gSKIN® Application Note: U-Value Measurement Case Study

Buildings represent around 40% of the primary energy consumption in most countries and in Europe alone , roughly 3,100 TWh are consumed in buildings every year. A large part of this energy use is due to heating and cooling which means that better insulated buildings could have a huge impact on the overall energy consumption. Still, a lot can be gained in this field since a large part of today's buildings have been constructed before 1980 using low insulation standards. These low insulation standards lead to large amounts of wasted energy and as a result, substantial financial costs to building owners and occupants. To reduce these costs, insulation of affected buildings can be improved through retrofitting and renovation. Due to the large saving potential, the market for retrofitting is growing and various attractive solutions are offered. However, to this day, the activities are not based on quantitative insulation data (i.e. U-value) of complete buildings and building elements since these values only commonly exist for the individual building components. The absence of U-values for complete building profiles hinders the determination of existing conditions, justification of investments and validation of completed improvements. Therefore, there is a large need to measure U-values of building elements empirically in order to obtain reliable and precise data on up-to-date U-values at a specific location.

In this application note, the three methods available for collecting information about insulation quality are discussed. It is shown that only one of these methods allows an expert to gain quantitative and meaningful information. After that, this application note describes the heat flux method and applies it to a typical Swiss residential building constructed in 1948.

Available methods to assess the insulation quality of building envelopes

Today, the insulation quality of building envelopes is measured using three different approaches:

1. **Thermography (i.e. infrared imaging)**
   This approach shows the thermal radiation of an object and produces an image showing spots with higher and lower radiation. Thermography helps to understand the overall quality of a building envelope and to identify thermal bridges and sections with inhomogeneous insulation. However, it does not produce quantitative data (e.g. U-value in W/m^2K) that can be used to interpret the insulation quality. Therefore this method can only be used to roughly approximate the U-value.

2. **Multiple temperature measurements**
   This approach is based on three or more temperature measurements inside and outside of a building element. By synchronizing these measurements, it is possible to calculate the heat flux indirectly, and from this information, derive the U-value of a building element. While this method generates quantitative data, it is hardly usable for in-situ measurements. To apply this method, a minimum temperature difference of 10 °C between the inside and outside temperature is required. Such temperature differences do not occur very often in most regions, and are most likely not achieved continuously throughout the year. Moreover, both the inside and outside conditions have to be constant during the measurement period and no solar radiation is allowed. These requirements make it very hard to obtain reliable data via multiple temperature measurements.

3. **Heat flux method**
   A heat flux through a material is caused as soon as a temperature difference between the opposite sides is present. Heat flows from the warmer part to the colder part. The heat flux method uses this effect and measures heat flux as well as the warm and cold temperatures directly. With this data, it is possible to calculate the U-value of any building material in-situ. The method for U-value measurements is described and standardized in ISO 9869, ASTM C1046 and ASTM C1155. This is the only method which delivers reliable quantitative information about a building envelope.

The short description above shows why methods 1 and 2 are less suitable for the establishment of meaningful quantitative insulation (data (i.e. U-value). The following paragraphs describe how the heat flux method is applied according to ISO 9869 and the results it generates.

The measurement equipment (heat flux method):

In order to make the measurements, this case study used the gSKIN® U-Value Kit (KIT-2615C). The Kit enables users to make measurements according to ISO 9869, ASTM C1046 and ASTM C1155. It contains all the required components:

- 2 temperature sensors
- 1 heat flux sensor
- 1 data logger

The data logger has an adjustable measuring frequency, battery for up to 1 month of measurements and memory for up to 2 million data points.

The Kit automatically records the following parameters:

- Heat flux through the building element in W/m^2
- Inside and outside temperatures in °C

Figure 1: heat flux sensor, temp. sensors and data logger

From the recorded data file, the software included in the gSKIN® U-Value Kit creates the following results automatically:

- Graphs of the heat flux and temperature measurements (see Figures 4 and 5 for examples, software version used until Oct. 2014).
- Calculation of the U-value (since Nov. 2014 directly included in graphics of new software)

The method step by step:

1. Heat Flux Sensor placement
   - Install the heat flux sensor on the indoor surface. Ensure that the sensor is protected from direct heating, convection, and solar radiation.
   - For mounting the heat flux sensor, apply adhesive tape to fix the sensor to the wall.
   - Optional: Use thermography to help identify representative/interesting spots for the heat flux sensor placement on your building element.
   - Optional: Cover the heat flux sensor with the same material as its surrounding material.
   - Optional: Use several sensors to obtain an average value for highly inhomogeneous building elements.
   - Additional information is available in the "Application Note: Building Physics".

2. Temperature sensor placement
   - Place two sensors at opposite sides of the wall at roughly the same position where the heat flux sensor is placed.
   - For U-value measurements, make sure that the ambient air temperature is measured (i.e. by measuring the temperature 2-10 cm away from the wall).
3. Data acquisition (according to ISO 9869)
   - Minimum measurement duration: 72 h
   - Requirement to end the measurement: the U-value does not deviate more than ± 5 % from the value obtained 24h earlier.
   - Typical recording frequency: 1 data point per 0.5 – 1 h (this case study uses 1 data point per 10 minutes)
4. Data Analysis
   - Using the gSKIN® U-Value Kit software, the measurement data is analysed automatically. If preferred, the measurement data can also be extracted via CSV file.
   - The U-value is obtained from the mean values of the heat flux through the building element and ΔT. To calculate the U-value, the following formula is used:

$$U\text{-}value = \frac{\sum_{j=1}^{n} \varphi_j}{\sum_{j=1}^{n} \Delta T_j} \qquad [W/(m^2K)]$$

where n is the total number of data points,
φ is the heat flux in W/m²,
ΔT is the temperature difference between outside and inside in °C.

The measurement object:

The building which was measured was constructed in 1948. Since then, the house has been renovated on several occasions. The renovations relevant to this case study are the renovation of the ceiling in 1979, and the renovation of the ground floor in 1999, where the insulation was renewed and adapted to the standards of the respective time periods. Two spots were chosen for measurements:

A Outer wall facing South-East
Exterior surface material: cinder brick, 25cm thick, built in 1948, not renovated since
Element separating the living room from the outside

B Floor on the ground level
Exterior surface material: Concrete, 20cm thick, ceramic floor tiles on ground floor, renovated in 1999
Element separating the ground level from the unheated cellar

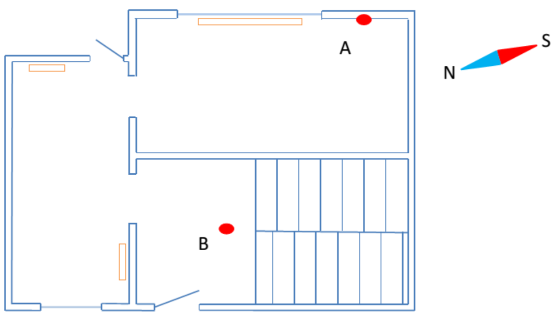
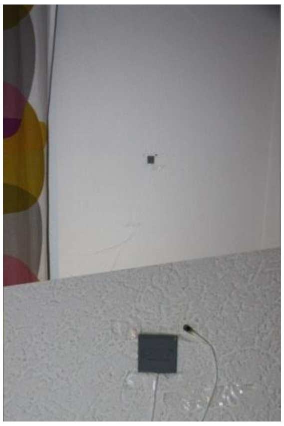


Figure 2. Ground floor: positioning of the measurement spots A and B.

The exact spots were chosen to avoid undesirable influences from heaters, lateral convection and solar radiation . The sensors were placed with a minimum distance of 1 m from heating sources.



Spot A – Outer wall

Spot B – Ground floor

Figure 3. Sensor mounting: general overview (top), detailed view (bottom)

Result of case study:

The following section shows the temperature and heat flux evolution over the measurement period obtained at each spot individually. The graphs are interpreted in order to provide an experience of the various effects occurring over the measurement period.

Spot A – Outer wall

Figure 4 shows the measurement results of spot A. The outside temperature fluctuates between -1 to 3°C, with the lowest temperature during the night just before sunrise. The inside temperature would fluctuate with the outside temperature, but is compensated for by the heating system. The heating system is turned off during the night, and the lowest temperature is reached shortly before the heating is turned on again. Both temperatures have a 24h cycle. The time lag between the temperatures results in a non-constant temperature difference across the wall and thus, fluctuations of the heat flux. The largest heat flux is observed during the afternoons when the outside temperature starts to drop and the inside is heated according to the heating cycle. The outlier at 10:04 on 14.12.2013 is caused by ventilation of the room (i.e. opening a window) which leads to a decrease of the inside temperature and thus, a lower heat flux.

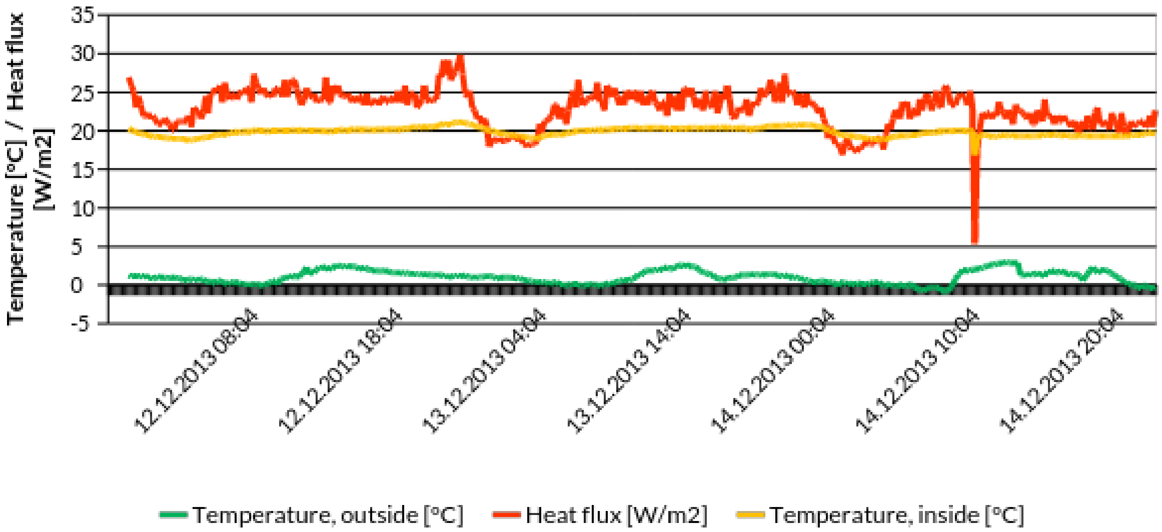


Figure 4. Temperature and heat flux of spot A. This graph was created using the (old) software included in the measurement device (new software version shows directly U-value graph).

Spot B – Ground floor

The temperature and heat flux measurements are very stable for an extended period of time during the weekend when the building is not occupied. Starting at 09:30 on 03.02.2014, both temperatures start to decrease as the doors to the basement and ground floor are opened. Then, the inside temperature recovers to its initial level with several drops as the door is opened and closed again. The outside temperature (i.e. the temperature in the cellar) does not increase as a window is left open for the remainder of the measurement. The heat flux is stable until both temperatures start changing, and then fluctuates with respect to changes of the inside temperature.

In order to calculate an accurate U-value, the temperature difference has to be greater than 5°C. In this measurement, the difference is mostly below 5°C, and therefore, the data should not be used for a U-value calculation. The measurement period should actually start on Monday 03.02.2014 when the difference between the temperature between the ground floor and the basement is above 5°C. This differential should be maintained for an additional 72 hours in order to get a U-value measurement that matches ISO standards.

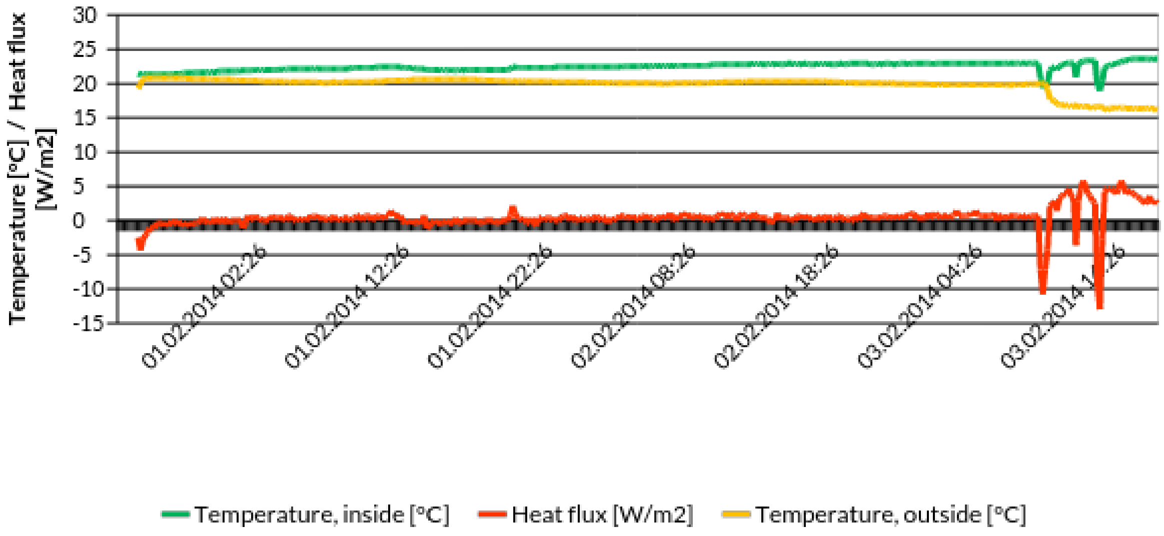


Figure 5. Temperature and heat flux graph of spot B. The outside temperature corresponds to the temperature in the cellar. This graph was created using the (old) software included in the measurement device (new software version shows directly U-value graph).

Table 1 summarizes the measurement results. For both building elements a typical U-value of the building element at the time of construction/renovation is mentioned as reference value. Comparing the results of the measurements and these reference U-values from literature, the following interpretations are made.

Spot A – Outer wall

While the U-value (1,21 W/m^2 K) of the wall is good compared to the standards at the time of construction, it is very poor compared to today's standards (0,25 W/m^2 K). Renovating the outer wall would improve its insulation capability substantially. As shown by the large estimated heating costs , insulation improvements could help save a significant amount of costs.

Spot B – Ground floor

As mentioned previously, in the interpretation of the data of spot B, the temperature difference is not great enough to allow for an accurate U-value calculation. Due to the insufficient temperature difference, the measured U-value (0.19 W/m^{2}K) is unreliable. In comparison with the reference values (0,2 W/m^2 K), this observation is further affirmed. This measured U-value cannot be used for any further processing.

	Spot A Outer wall	Spot B Ground floor
Average ΔT [°C]	18.84	2.52
Average heat flux [W/m^2]	22.88	0.48
Measured U-value [W/m^{2}K]	1.21	0.19 [1]
U-value of reference element [W/m^{2}K]	1.70 [2]	0.35 [3]
Achievable U-value through renovation [W/m^{2}K]	0.25	0.2
U-Value for new construction [W/m^{2}K]	< 0.15	< 0.2
Area [m^2]	50 [6]	38
Total heating energy per day [kWh]	27.46	n.a.[7]
Total heating costs per month [EUR] [6]	140.03	n.a.[7]

[1] This U-value is not accurate. A minimum temperature difference of 5°C is required to make accurate U-value measurements
[2,3] Source: Prof. Dr. Wolff, Kennwerte Aussenbauteile, Ostfalia Hochschule, http://www.energieberaterkurs.de/export/sites/default/de/Dateien_Kennwerte/kennwerte_aussenbauteile.pdf
[4] "Passivhaus" standard
[5] Area of the wall facing south-east on ground level
[6] Assuming 0.17 EUR/kWh, and 30 days/month
[7] Calculation not applicable as low ΔT led to a false U-value and resp. heat flux

Table 1: Summary of measurement results. Low U-Values indicate materials with high thermal insulation capability (i.e. low U-values are desired).

Conclusion

The measurements carried out in this case study were recorded in two consecutive steps. Alternatively, multiple U-Value Kits can be used to make simultaneous measurements of multiple spots. The measurement standards (ISO 9869, ASTM C1046 and ASTM C1155) allow for both the consecutive and simultaneous approaches. While the measurement setup time per spot took less than 10 minutes, the data analysis per spot also required less than 10 minutes, totalling around 15 minutes of working time per spot.

The measurements show that the U-value of a specific building element can be determined without much effort. By determining the insulation quality quantitatively, appropriate conclusions can be drawn. To get a complete overview of the building properties, various spots should be measured.

However, the two measurements conducted here allow for a first assessment of the building's condition and a rough estimate of possible reactive measures. The renovation of the outer wall is an option with a large energy saving potential. Considering that the biggest part of the outside facing elements (i.e. the outer wall) resulted in the highest U-value, the overall insulation properties of the building are very poor. Retrofitting the building envelope according to current insulation standards would therefore not only save energy, but lower the heating and cooling costs of the building considerably.

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Revision History

Date	Revision	Changes
11. February 2014	1.1 (first published)	Completed content
18. February 2014	1.4	Complemented conclusions
05. January 2015	1.5	Shortened case study
05. February 2015	1.6	Small adaptations
25 February 2015	1.7	Text revision

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