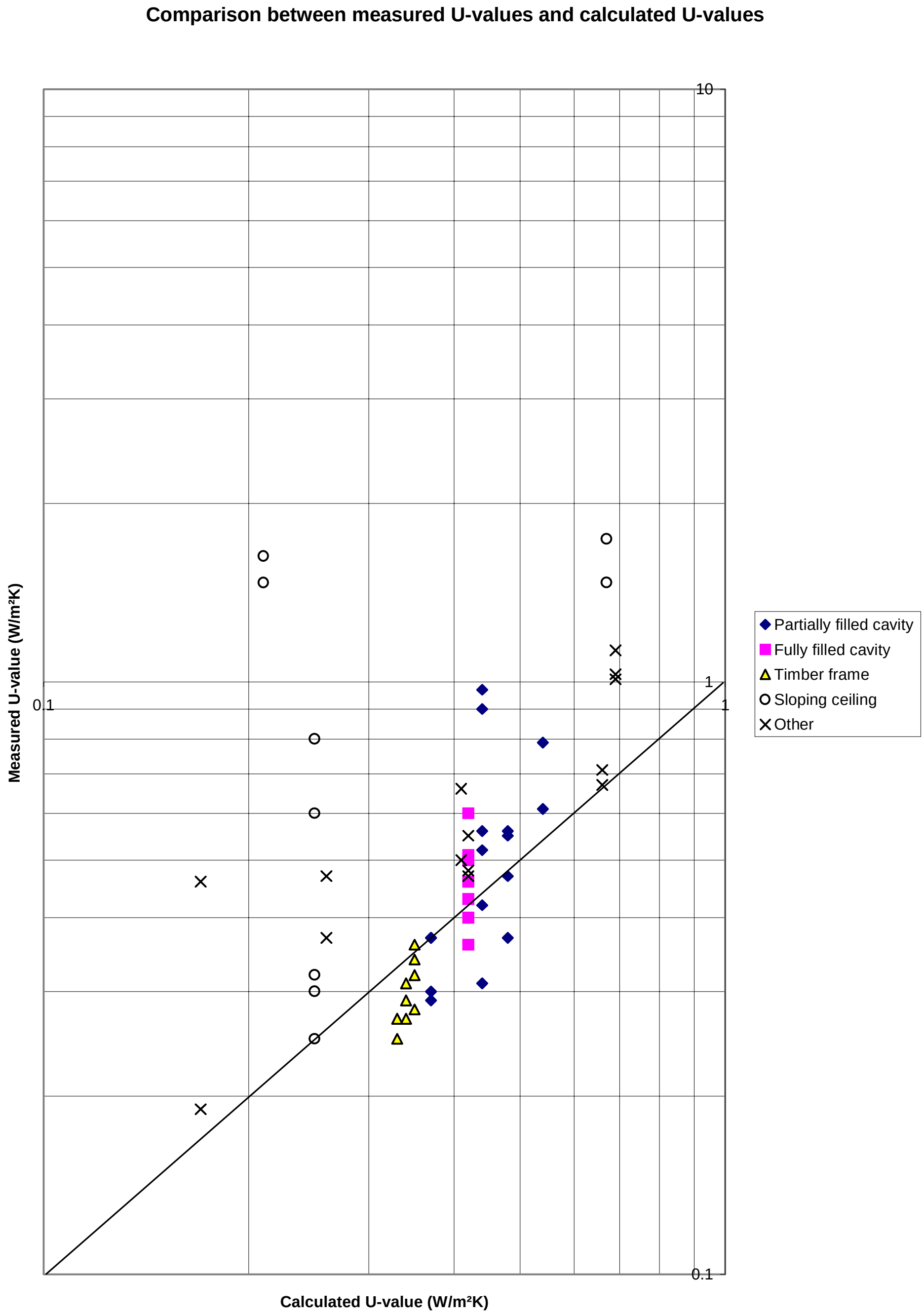


Figure 7 : A graph of measured U-value against calculated U-value shown for various construction types. Those points which lie above the diagonal line correspond to the measured U-value exceeding the calculated U-value whereas the points which lie below the line are cases where the measured U-value is less than predicted

As can be seen from Figure 7 the instances where the measured U-value exceeded the calculated U-value largely corresponded to internally-insulated walls or cavity walls or to sloping ceilings. The timber frame walls, however, showed better agreement than either the internally-insulated walls or cavity-insulated walls. Table 2 shows a comparison between the U-values as measured and as calculated showing that measured U-values generally exceeded calculated U-values.

Table 2 : Comparison between measured and calculated U-values

No.	Type	U-values				Corrected ÷ calculated (A + D)
		Calcu -lated (A)	Adju-sted (B)	Meas-ured (C)	Corr-ected (D)	
1a	internal insulation on clear cavity wall	0.41	0.50	0.66	0.66	1.6
1b	internal insulation on clear cavity wall	0.41	0.50	0.50	0.50	1.2
2a	cavity wall partially filled with EPS	0.44	0.44	0.98	0.90	2.0
2b	cavity wall partially filled with EPS	0.44	0.44	0.97	0.97	2.2
3a	timber frame wall	0.35	0.35	0.38	0.36	1.0
3b	timber frame wall	0.35	0.35	0.36	0.34	1.0
4a	cavity wall partially filled with PI	0.39	0.45	0.40	0.37	1.0
4b	cavity wall partially filled with PI	0.39	0.45	0.30	0.30	0.8
4c	cavity wall partially filled with PI	0.39	0.45	0.40	0.37	1.0
5a	cavity wall partially filled with EPS	0.45	0.45	0.59	0.55	1.2
5b	cavity wall partially filled with EPS	0.45	0.45	0.40	0.37	0.8
6a	cavity wall partially filled with EPS	0.44	0.44	0.42	0.42	1.0
6b	cavity wall partially filled with EPS	0.44	0.44	0.34	0.31	0.7
7	internal insulation on clear cavity wall	0.26	0.32	0.39	0.37	1.4
24	as for case 7	0.26	0.32	0.50	0.47	1.8
8	cavity wall partially filled with PI	0.37	0.44	0.32	0.29	0.8
9a	cavity wall partially filled with EPS	0.44	0.44	0.62	0.56	1.3
9b	cavity wall partially filled with EPS	0.44	0.44	0.57	0.52	1.2
10a	cavity wall partially filled	0.45	0.45	0.56	0.56	1.2
10b	cavity wall partially filled	0.45	0.45	0.47	0.47	1.0
11a	sloping ceiling with plasterboard laminate	0.25	0.31	0.34	0.32	1.3
11b	sloping ceiling with plasterboard laminate	0.25	0.31	0.33	0.30	1.2
12a	timber frame wall	0.34	0.34	0.26	0.25	0.7
12b	timber frame wall	0.34	0.34	0.29	0.27	0.8
13a	clear cavity wall with AAC	0.68	0.68	0.72	0.67	1.0
13b	clear cavity wall with AAC	0.68	0.68	0.76	0.71	1.0
14a	steel frame wall	0.17	0.17	0.20	0.19	1.1
14b	steel frame wall	0.17	0.17	0.49	0.46	2.7
15a	sloping ceiling, airspace behind pbd	0.22	0.22	1.47	1.47	6.7
15b	sloping ceiling, airspace behind pbd	0.22	0.22	1.73	1.63	7.4
16a	sloping ceiling	0.67	0.67	1.84	1.74	2.6
16b	sloping ceiling	0.67	0.67	1.47	1.47	2.2
17a	partially filled cavity wall	0.54	0.54	0.79	0.79	1.5
17b	partially filled cavity wall	0.54	0.54	0.66	0.61	1.1
18a	cladding panel	0.29	0.36	0.47	0.47	1.6
18b	cladding panel	0.29	0.36	0.55	0.55	1.9
18c	cladding panel	0.29	0.36	0.48	0.48	1.7
19a	cladding	0.42	0.42	0.64	0.64	1.5
19b	cladding	0.42	0.42	0.78	0.78	1.9
19c	cladding	0.42	0.42	0.65	0.65	1.5
19d	cladding	0.42	0.42	0.67	0.67	1.6
20a	fully filled cavity wall	0.42	0.42	0.51	0.51	1.2

20b	fully filled cavity wall	0.42	0.42	0.55	0.50	1.2
21a	fully filled cavity wall	0.42	0.42	0.47	0.43	1.0
21b	fully filled cavity wall	0.42	0.42	0.46	0.46	1.1
22	fully filled cavity wall	0.42	0.42	0.60	0.60	1.4
23a	fully filled cavity wall	0.42	0.42	0.42	0.40	1.0
23b	fully filled cavity wall	0.42	0.42	0.39	0.36	0.9
25a	cladding	0.29	0.31	0.37	0.34	1.2
25b	cladding	0.29	0.31	0.33	0.33	1.1
26a	sloping ceiling	0.25	0.31	0.25	0.25	1.0
26b	sloping ceiling	0.25	0.31	0.64	0.60	2.4
26c	sloping ceiling	0.25	0.31	0.85	0.80	3.2
27	timber frame wall	0.34	0.34	0.29	0.29	0.9
28a	timber frame wall	0.34	0.34	0.33	0.31	0.9
28b	timber frame wall	0.34	0.34	0.29	0.27	0.8
29a	clear cavity wall	0.69	0.69	1.03	1.03	1.5
29b	clear cavity wall	0.69	0.69	1.01	1.01	1.5
29c	clear cavity wall (Alba)	0.69	0.69	1.13	1.13	1.6
30a	timber frame wall	0.35	0.35	0.32	0.32	0.9
30b	timber frame wall	0.35	0.35	0.28	0.28	0.8
Average for timber frame:						0.9
Average for partially filled cavity walls:						1.2
Average for fully filled cavity walls:						1.1
Average for room in roof constructions:						3.1

A: Calculated using BS EN ISO 6946 with current manufacturers' conductivity values
B: Calculated using adjusted conductivity values (allowing for 25 year ageing). Since the buildings tested were mostly less than 2 years old the actual effect of ageing is expected to be relatively small.
C: Using nominal calibration factors for the heat flux meters but not allowing for mounting plate
D: Measured U-value allowing for the effects of the mounting plates
Note: For A and B the U-value was calculated for the point at which the heat flux meter was positioned, ie ignoring the effect of repeating thermal bridging.

It is notable that the ratio of corrected to calculated U-values tends to be lowest for timber frame constructions and fully filled cavity walls and highest for room-in-roof ceilings.

Actual wall U-values for this project were on average often found to be higher than U-values calculated using BS EN ISO 6946, particularly for certain types of construction, although the actual difference between measured and calculated U-values depended very much upon the type of construction being studied.

For some of the results the measured U-value was actually lower than the calculated. Although there may be some practical reasons for this, it is likely that some of this may be due to instrumentation factors particularly regarding the achievement of good thermal contact between the instruments and the element being tested.

The above results are based on nominal calibrations and do not take account of any calibration shifts, although account has been taken of thermal storage effects and other relevant factors such as metal mounting plates on the heat flux meters.

Room in roof constructions

Of all the types of constructions studied as part of this project, room-in-roof sloping ceilings presented the largest difference between measured and calculated U-values. Poorly fitted insulation and air ingress appear to have been the main reasons. Thermal imaging surveys, in conjunction with physical examination, revealed that there were often substantial gaps in the insulation layer due to missing or dislodged insulation and, in one case, there may have been excessive external air ingress immediately behind the plasterboard. The underperformance of the elements appears to have arisen from site-related factors or workmanship rather than underperformance of the insulation materials themselves. In one instance, loose irregularly shaped slabs of foam insulation were observed behind the ceiling (set in a kind of "crazy paving" arrangement) with gaps amounting to over 10% of the surface area, and it would appear that the insulation installer may have had to install the insulation after the other components of the roof, including the internal plasterboard, had already been installed.

Fully filled cavity wall constructions

In some cases the difference between measured and calculated U-values was quite large. This may have arisen partly as a result of the U-value for this construction type being very sensitive to the cavity width. For instance, if the cavity is just 10 mm less than the nominal width this can lead to an increase in the U-value of more than 0.05 W/m²K. Variation in the cavity width, as inferred from measured wall thicknesses, would appear to account for some of the difference between actual and calculated, since the actual wall thickness could differ from that specified in plans by perhaps 10 - 20 mm. This does not seem to account for the whole difference, however, and there would appear to be other factors involved.

Partially filled cavity wall constructions

This type of construction showed significant differences between measured and calculated U-values with measured U-values being up to twice as large as calculated U-values. Large variations between one section and another on the same wall were observed in a number of cases, suggesting that the way in which each individual section of insulation is fixed may be a factor.

Internally insulated wall constructions

For the internally insulated walls studied, measured U-values were substantially higher than those calculated. Physical examination showed that the observed discrepancies, in some cases at least, could be almost wholly explained by the very significant differences between the architect's specifications and the walls as actually built. Differences observed between actual and specified materials and between actual and specified thicknesses were such that the calculated U-values of the actual walls as built would have fell far short of the elemental requirements for U-values.

Timber frame constructions

Of the constructions studied, timber frame walls showed the closest agreement between measured and calculated U-values, suggesting that differences between calculated and measured U-values are relatively smaller for this type of construction type. In the course of the study several domestic timber frame constructions were tested with the surprising result that measured U-values were sometimes slightly less than U-values calculated according to BS EN ISO 6946 : 1997. The reason for this is not clear but a contributory factor may be compression of insulation as a result of placing a standard 100 mm quilt between studs which are less than 100 mm deep.

Wall constructions which involve timber framing with insulation between the studs generally use studs which are 89 mm or 95 mm, depending upon whether they use Canadian or European standard lumber dimensions. It is likely that an insulation quilt of a nominal thickness of 100 mm could be inserted between the studs in many cases. Such a quilt would, therefore, be compressed slightly and this compression would lead to a reduced thickness in the quilt but a slightly reduced conductivity as well. In the calculation of U-values, for such a situation, there would appear to be three possibilities:

1. The U-value could be calculated, using the nominal thermal conductivity of the quilt, but taking its thickness to be only 89 mm (Canadian timber) or 95 mm (European timber). Since the quilt would be compressed slightly, its conductivity would be reduced leading to a slight overestimation of the U-value.

2. The U-value could be calculated using the nominal quilt insulation thickness (eg. 100 mm) and the nominal conductivity of the insulation. This would lead to an underestimation of the U-value due to the inappropriate thickness being used in the calculation.

3. The U-value could be calculated using a nominal thermal *resistance* instead of a nominal conductivity and thickness for the 100 mm quilt. This would lead to an underestimation of the U-value since the thermal resistance of the quilt will be reduced as a result of it being compressed.

The first method is the most desirable for two reasons: Firstly, it leads to the smallest level of error, and secondly the error is in the more desirable direction. The first possibility corresponds to the method which was used for the comparisons in this project.

In principle, the U-value could be calculated where the conductivity of the quilt has been adjusted to account for the compression, and where the actual thickness of 89 mm (or 95 mm) is used. This would lead to the most accurate estimate of the true U-value but there would be difficulties in arriving at the best estimate of the appropriate conductivity at least for regulatory purposes.

It is possible that in some cases U-values may be being calculated using the second or third method above, which could lead to inaccuracies in the implementation of Regulations.

AAC blockwork

In the course of the measurements, one clear cavity wall involving AAC blockwork was studied. In another wall incorporating AAC blockwork the temperature difference across the AAC layer was specifically measured in order to determine the thermal performance of the AAC layer. In both cases, there was fair agreement (i.e. agreement at the 10% level) between measured and predicted thermal performance, suggesting that the in-situ performance of AAC blockwork layers is close to expected, at least in the cases studied.

Other constructions

In addition to the above, a small number of tests were carried out on some cladding walls and a steel frame wall. Measured U-values were generally higher than calculated U-values.

In the case of the steel frame construction, where the dwelling was less than 1 year old, pattern staining was observed in the living room. Although the living room wall did not have a U-value measurement carried out on it, a thermal imaging survey was carried out, revealing that the visible bands (pattern staining) covering one third of one wall in the living room corresponded to the locations of the steel studs behind the plasterboard.

As an example of what can happen, it was found that in one case the dwelling had no loft insulation. The occupants, whose house had only been built a few months before the U-value measurement, complained that the upstairs part of the house was very cold and a visual inspection of the loft confirmed that the roof insulation was missing completely. The cold water tank in the loft was also uninsulated. It transpired that this was the only house on the estate concerned with this particular problem. In this case the situation was readily identified, and the problem could be rectified, but if a problem of missing insulation were not visible, it would be more difficult to determine the nature of the problem and more costly to solve.

There were also a number of instances where insulation defects were observed at wall - ceiling junctions, suggesting that there may be site-related difficulties in fitting insulation properly and effectually in these areas.

Practice in Sweden

As part of this project, the approach used in Sweden for dealing with site-specific factors was considered and preliminary enquiries were made. Clearly construction practice in Sweden differs from that of the UK, and the Swedish approach would need to be adapted to account for UK conditions and building practice. The following serves as a brief summary of some aspects of the Swedish approach which could be adapted for the UK, making use of the results of the present work.

Current practice in Sweden is to apply adjustments to U-values in order to account for additional factors in the construction which can compromise thermal performance. Such factors can arise for a number of reasons, including uncertainties in workmanship, uncertainties in dimensions, services (eg. electrical conduits), in-situ material properties, mortar droppings on wall ties, the impact of nogging pieces and wall plates and various other factors which can affect the performance of the insulating layer. These adjustments to the U-value, known as "Delta-U" terms, are based upon the difference between the calculated U-value (eg. using EN ISO 6946) and the actual (measured) U-value of the construction.

Two correction terms are used. The first term, called ΔU_g, accounts for uncertainties in the properties and dimensions of the materials in the actual building element, and covers the inevitable variations in the resulting workmanship due to the conditions of its production. This term also offers a safety margin to allow for difficulties in estimating the level and frequency of these uncertainties. It is permissible to reduce this Delta-U term through adoption of more controlled/monitored conditions, and, in the case of prefabrication, through controlled factory conditions.

The second correction term, called ΔU_k, covers uncertainties in the properties and dimensions of materials in the actual building element which arise from the design and construction of the particular type of building element and its application in the envelope. This second correction term also covers the expected variations of the workmanship that arise due to the different levels of difficulties in achieving good insulation performance for that specific type of construction. This second factor in effect allows for electical conduits, improper location of studs, wall plates, nogging pieces, mortar droppings on ties and other factors which can create breaks, gaps or other deformations in the insulating layer. This second term, like the first, also includes a safety margin to reduce the likelihood of the true U-value being underestimated.

In practice, the two correction terms, ΔUg and ΔUk, typically add up to between 0.02 and 0.06 W/m²K. This would, for typical walls in Sweden, correspond roughly to a 5% - 20% adjustment in the U-value, and it is notable that the latter figure of 20% is similar to the average level of difference observed in the present work for wall U-values.

Sweden also has provision for a "type approval" system which makes it possible for good, controlled constructions to be assigned smaller Delta-U adjustments where these smaller adjustments can be shown to be appropriate.

It is suggested that certain aspects of the methodology used in other countries (eg. Sweden) could be adapted for use in the UK, and thereby eliminate much of the remaining discrepancies between true (measured) U-values and U-values obtained using BS EN ISO 6946. At this stage it is not clear whether the Swedish increments are the most appropriate, however it is suggested that further study of the methodologies in other countries, in conjunction with present measurement results, could assist in the development of a methodology for the UK being developed for future Regulations.

Comparison with previous work

The results of the present work have been observed to follow a similar pattern to previous work by BRE insofar as there was fairly good agreement between measured and calculated U-values for some types of constructions but larger differences between measured U-values and calculated U-values for other construction types.

The higher than expected U-values, in which measured wall U-values were on average higher than U-values calculated according to BS EN ISO 6946, appear to be in line with the results of previous work by Ward[9] where the measured U-values averaged around 30% higher than those calculated using the Proportional Area Method. As with the Ward study, the difference between measured and calculated U-values depended very much upon the particular type of wall construction being examined.

[9] T I Ward, private communication

Summary of results

Comparisons between the measured U-values and calculated U-values show that, for a building constructed after the introduction of the 1995 edition of Approved Document L, the measured U-value is often greater than the calculated U-value, and in a small number of instances the difference can be very large. On average, the measured wall U-values were often considerably larger than the calculated values.

The results suggest that for timber frame walls there is reasonable agreement between measured and calculated (using BS EN ISO 6946) U-values. For partially filled cavity walls the agreement was poorer. It is also evident that for the small number of internally insulated walls studied the measured U-values were significantly higher than the corresponding calculated U-values, although the difference as regards the internally insulated walls appears in part to result from the architect's specifications not being followed in practice. The largest differences between measured and calculated U-values were associated with sloping ceilings in room-in-roof constructions.

Results for each case study are given in Appendix A which provides information about the construction, measured U-values and experimental conditions for each case.

Conclusion and recommendations

The results of the present work, together with findings from previous research, show that the level of agreement between measured and calculated U-values varies widely. Results also suggest that as-built U-values of walls are typically around 20% (or 0.1 W/m²K) higher than U-values predicted by BS EN ISO 6946 (although the degree of difference depends very much upon the type of construction being examined). It cannot at this stage be established whether this difference arises from workmanship, ageing processes[10], weathering or defective insulation materials but the level of difference appears to depend upon the type of construction used.

Workmanship and on-site processes

As regards workmanship one possible solution could be to adopt an approach similar to that used in some other countries where adjustments are applied to calculated U-values (to reflect their expected as-built values) unless specific measures to ensure a high standard of workmanship (from a thermal quality point of view) are implemented. It may, for instance, be appropriate to assume, for certification or regulatory purposes, that the U-value of a wall is incremented under normal circumstances but that this increase be waived if a clerk of works, or other supervisory body, following a prescribed procedure or checklist, is assured to be monitoring the building process at all stages (or if there is a significant degree of off-site prefabrication). This monitoring would certainly need to include checking that the architect's plans are being followed and that the correct materials and thicknesses are being installed and fitted according to the directions given. It is possible that this may necessitate the development of a standard by which workmanship can be assessed, such as a future British Standard on the thermal quality aspects of workmanship for example. Developing a procedure or standard for assessing on-site workmanship (as regards thermal quality) would address some of the potential difficulties in estimating future national energy consumption as well improving the quality of input data used in SAP or other energy assessment methods for new buildings but there would be a risk that it could disadvantage small builders.

The implementation of a new standard for assessing the thermal quality of on-site workmanship may be costly or impractical in the case of small construction projects. In such situations one option may be to compensate for the lack of site supervision by specifying a greater level of insulation. The application of increments (or multiplying factors) to U-values may therefore be the most

[10] e.g. insulation ageing processes akin to those studied by CEN/TC 88 as mentioned earlier in this report

appropriate measure in such cases and a suitable level of increment could in the first instance be determined from the results of the present research programme.

Longer term performance

Since the regulation of new building works, as far as the conservation of fuel and energy is concerned, is designed to reduce life cycle energy use, fuel cost and long term emissions of carbon dioxide attributable to buildings in the UK, there may be cause for concern about the long term performance of insulation. Using certified conductivity (or emissivity) values for new insulants may be appropriate for calculating U-values for the first few years of a building's lifetime but may be less appropriate for assessing the whole life-cycle heat loss of the building. Since the present project has concentrated on fairly new constructions it cannot provide pointers to help identify the impact of ageing and weathering processes on insulation systems and a different approach may be needed. Whilst laboratory research has been carried out on some insulation systems (e.g. rigid polyurethane) using accelerated ageing processes, there is a need to establish better the rate and extent to which insulation systems in general become less effective with time. The impacts of air movement, dislocation, rain penetration, condensation, particle deposits and chemical and biological processes within built structures are still not well understood. It is suggested that some research may be needed in these areas, preferably involving participation from the major manufacturers of insulation and insulation systems. The short term impact of such work could be a more accurate assessment of the financial and environmental benefits of insulation whilst the longer term impact may be the development of measures to improve life-cycle performances. In this regard it may be worthwhile carrying out a research programme in partnership with a builder in order to build a U-value monitoring system into a sample of new buildings, where heat flows and temperatures could be monitored on an intermittent basis over a number of years.

Other factors

There is a clear international need for a better understanding of air and moisture movement within opaque building elements and of the benefits and risks of using barriers. Whilst the use of membranes (as used in North America for example) or paper facings around insulation may reduce heat loss their precise effects are not clearly understood and some barrier arrangements may be incompatible with summertime cooling. Whilst it is possible that future Regulations could examine ways of eliminating excessive air movement within wall and roof constructions, the need for barriers or other measures is not justified and laboratory-based work may be needed in order to arrive at a fuller understanding of such mechanisms.

Dissemination

As a result of the present work, together with previous findings by Ward, there is the potential to develop material for a series of workshops aimed at improving workmanship. Such workshops would be aimed at builders and designers and would seek to impart a better understanding of good construction techniques from a thermal efficiency point of view. It may, for example, be possible to disseminate this information through the Best Practice Programme, or a similar programme, by presenting some of the findings of this work as part of a workshop dealing with general insulation issues.

Summing up

The results of the present project, together with those of past projects by Ward, appear to indicate that existing calculation procedures such as BS EN ISO 6946:1997, as used for regulatory purposes, are underestimating true heat losses for walls by, in some cases, more than 30%. Whilst this level of difference may be less that that which ensued prior to the implementation of BS EN ISO 6946, there is still concern that present methods of calculating U-values are leading to an underestimation of the true heat loss from buildings. The results of the present work give an indication of the corrections to calculated U-values which would be necessary in order to arrive at actual heat losses and much of the results presented here could help to feed into a future revision of BS EN ISO 6946.

In the course of the work there were clear instances where the actual U-value was higher than the calculated U-value as a result of poor workmanship or deviations from the architect's specifications. Closer supervision on site could have the potential to alleviate this problem but would have a cost implication for building works. The practice in other countries, particularly Scandinavia, can give some guidance as to how to incorporate factors which are not properly accounted for, particularly in the area of workmanship.

The data collected in the present work shows that the actual difference between a calculated and a measured U-value can depend upon the type of construction, and in particular there was found to be better agreement for timber frame walls than for cavity or cladding walls. If an adjustment to the U-value were to be applied for U-value calculations for regulatory purposes it would need to be considered how the adjustment should be applied for the various construction types.

In order to develop a set of adjustments (Delta U-values), which would enable U-value calculation procedures to take fuller account of workmanship and site-related factors, further information needs to be obtained about the approaches used in other countries. The objective would be to achieve calculated U-values that more closely match actual thermal performance. The knowledge and experience from countries such as Sweden would be assessed with a view to incorporating, if appropriate, aspects of their methodology for use in the UK. Initially, adjustments to the U-value would be targeted towards constructions typically used for dwellings but the work programme would include consideration of whether and how this could be applied to methods of construction for non-domestic buildings. This would be likely to involve consulting installers and designers to identify practical problems (eg. sloping ceilings having been fitted before insulation is installed) and would make use of the findings from the in-situ U-value measurements in order to quantify the increments. (It may also be necessary to carry out focussed U-value measurements on specific types of constructions).

Appendix A : Description of wall and ceiling constructions

This appendix presents information about the individual U-value measurements which were undertaken. This information includes details about the constructions used, measurement conditions and U-values obtained. In each case the construction of the element is described in terms of the thicknesses and properties of its layers, and the U-value is calculated (using BS EN ISO 6946) for the part of the element under test. The F_i and F_e thermal storage factors given in the tables have been calculated according to ISO 9869.

In most case studies, two U-value measurements are carried out (labelled "A" and "B") and the measured U-value is given for "A" and "B" respectively. The measured U-values are given both with and without corrections for the experimental configurations, the main difference being due to the influence of the metal plate. The measured U-values given here have been corrected for thermal storage effects using the procedures described in Appendix B.

1. Wall : brick / cavity / block / internal insulation

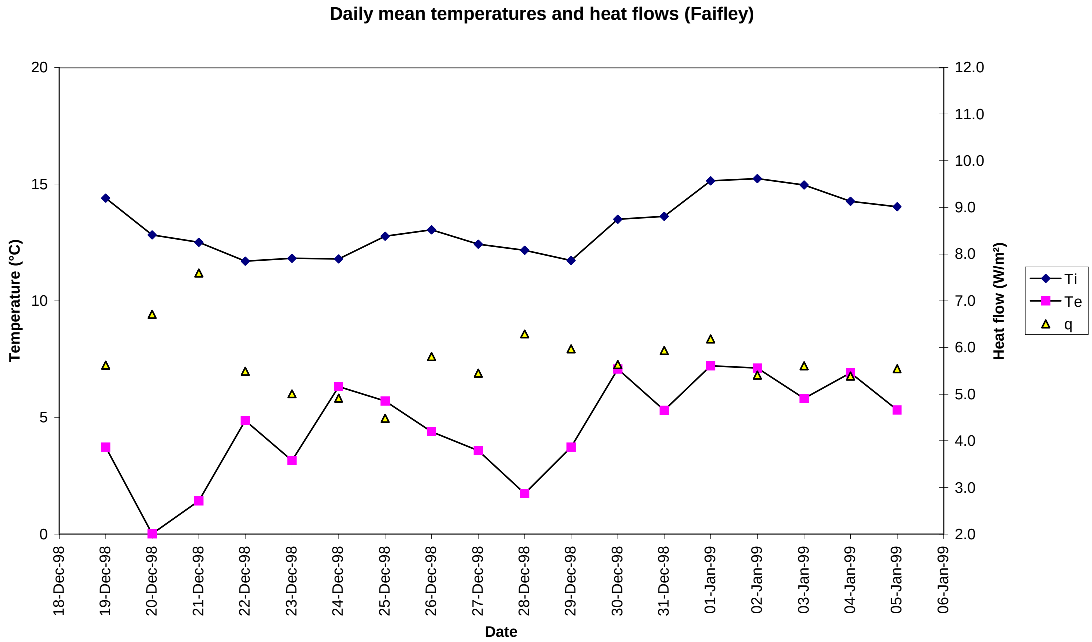
layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external roughcast	~19	0.5	1300	1000
2	outer leaf brickwork	102	0.77	1700	800
3	50 mm air cavity	50	-	-	-
4	concrete blockwork	~100	0.5	1400	1000
5	timber strapping / air space at 600 mm centres	50	-	-	-
6	27 mm of phenolic foam	27	0.018	~35	1400
7	9.5 mm vapour checked plasterboard	9.5	0.25	900	1000
expected thermal transmittance (W/m²K)			0.41, 0.50*		
thermal storage correction factors F_i, F_e			12082, 32364		

*Allowing for ageing of the phenolic foam giving a conductivity of 0.025 W/m·K

Information about the U-value measurement

	Values for measurements 1A & 1B
measured thermal transmittance (W/m²K)	0.66, 0.50
HFMs used (with nominal calibration values in brackets)	31.2405 (4.3), 31.2402 (4.3)
metal plates used?	no, no
corrected measured thermal transmittance (W/m²K)	0.66, 0.50
dates of measurement	Dec 1998 – Jan 1999
orientation of element (degrees clockwise from North)	020°, 110°
general exposure level (high, medium or low)	high, medium

In most cases two heat flux meters were placed on the same wall (or ceiling) in order to compare their results for the same element. In this case, however, the heat flux meters were placed against two different walls of the dwelling, partly because of practical difficulties in finding enough room to place the two heat flux meters beside one another without causing undue inconvenience to the occupants. The first heat flux meter was placed within a cupboard attached to a bedroom on the North facing gable wall. The residents had commented that the cupboard was prone to being cold and the actual temperatures measured in the cupboard were low despite the fact that external temperatures were not especially low. The measurement was, however, taken during a very windy period and this may have influenced the U-value – perhaps through increased ventilation or air leakage within the wall construction. The following graph shows temperatures in the cupboard, external temperatures and heat flows through the wall and it can be seen from the graph that internal temperatures were generally below 15°C. It is also clear from the graph that the highest heat flux values (shown as triangles) corresponded to the lowest external temperatures. The second heat flux meter was placed on the east facing wall of the bedroom facing the back garden. This second wall gave a U-value closer to that expected.



2. Wall : brick / cavity / insulation / block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	facing brick	102	0.77	1700	800
2	air cavity	60	-	-	-
3	XPS cavity wall insul. boards	40	0.028	25	1400
4a	concrete blocks (15 N/mm²)	140	0.5	1400	1000
4b	mortar between blocks	140	0.88	1300	1000
5	plaster	13	0.57	1300	1000
expected thermal transmittance (W/m²K) – panel U-value			0.44		
thermal storage factors Fi, Fe			164707.33, 30179.55		

Information about the U-value measurement

	Values for measurements 2A & 2B
heat flux meters used (identification labels)	hfm16/31.2402, hfm22/430145
measured thermal transmittance (W/m²K)	0.98, 0.97
metal plates used?	yes/yes, no/no
measured thermal transmittance (W/m²K) with plate corrections	0.90, 0.97
dates of measurement	5-1-99 to 20-1-99
orientation of element (degrees clockwise from North)	240°, 240°
general level of exposure	medium, medium

The above measurements were carried out in the kitchen of the second floor flat at a section of wall between two windows. The wall was facing South West into a back court. The heat flux meters were switched approximately half way through the measurement period.

3. Wall : timber frame with mineral wool insulation

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	brick (outer)	102	0.77	1700	800
2	air	50.5	-	-	-
3	plywood	9.5	0.14	500	1600
4a	mineral wool	90	0.04	12	1030
4b	bridging timbers (38 mm thick spaced 600 mm apart)	90	0.14	500	1600
5	plasterboard	12.5	0.25	900	1000
expected thermal transmittance (W/m²K)			0.35		
thermal storage correction factors Fi, Fe			7423.68, 7069.61		

Information about the U-value measurement

	Values for measurements 3A & 3B
heat flux meters used (identification labels)	hfm16, 31.2189
measured thermal transmittance (W/m²K)	0.38, 0.36
metal plates used?	yes, yes
corrected measured thermal transmittance (W/m²K)	0.36, 0.34
dates of measurement	21-12-98 to 4-1-99
orientation of element (degrees)	005°, 005°

The above refers to a dwelling which had just been constructed and was due to become occupied at the end of the measurement period. The gas central heating system was switched on continuously for the duration of the measurement and this led to greater stability in the results. The two heat flux meters were mounted on the North facing gable wall.

4. Wall, school : brick / cavity / insulation / block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	brickwork	205	0.77	1700	800
2	air cavity	50	-	-	-
3	polyisocyanurate board	35	0.020	~40	1400
4a	concrete blocks (7 N/mm²) probably lightweight aggregate	100	~0.5	1400	1000
4b	mortar between blocks	100	0.88	1300	1000
5	dense plaster	13	0.57	1300	1000
expected thermal transmittance (W/m²K)			0.39, 0.45*		
thermal storage correction factors Fi, Fe			99306.99, 27889.05		

*Allowing for ageing of the polyisocyanurate to give a conductivity of 0.025 W/m·K

Information about the U-value measurement

	Values for measurements 4A, 4B, 4C
heat flux meters	31.2189, 31.2405, hfm16
measured thermal transmittance (W/m²K)	0.40, 0.30, 0.40
metal plates used?	yes, no, yes
corrected measured thermal transmittance (W/m²K)	0.37, 0.30, 0.37
dates of measurement	8-1-99 to 22-1-99
orientation of element (degrees clockwise from North)	West
general level of exposure	high, high, high

The heat flux meters were installed in two different rooms in a school. Two of the heat flux meters were installed in the caretaker's office and the third heat flux meter was installed in the head teacher's office. The heating was switched off at weekends and this tended to cause some instability in the heat flows.

Although the architect and clerk of works had stated that there was only one layer of outer leaf brickwork (i.e. 102 mm) a borescope inspection and wall thickness measurement confirmed that there were in fact two layers of brickwork. Since the second layer of brickwork was sheltered by the first the actual conductivity of the second layer of brickwork is likely to be less than 0.77 W/m·K.

5. Wall, flats : brick / cavity / insulation / block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	dash render	18	0.57	~1000	1000
2	common brick	102	0.77	1700	800
3	air cavity	65	-	-	-
4	XPS batts	35	0.028	20	1450
5	Light concrete block	100	0.34	1300	1000
6a	air	~5			
6b	plaster dabs	~5	0.57	1300	1000
7	taper edged plasterboard	12.7			
expected thermal transmittance (W/m²K)			0.45 (between dabs)		
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 5A, 5B
heat flux meters used (identification numbers)	31.2402 (4.3), hfm22 (4.2)
raw measured thermal transmittance (W/m²K)	0.59, 0.40
metal plates used?	yes, yes
corrected measured thermal transmittance (W/m²K)	0.55, 0.37
dates of measurement	22-1-99 to 8-2-99
orientation of element (degrees clockwise from North)	285°, 285°
general level of exposure	medium, medium

The above measurement was carried out in a store room of a sheltered housing complex. The internal temperature was relatively stable which led to better stability in the heat flows.

*Blocks manufactured from selected screened clinker ash complying with BS 1165 and Portland cement to BS12

6. Wall, ground floor flat : brick / cavity / insulation / block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	facing brick	102	0.77	1700	800
2	air cavity	60	-	-	-
3	XPS cavity wall insul. boards	40	0.028	25	1400
4a	concrete blocks (15 N/mm²)	140	0.5	1400	1000
4b	mortar between blocks	140	0.88	1300	1000
5	plaster	13	0.57	1300	1000
expected thermal transmittance (W/m²K)			0.44		
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 6A & 6B
heat flux meters (identification labels)	31.2405, 31.2189
raw measured thermal transmittance (W/m²K)	0.42, 0.34
metal plates used?	no, yes
corrected measured thermal transmittance (W/m²K)	0.42, 0.31
dates of measurement	25-1-99 to 11-2-99
orientation of element (degrees clockwise from North)	240°, 240°
general level of exposure	low, low

The above measurement was carried out in a front bedroom of a ground floor flat as this was the only room which was suitable for the tenant. For security reasons it was not possible to measure the temperature on the outside of the wall being tested and therefore the external temperature had to be measured at the opposite side of the dwelling facing the enclosed back court. This is not expected to lead to a large error in the U-value measurement, however.

Although the U-value measurement on the external wall gave reasonable agreement with that expected from the construction, it was noted that there was evidence of condensation (mould growth) on another wall of the same room, adjacent to an unheated corridor.

7. Wall, : brick / cavity / lightweight blocks / internal insulation

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	102 mm facing brick	102	0.77	1700	800
2	50 mm air	50	-	-	-
3a	AAC block	115	0.11	~460	1050
3b	mortar between blocks	115	0.88	1750	-
4	reinforced dabs with air between	~5	-	-	-
5	polyurethane or phenolic foam as part of Thermal Board Super	40.5	0.018	~35	1400
6	plasterboard as part of Thermal Board Super	9.5	0.25	900	1000
expected thermal transmittance (W/m²K)			0.26, 0.32*		
thermal storage correction factors Fi, Fe			164541.45, 12809.59		

*Allowing for ageing of the polyurethane to a conductivity of 0.025 W/m·K

Information about the U-value measurement

	Values for one case only (case 7)
heat flux meters used (identification labels)	430145 (6.3 W/m² per mV)
raw measured thermal transmittance (W/m²K)	0.39
metal plates used?	yes
corrected measured thermal transmittance (W/m²K)	0.37
dates of measurement	27-1-99 to 2-2-99
orientation of element (degrees clockwise from North)	320°
general level of exposure	medium

The above measurements were carried out in the common room (day room) of a sheltered housing complex. The relatively stable internal temperatures were of benefit to the measurement as the heat flows did not fluctuate too greatly.

It should be noted that the above measurements and materials are those described in the architect's drawings. A later examination of the wall construction (shown in this report as example 24) revealed that the insulation material was not as stated in the plans and the insulation thickness was less than stated in the plans.

8. Wall, school : brick / cavity / insulation / brick

layer	material & description	thickness (mm)	conductivity (W/m·K)	thermal resistance	density (kg/m³)	specific heat capacity (J/kg·K)
e	external surface	0		0.060		
1	roughcast render	19	0.57	0.038	1300	1000
2	outer leaf brick	102	0.77	0.1190	1700	800
3	air	65	-	0.180	-	-
4	polyisocyanurate board	35	0.019	1.8421	~40	1400
5	inner leaf brick	215	0.62	0.3468	1700	800
6	plaster	13	0.57	0.026	1300	1000
i	internal surface	0		0.120		
total expected thermal resistance				2.732		
expected thermal transmittance (W/m²K)				0.37, 0.44*		
thermal storage correction factors Fi, Fe				242381.78, 38987.76		

*U-value allowing for ageing of polyisocyanurate to give a conductivity value of 0.025 W/m·K

Information about the U-value measurement

	Values for measurements 8A & 8B
heat flux meters	hfm22
raw measured thermal transmittance (W/m²K)	0.32
metal plates used?	yes
corrected measured thermal transmittance (W/m²K)	0.29
dates of measurement	10-2-99 to 25-2-99
orientation of element (degrees clockwise from North)	280°
general level of exposure	high
measured wall thickness (mm)	475

The above measurement was carried out in a well-heated school staff room. Both indoor and outdoor temperatures fluctuated considerably leading to relatively large thermal storage corrections. One of the heat flux meters developed a fault during the measurement and the results from that apparatus had to be omitted from the above results. Since the school was in a fairly exposed rural area and since the wall faced a large school playground, the level of exposure was high.

The school staffroom was identified as a suitable location as it afforded an easily accessible window for measuring external temperature and because it had a large area of external wall, enabling the heat flow meters to be situated more than 1 metre from the nearest window or corner in the room. The equipment was placed between two filing cabinets to reduce the risk of any staff accidentally disturbing the equipment. The heat flow meter used in this measurement was of reference number "hfm22" which had a nominal calibration of 4.2 W/m² per mV. Its configuration was as follows: hfm / bonding tape / metal disk / bonding tape / silicone-plasticene / polythene film / held against wallpaper. The height above the carpet was 1310 mm. The ceiling height was 2.6 m. The centre of the HFM was 1365 mm to the left of the window opening and well away from the nearest partition wall.

9. Wall, first floor flat : brick / cavity / insulation / block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	facing brick	102	0.77	1700	800
2	air cavity	60	-	-	-
3	XPS cavity wall insul. boards	40	0.028	25	1400
4a	concrete blocks (15 N/mm²)	140	0.5	1400	1000
4b	mortar between blocks	140	0.88	1300	1000
5	plaster	13	0.57	1300	1000
expected thermal transmittance (W/m²K)			0.44		
thermal storage correction factors Fi, Fe			164707.33, 30179.55		

Information about the U-value measurement

	Measurements 9A & 9B
heat flux meters used	
metal plates used?	yes, yes
U-value corrected for thermal storage only	0.62, 0.57
corrected measured thermal transmittance (W/m²K)	0.56, 0.52
dates of measurement	
orientation of element (degrees clockwise from North)	240°, 240°
general level of exposure	medium, medium

The above measurements were carried out in the master bedroom of a first floor flat. The wall was in an urban area, however across the road was a large open area which would have significantly increased the exposure of this wall.

10. Wall, bungalows : brick / cavity / insulation / block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	dash render	18	0.57	~1000	1000
2	common brick	102	0.77	1700	800
3	air cavity	65	-	-	-
4	XPS batts	35	0.028	20	1450
5	Light concrete block	100	0.34	1300	1000
6a	air	~5			
6b	plaster dabs	~5	0.57	1300	1000
7	taper edged plasterboard	12.7	0.16	~600	1000
expected thermal transmittance (W/m²K)			0.45 (between dabs)		
thermal storage correction factors Fi, Fe			105116, 30311		

Information about the U-value measurement

	Measurements 10A and 10B
heat flux meters used	220077, 430144/hfm16
raw measured thermal transmittance (W/m²K)	0.56, 0.46
metal plates used?	no, no/yes
corrected U	0.56, 0.47
dates of measurement	8-2-99 to 26-2-99
orientation of element (degrees clockwise from North)	010°, 010°
general level of exposure	very low, very low

The above measurements were carried out in a spare ground floor bedroom facing on to a sheltered back lane. The wall was situated in an exceptionally sheltered location and there was a roof covering over the portion of the lane adjacent to the wall.

11. Roof / sloping ceiling : tiles / felt / airspace / insulation / plasterboard

layer	material & description	thickness mm	conductivity W/m·K	density kg/m3	specific heat capacity J/kgK
e	external surface	0			
1	roof tiles	19	~1.0	~2000	~800
2	felt	2			
3	well ventilated air space	~50	-	-	-
4	rigid urethane, foil faced on both sides	75	0.020	32	~1400
5	plasterboard	9.5	0.25	900	1000
i	internal surface	0			

Information about the U-value measurement

expected thermal transmittance (W/m²K)	0.25, 0.31*
thermal storage correction factors Fi, Fe	6395, 1212
*Allowing for ageing of the urethane raising its conductivity to 0.025 W/m·K	
	Values for measurements 11A & 11B
measured thermal transmittance (W/m²K)	0.34, 0.33
dates of measurement	4-3-99 to 19-3-99
HFMs	31.2189 (5.4), 31.2402 (4.3)
metal disks?	yes, yes
corrected measured thermal transmittance (W/m²K)	0.32, 0.30

The above was carried out on a sloping ceiling of an end-terraced house in a rural location. The equipment was installed in an upstairs bedroom which had a large sloping ceiling area and a dormer window adjacent to it. The external surface temperature was monitored by attaching a thermocouple to the exterior of a roof tile using waterproof tape.

12. Wall : timber frame with mineral wool insulation

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	wet cast render	19	0.57	~1000	1000
2	concrete blockwork	100	0.5	~1000	1000
3	air	50	-	-	-
4	sheathing plywood with paper stapled to outer face	9	0.13	500	1600
5a	mineral wool quilt	89	0.04	12	1030
5b	timber studs at 400 mm centres (38 mm or 45 mm thick)	89	0.14	500	1600
6	plasterboard	25	0.16	~600	1000
7	surface finish	0			
expected thermal transmittance (W/m²K)			0.34		
thermal storage correction factors Fi, Fe			13991, 7947		

Information about the U-value measurement

	Values for measurements 12A & 12B
heat flux meters	430144, hfm16
raw measured thermal transmittance (W/m²K)	0.26, 0.29
metal plate used?	yes, yes
corrected measured thermal transmittance (W/m²K)	0.25, 0.27
dates of measurement	4-3-99 to 18-3-99
orientation of element (degrees clockwise from North)	030°, 030°
internal and external air monitored	

The above was carried out on a North facing gable wall of a first floor flat in a rural location. The apparatus was set up in the kitchen. The flat was well heated and unusually high temperatures were recorded. The average indoor temperature was above 20°C.

13. Wall : brick / cavity / lightweight block

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	facing brick (thermocouple on surface)	100	0.77	1700	800
2	air cavity	58	-	-	-
3a	AAC block	115	0.11	~460	1050
3b	mortar	115	0.88	1300	1000
4a	air between plaster dabs	5	-	-	-
4b	plaster dabs	5	0.57	1300	1000
5	plasterboard	12.5	0.25	900	1000
	thermocouple in air				
expected thermal transmittance (W/m²K)			0.68 (between dabs)		
thermal storage correction factors Fi, Fe			22567, 21927		

Information about the U-value measurement

	Values for measurements 13A & 13B
heat flux meters used	31.2104, hfm16
measured thermal transmittance (W/m²K)	0.72, 0.76
metal plates used to stabilise heat flux meters ?	yes, yes
corrected thermal transmittance	0.67, 0.71
dates of measurement	19-11-99 to 4-12-99
orientation of element (degrees clockwise from North)	300°, 300°
general level of exposure	medium, medium
height above carpet (mm)	1200, 1200
measured wall thickness (mm)	210

The external surface temperature was monitored for the first heat flux meter and the external air temperature was monitored for the second (upstairs) heat flux meter.

During the visit of this detached house, which was built earlier in the year, the occupants mentioned that there was no insulation in the loft and granted permission to examine the loft. Within the loft it was observed that there was no insulation in the loft at ceiling level and that there was no insulation at rafter level. In other words, the limiting U-value could not possibly have been achieved.

14. Wall,

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
ae	external air (thermocouple)				
se	external surface	-	-0.04	-	-
1	render	10	0.64	~1300	
2	composite insulation material with thermal resistance of 1.63 m²K/W	75	0.046		
3a	Lightweight mineral wool bridged by profiled steel sheet, proportion 0.991	150	0.037		
3b	profiled steel sheet (unsealed), proportion 0.009	150	50	7800	
4	plasterboard	12.5	0.25	900	1000
si	internal surface	-	-0.13	-	-
se	internal air (thermocouple)				
expected thermal transmittance (W/m²K)			0.17 (at panel) (Proportional Area U-value is 0.17)		
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 14A & 14B
heat flux meters used	31.2189, 31.2405
raw measured thermal transmittance (W/m²K)	0.20, 0.49
metal plates used?	yes, yes
measured thermal transmittance with corrections	0.19, 0.46
dates of measurement	6-12-99 to 13-12-99 to 20-12-99
orientation of element (degrees clockwise from North)	310°, 310°
general level of exposure	medium
height above carpet (mm)	1210, 1210
measured wall thickness (mm)	260

The heat flux meters were placed side by side on the west wall of an upstairs bedroom to measure the heat flux through the wall. A thermocouple thermometer was passed through the south-facing window in order to monitor external temperatures. Thermocouple thermometers were situated in front of the centres of the two heat flux meters about 10 mm in front in order to measure the air temperature in the vicinity of the HFMs.

Due to the presence of metal framing, there is no simplified method for calculating the U-value of this construction. The procedure is BS EN ISO 6946 suggests a higher U-value than the Proportional Area Method, the latter being rather optimistic for this particular construction. The panel U-value corresponding to the part of the wall tested, is easier to calculate and appears to be 0.17 whether the method in 6946 or the Proportional Area Method is used.

The difference in U-value between the two panels is surprisingly large suggesting significant variations in the construction.

15. Sloping ceiling

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
	thermocouple in external air				
e	external surface				
1	tiles (clay/concrete)	19	~1.0	~2000	~800
2	airspace between roof tiles and sarking (vented)	10	R = 0.10		
3	sarking board	18			
4	mineral wool between steel studs	150			
5	airspace (created by metal profile, unvented) next to foil backing (low-e)	25	-		
6	foil backed plasterboard	9.5	0.25		1000
i	internal surface		R = 0.10		
	thermocouple in internal air				
expected thermal transmittance (W/m²K)			0.22 (between studs)		
thermal storage correction factors Fi, Fe					

Proportional Area U-value calculated to be 0.21 (R=4.706)

Information about the U-value measurement

	Values for measurements 15A & 15B
heat flux meters used	430145, 31.2104
measured thermal transmittance (W/m²K)	1.74, 1.73
metal plates used?	no, yes
measured thermal transmittance (W/m²K) with corrections	1.74, 1.63
dates of measurement	6-12-99 to 20-12-99
orientation of element (degrees clockwise from North)	100°, 100°
general level of exposure	medium, medium
height above carpet (mm)	1300, 1600

The measured thermal transmittance for this ceiling was unexpectedly high, suggesting that there could be insulation missing or excessive ventilation in the inner air space. The ceiling and surrounding area was subsequently examined using an infrared camera in order to observe surface temperatures and this revealed that surface temperatures at the sloping ceiling were up to 3°C lower than the sufrace temperatures of the neighbouring walls indicating that the U-value did appear to be excessively high. It later transpired that the housing association had had a number of complaints about cold attic rooms and although the occupants of this dwelling had no complaints they did say that they found this room much cooler than the other rooms in the house.

When the infrared camera was used the surface temperatures of the sloping ceiling were found to vary considerably. The lowest temperatures were recorded towards the bottom of the ceiling and at the part of the ceiling adjacent to the gable wall where temperatures were varied from 16.5°C up to 18°C. Higher temperatures were recorded at the opposite end of the sloping ceiling where they were approximately 19°C. The flat ceiling immediately adjacent to the sloping ceiling was also at a low temperature (17.5°C) whereas most of the flat ceiling was at a temperature of 20°C. The gable wall had a fairly uniform surface temperature of 18 - 19°C, however the section of wall immediately below the sloping ceiling had a temperature of only 17 – 18°C.

In the same dwelling, in the living room downstairs, considerable pattern staining, showing vertical dark bands spaced 600 mm apart, was in evidence even although the dwelling was less than 1 year old. This would appear to suggest that insulation could have been loose or missing over part of the wall area.

16. Sloping ceiling

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	tiles (thermocouple attached)	19	~1.0	~2000	~800
2	felt	2			
3	sarking	-			
4	mineral wool between trusses	50	0.04		1030
5	plasterboard	12.5	0.25	900	1000
	internal surface	-	R = 0.10		
	thermocouple 10 mm from surface				
expected thermal transmittance (W/m²K)			0.67		

Information about the U-value measurement

	Values for measurements 16A & 16B
heat flux meters used	hfm16, hfm22
measured thermal transmittance (W/m²K)	1.84, 1.47
metal plates used?	yes, no
measured thermal transmittance (W/m²K) with corrections	1.74, 1.47
dates of measurement	15-12-99 to 29-12-99
orientation of element (degrees clockwise from North)	340°, 340°
general level of exposure	medium, medium
height above carpet (mm)	1780, 1810

Test was carried out on a North-facing sloping ceiling where the house was owned by a housing association. The sloping ceiling (in the bedroom) was ostensibly of plasterboard and mineral wool. A thermocouple was placed on the outer surface of the roof to monitore external surface temperatures.

17. Wall

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	100 facing brick	100	0.77	1700	800
2	air	25	-	-	-
3	mineral wool	50	0.04	~10	1030
4	dense concrete blockwork	140	~1.3		
	internal surface	-	0.13		
expected thermal transmittance (W/m²K)			0.54		

Information about the U-value measurement

	Values for measurements 17A & 17B
heat flux meters used	
measured thermal transmittance (W/m²K)	0.79, 0.66
metal plates used?	no, yes
measured thermal transmittance (W/m²K) with corrections	0.79, 0.61
dates of measurement	15-12-99 to 29-12-99
orientation of element (degrees clockwise from North)	
general level of exposure	medium, medium
height above carpet (mm)	~1200, ~1200

Tests were carried out on a living room wall with embossed wallpaper. The wall was south facing and the test was done on the wall between the window and the west party wall . As the occupant was particularly elderly the equipment was located behind the television set to avoid danger of equipment falling due to being disturbed.

18. Wall, commercial building

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	metal sheeting (box finish)		50		
2	polyisocyanurate	65	0.025		
3	metal sheeting (box finish)		50		
expected thermal transmittance (W/m²K)			0.36		

Information about the U-value measurement

	Values for measurements 18A & 18B
heat flux meters used	
measured thermal transmittance (W/m²K)	0.47, 0.55, 0.48
metal plates used?	no, no, no
measured thermal transmittance (W/m²K) with corrections	0.47, 0.55, 0.48
dates of measurement	January 2000
orientation of element (degrees clockwise from North)	west facing
general level of exposure	medium (urban but facing space)
height above floor/carpet (mm)	1200 above mezzanine deck
orientation	330° (i.e. North-facing)

Small heat flux meters were placed against cladding panels in the storage area of a commercial building. The composite panels were 1000 mm wide and had a box finish. The panels contained polyisocyanurate 65 mm thick completely enveloped within the metal (with no z-spacers). The surface consisted of alternate projected and indented surfaces, each only about 30 mm high running horizontally. Heat flux meters were placed against both the projected and indented parts but away from the edges of the panels in order to avoid the substantial thermal bridging which would be expected at the edges. The panels fitted together in a tongue and groove arrangement. The external temperature was monitored using a Gemini datalogger which was hidden inside a crash barrier at ground level near the loading bay.

19. Wall of educational building extension (metal cladding)

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
	thermocouple measures ext. air temp				
1	steel rainscreen panel (pre-stressed and powder coated)	10	50		
2	air space behind rainscreen panel	70	-		
3	mineral wool (filled after construction)	70	0.038		
4	vapour barrier	-	-	-	
5	inner leaf concrete blockwork	140	~0.5	2400	
expected thermal transmittance (W/m²K)			0.42		

Information about the U-value measurement

heat flux meters used	21.0520, 22.0651, 21.0652, 21.0529
measured thermal transmittance (W/m²K)	0.64, 0.78, 0.65, 0.67
metal plates used?	no, no, no, no
measured thermal transmittance (W/m²K) with corrections	0.64, 0.78, 0.65, 0.67
dates of measurement	2-2-00
orientation of element (degrees clockwise from North)	340°, 340°, 340°, 340°
general level of exposure	low, low, low, low
height above floor/carpet (mm)	1340, 1340, 1340, 1340

The U-value of a wall in an extension was tested using an array of four heat flux meters (room H219). Owing to the heating system incorporating a significant radiative element (provided by a heated ceiling panel) care had to be taken as regards measuring temperatures and a variety of methods were used. Two surface temperatures were monitored in addition to a black ball temperature, a silver tube temperature and a bare thermocouple air temperature. The external temperature was monitored by installing small thermistor-based loggers on the roof of the same building. The loggers in the roof area were placed in an I-beam in order to afford some shading from sunlight.An infrared thermographic survey revealed that the temperature distribution showed some stratification, with higher temperatures closer to the ceiling, but there were no noticeable defects in the wall.

According to the architect's drawings there was a 20 mm internal plaster finish, however when the wall was examined it appeared that the concrete block was painted with no plaster finish. It was not possible to obtain the blockwork density from the drawings, however the clerk of works was of the view that lightweight aggregate blocks were probably used.

20. Fully filled cavity wall

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external surface (thermocouple on surface)	-	-	-	-
2	weathered sand-blasted faced blockwork (F10:250)	100	~1.93	ca 1400	1000
3	insulation (F30:150) (mineral wool, mineral wool batts), bridged by BS 1243 double triangle wall ties of horizontal spacing 900 mm and vertical spacing 450 mm. The wall tie material is not known	75	ca 0.037		1030
4	blockwork (F10:350), probably dense concrete	100		ca 1400	1000
5	plaster (M20:210), probably dense	15	0.57	1300	1000
6	internal surface (thermocouple in air)	-	-	-	-
expected thermal transmittance (W/m²K)			0.42		

Information about the U-value measurement

	Values for measurements 20A & 20B
heat flux meters used	hfm22, 31.2104
nominal calibration of hfm's (W/m² per mV)	4.2, 4.3
measured thermal transmittance (W/m²K) without corrections	0.51, 0.55
metal plates used?	no, yes
measured thermal transmittance (W/m²K) with corrections	0.51, 0.51
dates of measurement	21-01-00 to 04-02-00
orientation of element (degrees clockwise from North)	340°, 340°
general level of exposure to weather	high, high
height of hfm above floor/carpet (mm)	1250, 1250
distance of hfm from window opening	300, 570
distance of hfm from party wall	530, 300

Heat flux meters were installed on the north-facing wall of this dwelling. Some driving rain guages (area 127 cm²) were installed in the garden to monitor the rainfall for the two week period and at the end of the period the driving rain was found to be only 1.81 mm from the North and nil from the South. The occupants confirmed that there had also been very little rain during the week prior to the start of the measurement. The external temperature was logged using Gemini logger TGU0073-103979 and Squirrel no. 1203-00421 was used for monitoring the internal temperature and heat flows. The measured wall thickness was 307 mm.

The occupants complained of rain penetration problems with significant salt staining on the internal wall finishings. This suggests that rainwater may have penetrated the cavity.

21. Fully filled cavity wall

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external surface (thermocouple on surface)	-	-	-	-
2	weathered sand-blasted faced blockwork (F10:250)	100	~1.93	ca 1400	1000
3	insulation (F30:150) (mineral wool batts), bridged by BS 1243 double triangle wall ties of horizontal spacing 900 mm and vertical spacing 450 mm. The wall tie material is not known	75	ca 0.037		1030
4	blockwork (F10:350), probably dense concrete	100		ca 1400	1000
5	plaster (M20:210), probably dense	15	0.57	1300	1000
6	internal surface (thermocouple in air)	-	-	-	-
expected thermal transmittance (W/m²K)					
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 21A & 21B
heat flux meters used (serial numbers)	31.2405, black hfm (430145?)
nominal calibration factors (W/m² per mV)	4.3, ?
measured thermal transmittance (W/m²K)	0.47, 0.46
metal plates used?	yes, no
measured thermal transmittance (W/m²K) with corrections	0.43, 0.46
dates of measurement	21-01-00 to 04-02-00
orientation of element (degrees clockwise from North)	340°, 340°
general level of exposure	high, high (open access to countryside)
sheltered (according to SAP document section 2.3) ?	no, no
height above floor/carpet (mm)	1300, 1300
distance from nearest window opening (mm)	390, 560
distance from nearest partition wall or corner (mm)	480, 320

Installed two heat flux meters in this house which was occupied by a family and several cats. Installed the hfm's in the living room approximately two feet away from an electric storage heater. Occupants complained about some dampness or rain penetration on some of the walls. The external temperature was monitored using a Gemini data logger which was placed within the shelter area above the front doors of the neighbouring houses. Squirrel 1203-00840.

22. Fully filled cavity wall

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external surface (thermocouple on surface)	-	-	-	-
2	weathered sand-blasted faced blockwork (F10:250)	100	~1.93	ca 1400	1000
3	insulation (F30:150) mineral wool, bridged by BS 1243 double triangle wall ties of horizontal spacing 900 mm and vertical spacing 450 mm. The wall tie material is not known	75	ca 0.037		1030
4	blockwork (F10:350), probably dense concrete	100		ca 1400	1000
5	plaster (M20:210), probably dense	15	0.57	1300	1000
6	internal surface (thermocouple in air)	-	-	-	-
expected thermal transmittance (W/m²K)					
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 22A & 22B
heat flux meters used	430144 (hfm9)
measured thermal transmittance (W/m²K)	0.60
metal plates used?	no
measured thermal transmittance (W/m²K) with corrections	0.60
dates of measurement	21-01-00 to 04-02-00
orientation of element (degrees clockwise from North)	160°
general level of exposure	high (facing street)
height above floor/carpet (mm)	900
external air or surface monitored	surface, surface
distance from window opening (mm)	330
distance from partition wall (mm)	450+330
logger no.	1203-841
measured wall thickness (mm)	301

The heat flux meters were positioned one above the other on the South facing wall, both attached to the same steel retort pole. The upper heat flux meter was 430144 (hfm9) and the lower heat flux meter was 31.2189 (nominal calibration of 5.4 W/m²K per mV), the first hfm was attached to channel 9 of the logger and the second to channel 10. The first hfm was located 900+440 mm above the carpet and I did not record the height of the second hfm. The first was located 330 mm to the left of the window opening and 450+330 mm to the right of the partition wall. The second hfm was located 320 mm to the left of the window opening and 450+340 mm to the right of the partition wall. An external thermocouple was attached to the South-facing wall using silvery grey sticky tape. In addition a Gemini logger was fitted under the covering of the doorway to record external temperatures. The second (heavier) heat flux meter became detached during the period of measurement leaving insufficient data for analysis of the point on the wall which it was monitoring.

23. Fully filled cavity wall

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external surface (thermocouple on surface)	-	-	-	-
2	weathered sand-blasted faced blockwork (F10:250)	100	~1.93	ca 1400	1000
3	insulation (F30:150) (mineral wool), bridged by BS 1243 double triangle wall ties of horizontal spacing 900 mm and vertical spacing 450 mm. The wall tie material is not known	75	ca 0.037		1030
4	blockwork (F10:350), probably dense concrete	100	~1.93	ca 1400	1000
5	plaster (M20:210), probably dense	15	0.57	1300	1000
6	internal surface (thermocouple in air)	-	-	-	-
expected thermal transmittance (W/m²K)					
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 23A & 23B
heat flux meters used	hfm16, 31.2402
nominal calibrations	~4.2, 4.3
measured thermal transmittance (W/m²K)	0.42, 0.39
metal plates used?	yes, yes
measured thermal transmittance (W/m²K) with corrections	0.40, 0.36
dates of measurement	21-01-00 to 04-02-00
orientation of element (degrees clockwise from North)	170°, 170°
general level of exposure	high, high
height above floor/carpet (mm)	1620, 1300
distance from window opening (mm)	2400, 2400
distance from partition wall or corner (mm)	450, 460
logger no.	1203-836

Upper heat flow meter had its signals fed to channel 9 of the squirrel and lower hfm had its signals sent to channel 10. Upper thermocouple was fed to channel 1 and lower thermocouple to channel 3. The external temperature was monitored by Gemini dataloggers at neighbouring houses. The U-value of the south-facing wall of this end-terraced house was measured. The thermal imaging survey revealed no particular defects in the wall construction but did show thermal bridging at the wall/ceiling junction and at certain points on the ceiling, suggesting poorly fitted loft insulation.

24. Wall, brick / cavity / lightweight blocks / internal insulation

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	Thermocouple on surface				
2	outer leaf brick	102	0.77	1700	800
3	air cavity (nominally unvented)	55*	-	-	-
4a	AAC block	115	0.11	~460	1050
4b	Mortar	115	0.88		
5	Air between battens	18	-	-	-
6	Material observed to be EPS	20*	0.04		
7	plasterboard	10*	0.25		
8	internal surface		-0.13		
9	Thermocouple in air				
expected thermal transmittance (W/m²K)			0.515		
thermal storage correction factors Fi, Fe					

*-measured thicknesses

Information about the U-value measurement

	Values for measurements 24A & 24B
heat flux meters used	hfm16
measured thermal transmittance (W/m²K)	0.505
dates of measurement	February 2000
orientation of element (degrees clockwise from North)	320°
general level of exposure	medium
height above floor/carpet (mm)	1330
distance from nearest opening (mm)	390
logger used	1203-836

A second visit was made to this site to investigate why the U-value was considerably higher than expected. The temperature in the room, within the space behind the plasterboard-insulation laminate, within the cavity between the bricks and blocks and on the external surface of the bare bricks were all monitored. This allowed airspace temperatures to be compared with their expected values. It was found, whilst drilling, that the overall thickness of the plasterboard insulation laminate was thinner than expected and that even the calculated U-value may have been lower than it should have been. This would suggest that an inappropriate thickness of laminate was installed at construction stage and that this wall may not have satisfied the requirements of the Regulations.

The overall agreement is close, provided that 20 mm of EPS is used in the calculation in place of the architect's specification. The thermal performance of the AAC blockwork was higher than expected whereas the performance of the outer leaf brick was poorer than expected.

To the left of the heat flux meter was an alarm unit. An infrared survey revealed that there was a cool area (ie. thermal bridging) running vertically below the alarm unit of about a few inches wide indicating a greater level of heat loss for that part of the wall.

The wall construction consisted of outer leaf brick, air cavity, inner leaf AAC blockwork, timber studs and insulation laminated to plasterboard. The plasterboard laminate was examined and found to be 30 mm thick in total, and by measurement was found to consist of about 10 mm of plasterboard and 20 mm of expanded polystyrene insulation. The cavity in the wall was measured to be 55 mm at the point of measurement and no wall ties were visible from that part of the wall.

Temperatures were measured for the inside air (Tai), the airspace between the timber battens (T1 and T1b), the air cavity between the concrete blocks and the bricks (T2) and the outer surface of the outer leaf brickwork (Tse). This permitted separate analyses of the various parts of the construction.

Analysis of the plasterboard-insulation laminate

Two thermocouples were placed behind the plasterboard-insulation laminate in order to measure the temperature within the airspace. A thermocouple was also used to measure the internal air temperature in the vicinity of the heat flux meter. The thermal transmittance between the internal space and the air space behind the laminate was measured to be 1.45 W/m²K.

By taking the internal surface resistance to be 0.13 m²K/W and the half-airspace resistance to be 0.09 m²K/W, and the 9.5 mm plasterboard 0.038 m²K/W, the thermal resistance of the 20 mm of insulation was found to be

(1 / 1.45) - 0.13 - 0.09 - 0.038 = 0.432 m²K/W

which is consistent with 20 mm of expanded polystyrene with a conductivity of around 0.045 W/m·K. This confirms what was observed when an inspection hole was drilled through the plasterboard.

Analysis of the AAC blockwork layer

Two thermocouples had been placed in the airspace between the plasterboard-insulation laminate and the AAC blockwork. A thermocouple had also been placed in the air cavity between the AAC blockwork and the outer leaf brickwork. These two temperatures permitted the thermal transmittance of the AAC layer to be analysed separately from the rest of the construction. The thermal transmittance for the AAC layer, including surface effects, was measured to be 0.9 W/m²K. Subtracting the surface resistances, which were both taken to be 0.09 m²K/W, a thermal resistance of 0.93 m²K/W was obtained for the AAC blockwork.

Resistance of the AAC blockwork (excluding surface resistances), based on measurement = (1 / 0.9) - 0.18 = 0.93.

The expected thermal resistance of 115 mm of AAC blockwork would be calculated as follows, where the AAC block fraction was taken to be 0.934 and the mortar fraction 0.066 :

Resistance of inner surface of AAC blockwork = 0.09
Resistance of outer surface of AAC blockwork = 0.09

Minimum resistance limit (omitting surface resistances) = 1/[0.934/(0.115/0.11) + 0.066/(0.115/0.88)] = 0.7151
Minimum resistance limit (including surface resistances) = 0.09 + 0.7151 + 0.09 = 0.8951
Resistance through main path = 0.09 + 0.115/0.11 + 0.09 = 1.225
Resistance through bridging path = 0.09 + 0.115/0.88 + 0.09 = 0.311
Maximum resistance limit (including surface resistances) = 1/[0.934/1.225 + 0.066/0.311] = 1.026
RT = 1.026 + 0.8951) / 2 = 0.961 (including surface resistances)
Resistance (excluding surface resistances) = 0.961 - 0.09 - 0.09 = 0.781

Thus the measured resistance of the AAC blockwork, of 0.93, was slightly higher (i.e. better) than the theoretical resistance, 0.78 m^2K.

Analysis of brickwork layer

Using the thermocouple in the air cavity and the thermocouple taped to the outer surface of the brickwork, a thermal transmittance of ~5.5 was obtained. Allowing for a half airspace resistance of 0.09, this gives a thermal resistance for the brickwork of

(1 / 5.5) - 0.09 = 0.092 m^2K/W

This is a little less than the expected resistance of

(0.102 m / 0.77 W/m·K) = 0.1325 m^2K/W

Possibly suggesting that there is an appreciable amount of ventilation in the cavity.

Summing up

In conclusion, the unexpectedly high U-value for the overall wall structure is principally due to the fact that the architect's specifications were not followed and because of the unexpectedly high thermal transfer from the air cavity (between the blockwork and the brickwork) to the external environment.

25. Health building

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
	thermocouple in air				
	external surface				
1	Aluminium rainscreen	3			
2	Air space	60			
3	mineral wool insulation	100	0.033		
4	in-situ concrete	200	1.93		
5	plaster	13	0.57		
6	wallpaper	0			
	internal surface				
	thermocouple in air				
expected thermal transmittance (W/m²K)			0.29		

Information about the U-value measurement

	Values for measurements 25A & 25B
heat flux meters used (reference numbers)	31.2402, 430144
measured thermal transmittance (W/m²K)	0.37, 0.33
metal plates used for mounting the hfms ?	yes, no
measured thermal transmittance (W/m²K) with corrections	0.34, 0.33
dates of measurement	February 2000
orientation of element (degrees clockwise from North)	325°, 325° (i.e. north west)
general level of exposure	low, low
location in building	room A265
loggers	1203-840, 1203-843

Two heat flux meters were used to measure the U-value of a wall in a health-education building. The room has a west facing window facing into a courtyard. The heat flux meters were positioned roughly adjacent to the centre of one of the external panels in order to avoid edge effects.

The thermal imaging survey revealed a slight dark patch at a distance of about 1350 mm to the right of the heat flux meters, approximately at the boundary between one external cladding panel and the next, but otherwise there were no visible defects.

The details of the wall construction in this instance are still to be sent by the architect but are expected within the next few weeks.

26. Second sloping ceiling

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
ae	external air (thermocouple)	-			
se	thermocouple on external surface	-	-	-	-
1	roof tiles	19	~1	~2000	~800
2	felt	2			
3	well ventilated airspace	50			
4a (90%)	rigid urethane, foil faced on both sides and laid over the plasterboard	75	0.020	32	~1400
4b (10%)	air gaps penetrating the rigid urethane due to poor workmanship	75	-		
5	plasterboard	9.5	0.25	900	1000
si	internal surface (R_{si} = 0.10 m²K/W)				
ai	thermocouple in internal air				
expected thermal transmittance (W/m²K)					
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 26A & 26B
heat flux meters used	black, 31.2104, 31.2405
measured thermal transmittance (W/m²K)	0.25, 0.64, 0.85
metal plates used?	no, yes, yes
measured thermal transmittance (W/m²K) with corrections	0.25, 0.60, 0.80
dates of measurement	22-2-00 to 8-3-00
orientation of element (degrees clockwise from North)	125° (for all three cases)
general level of exposure	high (rural)
height above floor/carpet (mm)	1600, 1550, 1600
distance from window to the left (mm)	670, 950, 1170
distance from party wall to the right (mm)	1240, 960, 740
distance from external wall just below sloping ceiling (mm)	900, 900, 900
logger	1203-00841

In this house the occupant had become aware of workmanship-related defects in the dwelling construction and in particular regarding the construction of the partition floor which had insulation missing allowing cold air to pass into the void (not strictly relevant to the U-value measurement). It was also noted that the insulation was laid loosely over the ceiling (as if the insulation had been inserted after the ceiling and roof tiles had been put up) and substantial gaps between the insulation board were visible. Overall, the gaps amounted to about one tenth of the total ceiling area. It was also noted that above the flat (horizontal) ceiling a mixture of different mineral wools (ie. different colours) was used and that in places the insulation was less than the requisite width as though it had not expanded to its nominal thickness.

The external surface temperature and external air temperature were both monitored. Due to the wet weather conditions, it was not possible to tape the thermocouple to the roof surface and 'blu-tac' had to be used instead.

27. Bedroom wall in mid-terraced timber frame house

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	thermocouple in external air	-	-	-	-
2	external surface	-	-	-	-
3	brickwork (outer leaf)	102	0.77	1700	800
4	vented air cavity	50	-	-	-
5	plywood	19	0.13	500	1600
6a	mineral wool between timber framing	95	0.042	12	1030
6b	45 mm thick Scandinavian timber framing at 600 or 400 mm centres with horizontal timbers at 2.4 m vertical intervals	95	0.13	500	1600
7	plasterboard	25	0.25	900	1000
8	internal surface	-	-		
9	thermocouple in internal air	-	-		
expected thermal transmittance (BS EN ISO 6946) (W/m²K)			0.38 (overall), 0.34 (between studs)		
thermal storage correction factors F_i, F_e (ISO 9869)			20430, 6295		

Information about the U-value measurement

	Values for measurement
heat flux meters used (serial no.)	hfm22 (4.2 W/m² per mV)
measured thermal transmittance (W/m²K)	0.29
metal plates used?	no
measured thermal transmittance (W/m²K) with mounting corrections	0.29
dates of measurement	8-3-00 to 21-3-00
orientation of element (degrees clockwise from North)	350°
general level of exposure	medium
height above floor/carpet (mm)	1450
distance from gable wall (mm)	270
distance from window (mm)	265

A thermal imaging (infrared) survey was carried out on the part of the wall being tested. The timber studs were clearly visible but there were no obvious defects in the wall. The thermal imaging (infrared) survey revealed a cold area just below the small sloping ceiling (on the gable wall side of this step-terraced house) and on part of the horizontal ceiling in the vicinity of the sloping ceiling. This suggests that there was defective insulation (poorly fitted or missing altogether) in the vicinity of the small sloping section of the ceiling.

It was noted that, despite the construction being only a few years old, the window seals were in an appalling condition and had become detached in places, implying poor draughtproofing of the windows.

As with a number of other timber frame walls, the measured thermal performance was slightly better than expected. Given that the timber studs were 95 mm deep, it is likely that a mineral wool quilt of nominal thickness 100 mm was inserted, leading the the mineral wool being compressed thereby having a slightly higher density than normal. The higher density would lead to a reduction in conductivity and therefore a better than expected U-value.

28. Downstairs bedroom north wall

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external air (thermocouple)				
2	external surface	-	-	-	
3	outer leaf brickwork	102	0.77	1700	
4	air cavity (slightly ventilated) with flexible stainless steel wall ties 600 mm horizontally and 375 mm verticall	50.5	0.025	1.2	1008
5	plywood	9.5	0.13	500	
6a	unfaced mineral wool quilt	89	0.038	12	
6b	timber framing (38mm by 89mm at maximum 600mm centres)	89	0.13	500	
7	plasterboard	12.5	0.25	900	1000
8	internal surface	-	-	-	
9	internal air (thermocouple)				
expected thermal transmittance (W/m²K)			0.39 (overall), 0.34 (at point tested)		
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 28A & 28B
heat flux meters used (8-3-00 to 15-3-00)	220077, hfm16
heat flux meters used (15-3-00 to end)	31.2104, hfm16
measured thermal transmittance (W/m²K) without corrections	0.33, 0.29
metal plates used?	yes, yes
measured thermal transmittance (W/m²K) with corrections	0.31, 0.27
dates of measurement	8-3-00 to 15-3-00; 15-3-00 to 21-3-00
orientation of element (degrees clockwise from North)	north facing
general level of exposure	medium
height above floor/carpet (mm)	1260, 1370
distance from partition wall (mm)	890, 350
distance from window (mm)	
measured wall width (mm)	299

The wall was viewed with an infrared camera which did not reveal any unusual features or contraindications. The vertical timber battens were visible, as expected.

The left heat flux meter became detached from the wall some 3 – 4 days before the end of the measurement involving heat flux meter no. 31.2104.

29. Clear cavity wall for comparison with Alba Building Sciences

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
1	external surface (thermocouple)	-	-	-	-
2	external render	20	0.57	1300	1000
3(a)	lightweight concrete (~93.4%)	100	0.16	600	1000
3(b)	mortar (~6.6%)	100	0.88	1750	1000
4	air cavity	60	-	-	-
5(a)	lightweight concrete (~93.4%)	100	0.16	600	1000
5(b)	mortar (~6.6%)	100	0.88	1750	1000
6	dense plaster	10	0.57	1300	1000
7	internal surface	-	-	-	-
	internal air (thermocouples)				
expected thermal transmittance (W/m²K)			0.69		
thermal storage correction factors Fi, Fe			46916, 23267		

Information about the U-value measurement

	Values for measurements 29A & 29B
heat flux meters used (serial numbers)	430144, 430145, thin wafer type
measured thermal transmittance (W/m²K) neglecting plates etc.	1.03, 1.01, 1.13
metal plates used?	no, no, no
measured thermal transmittance (W/m²K) w mounting corrections	1.03, 1.01, 1.13
dates of measurement	12:00 on 21-3-00 - 10:00 on 6-4-00
orientation of element (degrees clockwise from North)	10°, 10°, 10°
general level of exposure	medium (urban, facing uphill)
height above floor/carpet (mm)	1330, 1310, 1015
distance from partition wall (mm)	280, 610, 445
distance from window (mm)	950, 620, 785
measured driving rain against wall being measured (mm)	0.94

In this case study a direct comparison was made between the method of measuring U-values given in this report and a separate study involving a different type of measurement apparatus.

Unlike the other case studies in this report, the above measurement does not relate to new construction. The purpose of this case study was to draw a comparison between the techniques and apparatus used with those of another organisation also involved in the measurement of U-values, namely Alba Building Sciences.

Alba Building Sciences carried out a U-value measurement of the above wall concurrently with the BRE measurement with their heat flux meter situated 300 mm below the two BRE heat flux meters. Alba's heat flux meter was of a different kind and consisted of a wafer-thin flexible plastic material (thickness only ~1mm) which was connected to their own logging device, made by a different manufacturer to the one used by BRE. As well as measuring heat flux separately, Alba monitored the internal and external temperatures, again using their own logging apparatus. This study, therefore, permitted a direct comparison between the two separate measurements carried out on the same wall, using independently-developed techniques and apparatus.

The comparison was of mixed success. The internal air temperatures showed good agreement with a standard deviation in $T_{ai}^{BRE} – T_{ai}^{Alba}$ of only 0.41°C, and the external temperatures showed fair agreement, with a standard deviation in $T_{se}^{BRE} – T_{se}^{Alba}$ of 0.95°C. The agreement between the separate measurements of heat flux was poorer, however, with a standard deviation in $q^{BRE} – Q^{Alba}$ of 7.8 W/m².

The mean values showed reasonable agreement and are summarised as follows: Coincidentally the crude uncorrected U-values showed very good agreement.

Quantity	BRE measurement	Alba measurement
$\langle T_{ai} \rangle$ average internal air temperature	17.08°C	16.74°C
$\langle T_{se} \rangle$ average external surface temp.	5.29°C	3.92°C
<q> average heat flux	11.75 W/m²	12.80 W/m²
$\langle q \rangle \div (\langle T_{ai} \rangle - \langle T_{se} \rangle)$ crude uncorrected U-value*	1.00 W/m²K	1.00 W/m²K

* - ignoring mounting corrections and thermal storage corrections

30. North gable wall of semi-detached house

layer	material & description	thickness (mm)	conductivity (W/m·K)	density (kg/m³)	specific heat capacity (J/kgK)
	thermocouple in external air				
1	wet cast render	19	0.57	~1000	1000
2	concrete blockwork	100	0.5	~1000	1000
3	air (slightly ventilated)	50	-	-	-
4	sheathing plywood with paper stapled to outer face	9	0.13	500	1600
5a	mineral wool quilt	89	0.04	12	1030
5b	timber studs at 400 mm centres (38 mm or 45 mm thick)	89	0.13	500	1600
6	plasterboard (2 layers)	25	0.16	~600	1000
7	drywall topcoat	0			
	thermocouple in internal air				
expected thermal transmittance (W/m²K)			~0.39 (overall), ~0.35 (panel)		
thermal storage correction factors Fi, Fe					

Information about the U-value measurement

	Values for measurements 30A & 30B
heat flux meters used	430144, 430145
measured thermal transmittance (W/m²K)	0.32, 0.28
metal plates used?	no, no
measured thermal transmittance (W/m²K) with corrections	0.32, 0.28
dates of measurement	6-4-00 to 17-4-00
orientation of element (degrees clockwise from North)	10°, 10°
general level of exposure	high
height above carpet (mm)	1310, 1270
Distance from window (mm)	2400, 2400
distance from partition wall (mm)	460, 760
logger	1203-00836

* the house was situated in a rural area almost adjacent to open countryside
The wall was pre-viewed with an infrared camera before positioning the heat flux meters. One panel showed a vertical cold patch suggesting a steel beam or similar, and the heat flux meters were positioned so as to avoid this.

For the right hand heat flux meters one of the legs of the tripod was dislodged but this did not appear to cause a significant air gap behind the heat flux meter.

Appendix B : Correcting for thermal storage

In theory, the U-value of an element is calculated from

$$U = [\int q(t)\cdot dt\ ] / [\int (T_i(t) - T_e(t))\cdot dt\ ]$$

provided that the integral is summed over a long period of time. In the above, q is the heat flux (W/m²), T_i is the internal temperature (K or °C), T_e is the external temperature (K or °C), t is time (s) and U is the U-value (W/m²K). If n measurements are carried out over uniform time intervals then a good approximation is

$$U = [\sum_n q] / [\sum_n (T_i - T_e)]$$

This approximation, however, only holds good provided that the summation is taken over a sufficient period of time and provided that thermal storage effects are not too large.

During the course of the measurements it was found that heat flows were in some cases strongly modified by thermal storage effects particularly in cases where temperatures were varying widely or where the construction had a heavyweight inner leaf. Apparent U-values were generally enhanced whenever the internal temperature rose and, correspondingly, apparent U-values were depleted, and sometimes even became negative, when the internal temperature fell. The effect was particularly marked in some non-domestic buildings where the heating setpoint was reduced at weekends.

CORRECTING THE DATA FOR THERMAL STORAGE EFFECTS

The following table summarises the data which is measured for each U-value measurement. T_i and T_e are respectively the daily mean internal and external temperatures while q is the daily mean heat flux, expressed in W/m². Generally about 14 days of data were collected, however the table represents just 5 days of data in order to simplify this illustration.

Day	T_i	T_e	q
1	T_{i1}	T_{e1}	q_1
2	T_{i2}	T_{e2}	q_2
3	T_{i3}	T_{e3}	q_3
4	T_{i4}	T_{e4}	q_4
5	T_{i5}	T_{e5}	q_5

The following table illustrates how thermal mass corrections were applied to the above data, using the procedure described in section 7.2.2 of ISO 9869. $\sum T_i$ and

$\sum T_e$ represent the summed internal and external temperatures. $\sum q$ represents the cumulative heat flow without thermal storage corrections and $\sum q'$ represents the cumulative heat flow after appropriate thermal storage corrections have been made. U' represents the U-value with thermal storage corrections having been applied.

Day	$\sum T_i$	$\sum T_e$	δT_i	δT_e	$\sum q$	$\sum q'$	U	U'
1	T_{i1}	T_{e1}	$T_{i1}-T_{i1}$	$T_{e1}-T_{e1}$	q_1			
2	$T_{i1}+T_{i2}$	$T_{e1}+T_{e2}$	$T_{i2}-T_{i1}$	$T_{e2}-T_{e1}$	q_1+q_2			
3	$T_{i1}+..+T_{i3}$	$T_{e1}+..+T_{e3}$	$T_{i3}-T_{i1}$	$T_{e3}-T_{e1}$	$q_1+..+q_3$			
4	$T_{i1}+..+T_{i4}$	$T_{e1}+..+T_{e4}$	$T_{i4}-T_{i1}$	$T_{e4}-T_{e1}$	$q_1+..+q_4$			
5	$T_{i1}+..+T_{i5}$	$T_{e1}+..+T_{e5}$	$T_{i5}-T_{i1}$	$T_{e5}-T_{e1}$	$q_1+..+q_5$	$\sum q - (F_i\delta T_i+F_e\delta T_e)/\Delta t$	$\sum q/(\sum T_i-\sum T_e)$	$\sum q'/(\sum T_i-\sum T_e)$

The table above is reproduced several times by using different periods of data. The U-values derived from each successive period of data are plotted against the start time of the data. The F_i and F_e factors used in the thermal storage analysis represent the thermal response of the element and are calculated from the construction according to the procedure in ISO 9869.

An illustration showing the application of thermal mass corrections

The following table shows an example of a wall construction in a first floor flat which was studied during the winter of 1998-99. In this instance the F_i and F_e factors were calculated to be164707.3 and 30179.55 respectively. In the table the U-values are calculated from successive five-day periods.

Date	T_i °C	T_e °C	emf mV	q Wm^{-2}	$\sum T_i$	$\sum T_e$	δT_i	δT_e	$\sum q$	$\sum q'$		
16-2-99	15.588	4.433	1.278	5.495	-	-	-	-	-	-	-	-
17-2-99	15.000	2.917	1.635	7.031	-	-	-	-	-	-	-	-
18-2-99	16.129	7.933	1.910	8.213	-	-	-	-	-	-	-	-
19-2-99	16.033	7.696	1.179	5.070	-	-	-	-	-	-	-	-
20-2-99	14.558	5.208	0.630	2.709	77.31	28.19	-1.03	0.78	28.52	30.21	0.58	0.62
21-2-99	14.658	4.229	1.538	6.613	76.38	27.98	-0.34	1.31	29.64	29.83	0.61	0.62
22-2-99	15.658	4.292	1.890	8.127	77.04	29.36	-0.47	-3.64	30.73	32.90	0.64	0.69
23-2-99	15.179	3.813	1.460	6.278	76.09	25.24	-0.85	-3.88	28.80	31.78	0.57	0.62
24-2-99	16.079	4.925	2.003	8.613	76.13	22.47	1.52	-0.28	32.34	29.54	0.60	0.55
25-2-99	15.883	8.571	1.355	5.827	77.46	25.83	1.22	4.34	35.46	31.61	0.69	0.61
26-2-99	15.929	7.004	1.026	4.412	78.73	28.60	0.27	2.71	33.26	31.79	0.66	0.63

The U-value in the above case was found to be 0.62 ± 0.02 W/m²K. Although the corrected U-value in the above table, U', shows less statistical fluctuation than the uncorrected U-value, U, the improvement to the precision is relatively small.

A greater improvement to the overall precision can be achieved, however, if the thermal storage corrections are applied to the hourly data rather than the daily data as above. The following calculation, in which data was taken from case 4B, shows how this can be done.

Application of thermal storage corrections on an hourly basis

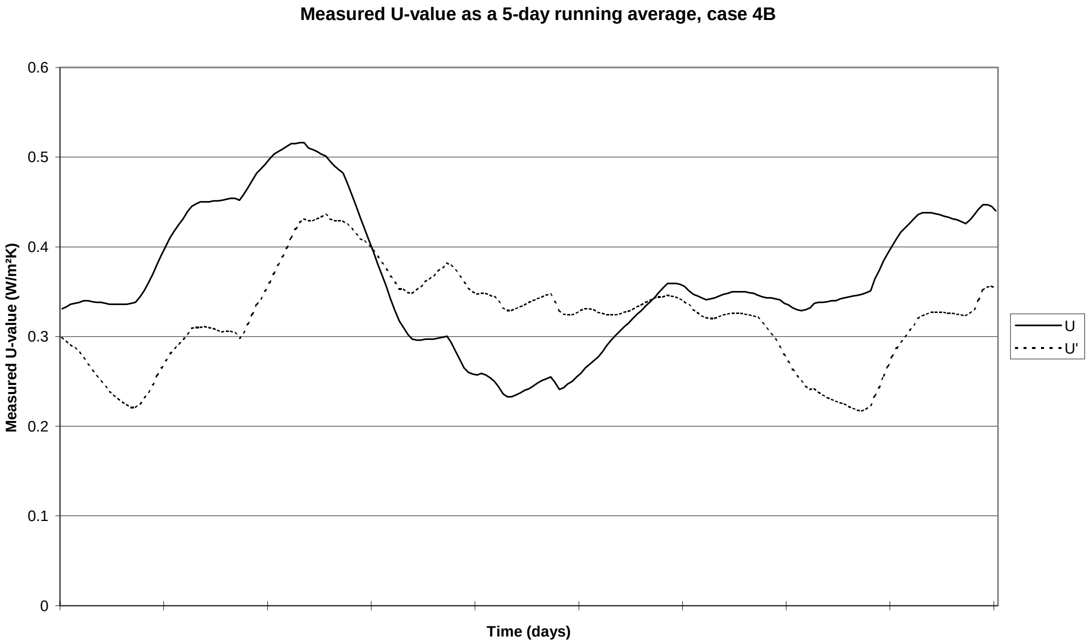
As in the above example, the corrected U-value is calculated using the data from successive 5-day periods. The appropriate running totals and running averages, however, are calculated for each successive hour giving hourly values for the U-value rather than daily values. When the corrections are applied on an hourly basis, as in this example, the thermal storage corrections can lead to a greater improvement in the precision of the U-value obtained.

In the following calculations, T_i represents the hourly mean internal air temperature (in °C), T_e represents the hourly mean external air temperature (in °C), ε represents the hourly mean electrical signal (mV) from the heat flux meter and q represents the hourly mean heat flux (W/m²). As in the previous calculations, U is the U-value derived from 5 days without thermal storage correction and U' is the U-value from 5 days with thermal storage correction. The thermal storage corrections for the wall construction, F_i and F_e, are calculated in this instance to be 99306.99 and 27889.05 respectively. The following table summarises the symbols used in the calculation procedure, together with their definitions:

Symbol	Definition of symbol
n	elapsed time in hours
m	number of hourly readings in the 5-day period, 120
$T_i(n)$	mean internal temperature (n^{th} reading)
$T_e(n)$	mean external temperature (n^{th} reading)
$\varepsilon(n)$	mean electrical signal from heat flux meter
k_{hfm}	calibration constant for heat flux meter, in W/m² per mV
q(n)	heat flux, $k_{hfm}\cdot\varepsilon(n)$
$S_{Ti}(n)$	sum of internal temperatures over the 5 days prior to reading n, $\sum_{k=n-m+1}^{k=n} T_i(k)$
$S_{Te}(n)$	sum of external temperatures over the 5 days prior to reading n, $\sum_{k=n-m+1}^{k=n} T_e(k)$
$\tau_i(n)$	mean temperature for the 24 hours period prior to reading n, $\frac{1}{24}\sum_{k=n-23}^{k=n} T_i(k)$
$\tau_e(n)$	mean temperature for the 24 hours period prior to reading n, $\frac{1}{24}\sum_{k=n-23}^{k=n} T_e(k)$
δT_i	change in mean internal temperature between the first 24 hours of the 5 day period and the last 24 hours of the 5 day period, $\tau_i(n) - \tau_i(n-m+24)$
δT_e	change in mean external temperature between the first 24 hours of the 5 day period and the last 24 hours of the 5 day period, $\tau_e(n) - \tau_e(n-m+24)$
$S_q(n)$	sum of heat flux values over 5 days prior to reading n, $\sum_{k=n-m+1}^{k=n} q(k)$
$S'_q(n)$	corrected sum of heat flux values for the 5 days immediately prior to reading n, $S_q(n) - (F_i\delta T_i + F_e\delta T_e)/3600$
U(n)	uncorrected U-value, $S_q(n)/(S_{Ti}(n) - S_{Te}(n))$
U'(n)	corrected U-value, $S_q'(n)/(S_{Ti}(n) - S_{Te}(n))$

The results for the U-value, both with and without thermal storage corrections, are shown in the following graph, showing that the U-value (U') with thermal storage corrections has less variation than the U-value (U) without corrections.

In this case, applying the thermal storage corrections improves the precision of the



U-value by 30%.

For completeness, the thermal storage calculations, used in case 4B, are shown in the following table:

A table showing how thermal storage corrections were applied for case 4B

n	$T_i(n)$	$T_e(n)$	$\varepsilon(n)$	q(n)	$S_{Ti}(n)$	$S_{Te}(n)$	$\tau_i(n)$	$\tau_e(n)$	δT_i	δT_e	$S_q(n)$	$S_q'(n)$	U(n)	U'(n)
1	19.8	4	-1.88	8.084	-	-	-	-	-	-	-	-	-	-
2	19.6	4.8	-1.52	6.536	-	-	-	-	-	-	-	-	-	-
3	19.5	4.8	-1.48	6.364	-	-	-	-	-	-	-	-	-	-
4	20.2	4.7	-1.89	8.127	-	-	-	-	-	-	-	-	-	-
5	20.9	4.2	-2.21	9.503	-	-	-	-	-	-	-	-	-	-
6	20.9	4	-2.12	9.116	-	-	-	-	-	-	-	-	-	-
7	19.5	3.9	-1.13	4.859	-	-	-	-	-	-	-	-	-	-
8	18.3	3.7	-0.36	1.548	-	-	-	-	-	-	-	-	-	-
9	17.6	3.1	0.03	-0.129	-	-	-	-	-	-	-	-	-	-
10	17	2.7	0.33	-1.419	-	-	-	-	-	-	-	-	-	-
11	16.5	2.3	0.54	-2.322	-	-	-	-	-	-	-	-	-	-
12	16.2	1.7	0.68	-2.924	-	-	-	-	-	-	-	-	-	-
13	15.8	0.7	0.77	-3.311	-	-	-	-	-	-	-	-	-	-
14	15.5	-0.2	0.86	-3.698	-	-	-	-	-	-	-	-	-	-
15	15.2	-0.4	0.93	-3.999	-	-	-	-	-	-	-	-	-	-
16	15	-0.3	0.95	-4.085	-	-	-	-	-	-	-	-	-	-
17	14.7	-1.1	0.97	-4.171	-	-	-	-	-	-	-	-	-	-
18	14.4	-0.3	0.98	-4.214	-	-	-	-	-	-	-	-	-	-
19	14.2	-0.3	0.95	-4.085	-	-	-	-	-	-	-	-	-	-
20	14	-1.3	0.94	-4.042	-	-	-	-	-	-	-	-	-	-
21	13.7	-1.6	0.93	-3.999	-	-	-	-	-	-	-	-	-	-
22	13.6	-1	0.85	-3.655	-	-	-	-	-	-	-	-	-	-
23	13.4	0	0.75	-3.225	-	-	-	-	-	-	-	-	-	-
24	13.3	1.2	0.65	-2.795	-	-	16.62	1.64	-	-	-	-	-	-
25	13.2	1.9	0.53	-2.279	-	-	16.34	1.55	-	-	-	-	-	-
26	13.2	2.4	0.44	-1.892	-	-	16.08	1.45	-	-	-	-	-	-
27	13.1	2.9	0.37	-1.591	-	-	15.81	1.37	-	-	-	-	-	-
28	13	2	0.34	-1.462	-	-	15.51	1.26	-	-	-	-	-	-
29	12.8	0.8	0.34	-1.462	-	-	15.17	1.12	-	-	-	-	-	-
30	12.6	-0.1	0.37	-1.591	-	-	14.83	0.95	-	-	-	-	-	-
31	12.4	-0.6	0.39	-1.677	-	-	14.53	0.76	-	-	-	-	-	-
32	12.2	-1	0.4	-1.72	-	-	14.28	0.56	-	-	-	-	-	-
33	12	-1	0.4	-1.72	-	-	14.04	0.39	-	-	-	-	-	-
34	11.9	-1.3	0.4	-1.72	-	-	13.83	0.23	-	-	-	-	-	-
35	11.7	-1.3	0.39	-1.677	-	-	13.63	0.08	-	-	-	-	-	-
36	11.6	-1.7	0.38	-1.634	-	-	13.44	-0.07	-	-	-	-	-	-
37	11.4	-2.2	0.38	-1.634	-	-	13.25	-0.19	-	-	-	-	-	-
38	11.2	-2.6	0.37	-1.591	-	-	13.08	-0.29	-	-	-	-	-	-
39	11.1	-2.9	0.37	-1.591	-	-	12.90	-0.39	-	-	-	-	-	-
40	11.7	-2.9	-0.18	0.774	-	-	12.77	-0.50	-	-	-	-	-	-
41	13.4	-3.3	-1.27	5.461	-	-	12.71	-0.59	-	-	-	-	-	-
42	11.8	-3.1	-0.32	1.376	-	-	12.60	-0.71	-	-	-	-	-	-
43	11.3	-3.2	-0.09	0.387	-	-	12.48	-0.83	-	-	-	-	-	-
44	11	-3.6	0.01	-0.043	-	-	12.36	-0.93	-	-	-	-	-	-
45	10.8	-3.4	0.06	-0.258	-	-	12.24	-1.00	-	-	-	-	-	-
46	13.1	-3	-1.56	6.708	-	-	12.22	-1.08	-	-	-	-	-	-
47	12.3	-1.8	-0.95	4.085	-	-	12.17	-1.16	-	-	-	-	-	-
48	11.4	-0.7	-0.49	2.107	-	-	12.09	-1.24	-	-	-	-	-	-
49	11.2	0	-0.4	1.72	-	-	12.01	-1.32	-	-	-	-	-	-
50	11.1	0.9	-0.38	1.634	-	-	11.92	-1.38	-	-	-	-	-	-
51	11	0.9	-0.36	1.548	-	-	11.83	-1.46	-	-	-	-	-	-
52	10.9	0.2	-0.33	1.419	-	-	11.75	-1.54	-	-	-	-	-	-
53	10.8	-0.9	-0.28	1.204	-	-	11.66	-1.61	-	-	-	-	-	-
54	10.6	-1.4	-0.22	0.946	-	-	11.58	-1.66	-	-	-	-	-	-
55	10.5	-1.4	-0.18	0.774	-	-	11.50	-1.70	-	-	-	-	-	-
56	10.6	-1.6	-0.29	1.247	-	-	11.43	-1.72	-	-	-	-	-	-
57	13	-1.8	-1.97	8.471	-	-	11.48	-1.75	-	-	-	-	-	-
58	11.5	-1.8	-0.83	3.569	-	-	11.46	-1.78	-	-	-	-	-	-
59	10.7	-2.2	-0.45	1.935	-	-	11.42	-1.81	-	-	-	-	-	-
60	10.5	-2.8	-0.32	1.376	-	-	11.37	-1.86	-	-	-	-	-	-

n	$T_i(n)$	$T_e(n)$	$\varepsilon(n)$	q(n)	$S_{Ti}(n)$	$S_{Te}(n)$	$\tau_i(n)$	$\tau_e(n)$	δT_i	δT_e	$S_q(n)$	$S_q'(n)$	U(n)	U'(n)
61	10.3	-2.8	-0.23	0.989	-	-	11.33	-1.88	-	-	-	-	-	-
62	12.8	-1.7	-2	8.6	-	-	11.39	-1.85	-	-	-	-	-	-
63	11.9	-1.2	-1.24	5.332	-	-	11.43	-1.78	-	-	-	-	-	-
64	11	-0.6	-0.68	2.924	-	-	11.40	-1.68	-	-	-	-	-	-
65	10.8	-0.5	-0.64	2.752	-	-	11.29	-1.56	-	-	-	-	-	-
66	14.7	-0.3	-3.55	15.265	-	-	11.41	-1.45	-	-	-	-	-	-
67	15.9	-0.1	-4.28	18.404	-	-	11.60	-1.32	-	-	-	-	-	-
68	16.2	-0.3	-4.43	19.049	-	-	11.82	-1.18	-	-	-	-	-	-
69	16.5	-0.3	-4.36	18.748	-	-	12.05	-1.05	-	-	-	-	-	-
70	16.7	-0.1	-4.28	18.404	-	-	12.20	-0.93	-	-	-	-	-	-
71	17.3	0.4	-4.51	19.393	-	-	12.41	-0.84	-	-	-	-	-	-
72	17.8	1.1	-4.6	19.78	-	-	12.68	-0.76	-	-	-	-	-	-
73	18.2	2	-4.51	19.393	-	-	12.97	-0.68	-	-	-	-	-	-
74	18.5	2.7	-4.39	18.877	-	-	13.28	-0.60	-	-	-	-	-	-
75	18.8	2.3	-4.48	19.264	-	-	13.60	-0.55	-	-	-	-	-	-
76	19.7	1.5	-4.73	20.339	-	-	13.97	-0.49	-	-	-	-	-	-
77	20	0.9	-4.61	19.823	-	-	14.35	-0.42	-	-	-	-	-	-
78	20.2	0.7	-4.35	18.705	-	-	14.75	-0.33	-	-	-	-	-	-
79	18	0.6	-2.39	10.277	-	-	15.07	-0.25	-	-	-	-	-	-
80	17.3	0.4	-3	12.9	-	-	15.35	-0.16	-	-	-	-	-	-
81	16.7	0.8	-1.73	7.439	-	-	15.50	-0.05	-	-	-	-	-	-
82	15.6	1	-0.42	1.806	-	-	15.67	0.06	-	-	-	-	-	-
83	15	1.4	-0.05	0.215	-	-	15.85	0.21	-	-	-	-	-	-
84	14.7	2.6	0.09	-0.387	-	-	16.03	0.44	-	-	-	-	-	-
85	14.5	3.9	0.11	-0.473	-	-	16.20	0.72	-	-	-	-	-	-
86	14.4	2.8	0.16	-0.688	-	-	16.27	0.90	-	-	-	-	-	-
87	14.1	2.2	0.22	-0.946	-	-	16.36	1.05	-	-	-	-	-	-
88	13.9	2.6	0.25	-1.075	-	-	16.48	1.18	-	-	-	-	-	-
89	13.9	2.4	0.19	-0.817	-	-	16.61	1.30	-	-	-	-	-	-
90	17.4	3.3	-2.3	9.89	-	-	16.72	1.45	-	-	-	-	-	-
91	18.6	4.7	-3.15	13.545	-	-	16.83	1.65	-	-	-	-	-	-
92	18.6	5.4	-3.18	13.674	-	-	16.93	1.89	-	-	-	-	-	-
93	19.1	5.4	-3.4	14.62	-	-	17.04	2.13	-	-	-	-	-	-
94	19.6	5.8	-3.67	15.781	-	-	17.16	2.37	-	-	-	-	-	-
95	19.7	5.1	-3.38	14.534	-	-	17.26	2.57	-	-	-	-	-	-
96	19.8	5.8	-3.25	13.975	-	-	17.35	2.76	-	-	-	-	-	-
97	18.3	5.3	-1.91	8.213	-	-	17.35	2.90	-	-	-	-	-	-
98	18.2	5.8	-1.74	7.482	-	-	17.34	3.03	-	-	-	-	-	-
99	18.6	5.5	-2.01	8.643	-	-	17.33	3.16	-	-	-	-	-	-
100	18.9	5.2	-2.18	9.374	-	-	17.30	3.32	-	-	-	-	-	-
101	20.1	4.3	-2.87	12.341	-	-	17.30	3.46	-	-	-	-	-	-
102	20.6	3.9	-3.05	13.115	-	-	17.32	3.59	-	-	-	-	-	-
103	18.7	4.4	-1.59	6.837	-	-	17.35	3.75	-	-	-	-	-	-
104	17.3	4.3	-0.53	2.279	-	-	17.35	3.91	-	-	-	-	-	-
105	16.3	4.5	0.03	-0.129	-	-	17.33	4.07	-	-	-	-	-	-
106	15.9	4.1	0.24	-1.032	-	-	17.34	4.20	-	-	-	-	-	-
107	15.6	4.6	0.37	-1.591	-	-	17.37	4.33	-	-	-	-	-	-
108	15.3	4.4	0.48	-2.064	-	-	17.39	4.40	-	-	-	-	-	-
109	15.1	3.8	0.53	-2.279	-	-	17.42	4.40	-	-	-	-	-	-
110	14.9	4.3	0.59	-2.537	-	-	17.44	4.46	-	-	-	-	-	-
111	14.7	4.9	0.6	-2.58	-	-	17.46	4.58	-	-	-	-	-	-
112	14.5	5.2	0.63	-2.709	-	-	17.49	4.68	-	-	-	-	-	-
113	14.6	5.4	0.49	-2.107	-	-	17.52	4.81	-	-	-	-	-	-
114	18.3	6	-2.13	9.159	-	-	17.55	4.92	-	-	-	-	-	-
115	19.5	6.1	-2.94	12.642	-	-	17.59	4.98	-	-	-	-	-	-
116	19.2	5.9	-2.85	12.255	-	-	17.62	5.00	-	-	-	-	-	-
117	19.1	5.5	-2.69	11.567	-	-	17.62	5.00	-	-	-	-	-	-
118	19.6	5.1	-3.07	13.201	-	-	17.62	4.98	-	-	-	-	-	-
119	19.6	4.6	-2.89	12.427	-	-	17.61	4.95	-	-	-	-	-	-
120	19.7	5.2	-2.87	12.341	1832.2	175.9	17.61	4.93	0.99	3.29	548.4	495.6	0.331	0.299
121	19.4	6.7	-2.38	10.234	1831.8	178.6	17.65	4.99	1.31	3.44	550.6	487.7	0.333	0.295
122	19.4	7.5	-2.25	9.675	1831.6	181.3	17.70	5.06	1.63	3.61	553.7	480.8	0.336	0.291
123	19.1	7.8	-1.77	7.611	1831.2	184.3	17.73	5.15	1.92	3.78	555.0	472.8	0.337	0.287
124	19.8	7.6	-2.19	9.417	1830.8	187.2	17.76	5.25	2.25	4.00	556.2	463.1	0.338	0.282
125	20.2	7.7	-2.33	10.019	1830.1	190.7	17.77	5.40	2.60	4.28	556.8	452.0	0.34	0.276

n	$T_i(n)$	$T_e(n)$	$\varepsilon(n)$	q(n)	$S_{Ti}(n)$	$S_{Te}(n)$	$\tau_i(n)$	$\tau_e(n)$	δT_i	δT_e	$S_q(n)$	$S_q'(n)$	U(n)	U'(n)
126	20.1	8.1	-2	8.6	1829.3	194.8	17.75	5.57	2.92	4.63	556.2	439.8	0.34	0.269
127	17.4	8.2	-0.19	0.817	1827.2	199.1	17.69	5.73	3.16	4.97	552.2	426.5	0.339	0.262
128	16.3	8	0.44	-1.892	1825.2	203.4	17.65	5.88	3.38	5.32	548.8	414.4	0.338	0.256
129	15.6	7.3	0.82	-3.526	1823.2	207.6	17.62	6.00	3.58	5.61	545.4	403.2	0.338	0.25
130	15.1	6.8	1.06	-4.558	1821.3	211.7	17.59	6.11	3.76	5.89	542.2	392.9	0.337	0.244
131	14.8	6.7	1.18	-5.074	1819.6	216.1	17.55	6.20	3.93	6.13	539.5	383.8	0.336	0.239
132	14.5	5.8	1.29	-5.547	1817.9	220.2	17.52	6.26	4.08	6.33	536.9	375.2	0.336	0.235
133	14.1	6.1	1.43	-6.149	1816.2	225.6	17.48	6.35	4.23	6.54	534.0	366.8	0.336	0.231
134	13.9	6.1	1.4	-6.02	1814.6	231.9	17.44	6.43	4.36	6.72	531.7	359.3	0.336	0.227
135	13.6	6.3	1.46	-6.278	1813	238.6	17.39	6.49	4.49	6.88	529.4	352.3	0.336	0.224
136	13.5	6.3	1.41	-6.063	1811.5	245.2	17.35	6.53	4.58	7.03	527.4	346.5	0.337	0.221
137	13.5	6.1	1.22	-5.246	1810.3	252.4	17.30	6.56	4.59	7.15	526.4	344.3	0.338	0.221
138	16.5	6	-0.78	3.354	1812.4	258.7	17.23	6.56	4.63	7.27	533.9	350.0	0.344	0.225
139	17.7	5	-1.68	7.224	1815.9	264	17.15	6.52	4.67	7.35	545.2	359.5	0.351	0.232
140	17.9	5.2	-1.92	8.256	1819.8	270.5	17.10	6.49	4.74	7.41	557.5	369.3	0.36	0.238
141	18.6	5.4	-2.61	11.223	1824.7	277.5	17.08	6.48	4.84	7.48	572.8	381.2	0.37	0.246
142	19.2	5.6	-2.94	12.642	1830.3	284.1	17.06	6.50	4.85	7.59	589.1	396.6	0.381	0.257
143	19.3	5.5	-2.91	12.513	1836.2	289.6	17.05	6.54	4.88	7.70	604.8	410.6	0.391	0.265
144	19.6	5.6	-2.95	12.685	1842.5	294	17.05	6.56	4.95	7.80	620.3	423.2	0.401	0.273
145	19.8	5.8	-3.01	12.943	1849.1	297.9	17.06	6.52	5.05	7.84	635.5	435.4	0.41	0.281
146	19.9	6.2	-2.88	12.384	1855.8	301.7	17.08	6.47	5.16	7.85	649.8	446.6	0.418	0.287
147	19.4	6.4	-2.28	9.804	1862.1	305.2	17.10	6.41	5.26	7.87	661.2	455.0	0.425	0.292
148	19.9	6.2	-2.34	10.062	1869	309.4	17.10	6.35	5.35	7.89	672.7	463.9	0.431	0.297
149	20.7	5.7	-2.7	11.61	1876.9	314.3	17.12	6.27	5.46	7.88	685.8	474.2	0.439	0.303
150	20.2	5.2	-2.21	9.503	1884.5	319.6	17.13	6.15	5.55	7.81	696.9	483.4	0.445	0.309
151	18.2	5.4	-0.71	3.053	1890.3	325.6	17.16	6.03	5.66	7.73	701.6	485.7	0.448	0.31
152	16.8	5	0.13	-0.559	1894.9	331.6	17.18	5.90	5.75	7.63	702.7	485.2	0.45	0.31
153	16.2	5.3	0.46	-1.978	1899.1	337.9	17.20	5.82	5.73	7.58	702.5	485.8	0.45	0.311
154	15.9	6.2	0.58	-2.494	1903.1	345.4	17.24	5.80	5.78	7.57	701.7	483.6	0.45	0.31
155	15.8	6	0.63	-2.709	1907.2	352.7	17.28	5.77	5.86	7.58	700.7	480.3	0.451	0.309
156	15.7	5.9	0.61	-2.623	1911.3	360.3	17.33	5.77	5.96	7.63	699.7	476.2	0.451	0.307
157	15.5	6.5	0.62	-2.666	1915.4	369	17.39	5.79	6.06	7.67	698.7	472.0	0.452	0.305
158	15.5	6.4	0.54	-2.322	1919.7	378	17.45	5.80	6.06	7.65	697.9	471.5	0.453	0.306
159	15.5	5.8	0.49	-2.107	1924.1	386.7	17.53	5.78	6.11	7.55	697.4	470.4	0.454	0.306
160	15.4	6.9	0.48	-2.064	1927.8	396.5	17.61	5.80	6.22	7.48	694.6	465.1	0.454	0.304
161	15.4	8.2	0.36	-1.548	1929.8	408	17.69	5.89	6.40	7.45	687.6	453.2	0.452	0.298
162	18.8	8.4	-1.99	8.557	1936.8	419.5	17.79	5.99	6.38	7.44	694.8	461.2	0.458	0.304
163	19.8	8.3	-2.72	11.696	1945.3	431	17.88	6.13	6.28	7.45	706.1	475.3	0.466	0.314
164	19.4	8.2	-2.47	10.621	1953.7	442.8	17.94	6.25	6.12	7.43	716.7	490.3	0.474	0.325
165	19.4	8.5	-2.41	10.363	1962.3	454.7	17.97	6.38	5.92	7.43	727.3	506.5	0.482	0.336
166	19.8	9	-2.63	11.309	1969	466.7	18.00	6.53	5.79	7.45	731.9	514.4	0.487	0.342
167	19.5	9.5	-2.29	9.847	1976.2	478	18.00	6.69	5.59	7.53	737.7	525.1	0.492	0.351
168	19.5	10.3	-2.11	9.073	1984.3	489	18.00	6.89	5.32	7.65	744.7	538.6	0.498	0.36
169	19.3	10.1	-1.88	8.084	1992.4	499.1	17.98	7.07	5.01	7.75	751.0	552.9	0.503	0.37
170	19.2	8.8	-1.64	7.052	2000.5	507	17.95	7.18	4.67	7.78	756.5	567.3	0.506	0.38
171	19	7.7	-1.37	5.891	2008.5	513.8	17.93	7.23	4.33	7.78	760.8	581.1	0.509	0.389
172	19.4	7.3	-1.48	6.364	2017	520.9	17.91	7.28	3.94	7.77	765.7	596.8	0.512	0.399
173	19.4	7.1	-1.32	5.676	2025.6	528.9	17.86	7.33	3.50	7.75	770.2	613.5	0.515	0.41
174	17.7	6.8	-0.26	1.118	2032.7	537.1	17.75	7.40	3.00	7.73	770.4	627.8	0.515	0.42
175	17.8	6.6	-0.35	1.505	2040	545.1	17.74	7.45	2.67	7.70	771.1	637.8	0.516	0.427
176	17.4	6.1	-0.08	0.344	2046.8	552.8	17.76	7.50	2.42	7.66	770.2	644.2	0.516	0.431
177	16.8	5.9	0.28	-1.204	2050.6	560.5	17.79	7.52	2.29	7.58	760.5	638.8	0.51	0.429
178	16.7	5.7	0.33	-1.419	2055.8	568	17.82	7.50	2.15	7.44	755.6	638.6	0.508	0.429
179	16.3	5.3	0.53	-2.279	2061.4	575.5	17.84	7.47	1.99	7.26	751.3	640.2	0.506	0.431
180	15.9	4.6	0.67	-2.881	2066.8	582.9	17.85	7.42	1.83	6.98	747.1	642.7	0.503	0.433
181	15.9	4.3	0.65	-2.795	2072.4	590	17.87	7.33	1.67	6.61	743.3	646.1	0.501	0.436
182	15.7	4.6	0.7	-3.01	2075.3	596.3	17.88	7.25	1.61	6.35	731.7	638.2	0.495	0.431
183	15.5	4.4	0.71	-3.053	2078.9	601.9	17.88	7.19	1.52	6.15	723.3	633.9	0.49	0.429
184	15.3	4.3	0.72	-3.096	2083.2	606.8	17.87	7.08	1.39	5.90	717.3	633.2	0.486	0.429
185	15.2	4.2	0.71	-3.053	2087.6	611.5	17.86	6.92	1.25	5.62	711.5	633.4	0.482	0.429
186	15	4.3	0.68	-2.924	2087.9	616.1	17.70	6.75	0.98	5.30	693.3	625.1	0.471	0.425
187	14.8	4.3	0.67	-2.881	2086.8	620.5	17.50	6.58	0.66	4.93	672.0	615.5	0.458	0.42
188	14.7	4.5	0.66	-2.838	2085.3	625.3	17.30	6.43	0.37	4.54	650.1	604.9	0.445	0.414
189	14.5	4.3	0.66	-2.838	2083.3	629.9	17.10	6.25	0.05	4.13	628.5	595.1	0.432	0.409
190	14.4	4.5	0.6	-2.58	2081	634.5	16.87	6.06	-0.29	3.69	607.5	587.0	0.42	0.406

n	$T_i(n)$	$T_e(n)$	$\varepsilon(n)$	q(n)	$S_{Ti}(n)$	$S_{Te}(n)$	$\tau_i(n)$	$\tau_e(n)$	δT_i	δT_e	$S_q(n)$	$S_q'(n)$	U(n)	U'(n)
191	14.3	4.6	0.54	-2.322	2078	638.7	16.65	5.86	-0.61	3.29	585.8	577.1	0.407	0.401
192	14.2	4.8	0.47	-2.021	2074.4	642.4	16.43	5.63	-0.91	2.87	564.0	567.0	0.394	0.396
193	14.1	5	0.43	-1.849	2070.3	645.4	16.22	5.42	-1.13	2.52	542.8	554.6	0.381	0.389
194	14	5.3	0.39	-1.677	2065.8	648	16.00	5.27	-1.34	2.24	522.2	541.8	0.368	0.382
195	13.9	4.9	0.37	-1.591	2060.9	650.6	15.79	5.15	-1.54	1.99	501.4	528.5	0.356	0.375
196	13.8	5.1	0.38	-1.634	2055	654.2	15.55	5.06	-1.74	1.75	479.4	513.9	0.342	0.367
197	13.6	4.7	0.41	-1.763	2048.6	658	15.31	4.96	-1.99	1.50	457.8	501.0	0.329	0.36
198	13.5	4.7	0.38	-1.634	2041.9	662	15.14	4.88	-2.18	1.28	437.5	487.7	0.317	0.353
199	13.4	4.7	0.37	-1.591	2037.3	666.1	14.95	4.80	-2.39	1.05	425.6	483.5	0.31	0.353
200	13.3	4.5	0.33	-1.419	2033.3	670.2	14.78	4.73	-2.56	0.82	411.3	475.7	0.302	0.349
201	13.2	4.3	0.31	-1.333	2029.8	673.7	14.63	4.66	-2.70	0.60	402.5	472.3	0.297	0.348
202	13.2	4.5	0.27	-1.161	2027.4	677.2	14.49	4.61	-2.85	0.42	399.6	475.1	0.296	0.352
203	13.1	4.5	0.23	-0.989	2025.5	680.3	14.35	4.58	-3.01	0.25	398.4	479.5	0.296	0.356
204	13	4.4	0.2	-0.86	2023.8	682.1	14.23	4.57	-3.16	0.17	397.9	483.7	0.297	0.361
205	13	3.9	0.17	-0.731	2022.3	682.1	14.11	4.55	-3.30	0.15	397.6	487.6	0.297	0.364
206	12.8	3.9	0.18	-0.774	2020.7	683.2	13.99	4.53	-3.45	0.06	397.5	492.1	0.297	0.368
207	12.7	4	0.2	-0.86	2019.3	685	13.88	4.51	-3.59	-0.07	397.6	497.1	0.298	0.373
208	12.6	4	0.18	-0.774	2018	686.4	13.76	4.50	-3.73	-0.19	397.9	502.1	0.299	0.377
209	12.6	4.2	0.14	-0.602	2016.7	688.2	13.65	4.50	-3.86	-0.31	398.1	507.1	0.3	0.382
210	12.5	4	0.1	-0.43	2011.8	688.9	13.55	4.48	-4.00	-0.44	387.8	501.7	0.293	0.379
211	12.4	4.4	0.09	-0.387	2005.6	688.6	13.45	4.49	-4.14	-0.49	373.9	491.9	0.284	0.374
212	12.4	4.3	0.05	-0.215	1999.4	687.5	13.35	4.48	-4.26	-0.52	360.0	481.6	0.274	0.367
213	12.4	4.5	-0.04	0.172	1992.7	686.6	13.27	4.49	-4.35	-0.52	345.5	469.5	0.265	0.36
214	15.3	5.1	-1.99	8.557	1988.4	685.9	13.30	4.51	-4.31	-0.46	338.3	460.9	0.26	0.354
215	16.2	5	-2.57	11.051	1984.9	685.8	13.38	4.53	-4.23	-0.43	334.8	454.8	0.258	0.35
216	16.9	5.2	-3.01	12.943	1982	685.2	13.50	4.55	-4.11	-0.38	333.8	450.2	0.257	0.347
217	15.9	5.7	-2.21	9.503	1979.6	685.6	13.57	4.58	-4.08	-0.41	335.1	450.9	0.259	0.348
218	14.2	6.1	-1.03	4.429	1975.6	685.9	13.58	4.61	-4.13	-0.45	332.0	449.3	0.257	0.348
219	13.8	6.1	-0.75	3.225	1970.8	686.5	13.58	4.66	-4.15	-0.50	326.6	444.9	0.254	0.346
220	13.7	6.2	-0.57	2.451	1965.6	687.5	13.57	4.70	-4.19	-0.55	319.7	439.6	0.25	0.344
221	13.5	6.2	-0.45	1.935	1959	689.4	13.57	4.77	-4.20	-0.63	309.3	430.0	0.244	0.339
222	13.5	5.6	-0.37	1.591	1951.9	691.1	13.57	4.80	-4.18	-0.77	297.8	419.0	0.236	0.332
223	13.4	5.7	-0.29	1.247	1946.6	692.4	13.57	4.85	-4.13	-0.88	292.2	412.8	0.233	0.329
224	13.3	6.1	-0.24	1.032	1942.6	694.2	13.57	4.91	-4.08	-0.97	290.9	411.1	0.233	0.329
225	13.2	6.2	-0.19	0.817	1939.5	695.9	13.57	4.99	-4.05	-1.01	291.9	411.5	0.235	0.331
226	13.1	6.4	-0.15	0.645	1936.7	698.2	13.56	5.07	-4.03	-1.04	293.6	412.7	0.237	0.333
227	13.1	6.4	-0.12	0.516	1934.2	700	13.56	5.15	-3.99	-1.05	295.7	413.9	0.24	0.335
228	13	6.2	-0.1	0.43	1931.9	701.8	13.56	5.23	-3.96	-1.03	298.2	415.4	0.242	0.338
229	12.9	5.8	-0.08	0.344	1929.7	703.8	13.56	5.30	-3.92	-1.05	300.8	417.1	0.245	0.34
230	12.9	4.5	-0.08	0.344	1927.7	704	13.56	5.33	-3.88	-1.10	303.7	419.1	0.248	0.342
231	12.8	4.4	-0.05	0.215	1925.8	703.5	13.57	5.35	-3.83	-1.14	306.5	420.8	0.251	0.344
232	12.7	4.7	-0.03	0.129	1924	703	13.57	5.38	-3.78	-1.16	309.3	422.5	0.253	0.346
233	12.7	5	-0.03	0.129	1922.1	702.6	13.58	5.41	-3.73	-1.15	311.5	423.3	0.255	0.347
234	12.5	4.9	-0.01	0.043	1916.3	701.5	13.58	5.45	-3.65	-1.12	302.4	411.9	0.249	0.339
235	13	5.2	-0.4	1.72	1909.8	700.6	13.60	5.48	-3.55	-1.04	291.5	397.6	0.241	0.329
236	16.7	5.8	-3.33	14.319	1907.3	700.5	13.78	5.54	-3.32	-0.95	293.6	392.5	0.243	0.325
237	17.4	5.7	-3.69	15.867	1905.6	700.7	13.99	5.59	-3.09	-0.89	297.9	390.1	0.247	0.324
238	17.8	6.2	-3.78	16.254	1903.8	701.8	14.09	5.64	-2.97	-0.87	300.9	389.6	0.25	0.324
239	18.2	6.7	-3.85	16.555	1902.4	703.9	14.18	5.71	-2.88	-0.83	305.0	390.8	0.255	0.326
240	18.9	6.5	-4.1	17.63	1901.6	705.2	14.26	5.76	-2.79	-0.80	310.3	393.4	0.259	0.329
241	19	6.8	-3.81	16.383	1901.2	705.3	14.39	5.81	-2.68	-0.71	316.5	395.8	0.265	0.331
242	18.9	7.2	-3.42	14.706	1900.7	705	14.58	5.85	-2.50	-0.61	321.5	395.2	0.269	0.331
243	18.8	8	-3.02	12.986	1900.4	705.2	14.79	5.93	-2.30	-0.47	326.9	394.1	0.273	0.33
244	19.1	8.4	-3.13	13.459	1899.7	706	15.02	6.03	-2.08	-0.32	330.9	390.9	0.277	0.327
245	20.6	8.3	-4.02	17.286	1900.1	706.6	15.31	6.11	-1.81	-0.15	338.2	389.3	0.283	0.326
246	21.2	7.8	-4.04	17.372	1901.2	706.3	15.63	6.20	-1.49	0.06	347.0	387.7	0.29	0.324
247	19	7.7	-2.01	8.643	1902.8	705.8	15.87	6.29	-1.29	0.26	354.8	388.4	0.296	0.324
248	17.8	7.4	-1.06	4.558	1904.3	705.2	16.05	6.34	-1.12	0.44	361.2	388.9	0.301	0.324
249	17.3	7.3	-0.66	2.838	1906	705.2	16.23	6.39	-0.98	0.57	367.6	390.2	0.306	0.325
250	16.9	7.3	-0.38	1.634	1907.8	705.7	16.38	6.43	-0.85	0.63	373.8	392.5	0.311	0.327
251	16.6	7.4	-0.17	0.731	1909.6	706.4	16.53	6.47	-0.75	0.70	379.6	394.9	0.315	0.328
252	16.4	7.3	-0.05	0.215	1911.5	707.9	16.67	6.51	-0.66	0.74	385.4	397.8	0.32	0.33
253	16.2	7.6	0.06	-0.258	1913.6	709.4	16.81	6.59	-0.58	0.80	391.3	401.0	0.325	0.333
254	15.9	8.1	0.13	-0.559	1915.6	711.4	16.93	6.74	-0.52	0.94	396.7	403.8	0.329	0.335
255	15.9	8.7	0.14	-0.602	1917.9	713.8	17.06	6.92	-0.47	1.14	402.4	406.6	0.334	0.338

n	$T_i(n)$	$T_e(n)$	$\varepsilon(n)$	q(n)	$S_{Ti}(n)$	$S_{Te}(n)$	$\tau_i(n)$	$\tau_e(n)$	δT_i	δT_e	$S_q(n)$	$S_q'(n)$	U(n)	U'(n)
256	15.8	9.1	0.16	-0.688	1920.2	716.6	17.19	7.10	-0.42	1.30	407.8	409.3	0.339	0.34
257	15.8	9.4	0.09	-0.387	1922.5	719.9	17.32	7.28	-0.37	1.39	412.6	412.1	0.343	0.343
258	19.3	9.3	-2.38	10.234	1925.3	723.2	17.60	7.47	-0.18	1.48	419.5	413.1	0.349	0.344
259	20.4	8.9	-3.11	13.373	1928	727.1	17.91	7.62	0.04	1.49	425.7	413.1	0.354	0.344
260	20.3	8.9	-3.01	12.943	1930.4	730.8	18.06	7.75	0.13	1.50	430.3	415.3	0.359	0.346
261	19.8	8.6	-2.59	11.137	1931.6	734	18.16	7.87	0.19	1.49	430.3	413.4	0.359	0.345
262	20	8.6	-2.66	11.438	1932.4	737	18.25	7.97	0.26	1.45	429.1	410.7	0.359	0.344
263	20	8.5	-2.41	10.363	1933.1	740	18.33	8.05	0.32	1.35	426.9	407.4	0.358	0.342
264	19.8	8.2	-2.12	9.116	1933.3	742.6	18.37	8.12	0.37	1.23	423.3	403.7	0.356	0.339
265	19.3	8.8	-1.59	6.837	1932.8	745.6	18.38	8.20	0.40	1.13	417.2	397.4	0.351	0.335
266	19.4	8.9	-1.5	6.45	1932.3	748.3	18.40	8.27	0.45	1.10	411.3	390.4	0.347	0.33
267	19.2	9.2	-1.4	6.02	1932.1	751.1	18.42	8.32	0.48	1.09	407.5	385.7	0.345	0.327
268	19.6	8.8	-1.48	6.364	1931.8	753.7	18.44	8.34	0.53	1.06	403.8	381.1	0.343	0.323
269	20.6	8.6	-2.09	8.987	1931.7	756.6	18.44	8.35	0.58	1.02	401.2	377.3	0.341	0.321
270	20.7	8.6	-2.07	8.901	1932.2	760	18.42	8.38	0.66	0.98	400.6	374.7	0.342	0.32
271	19.2	8.3	-0.86	3.698	1933.2	762.9	18.43	8.41	0.69	0.96	401.2	374.8	0.343	0.32
272	18.4	8.2	-0.27	1.161	1934.8	766.1	18.45	8.44	0.69	0.95	403.0	376.7	0.345	0.322
273	18	8.1	-0.01	0.043	1936.6	768.9	18.48	8.48	0.69	0.95	405.0	378.5	0.347	0.324
274	17.6	7.8	0.17	-0.731	1938.3	770.5	18.51	8.50	0.69	1.00	406.7	380.1	0.348	0.325
275	17.4	7.5	0.28	-1.204	1939.9	772	18.54	8.50	0.70	1.03	408.2	381.0	0.35	0.326
276	17.1	7	0.39	-1.677	1941.3	773.1	18.57	8.49	0.72	1.07	409.2	381.0	0.35	0.326
277	16.8	6.5	0.47	-2.021	1942.6	773.1	18.60	8.44	0.73	1.12	409.8	381.1	0.35	0.326
278	16.6	5.9	0.55	-2.365	1943.7	772.6	18.63	8.35	0.75	1.10	409.8	380.6	0.35	0.325
279	16.2	5.3	0.66	-2.838	1944.4	772.1	18.64	8.21	0.76	1.02	409.1	380.1	0.349	0.324
280	16	5.6	0.71	-3.053	1945	770.8	18.65	8.06	0.77	0.98	408.1	379.1	0.348	0.323
281	16	5.6	0.64	-2.752	1945.6	768.2	18.65	7.90	0.79	0.99	406.9	377.4	0.346	0.321
282	19.6	5.7	-1.91	8.213	1946.4	765.5	18.67	7.75	0.96	1.01	406.5	372.2	0.344	0.315
283	20.7	5.7	-2.65	11.395	1947.3	762.9	18.68	7.62	1.18	1.04	406.2	365.5	0.343	0.309
284	20.6	6.4	-2.64	11.352	1948.5	761.1	18.69	7.52	1.39	1.09	407.0	360.1	0.343	0.303
285	20.4	6.6	-2.45	10.535	1949.5	759.2	18.72	7.43	1.62	1.18	407.1	353.2	0.342	0.297
286	20.5	6.8	-2.49	10.707	1950.2	757	18.74	7.36	1.87	1.30	406.5	345.0	0.341	0.289
287	19.5	7.3	-1.56	6.708	1950.2	754.8	18.72	7.31	2.06	1.45	403.4	335.3	0.337	0.28
288	19.4	7.7	-1.54	6.622	1950.1	752.2	18.70	7.29	2.27	1.66	400.9	325.6	0.335	0.272
289	19.2	7.8	-1.29	5.547	1950	749.9	18.70	7.25	2.48	1.83	398.4	315.8	0.332	0.263
290	19.1	8	-1.16	4.988	1949.9	749.1	18.68	7.21	2.68	1.94	396.3	307.3	0.33	0.256
291	19	7.8	-1.08	4.644	1949.9	749.2	18.68	7.15	2.89	2.00	395.1	300.0	0.329	0.25
292	20	7.6	-1.73	7.439	1950.5	749.5	18.69	7.10	3.14	2.04	396.2	293.8	0.33	0.245
293	20.5	7.7	-1.9	8.17	1951.6	750.1	18.69	7.06	3.38	2.10	398.7	289.3	0.332	0.241
294	20.5	7.4	-1.76	7.568	1954.4	750.7	18.68	7.01	3.54	2.14	405.1	290.8	0.337	0.242
295	19	7.4	-0.65	2.795	1955.6	751.5	18.67	6.98	3.72	2.18	406.4	287.0	0.338	0.238
296	18.3	7.3	-0.25	1.075	1956.5	752.7	18.67	6.94	3.88	2.21	407.1	282.9	0.338	0.235
297	17.8	7.1	0.04	-0.172	1957.5	753.9	18.66	6.90	4.03	2.23	408.2	279.8	0.339	0.232
298	17.4	6.8	0.23	-0.989	1958.2	755	18.65	6.85	4.16	2.24	408.6	276.4	0.34	0.23
299	17.2	6.6	0.33	-1.419	1959.1	756.3	18.64	6.82	4.29	2.24	409.4	273.8	0.34	0.228
300	16.9	6.4	0.39	-1.677	1960.1	758.1	18.63	6.79	4.40	2.22	410.7	272.1	0.342	0.226
301	16.8	6.3	0.43	-1.849	1961	760.1	18.63	6.78	4.52	2.23	411.6	269.6	0.343	0.225
302	16.6	6.2	0.46	-1.978	1961.9	761.7	18.63	6.80	4.64	2.27	412.6	267.0	0.344	0.222
303	16.4	6.1	0.47	-2.021	1962.8	763.4	18.64	6.83	4.77	2.32	413.7	264.2	0.345	0.22
304	16.2	6.3	0.46	-1.978	1963.7	765.4	18.65	6.86	4.89	2.36	414.8	261.7	0.346	0.218
305	16.1	6.2	0.46	-1.978	1964.6	767.4	18.65	6.88	5.00	2.39	415.9	259.4	0.347	0.217
306	16.1	6.2	0.31	-1.333	1965.7	769.3	18.51	6.90	4.96	2.42	417.4	261.9	0.349	0.219
307	16.5	5.7	0	0	1967.4	770.7	18.33	6.90	4.88	2.42	420.3	266.9	0.351	0.223
308	20.5	5.3	-3.24	13.932	1973.2	771.5	18.33	6.86	4.98	2.38	437.1	281.4	0.364	0.234
309	19.8	5.8	-2.48	10.664	1978.5	773	18.30	6.83	5.04	2.34	450.6	293.5	0.374	0.243
310	19.9	6.2	-2.52	10.836	1984	774.7	18.28	6.80	4.98	2.29	464.0	309.1	0.384	0.256
311	20.1	6.7	-2.43	10.449	1989.8	776.8	18.30	6.78	4.92	2.25	476.8	323.6	0.393	0.267
312	19.9	7	-2.14	9.202	1995.5	779	18.33	6.75	4.83	2.20	488.0	337.7	0.401	0.278
313	20.1	7.5	-2.26	9.718	2001.5	781.5	18.36	6.73	4.79	2.16	499.6	350.7	0.409	0.287
314	19.8	6.9	-1.85	7.955	2007.3	783.1	18.39	6.69	4.81	2.08	509.2	360.3	0.416	0.294
315	19.4	6.4	-1.46	6.278	2012.8	784.6	18.41	6.63	4.83	1.97	517.1	368.5	0.421	0.3
316	19.6	6.4	-1.55	6.665	2018.6	785.9	18.39	6.58	4.82	1.88	525.4	377.9	0.426	0.307
317	19.7	6	-1.5	6.45	2024.7	787.2	18.36	6.51	4.79	1.74	533.6	387.9	0.431	0.313
318	19.8	6	-1.5	6.45	2031	788.5	18.33	6.45	4.76	1.65	541.7	397.5	0.436	0.32
319	18.5	5.9	-0.58	2.494	2036.1	789.7	18.31	6.39	4.74	1.54	545.8	403.0	0.438	0.323
320	17.5	5.6	-0.02	0.086	2040.3	790.8	18.28	6.32	4.71	1.40	547.3	406.5	0.438	0.325

321	17.2	5.8	0.18	-0.774	2044.3	792.3	18.25	6.26	4.68	1.27	547.8	408.8	0.438	0.327
322	16.9	6.1	0.28	-1.204	2048	793.9	18.23	6.23	4.67	1.16	547.8	410.0	0.437	0.327
323	16.7	6.1	0.36	-1.548	2051.6	795.5	18.21	6.21	4.65	1.06	547.2	410.8	0.436	0.327
324	16.5	6.2	0.41	-1.763	2055.1	797.3	18.19	6.20	4.63	0.98	546.3	411.0	0.434	0.327
325	16.3	6	0.48	-2.064	2058.4	799.4	18.17	6.19	4.61	0.89	545.0	410.9	0.433	0.326
326	16.1	5.9	0.49	-2.107	2061.7	801.4	18.15	6.18	4.59	0.85	543.6	410.5	0.431	0.326
327	16	5.8	0.49	-2.107	2065	803.2	18.13	6.17	4.57	0.82	542.4	410.1	0.43	0.325
328	15.8	5.7	0.53	-2.279	2068.2	804.9	18.12	6.14	4.55	0.77	540.9	409.6	0.428	0.324
329	15.8	5.5	0.46	-1.978	2071.4	806.2	18.10	6.11	4.53	0.70	539.5	409.1	0.426	0.323
330	18.8	5.3	-1.56	6.708	2077.7	807.5	18.22	6.08	4.64	0.63	546.7	413.7	0.43	0.326
331	19.6	5.3	-2.15	9.245	2084.9	808.4	18.35	6.06	4.75	0.58	556.3	420.9	0.436	0.33
332	19.8	5.3	-2.42	10.406	2092.3	809.4	18.32	6.06	4.54	0.52	566.9	437.7	0.442	0.341
333	19.5	5.6	-2.29	9.847	2099.4	810.5	18.30	6.05	4.32	0.46	576.6	454.0	0.447	0.352
334	19.7	6	-2.37	10.191	2103.8	811.4	18.30	6.04	4.20	0.40	578.2	459.1	0.447	0.355
335	19.3	6.3	-1.89	8.127	2106.9	812.7	18.26	6.03	4.09	0.32	575.3	460.1	0.445	0.356
336	19.2	6.8	-1.79	7.697	2109.2	814.3	18.23	6.02	3.98	0.25	570.1	458.4	0.44	0.354

Appendix C : Precision of U-value over shorter periods

A brief analysis of data from the U-value measurements was carried out to determine how much information was necessary in order to obtain a reliable measurement of a the U-value of a given building element. The data, based on walls constructed since 1995, indicated that the precision of the U-value was dependent on the type of wall construction studied. For each wall, the U-value was calculated using consecutive 5-day periods of data and the variation of the calculated U-values for the given wall was observed. This variation, expressed as a standard deviation, could vary between 0.02 W/m²K and 0.10 W/m²K. The lower variations were associated with lightweight structures such as timber frame walls whilst the higher variations corresponded to walls with dense concrete inner leaves.

The 5-day U-values were studied for several of the measurements in order to determine to what precision a U-value could be determined from just 5 days of data. The standard deviations of the 5-day U-values are shown in the following table:

Case	U (5-day)	standard dev. (5-day U)*	relative precision	construction
1	0.69	0.04	0.06	int. ins.
7	0.39	0.05	0.13	int. ins.
4A	0.46	0.10	0.22	masonry
4B	0.31	0.05	0.16	masonry
4C	0.48	0.07	0.15	masonry
5	0.40	0.02	0.05	masonry
10A	0.57	0.03	0.05	masonry
10B	0.48	0.02	0.04	masonry
8	0.32	0.05	0.16	masonry
6A	0.45	0.10	0.22	masonry
6B	0.36	0.09	0.25	masonry
9A	0.62	0.04	0.06	masonry
9B	0.57	0.03	0.05	masonry
3	0.36	0.03	0.08	timb. frame
12	0.27	0.03	0.11	timb. frame

* standard deviation of U-value without thermal mass corrections

It is notable from the table that the walls with the highest standard deviations (i.e. poorest precision) are all of a heavy construction type and that the walls with low standard deviations are mostly of either a light construction type or are internally-insulated. The table shows that if the U-value is measured over only 5 days, the precision, which is an indicator of the measurement error, varies from about 10% for lightweight constructions up to about 25% for some heavyweight wall constructions. This would appear to indicate that the measurement time required for lightweight constructions, such as timber framed constructions, is considerably less than the measurement time necessary in order to obtain an accurate measurement of the U-value.

Further analysis is being carried out to examine in more detail the relationship between measurement precision, length of measurement and type of wall construction and more detailed conclusions should be available for the final report.

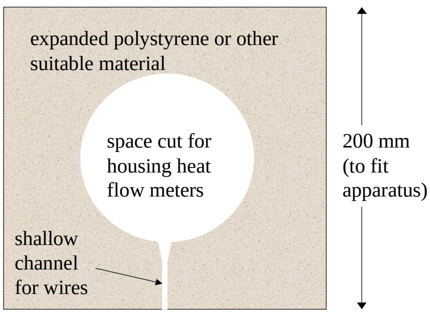
Appendix D : Calibration of heat flux meters

As part of the project, Gearing Scientific were commissioned to carry out calibration tests of the heat flux meters using apparatus which is normally designed for measuring thermal conductivities. The results give an indication of the influence of the metal disks on the measured heat loss and assist in determining whether any significant calibration drifts had occurred since the heat flux meters were manufactured.

Further consideration has to be given to the results of the calibrations, which may involve additional thermal modelling, however preliminary indications are that the calibration constants have drifted relatively little in all cases. The results suggest that the U-value correction factors for the metal plates should be 0.86 for the grey heat flow meters and 0.89 for the black heat flow meters, however these factors may need to be revised in the light of more detailed analysis.

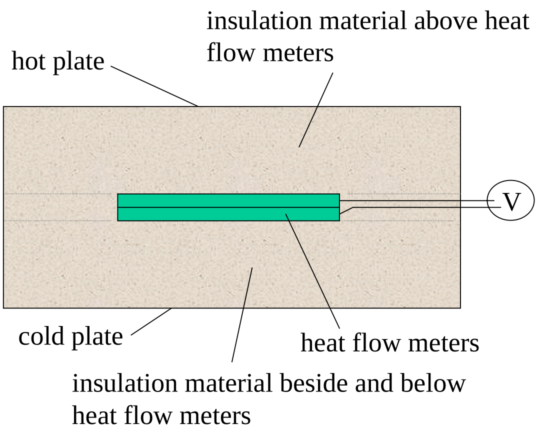
The following describes how the calibration of heat flux meters were carried out by Gearing Scientific using the thermal conductivity instrument. The heat flux meters were tested in pairs in order to save time and the pairs were bonded together (by BRE) to ensure that there was good thermal contact between them.

Each sample was encased or embedded in the insulation material with a circle cut from the centre of the insulation material in order to house the sample, as illustrated. The heat flux meters, around 100 – 105 mm in diameter and each bonded pair of heat flux meters was approximately 6 mm thick.



As indicated in the diagram a small channel of approximately 2 mm deep, was cut in order to house the wires leading from the pair of heat flux meters.

Approximately 10 mm of insulation was placed both above and below the heat flux meters so that the overall heat flux would not be too high or too low. The material surrounding the heat flux meters was cut and placed in such a way that there was reasonable thermal contact on all sides between the heat flux meters and the surrounding insulation.



The materials and the thicknesses of insulation material surrounding the heat flux meters were noted carefully in order to enable computer modelling of the measurement to be carried out by BRE.

The hot plate were set to appropriate fixed temperatures in order to achieve the correct average temperature as well as to achieve a suitable level of heat flux. This was done so that the heat flux would be of the same order of magnitude as it would be under the normal operation of the heat flux meters.

The two terminals of a heat flux meter were connected to a Thurlby 1906 Computing Multimeter using crocodile clips attached to the appropriate sockets. The 9-hole socket at the back of the multimeter was connected to a serial port of a PC using the connecting cable provided. The program “HFMcalib.EXE”, written by BRE, was then executed on the PC while the thermal conductivity measurement was carried out. This program recorded the output signals from the heat flow meters in order to observe their variation and the data were subsequently compared with the heat flow information supplied by the thermal conductivity apparatus.

The “HFMcalib.EXE” program was then re-run with the multimeter connected to the terminals of the second heat flux meter instead of the first in order to determine its parameters.

The following pairs of heat flux meters were tested

Test no.	Pair tested (identification numbers)	With or without metal plates attached
insulation material only	-	-
1(a)	31.2402; 31.2405	without
1(b)	31.2402; 31.2405	with
2	31.2189; HFM 22	with
3	31.2104; HFM 16	with
4	430144; 430145	with

Appendix E : The measurement procedure

The in-situ measurements were carried out using circular disk heat flow meters. These meters, constructed of PVC and incorporating embedded thermocouple junctions, are designed to generate an emf signal which is proportional to the heat flow through the disk. The heat flux meters were used to determine the level of heat flux, or heat current density (in W/m²), passing through each wall or ceiling, and together with the recorded temperatures, enabled U-values to be determined. The heat flux meters which were used were approximately 100 mm in diameter and 3 mm thick and the output emf signals generated by the heat flux meters were recorded using Squirrel data loggers. In order to assist in providing adequate thermal contact, particularly in the case of sloping ceilings, the disks were bonded to thin metal disks to provide better rigidity. The measurements were carried out mainly in occupied dwellings and the heat flux meters were pressure-fixed against the element in a way which enabled damage to internal finishings to be avoided through the use of a purpose-designed pulley system. Since in many cases the internal surface was uneven (e.g. wallpapers or pitted plasterboard surfaces) a substrate made of a silicone-clay compound was applied as a substrate to the heat flux meters in order to improve the thermal contact, and hence the accuracy of the measurements. Prior to locating each heat flux meter, measures were taken to avoid placing the meter over repeating thermal bridges such as battens or plaster dabs, however as a result of this care had to be taken in calculating the expected U-value in an appropriate way, but still based on the methodology of BS EN ISO 6946.

Internal and external temperatures were measured using type T thermocouples coated with fresh solder to provide a low emissivity surface. The thermocouple wire had the advantage of being sufficiently thin to pass through closed windows and doors as necessary. In some cases thermocouple readings were backed up by readings from alternative devices such as thermistor-based logging devices, however no major discrepancies between the two methods of temperature measurement occurred.

In order to check the accuracy of the nominal calibrations of the heat flux meters, calibration tests were carried out in October 1999 by Gearing Scientific, using a thermal conductivity device. A description of how the calibration tests were carried out is presented in Appendix D. The results of these recalibrations have still to be analysed fully but preliminary analysis suggests that small adjustments to the heat fluxes measured by the heat flux meters may be appropriate. More information on this is given in the Appendix.

Corrections were applied to the U-value measurements to compensate for a number of factors including thermal storage, calibration shifts and the effects of the metal plate and substrate. The thermal storage effects were corrected for using the procedure given in ISO 9869 and involved the application of the F_i and F_e thermal mass factors calculated from the details of the element’s construction. The calibration shifts were determined from measurements carried out by

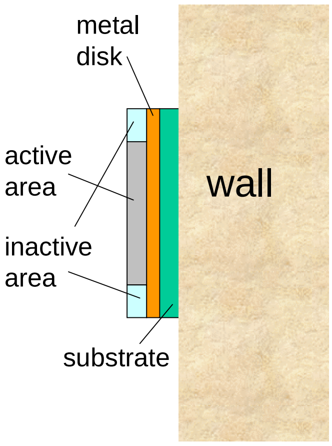
Gearing Scientific, whilst the effects of the metal plate and substrates were corrected for using finite-element analysis.

In addition to the corrections which were applied various sources of random error have been identified and applied to the data. The estimated random errors in the final U-values were based upon the following contributions:

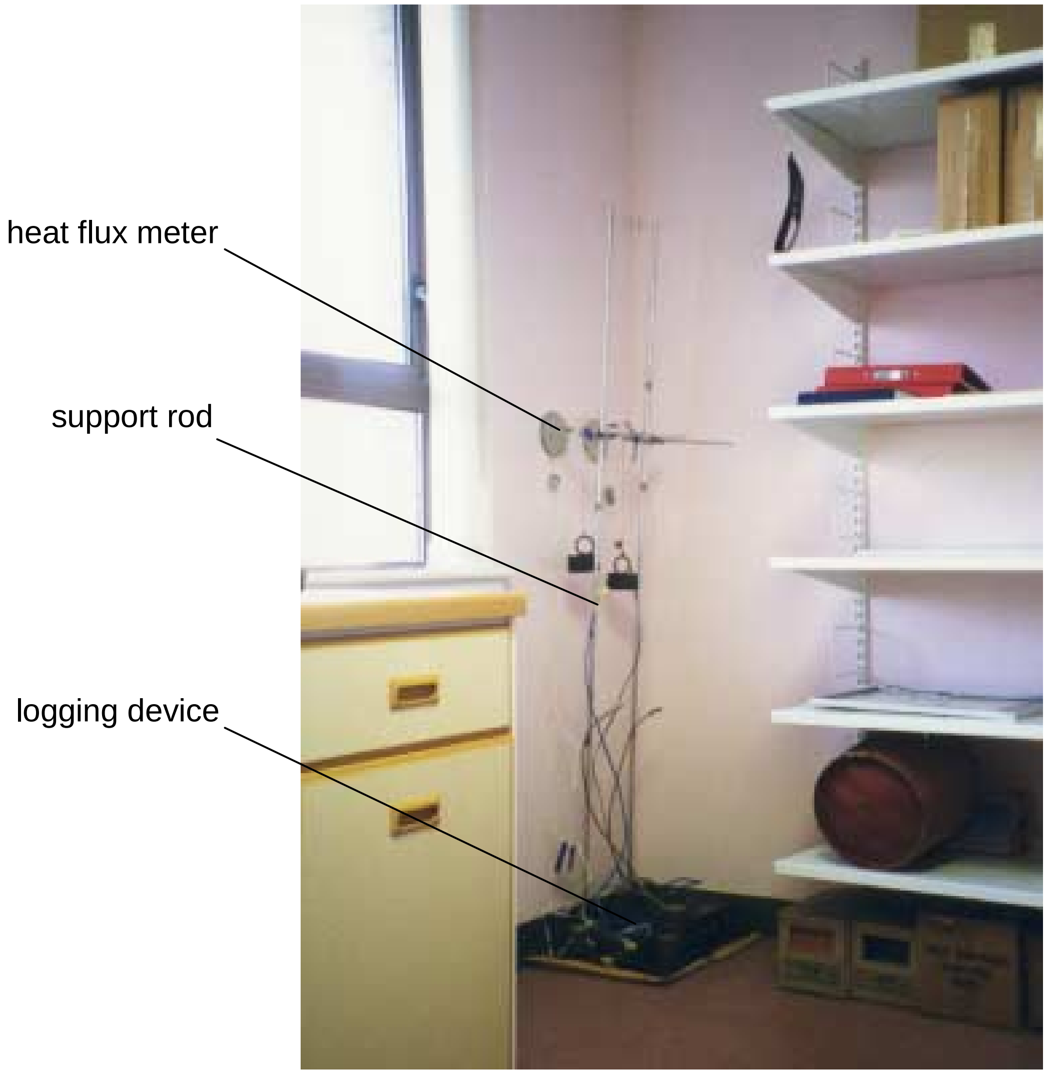
1. Intrinsic calibration of the heat flow meter – 5% (based on the nominal calibrations).
2. Correction for thermal storage effects – 5% (due to uncertainties in the determination of the F_i and F_e factors)
3. Correction for in-situ use – 2% (due to errors in the results obtained from thermal modelling of the metal plate and substrates)
4. Accuracy of temperature difference – 3% (related to the resolution of the logging device)
5. Repeatability of system – 10% (related to the practicality of ensuring a good thermal contact with the element being tested)

Combining the errors in quadrature leads to a total random error of 13% in each individual U-value measurement. Since this error is comparable to the typical 20% difference between measured and calculated wall U-values there are likely to be some instances where the measured U-value is actually lower than the calculated U-value, as observed in Figure 7.

The following diagram illustrates how the heat flux sensor was arranged (for walls). The sensor was bonded to a thin metal disk (2 mm thick approx.) in order to prevent deformation during the monitoring period. The metal plate was in turn bonded to a pliable silicone-clay substrate (3 mm thick) in order to provide a good thermal contact with the wall surface. The whole assembly was fixed to the wall by a plastic tripod and pulley system which applied a pressure of approximately 10 N distributed evenly over three points on the inactive area of the sensor. This pressure was sufficient both to hold the assembly in place and to cause the substrate to accommodate the roughness of the finished wall surface.



In order to assess repeatability and obtain an indication of the degree of variation in the U-value of the wall or ceiling construction being examined, two heat flux meters were installed in most cases. The heat flux meters were mostly 100 mm in diameter and were supported on aluminium retort poles as illustrated in the following picture. In order to avoid any damage to internal furnishings, the heat flux meters were pressure-fixed, rather than glued, to the wall or ceiling.



The picture shows two circular heat flux meters, which were pressed against the wall with a force of 10 N. This resulted in a pressure of approximately 1300 Pa between the heat flow meters, the substrate and the wall finish, and this pressure was considered to provide a sufficiently good thermal contact but without causing any damage to the wall finish. The pressure was achieved by using 1 kg weights suspended on a purpose-built pulley and tripod system. Approximately 1 cm from the centre of each heat flux meter a small thermocouple thermometer was positioned in order to monitor indoor air temperatures. The heat flux meters and thermocouple thermometers were connected to a data logging device (called a "Squirrel" logger) which recorded the heat flows and temperatures.

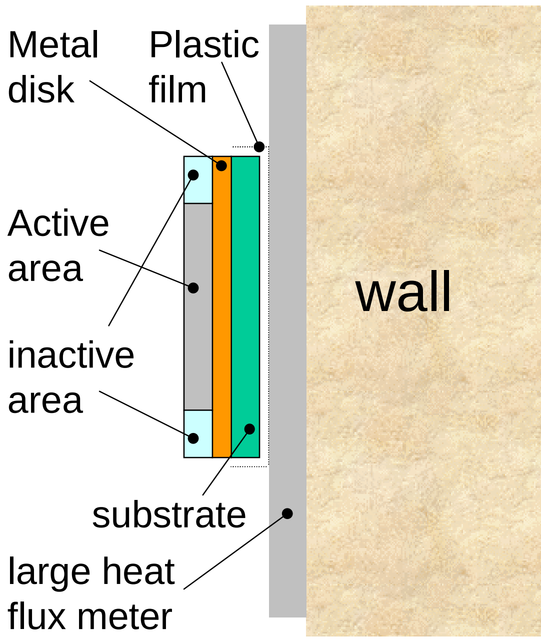
For each of the above locations two PVC heat flux meters were fixed against the wall (or sloping ceiling) for a period of approximately fourteen days. This allowed comparison between two measurements on the same wall (or ceiling).

Duplication of heat flow measurements was also important because in a small number of cases (notably cases 7 and 8) one of the heat flux meters developed an electrical contact fault during the monitoring period. The thermocouple thermometers proved to be more reliable than the heat flux meters and no faults arose with them in any of the measurements. The thermocouple probes were of type T (copper & copper-nickel) and were manufactured to the specifications in BS 4937.

For the measurements the instantaneous heat flow was recorded every 30 seconds and averaged over hourly intervals. Similarly, the instantaneous air temperatures inside and outside were recorded every 30 seconds and averaged over hourly intervals. The (hourly) average heat flows were compared with the corresponding internal and external temperatures in order to carry out the analysis and so determine the U-values.

Appendix F : Additional checks on the calibrations

The calibrations of the heat flux meters, assembled vertically using pressure fixing, could not be determined directly, however the calibrations of each detector could be compared with one another using the arrangement shown in the following diagram:-



The emf signals from a given PVC heat flux meter were compared with the readings from a large square (length 495 mm) heat flux meter bonded to the laboratory wall. Heat flows through the two detectors were monitored each hour for at least 12 hours and the averaged signals were compared in order to effect a relative calibration test of each PVC heat flux meter.

The nominal and relative calibrations are summarised in the following table:

HFM ref. no.	nominal calibration W/m² per mV	average signal of test HFM (mV)	average signal of large HFM (mV)	relative calibration constant	relative ÷ nominal
31.2189	5.4	0.70	0.62	1.12	0.21
hfm22	4.2	1.06	1.42	0.75	0.18
hfm16	4.3	0.56	0.73	0.77	0.18
430144	6.3	1.15	1.05	1.10	0.17
220077*	17.3	0.91	0.34	2.68	0.15*

*without metal plate attached to heat flux meter

There are a number of uncertainties as regards the interpretation of this crude test, however it suggests that there may be some variation in the nominal calibrations of some of the heat flux meters.

Appendix G : Project review and recommendations

In the course of this work a number of lessons were learned about the most effective ways of carrying out in-situ U-value measurements. Suggestions for overcoming practical difficulties and recommendations for a future similar project are given in the following text:

Locating suitable dwellings for which the occupants were willing to participate proved to be a significant task and as a result much experience has been gained on the best way to do this. For domestic buildings the best strategy appeared to be, rather than contacting householders directly, to contact a number of housing associations and identify which housing associations had built in the last few years. Housing associations generally had information about which dwellings were likely to have cooperative occupants and could seek permission from them directly. This tended to make the householders more willing to participate. For non-domestic buildings a variety of sources were explored, including contacting the owners of the building directly. Certain Local Authorities were particularly helpful in this regard and were able to identify very quickly suitable buildings that were owned by the Authority and had been built according to the current insulation standards. Some Local Authorities were particularly helpful in identifying suitable buildings and supplying plans for them, particularly in the case of the schools and sheltered housing schemes which were studied.

2-3 weeks per measurement had to be allowed for in most of the measurements and was very important for constructions of high thermal mass. A disturbance allowance of £20.00 per household was used which tended to be appreciated by householders on lower incomes. There was one householder who refused to take part ostensibly on the basis of the allowance being too small.

The arrangement used for mounting the equipment had some distinct advantages. It ensured good thermal contact with the wall or ceiling and it caused no damage to internal furnishings (this allowed it to be used even on embossed wallpaper). It is recommended that in any future similar studies the substrates for the heat flux meters should continue to be applied as was done in the present project.

Aluminium poles were used to support the heat flux meters in most cases. Although they were lighter in weight than the steel supporting poles used in the past, they tended to bend and this made it impracticable to support two heat flux meters on the same rod (due to excessive bending of the rod) leading to practical limitations in the use of the equipment. By and large, the disadvantages of using aluminium poles instead of steel poles outweighed the advantages. The arrangement by which the heat flux meters were supported, using the pulley systems and supporting poles, caused no damage to the internal furnishings, however occupants sometimes complained about the apparatus being unsightly, particularly when a large number of weights had to be used to provide additional stability to the supporting stands.

The use of three of more heat flux meters, as was done is a small number of cases, was found to be beneficial in interpreting the data. This could not be done in most cases due to limitations in the numbers of apparatus, but could usefully be done during those occasions when there was spare apparatus available. It is suggested that future measurements could be done better if provision was made for three heat flux meters to be used on each wall or ceiling studied.

Whilst the retort pole arrangement worked fairly well for walls it was less satisfactory for sloping ceilings as it provided less flexibility in setting the height of the heat flux meter. This was not a major problem in most cases as most sloping ceiling heights could be accommodated in practice, but there was one instance where it was necessary to support the base of the rod on a pile of books in order to reach the ceiling. For future work it is recommended that aspects of the experimental design be reconsidered, particularly for measurements on sloping ceilings.

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