# IN-SITU U-VALUE MEASUREMENT: RELIABLE RESULTS IN SHORTER TIME BY DYNAMIC INTERPRETATION OF MEASURED DATA

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## ABSTRACT

The U-value is defined only for steady-state conditions by the ratio of the heat flow to the temperature difference between both sides of a building element. Since steady-state conditions do not exist in situ, the classic method for figuring ratio is to measure the mean heat flow and mean temperature difference over a long period of time to obtain reliable results.

A dynamic method, based on Ahvenainen, Kokko and Aittomäkki's work (1980) models the measured element using the heat equation and several parameters, including the U-value and up to three time constants. These parameters are adjusted to fit the measured data.

To determine the limits of two methods used to analyze recorded data for on-site U-value measurements, nine building elements (from very light to very heavy) were analyzed. Heat flow densities given by heat flow meters as well as surface temperatures of both sides of the elements were recorded at short intervals over long time periods.

The data collected over long periods were cut into shorter periods to simulate numerous measurements. These data were analyzed using both classic and dynamic methods for various time periods. In this way, results for more than 1800 U-value measurements have been obtained and statistical evaluation of the analyzing method can be done.

For very light elements, if the element is not submitted to solar radiation, both analytical methods give good results when applied to the data taken over short periods of measurement (6 to 12 hours). Therefore, one night is long enough to give reliable results. For heavier elements, if the indoor temperature is constant before and during the measurement, both the classic method and the dynamic method give stable results in the same time of measurement. However, the results of the classic method are slightly higher than those obtained by the dynamic method. If the indoor temperature is not constant, or if variable heat sources (e.g., solar radiation) are important indoors, the dynamic method gives reliable results in a shorter measurement time than the classic method. In addition, criteria have been found to test the validity of a unique measurement when interpreted by the dynamic method.


## INTRODUCTION

The thermal transmittance of building elements (U-value) is defined by ISO 7345 as the "average heat flow rate per area in the steady-state divided by the temperature difference between the surroundings on each side of a system". The U-value can be obtained theoretically by measuring the heat flow rate with a heat flow meter or a calorimeter as well as measuring the temperatures on both sides of the element under steady-state conditions. However, since the steady-state is never really encountered on site, such a simple measurement is not possible.Insted, the steady-state may be imposed by using a hot and a cold box. This method is commonly used in the laboratory but is cumbersome in the field. Other methods for estimating the steady state include the following.

- Monitor the mean values of the heat flow rate and temperatures over a sufficiently long period of time. This method is widely used (Anderson, 1983) but may lead to long periods of measurement and may give erroneous results in peculiar cases.

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- Bore a hole in the building element to analyse the element's structure (thicknesses of the various layers and materials used) and compute the U-value from these data. This is a simpler and faster way of finding a U-value but the element is damaged.
- Take into account the fluctuations of the heat flow rate and temperatures in the analysis of the recorded data. This method, first proposed by Aittomäki and co-workers (Aittomäki 1972; Kupke 1976; Ahvenainen et al. 1980) is especially examined in this work.

There are other known problems, such as the determination of the location of the probes, their installation, and the perturbations caused by the probes, which were examined (Roulet et al. 1985) but are not reported here.

## METHOD OF WORK

Heat flow meters (HFM) and temperature sensors were installed on nine building elements located at EPFL (Ecole Polytechnique Fédérale, Lausanne) and EMPA (Eidgenössische Materialprüfungs- und Versuchsanstalt, Dübendorf) and described in Table 1.

At least two HFMs, about 100 mm lateral dimension, and several surface temperature sensors were used on each element. Heat flow densities on the indoor side and surface temperatures on both sides were recorded by automatic data loggers at intervals of 15 or 30 minutes. These measurements were taken over time periods of 160 to 1700 hours.

In order to simulate numerous measurements of various durations, these records were each cut into 40 parts, the duration of these parts lying between 6 and 1200 hours (50 days). In this way numerous files of thermal flow density and temperature data of various durations were obtained, similar to the files that could be obtained through numerous independant measurements. These data were then interpreted using the classic method as well as the dynamic one. Forty results were obtained for each element and for each measurement time to be interpreted statistically.

With the dynamic method, some parameters were varied to see their effect on the results, and various computation algorithms have been tested. This part of the work is described by Roulet et al (1985).

## INTERPRETATION METHODS

### Classic Method

This method is already widely used and even standardized in some countries. It assumes that the U or $\Lambda$ value can be obtained by dividing the mean density of heat flow rate by the mean temperature difference, the average being taken over a sufficient period of time. If the index j enumerates the individual measurements,then

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{sij} - T_{sej})} \qquad (1)$$

where

$q$ = the areal density of heat flow rate ($W/m^2$)

$T_{si}$, $T_{se}$ = the internal and external surface temperature of the building element.

When this estimate is computed after each measurement, a convergence to an asymptotic value is observed (Figure 1). This asymptotic value is equal to the real value if the heat content of the element is the same at the end and the beginning of the measurement, and if the solar radiation has a negligible influence on the heat flow meter and the temperature sensors. If these conditions are not fulfilled, misleading results may be obtained (Figure 2).

### Dynamic Method

This more sophisticated method takes into account the thermal variations by the use of the heat equation (Aittomäki 1972; Kupke 1976; Ahvenainen 1980). The building element is represented in the model by its thermal conductance and several time constants. These unknown parameters are obtained by fitting values of the heat flow rate computed from the temperature measurements to the actual measured heat flow rates. With this approach, a set of linear equations must be solved, which can be done by a microcomputer in a few minutes. This set of equations can be written in a matrix form

$$\underline{q} = (X)\,\underline{Z} \qquad (2)$$

where

$\underline{q}$ = a vector, the M components of which are the last M heat flow density data, $q_i$. The value of M is greater than the number of unknown parameters, N.

$\underline{Z}$ = a vector, the N components of which are the unknown parameters. The first component is the U or the Λ-value.

(X)= a rectangular matrix with M lines and N columns. The matrix elements depend on the measured temperatures and the time constants.

The overdetermined set of equations gives an estimate, $\underline{Z}^*$, of the vector $\underline{Z}$

$$\underline{Z}^* = \{(X)^T(X)\}^{-1} (X)^T \underline{q} = (Y)(X)^T \underline{q} \tag{3}$$

where

$(X)^T$ = the transposed matrix of (X).

In fact, the time constants are unknown. They are to be found by looking for the best estimate of $\underline{Z}$ by varying the time constants in an iterative procedure. It is possible, however, that this procedure does not converge. In this case, the recorded data cannot give a reliable U-value.

## RESULTS

### Quality Criteria

Quality criteria are needed to indicate the confidence in the results when a single measurement is used to estimate the U-value. They have to be such that if they are fulfilled for a given unique measurement there is a good confidence (perhaps 90% probability) that the result will be close enough to the "true" value (e.g., less than ± 10% of it).

In the case of the classic interpretation method, the only criterion is that the measurement time be long enough. Of course, if the recorded data show a quasi-steady-state, the measurement has a high probability of giving a good result. However, if the temperatures or heat flow vary strongly just before the beginning of the measurement, the final result will be erroneous as the measurement time was not long enough to "forget" the preliminary events.

Such a criterion has been found in the case of the dynamic interpretation method. The confidence interval for the estimate of the conductance given by Equation 3 is

$$I_c = \sqrt{\frac{S^2\ Y(1,1)}{M - 2m - 4}}\ F(P,\ M - 2m - 5) \tag{4}$$

where

$S^2$ = the total square deviation between the computed and measured heat flow densities

Y(1,1) = the first element of the matrix inverted in Equation 3

M = the number of equations in system (2) and m the number of time constants

P = the significance limit of the student distribution, where P is the probability and M-2m-5 the degree of freedom.

If this confidence interval for P = 0.9 is smaller than, for example, 5% of the conductance, the computed conductance is generally very close to the "true" value, which in this case is the value obtained under good conditions (nighttime steady-state for light elements, long measurements for heavy ones). This is illustrated in Figure 3. For a given measurement time, the smaller the confidence interval, the narrower the distribution of the results. This criterion, however, is not sufficient since the distribution is still large for short periods of measurement and the mean value may be erroneous (generally too low).

### Results on Windows

These very light elements quickly reach the steady-state in absence of solar radiation. Therefore, reliable results are obtained with the classic and dynamic method when applied to nighttime recorded data. Results for measurements taken anytime in the day show that

- the classic method gives very high dispersion and a mean value that is much too low. In fact, the long term average takes into account the solar radiation on the HFM through the window and has no physical meaning.
- the dynamic method gives good results for 6- 12- and 24-hour periods of measurement. Results are not as good if this time is longer.

Results on Light Sandwich Panels

Two sandwich panels, located on a south facade, were studied. The remarks made for the windows are also valid for these very light elements. Nighttime results are close to the real values, the dynamic method giving less scatter than the classic method.

Daylong measurements show that it takes at least 24 hours to have reproducible results with the classic method. When no rapidly varying heat perturbations occur, the dynamic method gives reproducible results in just 12 hours. The probability of having reliable results is about 50% in 12 hours, but increases quickly to 100% in 48 hours. The results obtained in more than 12 hours are, however, slightly lower than the nighttime results. It is because the solar radiation on the panel have an influence on the measurements. The solar gains are not related to the U-value, however, and these measurements must be be considered erroneous.

Results on Heavy Elements, Fairly Steady Indoor Temperature

Heavy elements include (1) the typical flat roof covering an unheated space where the temperature is between 14 and 16 $^oC$, the heat coming from neighboring rooms, (2) the double brick wall that is the facade of a machine hall where the temperature is about 23 $^oC$ and (3) an aerated concrete wall with an additional outer layer of polystyrene insulation. This element is the west wall of a passive solar test cell. The south window was protected from the solar radiation by a double aluminium foil.

For these medium to heavy elements, one night is not enough to obtain a steady-state. The results show that the classic method gives reproducible results after 48 hours, even after 24 hours for the double brick wall. These short periods of measurement can be used because the indoor temperature is steady before and during the measurement. The minimum period of measurement is not reduced by using the dynamic interpretation method, nor is the scatter of results. Quick variations of the heat flow lead to a bad performance of the dynamic method, and the scatter of the results is therefore always larger for the dynamic method than for the classic method. These quick variations come from on and off switching of the heaters when they are close to the HFMs

Results on Heavy Elements, Varying Indoor Temperature

This category includes the heavy, highly insulated elements located on the top floor of the experimental passive solar building at the EPFL (LESO building). Their inner sides are in a direct gains room which is also used as a laboratory. Solar radiation does not directly reach the heat flow meters but leads to large, slowly varying heat flow fluctuations. Even heat flow inversions can be observed. They are caused by solar energy coming from the south facade, stored in the elements by day and given off in the room at night.

Results show that at least 50 days are necessary to obtain reproducible results (less than a 10 % confidence interval) on the west wall with the classic method. This time is not enough for the roof. The minimum period of measurement for confidence interval of less than 1 % is 20 days for the wall and a little more than 50 days for the roof. If a high accuracy is not needed (where the confidence interval can be 25% of the mean), a drastic reduction of the period of measurement occurs when the dynamic method is used. In addition, scatter of the results obtained by the dynamic method is always smaller than scatter for the classic method.

Influence of the Indoor/Outdoor Temperature Difference

A study of the effect of the average indoor/outdoor temperature difference on the scatter of the results was done at EMPA on a concrete wall with an outside fiberglas insulation. This wall was installed between two temperature-controlled rooms. A constant temperature of 25 degrees was maintained on the warm side. On the other side, the temperature reflected the real outdoor temperature of 4 cool winter days, repeated once to give 8 days measurements. The average temperature difference was about 30 K. Since the exact U-value of this wall was known, measured by a calibrated hot box under steady-state, the recorded data of outside temperature, $T_e$, and heat flow, q, were then modified to simulate a smaller average temperature difference of about 5 K.

The classic method gave results which are presented in Figure 4. With a high temperature difference reliable results were obtained after only one day. With the reduced temperature difference at least 6 days were necessary to stabilize the result to within 5% of the mean.

The recorded data were also interpreted with the dynamic method. Forty-eight computations were made for both the full and reduced temperature differences. Simulated periods of measurement from two to eight days were used. Statistical results are shown in Figures 5 and 6. It is obvious that with the full temperature difference all the results lie within $\pm$ 5% of the mean value. The dispersion is much larger ($\pm$ 14%) with the reduced temperature difference.

However, taking only the longer periods of measurement (Figure 6) the dispersion is reduced to ± 7%.

Since a 30 K temperature difference is a very good measuring condition and 5 K temperature difference not so good, the conclusions of this test are as follows. The smaller the average temperature difference, the larger the necessary period of measurement, though this augmentation of measurement time is smallest with the dynamic method.

## CONCLUSION

On nine different building elements, a large number of U-value measurements were made over measurement times ranging from 6 hours to up to 50 days. Two methods of analysis were used, the usual mean method and a dynamic one.

Important results are as follows.

- Measurements can be made even when the mean temperature difference is not very large. The accuracy and/or the measurement time, however, are not as reliable.
- For very light elements, one night suffices for a reliable measurement.
- For heavier elements, if the indoor temperature is constant before and during the measurement, the classic and the dynamic methods will give stable results in the same measurement time. However, the results of the classic method are slightly higher than those obtained by the dynamic method.
- If the indoor temperature is highly variable or if variable heat sources (e.g., solar radiation) are important indoors, leading to heat flow inversions through the HFM, the dynamic method gives reliable results in a shorter measurement time than the classic method. However, accuracy is limited.
- Criteria have been found to check the validity of a unique measurement when interpreted by the dynamic method.
- A code of practice has been written describing the interpretation methods and the quality criteria.

## REFERENCES

Ahvenainen, S.; Kokko, E.; Aittomäki, A. 1980. Thermal conductances of wall structures. LVI-tekniikan laboratorio, report 54, Espoo (Finland)

Aittomäki, A. 1972. Determination of the overall heat transfer coefficient of multilayer structures under non-steady-state conditions. Working paper, CIB session 1972, Tegernsee/Obb.

Anderson, B. R. 1983 Methods in use for testing thermal performance in situ. Building Research Establishment note N85/83, Glasgow.

Kupke, Chr. 1976. Untersuchung über ein Wärmedämm - Schnellmeßverfahren. Institut für Bauphysik, Stuttgart, BW 148/76

Roulet, C.-A.; Gass, J.; Markus, I.; Cerkez Th. 1985. Investigations on the on site measurement of the thermal transmittance of building elements. EPFL - GRES report Nr 85-01-09, Lausanne.

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TABLE 1
Measured elements

| Elements | U-Value ($W/m^2K$) |
|---|---|
| Double-glazed window selective-coated and argon filled. | 1.2 |
| High insulation window with two inner selective plastic films. | 0.7 |
| 100 mm thick polyurethane sandwich panel | 0.2 to 0.3 |
| 140 mm thick fiberglass sandwich panel | 0.3 |
| Typical double brick wall | 0.9 |
| Aerated concrete wall with additional outside insulation | 0.3 |
| Heavy, higly insulated double wall | 0.2 |
| Typical flat roof | 1.2 |
| Heavy, highly insulated flat roof | 0.2 |

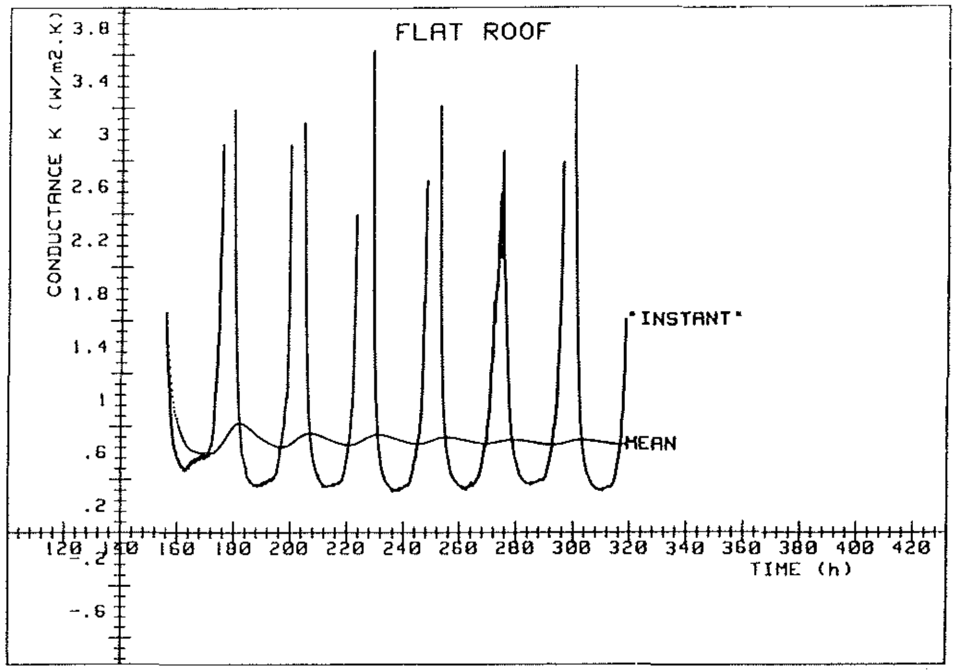


*Figure 1. Asymptotic convergence of thermal conductance obtained by Equation 1. Largely fluctuating line is ratio of heat flow to temperature difference for each measurement ("instantaneous" conductance). Measurements made on typical flat roof*

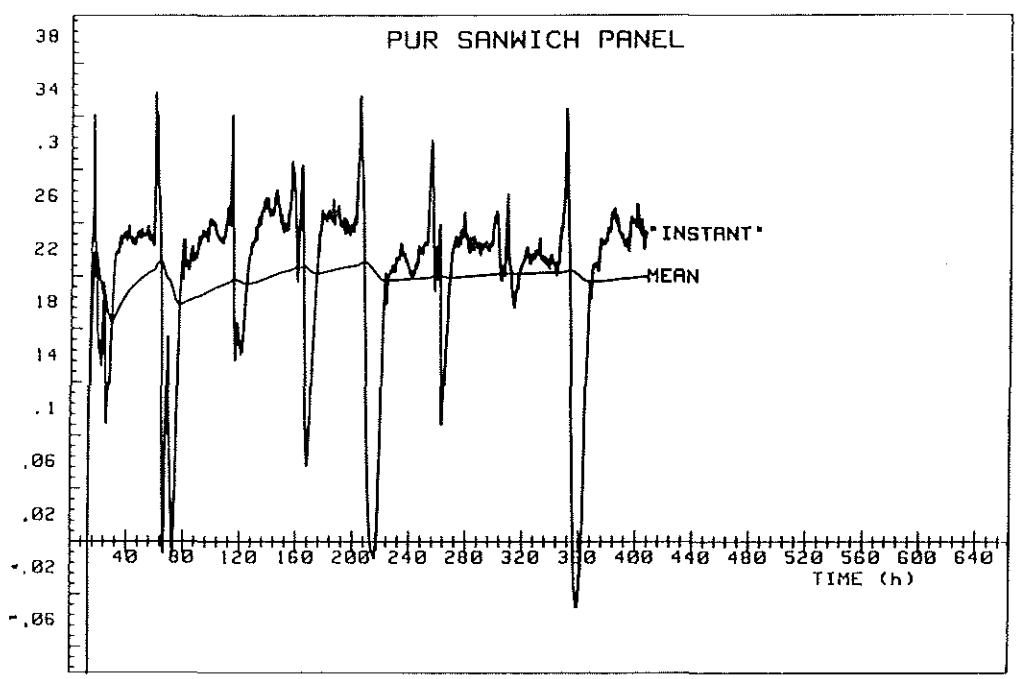


*Figure 2. Same as Figure 1 but for a light south-oriented polyurethane sandwich panel. During the night, the "instantaneous" conductance stabilizes around the real value but the mean conductance tends asymptotically towards a false lower value because of solar radiation*

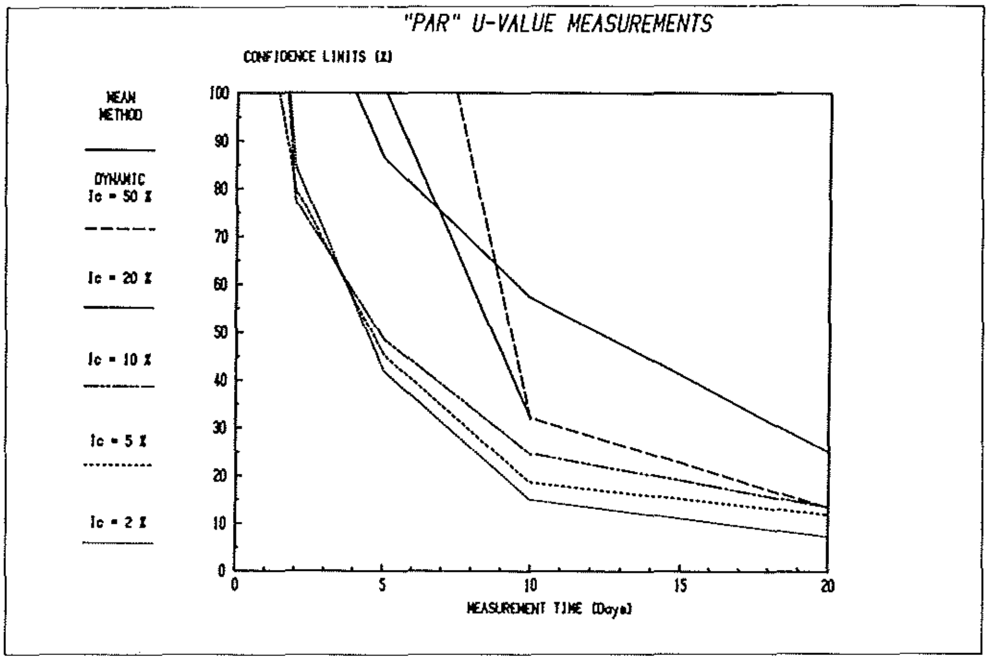


*Figure 3. Confidence intervals of the distribution of numerous measurements of various durations on a heavy insulated wall. For dynamic interpretation, data are selected according to the value of the confidence interval, Ic, computed in Equation 4. Meant method: classic interpretation method, every result; dynamic: only results having a confidence limit on the conductance Ic lower than the value given are taken*

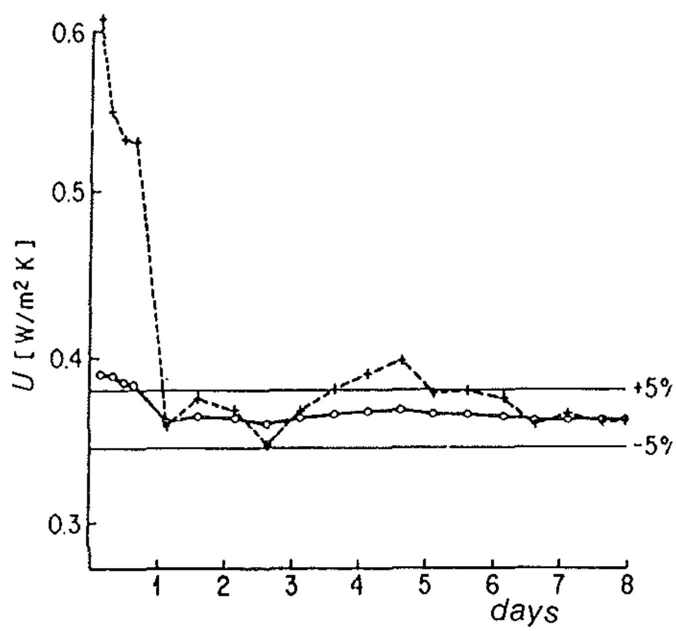


*Figure 4. Evolution of the U-value obtained by the classic method vs. measurement time. o———o: mean temperature difference = 30 K; +-----+: mean temperature difference = 5 K*

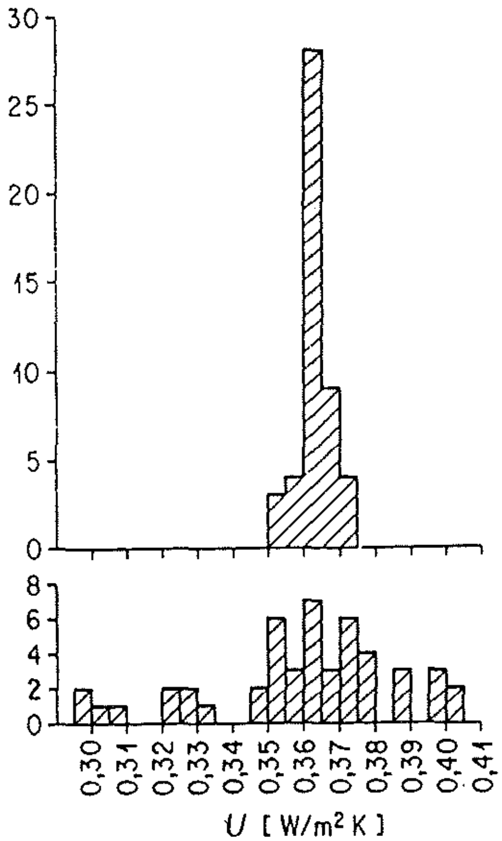


*Figure 5. Distribution of the 48 dynamic results; temperature difference = 30 K (top) and 5 K (bottom)*

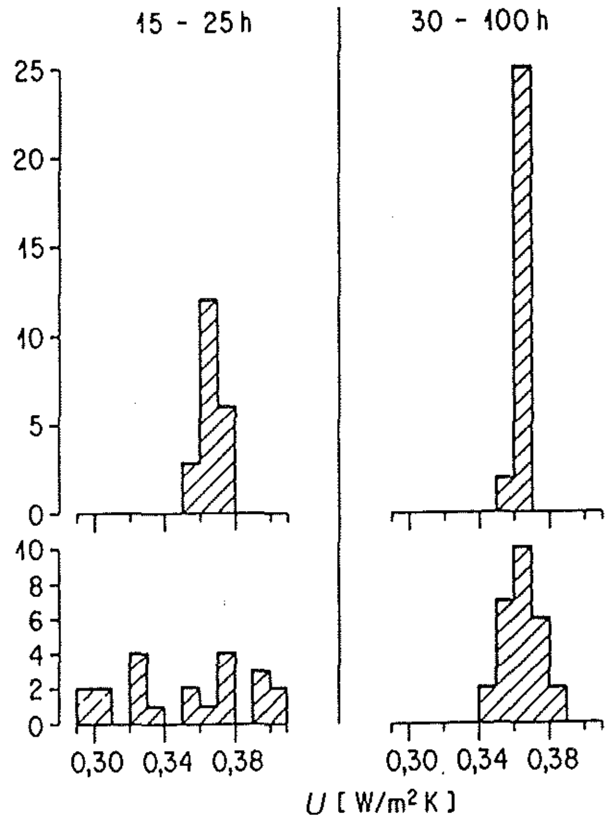


*Figure 6. Distributions with the results grouped in two classes: short measurement time (left) and long measurement time (right)*