In-situ measurement of U-value

Ludmilla Kosmina, BRE September 2016

1. Introduction.

U-value can be established by several theoretical calculation methods:

a) Calculation by using a simplified method (defined in BS EN ISO6946, BS EN ISO 13370, BS EN ISO 10077-1); for BRE U-value calculator see www.bre.co.uk/uvalues.

b) Calculation by "numerical methods" by using a detailed computer simulations that allow for multi-dimensional heat flow using software like TRISCO.

c) Numerical and simplified calculations can be used together (e.g. numerical calculation can be used to calculate thermal resistance of a layer, then the results can be used in the calculation using the simplified method.

The above methods are described in BRE publication "Conventions for U-value calculations" available from BRE Bookshop. For the publication and BRE U-value calculator see www.bre.co.uk/uvalues.

In existing dwellings theoretical evaluation of the thermal resistance (R value) or thermal transmittance (U-value) can be difficult for the following reasons:

- materials traditionally used in buildings are not homogeneous and their thermal conductivity values are not available;

- establishing the exact dimensions of layers of materials require destructive methods which may be not possible in most cases.

In principle, the U-value can be obtained by measuring heat-flow through an element with a heat-flow meter, together with recording the temperature on both sides of the element under steady-state conditions. Since steady-state conditions are never achieved on site in practice, there are several methods of overcoming this difficulty:

a) Achieving steady-state condition by using hot and cold box; this method is commonly used in laboratory (ISO 8990).

b) Assume that mean values of heat flow rate and temperatures over a long period of time give an estimate of the steady-state condition.

c) Using dynamic theory to take into the account fluctuations of the heat flowrate and temperatures in the analysis of the recorded data.

BS ISO 9869-1:2014 "Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance" provides the description of a method which allows U-values of walls in existing dwellings to be established by in-situ measurements.

This paper explains the approach given in BS ISO 9869-1:2014, based on assuming that mean values of heat flow rate and temperatures over a reasonably long period of time (minimum 72 hours) give an estimate of the steady-state condition, provides information on the methodology used for in-situ measurements and gives examples of data analysis.

2. Definitions and measurement methods

Thermal transmittance of a building element (U-value) is defined in ISO 7345 as the "Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system".

The U-value can be obtained by measuring the heat flow rate through an element with a heat flow meter (HFM), together with monitoring the temperatures on both sides of the element under steady state conditions.

Heat flow meter is a thin, thermally resistive plate with temperature sensors arranged in such way that the electrical signal given by the sensors is directly related to the heat flow through the plate.

A steady-state condition of a system or process is the condition that does not change in time; broadly it is a condition that changes only negligibly over a specified time.

According to BS ISO 9869-1:2014, U-value can be obtained by measuring the heat flow rate through an element with a heat flow meter, if the temperatures on both sides of the element are under steady-state conditions. However, steady-state conditions are never achieved on a site in practice.

The steady-state conditions can be achieved in the laboratory and U-values can be measured according to BS ISO 8990, but is cumbersome in the field.

According to BS ISO 9869-1:2014, there are ways of overcoming the problem of achieving the steady-state condition by assuming that the mean values of the heat flow rate and temperatures over a sufficiently long period of time give a good estimate of the steady-state.

This method is valid only if:

1) the thermal properties of the materials and the heat transfer coefficients are constant over the range of temperature fluctuations occurring during the test;

2) the change of amount of heat stored in the element is negligible when compared to the amount of heat going through the element.

The method may lead to long periods of measurement and may give erroneous results in certain cases and require several tests on a property to establish average resultant U-value, therefore would not be suitable for establishing U-values for the purposes of RdSAP EPC.

BS ISO 9869 provides several methods of data analysis. This paper concentrates on "the average method" and does not include the details of "Dynamic analysis method" which is data analysis by using a more sophisticated dynamic theory to take into account the fluctuations of the heat flow rate and temperatures in the analysis of the recorded data or "storage effect".

3. Description of in-situ U-value measurement according to BS ISO 9869-1:2014 (average method)

3.1 Stages of in-situ U-value measurement

The Standard describes the heat flow meter method for the measurement of the thermal transmission properties of plane building components, primarily consisting of opaque layers perpendicular to the heat flow, e.g. walls.

The properties which can be measured are: the total thermal resistance, R_T, and transmittance from environment to environment, U, if the environmental temperatures of both environments (internal and external temperature) are well defined.
This method is not intended as a high precision method replacing the laboratory instruments such as hot boxes.

The standard describes the measurement instrumentation, the installation and measurement procedure and the thermal resistance calculation method.

There are several stages/components of U-value measurement:

1) Selecting appropriate heat flow meters, - (minimum Accuracy of +/- 5%) taking into the account that larger heat flow meters have higher sensitivity but are more difficult to attach to the wall;

2) Selecting appropriate temperature sensors, - (minimum Accuracy of 0.3K) these should be chosen according to the temperature to be measured; if the U-value is defined by the ratio of density of heat flow rate to the air temperature difference, air temperature sensors are to be used (not surface temperature sensors).

3) Calibration of heat flow meters and temperature sensors (i.e. calibrated to ISO 8301 within the previous 24months);

4) Measurement (includes considering location of the measured area, installation of heat flow meter and temperature sensors and data acquisition);

5) Analysis of the data.

3.2 Conditions

This method assumes that the conductance or transmittance can be obtained by dividing the mean density of heat flow rate by the mean temperature difference, the average being taken over a long enough period of time.

An estimate of the thermal transmittance, U-value, is obtained by a formula in section 3.5.

This value is close to the real value if the following conditions are met:

a) the heat content of the element is the same at the end and the beginning of the measurement (same temperatures and same moisture distribution);
b) the HFM is not exposed to direct solar radiation.
c) the thermal conductivity (λ) of the element is constant during the test.

If these conditions are not fulfilled, misleading results can be obtained.

For light elements (e.g. timber framed walls), which have a specific heat capacity (κ-value) per unit area of less than 20 kJ/(m2 K), it is recommended that the analysis is carried out only on data acquired at night (from 1 h after sunset until sunrise), to avoid the effects of solar radiation. The test may be stopped when the results after three subsequent nights do not differ by more than ± 5 %. Otherwise, it shall be continued.

For heavier elements (e.g. masonry walls), which have a specific heat capacity (κ-value) per unit area of more than 20 kJ/(m2 K), the analysis shall be carried out over a period which is an integer multiple of 24 h. The test shall be ended only when the following conditions are fulfilled:

The test can be completed when the following conditions are fulfilled:

<u>Condition 1</u> — the duration of the test exceeds 72 hours (three days) if the temperature is stable around the heat flow meter, otherwise the duration may be much longer; however, the actual duration of test shall be determined by applying criteria to values obtained during the course of the test. These values shall be obtained without interrupting the data acquisition process.

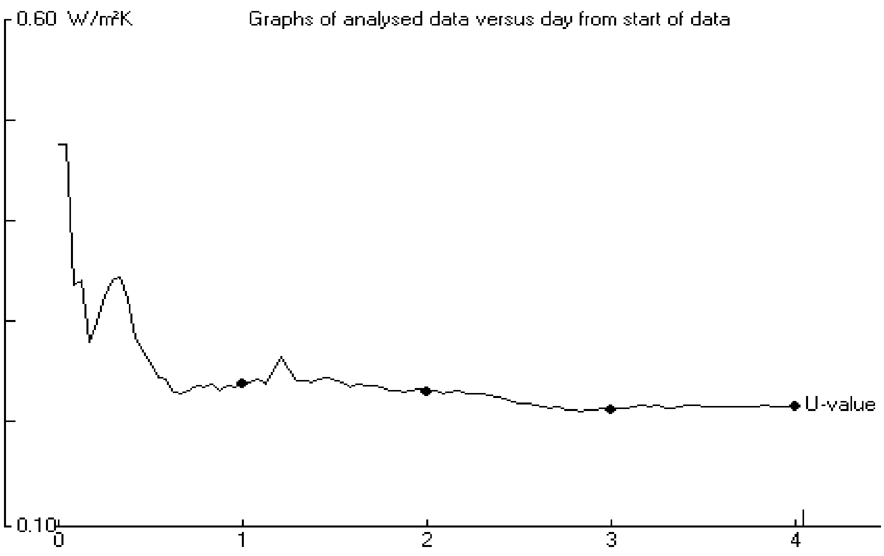
In building with large heat capacities, the average thermal transmittance of a component can be obtained by measurement over an extended period (not less than 96 hours) and thermal mass factors are used in the analysis, or the apparent transmittance of the part can be estimated by a dynamic analysis of its thermal absorption response.

<u>Condition 2</u> — the R-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before;

<u>Condition 3</u> — the R-value obtained by analysing the data from the first time period during INT(2 x DT/3) d does not deviate by more than ± 5 % from the values obtained from the data of the last time period of the same duration. DT is the duration of the test in days; INT is the integer part;

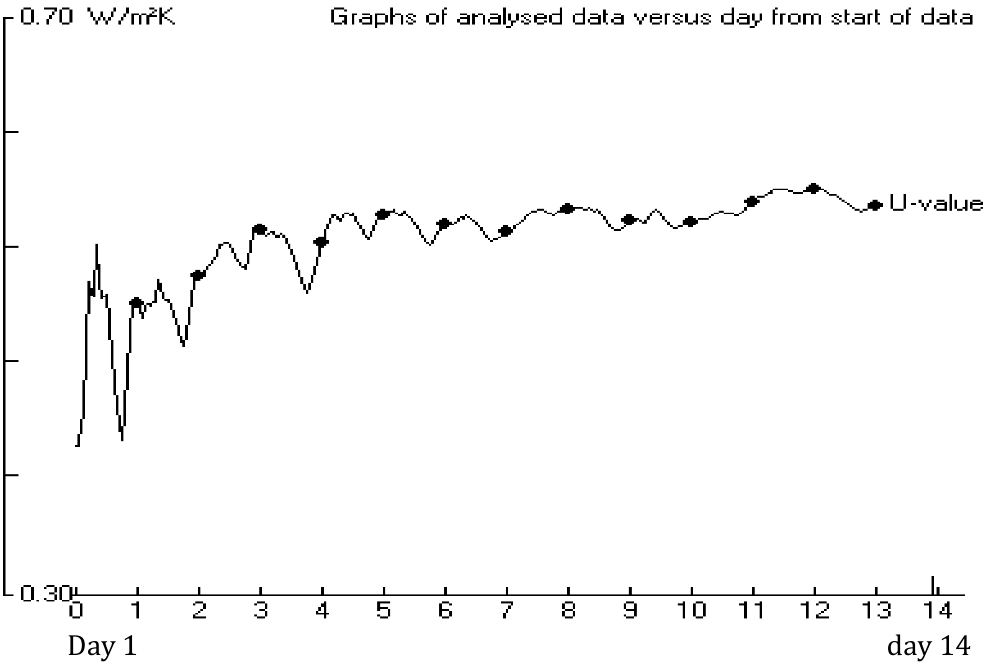
The graphs below shows fluctuating the measured U-value with the time; it is not stable during the first day or so, and become rather stable thereafter. This explains why short periods of measurements would not be sufficient.

Example 1



day 1 day 2 day 3 day 4

Example 2



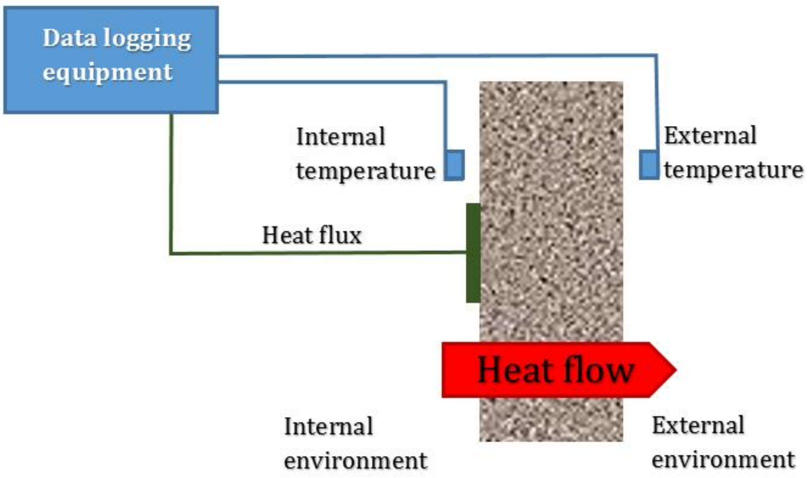
3.3 Measurement

The sensors (HFMs and thermometers) are mounted according to the purpose of the test.

The most appropriate location may be investigated by thermography (in compliance with ISO10878:2013). Sensors are mounted in such a way so as to ensure a result which is representative of the whole element. The HFM should be in direct thermal contact with the surface of the wall over the whole area of the sensor. It can be appropriate to install several HFMs so as to obtain a representative average.

To measure the U-value or the total resistance, environmental (ambient) temperature sensors should be used. These sensors will measure the temperature used in the definition of the U-value, i.e. the air temperature (not the wall surface temperature). They are chosen and installed accordingly at both sides of the element being measured.

This is a schematic diagram of the test:



3.4 Data acquisition

The electrical data from the HFM and the temperature sensors are recorded continuously or at fixed intervals 10 to 30 minutes fixed intervals over a period of complete days.

The maximum time period between two records and the minimum test duration depends on
— the nature of the element (heavy, light);
— indoor and outdoor temperatures (average and fluctuations, before and during measurement);
— the method used for analysis.

The minimum test duration is 72 h (3 d) if the temperature is stable around the HFM.

3.5 Analysis of the data

This method assumes that the U-value can be obtained by dividing the mean
density of heat flow rate by the mean temperature difference, the average being taken over a long period.

An estimate of U-value is obtained by:

$$U = \frac{\sum q}{\sum (T_i - T_e)}$$

Where:
q – density of heat flow arte, W/m2;
T_e - external air temperature, °C or K
T_i - external air temperature, °C or K

4. Conclusions

The Average method is suitable for in-situ measurements of U-values but may lead to long periods of measurement and may give erroneous results in certain cases, therefore this method would not be suitable for establishing U-values for a single dwelling for the purposes of EPC.

The procedure applies only where a defined number of measurements are undertaken for a development at different times to calculate an average U-value figure.

The correct process of establishing U-values by means of in-situ measurement requires quite high level of skills and experience of using the equipment and analysis of data, it is also very time consuming and therefore expensive.

However, in-situ method of establishing U-values can be used for other purposes, e.g. obtaining representative U-value of walls for wider developments, for example it can provide refined wall U-value for the purposes of refurbishment projects by Local Authorities where dwellings are of the same wall construction, suspected bad workmanship on the development, investigating moisture problems, ageing of materials, etc., assuming that measurements and analysis are carried out in accordance with BS ISO 9869.

To undertake the tasks in compliance with BS ISO 9869-1:2014, and to comply with the defined methodology, staff will require to have relevant experience / education to demonstrate competency and process. The in-situ testing itself and the calculation of the must be a subject of independent third party audit.

As the in-situ U-value measurement method becomes a wider practice, Certification Schemes should consider the development of mechanisms for monitoring and data-set audit. These should include review of all equipment and methodology together with “side-by-side” comparative measurements testing to ensure compliance with the BS ISO 9869-1:2014.

APPENDIX 1: Example of data analysis leading to NOT satisfied conditions.

Below is an example of data required for the analysis:
Data starts 15 February 2016 at 12:40
Data ends 19 February 2016 at 12.40

Date and Time	Heat flow data from data logger	Calibration factor	Calculated Heat flux q	T internal	T external
	mV	-	W/m^2	°C	°C
	A	B	C=A/B*1000	D	E
15/02/2016 12:40					
15/02/2016 16:40	0.2596	55	4.7200	20.9219	4.2188
15/02/2016 20:40	0.4756	55	8.6469	20.9766	-0.9036
16/02/2016 00:40	0.1346	55	2.4477	20.8854	-1.1068
16/02/2016 04:40	0.1652	55	3.0043	20.9688	0.1745
16/02/2016 08:40	0.2835	55	5.1546	21.0964	2.7500
16/02/2016 12:40	0.2093	55	3.8050	21.2500	5.4245
16/02/2016 16:40	0.3015	55	5.4825	21.1302	5.7422
16/02/2016 20:40	0.1107	55	2.0130	20.8177	6.7813
17/02/2016 00:40	0.2244	55	4.0795	21.0729	5.0625
17/02/2016 04:40	0.2177	55	3.9575	21.0781	1.1250
17/02/2016 08:40	0.2172	55	3.9498	21.1276	0.5964
17/02/2016 12:40	0.2298	55	4.1786	21.2630	1.3594
17/02/2016 16:40	0.2378	55	4.3235	21.1172	4.3672
17/02/2016 20:40	0.1992	55	3.6219	21.2240	1.3568
18/02/2016 00:40	0.1493	55	2.7146	21.2865	-1.0521
18/02/2016 04:40	0.1904	55	3.4618	21.3542	-1.3438
18/02/2016 08:40	0.2160	55	3.9270	21.1224	-0.5286
18/02/2016 12:40	0.2500	55	4.5446	21.2630	2.2448
18/02/2016 16:40	0.2814	55	5.1165	21.1432	4.5208
18/02/2016 20:40	0.1493	55	2.7146	20.9714	2.1250
19/02/2016 00:40	0.2860	55	5.2004	21.0365	0.9688
19/02/2016 04:40	0.2395	55	4.3540	21.1042	2.0078
19/02/2016 08:40	0.2562	55	4.6590	21.1432	1.5755
19/02/2016 12:40	0.1715	55	3.1187	21.2552	4.3099
Average			4.1332	21.1087	2.1573

Average U-value: W/m^{2}K $U = 4.1332/(21.1087-2.1573)=0.2181$

For the purpose of this example, the table shows data recorded at 4 hours interval. In practice data should be recorded at fixed intervals from 10 to 30 minutes intervals.

The average internal-external temperature difference over the duration of the test is 18.95°C.

The final result should be derived from a whole number of 24 hour periods.

The U-value is valid when the following conditions are all fulfilled:

Condition 1 — the duration of the test exceeds 72 hours (three days) – satisfied.

Condition 2 — the *R*-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before;

U-value obtained at the end of the period: U=0.2181 W/m²K
U-value obtained 24 hours before the end of period: U=0.2154 W/m²K

These U-values are used for calculating *R*-values and evaluating whether the *R*-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before.

The following formula is used to calculate R-values:

$$R = \frac{1}{U} - R_{si} - R_{se} \quad \text{m}^2\text{K/W}$$

where:

U - U-value
R_{si} - internal surface resistance, R_{si} = 0.13 for walls
R_{se} - external surface resistance, R_{se} = 0.04 for walls

R-value obtained at the end of the period: (when U-value was 0.2181 W/m²K)

$$R_{END} = \frac{1}{0.2181} - 0.13 - 0.04 = 4.4152 \quad \text{m}^2\text{K/W}$$

R-value obtained 24 hours before the end of period: (when U-value was 0.2154 W/m²K)

$$R_{24-hours-before-END} = \frac{1}{0.2154} - 0.13 - 0.04 = 4.4724 \quad \text{m}^2\text{K/W}$$

This is 1.29% difference, which means that the condition is satisfied.

Condition 3 — the *R*-value obtained by analysing the data from the first time period during INT(2 x D_T/3) days does not deviate by more than ± 5 % from the values obtained from the data of the last time period of the same duration. D_T is the duration of the test in days; INT is the integer part.

The duration of the test is 4 days.

INT(2 x D_T/3)= INT(2 x 4/3) =INT(2.67)=2

So, for this example, the *R*-value obtained by analysing the data from the first time period during 2 days does not deviate by more than ± 5 % from the values obtained from the data of the last 2 days.

U-value obtained at the end of the first 2 days: U=0.2324 W/m²K
U-value obtained at the end of the last 2 days: U=0.2045 W/m²K

These U-values are used for calculating *R*-values and evaluating whether the *R*-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before.

R-value obtained at the end of the first 2 days: (when U-value was 0.2324 W/m²K)

$$R_{First-2-days} = \frac{1}{0.2324} - 0.13 - 0.04 = 4.1334 \text{ m}^2\text{K/W}$$

R-value obtained of the end of the last 2 days: (when U-value was 0.2045 W/m^{2}K)

$$R_{Last-2-days} = \frac{1}{0.2045} - 0.13 - 0.04 = 4.7187 \text{ m}^2\text{K/W}$$

This is 13.22% difference, which means that the condition 3 is NOT satisfied, and measurement needs to be carried out for longer period.

Since Condition 3 was not satisfied, the measured U-value is not valid the measured U-value is not valid and the measurement needs to be carried out for longer period.

APPENDIX 2: Example of data analysis leading to satisfied conditions.

For the Purpose of this example, the table shows data recorded at 3 hour intervals. In Practice data should be recorded at fixed intervals up to a maximum of 30 minute intervals.

Below is an example of data required for the analysis:
Data starts 08 December 2014 at 22.26
Data ends 13 December 2014 at 22.26

Date and Time	Heat flow data from data logger	Calibration factor	Calculated Heat flux q	T internal	T external
	mV	-	W/m^2	°C	°C
	A	B	C=A/B*1000	D	E
08/12/2014 22:26					
09/12/2014 01:26	0.0740152	56	1.3217	15.3500	1.3083
09/12/2014 04:26	0.1098888	56	1.9623	14.3667	1.9000
09/12/2014 07:26	0.12726	56	2.2725	14.0500	3.7667
09/12/2014 10:26	0.1223488	56	2.1848	13.9667	5.8333
09/12/2014 13:26	0.0876064	56	1.5644	13.8667	9.0000
09/12/2014 16:26	0.1136632	56	2.0297	14.1000	9.5167
09/12/2014 19:26	0.1219736	56	2.1781	14.5917	8.1750
09/12/2014 22:26	0.1197056	56	2.1376	14.9250	7.1000
10/12/2014 01:26	0.1046024	56	1.8679	14.6917	6.4083
10/12/2014 04:26	0.1159312	56	2.0702	14.4917	6.0000
10/12/2014 07:26	0.1166872	56	2.0837	14.6167	6.6250
10/12/2014 10:26	0.084588	56	1.5105	14.4833	6.8417
10/12/2014 13:26	0.0777896	56	1.3891	14.2083	6.6750
10/12/2014 16:26	0.0781704	56	1.3959	13.7583	6.5417
10/12/2014 19:26	0.09856	56	1.76	13.8833	6.5000
10/12/2014 22:26	0.1072456	56	1.9151	14.3000	6.0250
11/12/2014 01:26	0.0921424	56	1.6454	14.2667	5.6917
11/12/2014 04:26	0.097048	56	1.733	14.1750	4.7333
11/12/2014 07:26	0.0966728	56	1.7263	14.1917	4.2250
11/12/2014 10:26	0.0811888	56	1.4498	13.8833	3.7417
11/12/2014 13:26	0.0766584	56	1.3689	13.4167	4.2833
11/12/2014 16:26	0.081564	56	1.4565	13.2000	4.5667
11/12/2014 19:26	0.1200864	56	2.1444	13.5083	4.3083
11/12/2014 22:26	0.1106448	56	1.9758	13.9083	3.4750
12/12/2014 01:26	0.1087576	56	1.9421	13.8333	3.1167
12/12/2014 04:26	0.1098888	56	1.9623	13.6500	2.4667
12/12/2014 07:26	0.095536	56	1.706	13.2333	1.1750
12/12/2014 10:26	0.112532	56	2.0095	13.0833	1.3333
12/12/2014 13:26	0.124236	56	2.2185	13.1250	3.0167
12/12/2014 16:26	0.1178184	56	2.1039	13.2333	4.0417
12/12/2014 19:26	0.1114008	56	1.9893	13.1167	3.3167

12/12/2014 22:26	0.335328	56	5.988	15.3500	2.5750
13/12/2014 01:26	0.0766584	56	1.3689	14.8667	1.5667
13/12/2014 04:26	0.1159312	56	2.0702	13.6667	0.6000
13/12/2014 07:26	0.1378328	56	2.4613	13.6583	0.5000
13/12/2014 10:26	0.1106448	56	1.9758	13.1083	0.4000
13/12/2014 13:26	0.1499176	56	2.6771	13.2750	2.5833
13/12/2014 16:26	0.1136632	56	2.0297	13.4417	3.5500
13/12/2014 19:26	0.1487808	56	2.6568	13.5167	4.0917
13/12/2014 22:26	0.1246168	56	2.2253	14.0167	5.1250
Average			2.0132	13.9594	4.3175

Average U-value: W/m²K U = 2.0132/(13.9594-4.3175)= 0.2088

The average internal-external temperature difference over the duration of the test is 9.64°C.

The final result should be derived from a whole number of 24 hour periods.

<u>Condition 1</u> — the duration of the test exceeds 72 hours (three days) – satisfied.

<u>Condition 2</u> — the *R*-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before;

U-value obtained at the end of the period: U=0.2088 W/m²K
U-value obtained 24 hours before the end of period: U=0.2141 W/m²K

These U-values are used for calculating *R*-values and evaluating whether the *R*-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before.

The following formula is used to calculate R-values:

$$R = \frac{1}{U} - R_{si} - R_{se} \text{ m}^2\text{K/W}$$

where:

U - U-value

R_{si} - internal surface resistance, R_{si} = 0.13 for walls

R_{se} - external surface resistance, R_{se} = 0.04 for walls

R-value obtained at the end of the period: (when U-value was 0.2181 W/m²K)

$$R_{END} = \frac{1}{0.2088} - 0.13 - 0.04 = 4.6193 \text{ m}^2\text{K/W}$$

R-value obtained 24 hours before the end of period: (when U-value was 0.2154 W/m²K)

$$R_{24-hours-before-END} = \frac{1}{0.2141} - 0.13 - 0.04 = 4.5001 \text{ m}^2\text{K/W}$$

This is 2.60% difference, which means that the condition is satisfied.

<u>Condition 3</u> — the *R*-value obtained by analysing the data from the first time period during INT(2 x D_T/3) days does not deviate by more than ± 5 % from the values obtained from the data of the last time period of the same duration. D_T is the duration of the test in days; INT is the integer part.

The duration of the test is 5 days.

INT(2 x D_T/3)= INT(2 x 4/3) =3

So, for this example, the *R*-value obtained by analysing the data from the first time period during 2 days does not deviate by more than ± 5 % from the values obtained from the data of the last 2 days.

> U-value obtained at the end of the first 3 days: U=0.2085 W/m²K
> U-value obtained at the end of the last 3 days: U=0.2001 W/m²K

These U-values are used for calculating *R*-values and evaluating whether the *R*-value obtained at the end of the test does not deviate by more than ± 5 % from the value obtained 24 h before.

R-value obtained at the end of the first 2 days: (when U-value was 0.2085 W/m²K)

$$R_{First-2-days} = \frac{1}{0.2085} - 0.13 - 0.04 = 4.6270 \text{ m}^2\text{K/W}$$

R-value obtained of the end of the last 2 days: (when U-value was 0.2001 W/m²K)

$$R_{Last-2-days} = \frac{1}{0.2001} - 0.13 - 0.04 = 4.8264 \text{ m}^2\text{K/W}$$

This is 4.22% difference, which means that the condition 3 is satisfied, and measurement is valid.

The average internal-external temperature difference over the duration of the test is 9.64 K.

The final result should be derived from a whole number of 24 hour periods.

All conditions are satisfied; this means that the measurement is valid.