Inverted Roofs with Reduced Heat Losses Due to a Water-Repellent Separating Layer

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ABSTRACT

The reduction of heat losses in building constructions gains more and more significance as further energy savings will be demanded in the future. Heat loss occurs in inverted roofs due to the drainage of warm rainwater beneath the thermal insulation boards. This rainwater cooling effect has to be considered as an additional heat loss ΔU, which must be added to the designed U-factor for the roof construction.

An improved inverted roof construction with reduced heat losses has been developed. It was the idea to install a second drainage layer above the insulation boards, which has to be water resistant and vapor permeable at the same time. The water-repellent layer, consisting of loose-laid overlapping sheets of a special nonwoven fleece MK, replaces the usual separating layer laid between the insulation and ballast. The water-repellent layer prevents most of the rainwater from reaching the waterproofing membrane beneath the XPS boards, thereby almost completely eliminating the rainwater cooling effect. The scientific investigations, which led to official regulations in Germany and other European countries, are presented.

THE INSULATING INVERTED FLAT ROOF PRINCIPLE

An inverted roof is a nonventilated flat roof or low-pitch roof. In contrast to a conventional nonventilated flat roof—also called a warm roof—the insulation is laid over the waterproofing layer and suitably loaded to restrain it against wind uplift. In an inverted roof, the waterproofing layer is protected from excessive temperature fluctuations, UV radiation, and mechanical stress during the construction and usage phases.

The suitability of inverted roof systems has been proven on a global scale. Institutes and regulatory bodies throughout Europe have officially approved use of XPS insulation material in inverted roofs for years. The extension of the product range of extruded polystyrene foam has also entailed a further development of inverted roofs, especially for applications as green roofs (roof garden) or car parking roofs (Cziesielski et al. 2001).

HEAT TRANSFER IN INVERTED ROOFS

Inverted roofs, compared to conventional nonventilated flat roofs, have additional heat losses, which is due to the fact that precipitation water can run off on the waterproofing layer below the insulation boards.

Experiments have shown (Künzel 1978) that in dry nonprecipitating periods, the temperature conditions in

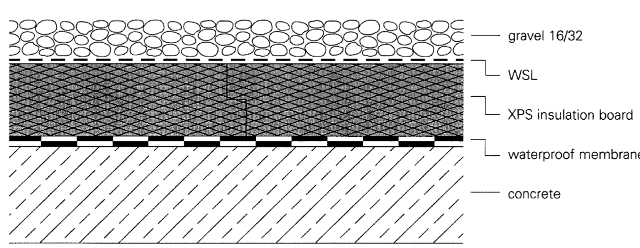

Figure 1 *Inverted roof principle.*

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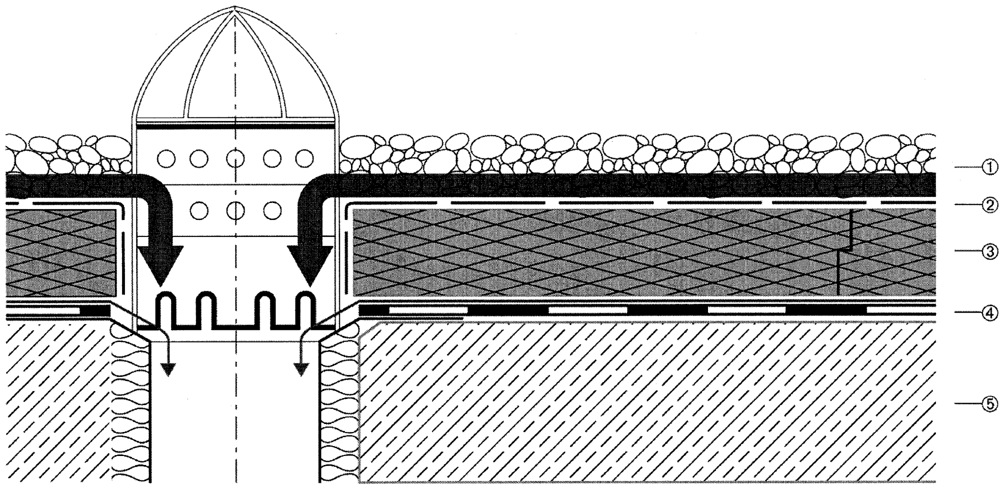

Figure 2 *Inverted roof with water repellent separating layer above the insulation, water drainage into the roof outlet.*
① gravel 16/32 mm
② water-repellent layer WSL
③ XPS insulation
④ waterproof membrane
⑤ concrete

inverted roofs are practically no different from those in conventional flat roofs. This proves that the impact of airflow below heat insulation boards is negligible. In contrast to this, the heat transport by precipitation water runoff has to be considered in thermal protection design and rating. Experiments during the international HAMTIE (Heat, Air, and Moisture Transfer in Insulated Envelope Parts) project have shown (Kießl and Künzel 1997) that, on average, such heat losses do not cause an increase of the U-factor by more than 0.05 $W/(m^2 \cdot K)$ for the climatic conditions in Germany.

MEASURES TO REDUCE HEAT LOSSES—THE WATER-REPELLENT SEPARATING LAYER

The heat losses due to water flow below the heat insulation boards can be reduced by a suitable water-repellent separating layer (WSL) above the thermal insulation.

The WSL consists of loose-laid sheets of a special nonwoven fleece (MK). This layer and the fleece, respectively, have to comply with a number of building physics and material requirements.

A water-repellent separating layer (WSL) has to be water resistant but must not adversely impact the vapor transport. Otherwise there may be an inadmissible accumulation of moisture in the insulation material. In addition, the fleece that is used for the WSL has to be tear- and rot-resistant. The fleece must not be chemically degradable in the long term (i.e., it should not become significantly brittle).

A water-repellent separating layer does not fulfill the function of a waterproofing membrane since the joints between the sheets in the assembly remain open.

Figure 2 is a schematic drawing of the layer structure of an inverted roof with a water-repellent separating layer (WSL).

HYGROTHERMAL ANALYSES OF INVERTED ROOFS WITH WSL

The hygrothermal effect of a water-repellent separating layer was analyzed with different laboratory testing methods. In addition, the system has been tested on roofs of existing buildings. These tests have been controlled by institutes in Switzerland and Germany. Both the system of an inverted roof with a WSL above the XPS insulation and the material used for the WSL have been investigated. The analyses of the system were aimed at verifying that a water-repellent separating layer laid between the insulation boards and ballast can reduce the heat loss by rainwater, cooling off the structural deck without increasing the moisture absorption of the extruded polystyrene (XPS) insulation material. The material analyses were aimed to demonstrate the suitability of the special fleece, MK.

PRACTICAL EVALUATION OF DIFFERENT MATERIALS FOR THE WSL

The suitability of different materials as a separating layer was to be tested. These tests were carried out under external climatic conditions on existing roofs. Four different sheets were used for evaluation. The sheets were loose-laid on XPS boards of 50 mm and 100 mm thickness and weighted with 5 cm of gravel.

The aim of the test was to measure the water accumulation in the XPS boards depending on the type of sheet material used

TABLE 1
Water Absorption of XPS (50 mm thick) Covered by Different Fleece Layers

Date of sampling	Fleece A	Fleece B	Fleece C	PE-foil
16.8.91	0	0	0	0
25.5.93	0.5	0	0	2.4
8.7.94	0.22	0.01	0.14	3.54
19.7.95	0.22	0.07	0.11	4.54

for the WSL. The results have been compared with results of long-term water absorption in inverted roofs with a non-water-resistant layer. The results of the long-term tests are shown in Tables 1 and 2.

The typical rise of the moisture content under a separating layer of PE film can be recognized. The 100-mm-thick extruded polystyrene foam board, which was installed in the roof years ago and had a initial moisture content at the beginning of the test, dried out under layers B and C. There was no long-term moisture accumulation in the insulation boards under these types of layer materials. Based on these results, a special fleece (layer B), further called MK, was selected as the appropriate component for a WSL.

Experimental Investigations of the Drainage Behavior in Inverted Roofs with WSL

The effect of a WSL consisting of 3-m-wide sheets of MK was also experimentally analyzed at roofs under external climatic conditions. The leakage rate was especially of topical interest. The leakage rate reflects the ratio between water drained above the separating layer to water drained below the insulation.

In order to determine the leakage rate, a test roof of 54 m^2 was built. An irrigation plant was used to simulate the rain. Figure 3 shows the results of the measured leakage rates at the test roof where a WSL was used in place of the usual separating layer consisting of water-permeable polypropylene non-woven fleece. The water volumes running off below the insulation and above the WSL were collected separately in collection tanks and determined by weighing.

The leakage rate depends on the precipitation intensity. High precipitation volumes run off predominantly above the separating layer, while smaller precipitation volume can seep through the joints between the runs of the separating layer.

Since it is difficult to determine the influence of wind velocity and rain intensity under outside climatic conditions, it was decided to carry out large-scale laboratory tests under defined climatic conditions. In order to determine the influence of different wind velocities and rain intensities on the leakage rate, a ca. 30 m^2 test roof was built in a wind channel

TABLE 2
Water Absorption of XPS (100 mm thick) Covered by Different Fleece Layers (Negative Values are Due to the Drying Process of a Wet Board)

Date of sampling	Fleece A	Fleece B	Fleece C	PE-foil
16.8.91	0	-	-	0
25.5.93	0.37	0	0	0.64
8.7.94	0.31	-0.21	-0.07	1.18
19.7.95	0.32	-0.28	-0.14	1.73

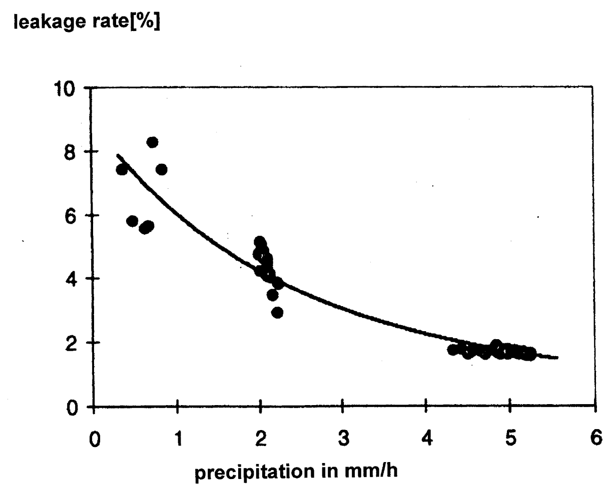

Figure 3 *Measured leakage rate of the test roof.*

to analyze the drainage behavior of the WSL (Villain 1996). Five tests were conducted in which the rain intensities varied between 29.5 mm/h and 58.75 mm/h, and the wind velocities were 0 to 10 m/s. The precipitation water runoff was measured 30 minutes after the test was finished. In some cases the water running off was again measured after 13 to 16 hours in order to determine the amount of water that was held back by the gravel layer on top of the WSL. After dismantling the roof, the amount of water remaining on the waterproof membrane beneath the XPS boards was measured as well. Therefore, the leakage rate could be determined very precisely. Leakage rates from 0.26% to 2.93% were measured. A complete description of the tests and the test equipment is given in Villain (1996).

The water resistance of the joints between the loose-laid sheets of the WSL was examined separately (Cziesielski and Fechner 1999). The WSL, consisting of two overlapping sheets, was laid on a metal sheet with holes. The sample area was about 0.5 m × 0.5 m. A 5-cm-thick gravel layer covered the WSL. Test equipment is shown schematically in Figure 4.

For a water height between 5 cm and 85 cm, the leakage rate was determined to be lower than 0.3%. This result is in good agreement with the results of the roof tests.

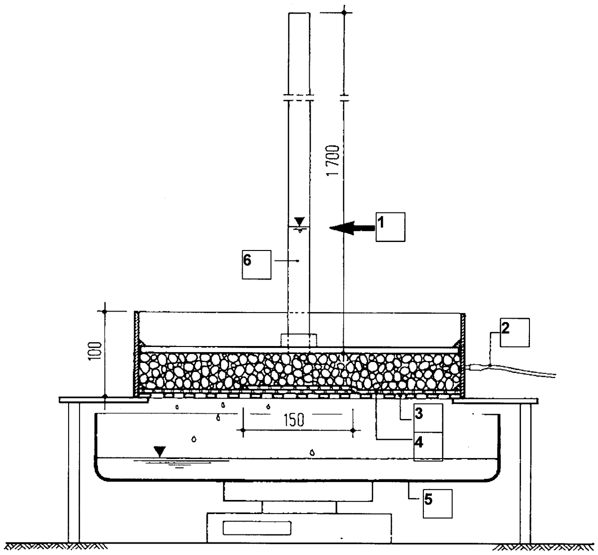

Figure 4 *Determination of water resistance of joints between loose laid sheets. The test equipment is labeled as follows: (1) water level, (2) water inlet, (3) metal sheet with holes, (4) MK fleece, (5) bath, and (6) pipe.*

Quantification of Precipitation-Conditioned Heat Losses in Inverted Roofs with WSL

The experimental findings of the HAMTIE project have shown (Kießl and Künzel 1997) that the method best suited for the determination of heat loss is measuring the temperature and volume of the falling and running-off precipitation water.

The laboratory test set-up used by Cziesielski and Fechner (1999) included a 4.2 m² inverted roof with a WSL laid between the XPS insulation boards and the ballast. A ca. 5-cm-thick gravel layer, also used under practical conditions, was applied for protection and ballast. A continually heated room was located beneath the roof area. Both volume and temperature of the drained water were measured. The water volumes running off below the insulation and above the separating layer were separately collected in a collection tank and determined with a mass flow sensor. A total of 19 tests were made. The tests varied in their rain intensities and the rain duration. Rain intensities varied between 1.7 mm/h (normal rainfall) and 60 mm/h (very heavy rainfall) and the rain duration between 90 minutes and 24 hours.

The additional heat loss caused by under-flowing of the heat insulation boards is adequately described by Equation 1:

$$\Delta U = [m_u \cdot c(\theta_A - \theta_N)] \cdot r/(\theta_1 - \theta_N) \qquad (1)$$

where

θ_1 = air temperature in the room

θ_N = mean precipitation temperature (average value of water temperature at the “rain die” and the temperature in the middle of the gravel layer)

θ_A = water temperature at the roof outlet

TABLE 3
Summary of Measured and Calculated ΔU-Factors

Precipitation (mm/h)	Leakage Rate (%)		ΔU-factor (W/[m²·K])
	min. / max.	mean	
0.5-1.0	5.5 – 8.5	7.0	0.0035
~ 2.0	3.0 – 5.5	4.3	0.002
4.3 – 5.4	1.7 – 1.9	1.8	0.0009
30	0.49		0.00025
60 / 30	1.39		0.0007
60	0.26		0.00013
60 / 30	0.8		0.0004
60	2.93		0.0015
61.4	0.7– 7.8	3.0	0.01
1.7	0.5		0.0025

m_u = intensity of water runoff below the insulation boards

c = specific heat capacity of water

The factor r is the quotient of the mean daily precipitation during the heating period and the mean daily total of precipitation during the test period. By introducing this factor, the findings become comparable even with different rainfall intensities.

The value of the factor r was determined to be 0.0277 during the test. Equation 1 yields a ΔU value of

$$\Delta U = 0.00083 < 0.001 \text{ W/(m}^2 \cdot \text{K)}.$$

The ΔU value, according to Kießl and Künzel (1997), is given by the expression

$$\Delta U = 0.03 \cdot R \qquad (2)$$

where

R = mean precipitation volume during the heating period.

The above result is based on the assumption that 100% of the falling precipitation runoff was below the insulation boards.

However, when a WSL was applied, only a small portion of the precipitation water ran off below the insulating material. This water volume is characterized by the so-called leakage rate. Equation 2 is extended by a factor L, which then describes the leakage rate as

$$\Delta U = 0.03 \cdot R \cdot L. \qquad (3)$$

In case 100% of the precipitation runs off below the insulating material, L = 1. If ΔU is calculated according to Equation 3 with a maximum leakage rate of 10%, then L = 0.1, and at a precipitation volume R = 1.7 mm/d, the following value results:

$$\Delta U = 0.005 \text{ W/(m}^2 \cdot \text{K)}.$$

Table 3 shows a summary of the determined ΔU values.

TABLE 4
Elastic Modulus of the MK-Fleece after Different Aging Procedures (Cziesielski and Fechner 1999)

Age	New	Artificial UV radiation	Inverted roof after five years of exposure
E-Modulus	355 N/mm²	332 N/mm²	253 N/mm²

SELECTED FINDINGS OF MATERIAL TESTING

The material behavior of the MK fleece was analyzed both in new and in aged samples of the fleece. The following properties, among others, were analyzed:

- Vapor diffusion resistance
- Behavior under admission of water pressure
- Strength at mechanical stress

Diffusion Behavior

The diffusion behavior of the WSL was analyzed as defined in DIN 52615 (DIN 1987). The thickness of a diffusion equivalent air layer s_d is found by determining the steady-state vapor diffusion at a partial vapor pressure difference across the sample. The mean thickness of a diffusion equivalent air layer at different levels of relative air humidity between 0% and 50%, as well as 50% and 100%, was determined to be $s_d = 0.02$ m.

Resistance to Mechanical Perforation

The background of this test is a possible perforation of the separating layer when the gravel layer (ballast) is walked upon. An area of approximately the size of a human foot was tested with different loads. It could be shown that the separating layer is not perforated by gravel grains, even at loads of ca. 0.30 N/mm², which correspond to the compressive strength of XPS foam (i.e., far above the expected practical loads of the roof area).

Testing of Water Resistance in Hydrostatic Pressure Test

These tests were aimed at determining the resistance of the MK fleece against water seepage in case of an accumulation of water above the fleece.

A sample was subjected to a continually rising water pressure until water seeped through in drops at three spots. This test was made following EN 20811 (EN 1992).

The measurement at freely weathered samples from an inverted roof after a useful life of five years yielded a pressure head of 32 cm. This means that the WSL, under the practical use conditions of a roof, is waterproof, even if there may be a temporary water accumulation due to a partially closed roof outlet.

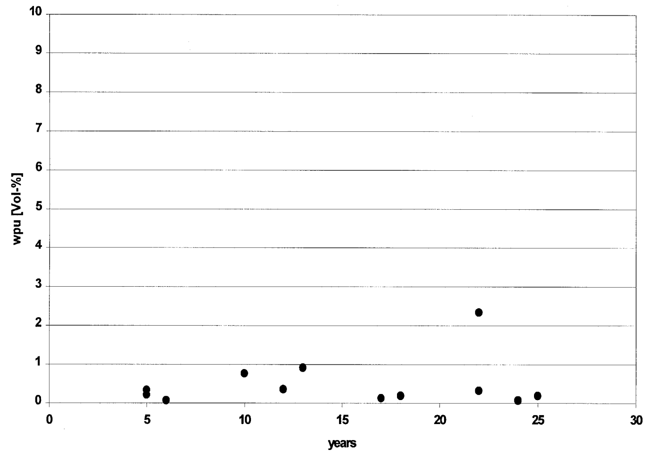

Figure 5 *Long-term water absorption (wpu) of XPS-insulation boards (d = 50 mm) in inverted roofs with gravel.*

Elastic Modulus of the MK Fleece

The elastic modulus of the MK fleece has been determined in order to characterize its long-term mechanical performance. The samples tested were aged in two different ways:

- aging under artificial UV radiation and
- aging under normal application conditions in an inverted roof.

The results are shown in Table 4.

In relation to the non-aged sample, the sample aged under roof application conditions below the gravel layer becomes more “soft” than the sample aged artificially under UV radiation. This means that the MK fleece under end-use conditions can better resist mechanical impacts, which leads to a lower perforation risk.

LONG-TERM BEHAVIOR OF INVERTED ROOFS WITH WATER-REPELLENT SEPARATION COURSE

Moisture Absorption of XPS Heat Insulation Boards

It is known from numerous tests that the moisture content of XPS insulation boards in inverted roofs with gravel in the long term is below 2 Vol-%—in the majority of cases even below 1 Vol-% (Merkel and Boy 1996) (Figure 5).

This long-term behavior must not deteriorate by the installation of the WSL.

To prove the long-term performance of XPS insulation boards under the WSL, samples of boards were removed from a test roof in both the summer and the winter. In one area, the insulation boards were covered with the WSL, and in another area with a conventional polypropylene, the boards were covered with nonwoven fleece. Gravel with a thickness of ca. 5 cm was provided as ballast. The sampling results for one year each after heating and summer periods are compiled in Tables 5 and 6.

TABLE 5
Moisture Content of Insulation Boards in an Inverted Test Roof after the Summer Period (Cziesielski and Fechner 1999)

XPS sample No.	Water content (g)	Water content (Vol-%)
1: under WSL (area 1)	4.3	0.15
2: under polypropylene fleece (area 1)	14.3	0.65
3: under WSL (area 2)	96.7	1.25*
4: under WSL (area 3)	31.6	0.53
5: under polypropylene fleece (area 1)	20.5	0.64
6: under polypropylene fleece (area 3)	35.1	0.60

* Boards installed in 1982 under a polypropylene fleece.

TABLE 6
Moisture Content of Insulation Boards in an Inverted Test Roof after the Heating Period (Cziesielski and Fechner 1999)

XPS sample No.	Water content (g)	Water content (Vol-%)
10: under WSL (area 1)	23.2	0.73
11: under polypropylene fleece (area 1)	33.8	0.94
12: under WSL (area 3)	63.9	0.75
13: under Roofmate MK (area 3)	58.9	0.60

Figure 6 shows the long-term water absorption of XPS insulation boards measured continuously over a period of six years.

The XPS insulation boards have very low moisture contents in both systems. If the amount of water released during the summer period is analyzed, it becomes evident that the diffusion capability of a WSL is better than that of a nonwoven polypropylene fleece. One reason for this is that more dirt can accumulate in the structure of the polypropylene fleece, which slightly reduces the diffusion capability.

Diffusion Capability of the WSL

The determination of the thickness of a diffusion-equivalent air layer with five-year-old samples from an existing roof did not yield an increase of values as compared to new material. The value remained at 0.02 m.

PRACTICAL IMPLEMENTATION

Table 7 is a compilation of typical U-factors for inverted roofs with a WSL.

The WSL should be loose-laid over the insulation at right angles to the slope with 150 mm laps running down the slope. At upstands and penetrations it should be turned up to finish above the surface of the ballast. At the roof parapet, the WSL is to be laid upward between the insulation and waterproofing membrane for at least 15 cm.

During installation, the separating layer is to be protected in a suitable manner against wind uplift (e.g., by partial filling of gravel) until the entire ballast is applied.

The WSL can also be applied in green roofs below a drainage layer of gravel or in car parking roofs between the XPS insulation and the concrete road surface.

TABLE 7
U-Factors for Inverted Roofs with WSL (According to German Standards for Thermal Design of Buildings)

	Heat insulation system with		
	XPS-A d =140 mm λ= 0.040W/(m·K)	XPS-A d= 160 mm λ = 0.040W/(m·K)	XPS-X d=180 mm λ = 0.035W/(m·K)
U-factor* W/(m²·K)	0.27	0.24	0.19

* Load-bearing system of 160 mm reinforced concrete, 10 mm bitumen moisture-proof roofing.

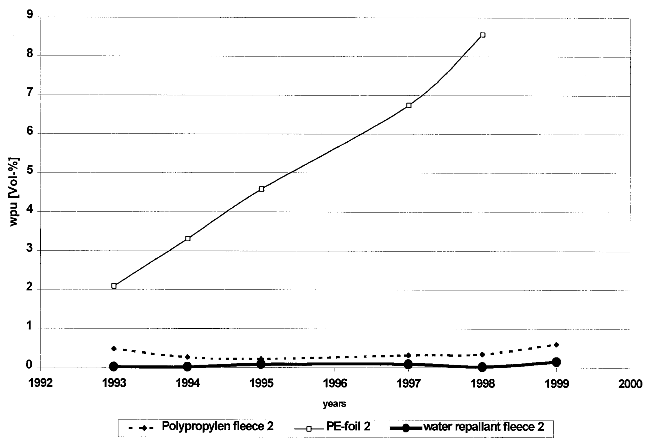

Figure 6 *Long-term water absorption (wpu) of XPS insulation boards covered with different separating layers.*

SUMMARY

The inverted roof system with a water-repellent separating layer WSL, consisting of loose-laid overlapping sheets of a special nonwoven MK fleece above the insulation, was developed with the aim of reducing precipitation-conditioned heat loss (ΔU-factor) to such an extent that the ΔU-factor becomes negligible.

- Tests have shown that the amount of rainwater reaching the waterproofing layer is reduced to such an extent that the mean ΔU-factor is only about 0.001 W/(m²·K). This order of magnitude is negligible in comparison to the heat losses of other building components.

- The newly developed separating layer has a sufficient diffusion capability also after several years of use. There is no inadmissible increase of the moisture content in XPS insulation boards.
- The mechanical properties and the waterproofing of the WSL and the MK fleece itself are more than sufficient for practical stresses.

Hence, the water-repellent separating layer WSL complies with the essential requirements for application in inverted roof systems:

- safe drainage of precipitation water,
- prevention of moisture accumulation in the thermal insulation, and
- longevity of the roof system.

Hence, the ΔU-factor can be left unconsidered for WSL applications:

$$\Delta U = 0.$$

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