Thermal and Moisture Performance of a Sealed Cold-Roof System with a Vapor-Permeable Underlay

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ABSTRACT

A sloped-roof structure, having only one ventilation airspace, is studied in this paper. In this sealed cold-roof system, the underlay foil forms a nonventilated airspace above the thermal insulation, which improves the thermal performance of the roof. The internal moisture loads can be transported by diffusion through the highly vapor-permeable underlay to the ventilation cavity. The sealed underlay system works also as an additional resistance against air leakages.

The thermal and moisture performance of the sealed and conventional roofs were studied in field experiments done in a test building in southern Finland. Different roof sections have been studied for three heating seasons.

The experiments show that the sealed roofs have as good a moisture performance as conventional roofs. With similar air leakage paths and pressure differences, the sealed underlay system could decrease the leakage airflow rate by 15% and the total heat losses through the ceiling by 23% when compared to a conventional roof.

INTRODUCTION

The objective of this research was to study the thermal and moisture performance of a lightweight sloped-roof structure that had only one ventilation airspace above a highly vapor-permeable underlay foil. In Finland, sloped roofs typically have ventilation above and below the underlay. The underlay protects the roof against liquid moisture from above (leaks or condensation), and the ventilation above the underlay is meant to dry out the condensed water. Because the underlay material is typically relatively vapor-tight, ventilation below the underlay is necessary to dry out the moisture coming from the inner material layers and from the indoor air.

In the roof solution presented here, the underlay foil has a low air permeance and it forms a closed, nonventilated airspace above the thermal insulation (sealed cold roof system). Due to the very high vapor permeability of the underlay (vapor resistance Sd < 0.02 m), moisture will be transported by diffusion through the layer to the only ventilation airspace above it. The underlay protects the thermal insulation against wind forces. Because of the low convection in the lower airspace or attic space, the temperature field of the roof (in the lower airspace and thermal insulation layer) is more uniform and temperature levels are slightly higher than in conventional roof applications, which is likely to improve the thermal and moisture performance of the roof.

Air leakage and indoor air exfiltration into the structure may cause severe risks for the moisture performance of the structure (Ojanen and Kumaran 1992; Janssens and Hens 1998; Hens and Mohamed 1998). Air leakage may cause additional heat losses and air infiltration problems with indoor thermal comfort. Typically, structures may have cracks by the joints of material layers or holes due to electric wiring, etc., which produce possible air-leakage routes. In cold climates, the indoor and outdoor temperature difference may cause internal overpressure, especially in higher parts of the building, such as near the ceiling. To avoid problems with air leakage, the leakage flow rate should be as low as possible. The uniform underlay layer forms an additional resistance against air leakage through the roof. Lower air leakage means reduced convective heat losses and moisture loads into the roof.

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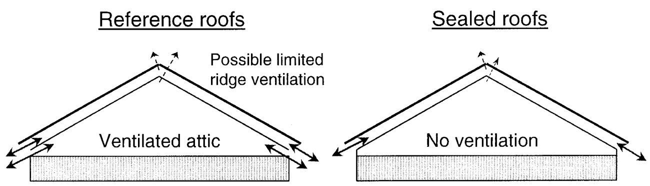

Figure 1 *Ventilation principles of the roof structures used in the experiments.*

The moisture loads caused by the climate and the indoor air set requirements for the drying efficiency of the roofs. This work studies the moisture conditions of roofs in Finnish climatic conditions when the moisture load from indoor air is at a realistic level. The main interest was in the moisture performance of the sealed cold-roof system presented compared to typical roofs having two ventilation routes. Both the conventional roofs and the roofs having a sealed underlay system were studied using full-scale field experiments. This paper presents the moisture and thermal performance findings of the roof systems analyzed.

CONTENTS OF THE RESEARCH

Figure 1 presents the ventilation principles of the roof structures studied. In conventional roofs, there are two ventilation routes on both sides of the vapor-tight underlay layer. In these reference roofs, wind may cause forced convection in the thermal insulation and increase the heat losses through the roof (Silberstein et al. 1991; Uvslokk 1996). The sealed roof system protects the thermal insulation against the wind forces and the roof can dry out through the highly vapor-permeable underlay.

The objective was to compare the thermal and moisture performance of the presented roof structures in well-monitored field experiments. The main interest in this paper is on the effect that the sealed roof system has on the convective heat losses and moisture loads due to air leakage through the roof structure. In the following sections, the research methods are presented and the research findings are studied.

EXPERIMENTAL RESEARCH

Test Roof Setup

A test building was built at the VTT test site in Espoo, Finland (Figure 2). The width of the test building was 6 m and the sloped (1:2) roof panes were facing north and south. The roof was divided into five 1.2-m-wide independent roof sections. The roof sections were separated from each other by partition walls so that there was no air, moisture, or heat flow between them. The horizontal thermal insulation was a 250-mm-thick glass-wool layer made of two (150 mm and 100 mm) batts. At the inside surface of the insulation there was a uniform PE -foil that formed a sufficient air and vapor barrier for the roofs. In cases with air leakage, the airflow through each roof section was controlled.

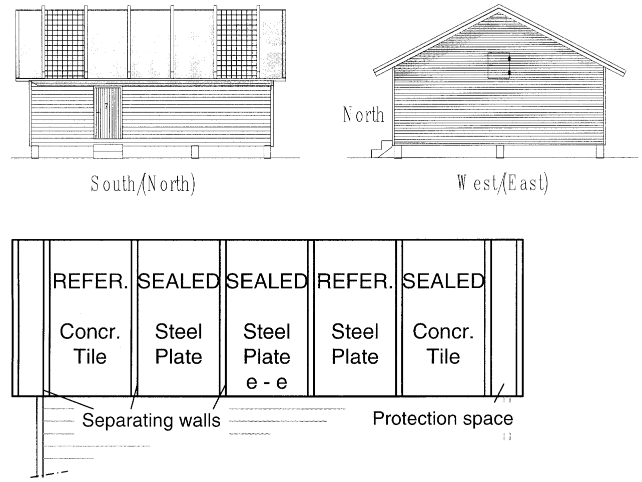

Figure 2 *Roof test house at VTT test site in Espoo, in southern Finland (upper), and five different roof sections used in the experiments (lower). In the sealed roof section in the middle, there was only eaves-to-eaves ventilation (e-e).*

Two reference roofs and three roofs with sealed roof systems were studied. Apart from the underlay material and the ventilation solution, the roofs were the same. The reference roofs that correspond to typical roof construction in Finland had ventilation above and below a relatively vapor-tight and airtight underlay plastic foil. In the sealed roof system, there was ventilation only above the highly vapor-permeable flash-spun HDPE underlay foil. The material properties of the underlay used in the sealed roof system were (1) vapor resistance Sd < 0.02 m and (2) airflow permeance < 3.3 $\cdot 10^{-6}$ $m^3/(s\ m^2\ Pa)$ (< 300 $[cm^3/min]$ /10 cm^2 at 1.5 kPa). The underlay material also had good resistance against water penetration (1.5 m water column with no penetration), which means there will be safety against rain if there are leaks through the roofing. High airtightness means low air leakage through the material layer and significant potential to improve and ensure the total airtightness of the structure with the sealed roof system.

The roofing was made either from steel plate or concrete tile. The steel plate roofing was uniform, made with standing seams (no open joints, ventilation only by the eaves), and the concrete tile roof was made of brick-type blocks also allowing some ventilation through the joints between the blocks. The timber used in the roofs was pine and the wind barrier board at the cold side of the wall insulation was made of 12-mm-thick porous wood fiberboard. This board formed the vertical side protection by the eaves for the thermal insulation on the ceiling.

Instrumentation of the Test Roofs

The thermal and moisture performances of the roof sections were determined by using the measured temperature, moisture content, and relative humidity values. The temperatures were measured from airspaces and material layer surfaces and humidity values from the airspaces above and below the underlay—at about the middle height of the attic airspace (Figure 3). The temperatures and relative humidity values were measured continuously at one-hour intervals.

The main criterion for the moisture performance of the studied roof constructions is the moisture balance of the wooden construction in the attic space. The moisture balance of the attic space depends on the drying efficiency of the system and the moisture loads.

The moisture content of the wooden roof truss (50-by-100 mm) in the middle of each roof section was measured at four points. The measurements were done two ways: (1) by using electric resistance measurement and (2) by weighing wood samples (about 100-by-20-by-2 mm) that were placed on the surface of the studied wooden beam. The wood samples were placed at about the same places as the electric resistance sensors. The four measuring points were about 0.5 m from the eaves and about 0.5 m from the ridge both on the south- and north-facing roof panes (Figure 3). The electric moisture content measurement was done weekly, and the weighing of wood samples was done at two- to three-month intervals. The weighing of wood chips was also used to confirm the moisture conditions in both the airspaces in each roof.

Measurement Accuracy. The uncertainty in the moisture content measured with moisture pins (electric resistance) under steady-state conditions is approximated to be ±1% (weight). The dependence of the measured moisture content on temperature was approximately -0.02% to 0.05% (weight)/K at different relative humidity levels.

Under dynamic conditions, the moisture content will be different on the surface and at 15 mm depth (moisture pins were installed at about 15 mm depth in the wooden beam) in the specimen. Thus, the method gives approximation for the average moisture content between the wood surface and 15 mm depth. Due to the slow moisture transfer in wood, these measurements show significantly slower changes in moisture content than the weighing method, where 2-mm-thick wood samples were used. Before the tests, the moisture pins were calibrated at the same moisture content, and the difference between the moisture content level in different roofs should be lower than the absolute error in the measured moisture contents. Each roof section had four measuring points, which also decreases the error in the average moisture content level. The electric-resistance measurements give an idea of the moisture performance of the roofs during the tests, and the weighing method gives more a accurate moisture content level by the surface of the wood layer. The uncertainty of the temperature measurements was approximately ±0.1 K.

Experimentally Studied Cases and Periods

Lengthy field tests were carried out in order to study the thermal and moisture loads and performances of the sealed and conventional roof systems in northern climatic conditions. In this research, the moisture and thermal performance of both conventional roof construction and the sealed roof system were studied.

The indoor and outdoor climatic conditions were about the same for all the roofs. The outdoor temperature, humidity, solar radiation, and wind conditions can be considered equal for all the roofs. The indoor temperature was also uniformly distributed in the test house and, thus, the indoor temperature conditions were quite close to similar for different roof sections. In order to study the moisture behavior of the roofs, there had to be some internal moisture load to represent normal occupation.

The experiments were carried out in two parts. In the first part, the internal moisture load was the same for all the roof sections and moisture was evaporated into the attic. In the second part there was air leakage through the ceiling of the roof sections, either indoor air leakage (exfiltration) through the ceiling into the attic airspace or air leakage to the indoor air from the attic (infiltration). The pressure difference between indoor and outdoor air was the same for all the roof sections. In the air leakage cases, the size and location of the leakage paths through the ceiling were identical for all the roofs, but

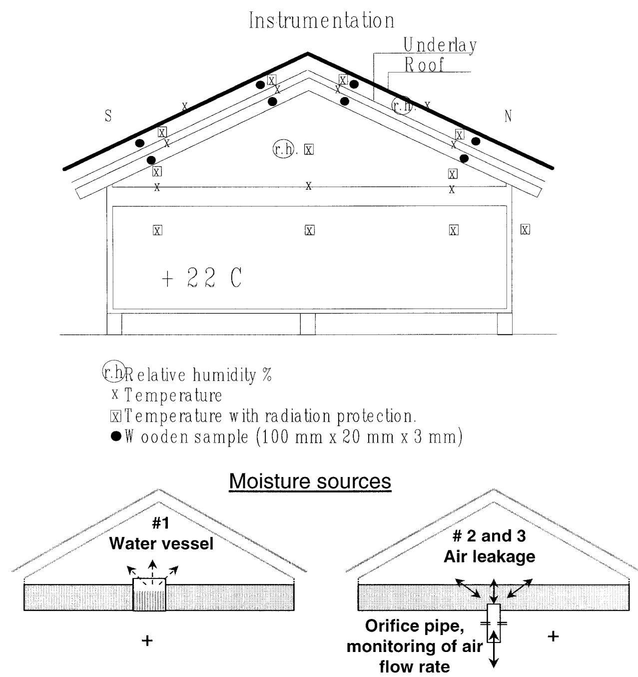

Figure 3 *Instrumentation of the test roofs (upper) and moisture load mechanisms used in the experiments (lower). Moisture content of the wooden roof truss was measured at four points in each roof section. Water vessel open from above to the lower airspace (lower, left) was used in test period 1, and controlled air leakage through similar orifice pipes in each roof section (right) was used in test periods 2 and 3.*

because the sealed underlay caused a slightly higher flow resistance than what occurs in conventionally ventilated reference roofs, the leakage flow rates were different with the same air pressure difference. This caused differences in moisture loads and ventilation losses between the roof sections.

The test periods carried out in the experiments were the following:

- **Test period 1.** October 1998 to October 1999, equal moisture loads from water vessels, water vapor evaporated into the attic airspace.
- **Test period 2.** January 2000 to June 2000, indoor air flow through the ceiling into the attic airspace (air exfiltration), indoor air about 35% RH, about 20 Pa indoor overpressure compared to outdoor air.
- **Test period 3.** October 2000 to May 2001, air infiltration from attic airspace through the ceiling, about 20 Pa indoor underpressure compared to outdoor air.

The 20 Pa pressure difference between the outdoor airspace and the indoor air is relatively high compared to typical values in buildings (< 10 Pa without the possible effect of the wind). This level was chosen because the airflow measurements were done by measuring the pressure differences in calibrated orifice plate pipes installed in each roof section. These orifice pipes represented the similar air leakage openings through the air/vapor barrier layer of each ceiling. In order to have good measuring accuracy, the total pressure difference (including that of the ceiling and the orifice pipe) was set to be about 20 Pa. The leakage airflow rate can be considered the main parameter in these measurements. With the selected pressure difference, the leakage flow rates were in typical range for ceiling structures—about 2 L/s, corresponding to about 0.28 L/(s m^2) leakage per ceiling area.

The attic space air pressure levels were, in the reference cases with a ventilated attic, about that of the outdoor air, and in the sealed roofs, the pressure difference over the sealed underlay system was very low (< 2 Pa) when compared to that between the indoor and outdoor air (20 Pa).

Test periods 1 and 2 represent typical indoor moisture loads into the roof. Due to the temperature difference between indoor and outdoor airspaces during a cold period and the building height, indoor air may have a higher pressure level than the outdoor air at the ceiling level. The overpressure may cause air exfiltration from indoor air through the ceiling, as in test period 2. Problems with moisture accumulation caused by air exfiltration or indoor airflow into the structure are known (Ojanen and Kumaran 1992; Ojanen and Simonson 1995), and in cold climates the aim is to avoid a long period of indoor air leakage through the structures by having indoor underpressure as the predominant condition. This requires a relatively airtight building envelope with a high enough net exhaust ventilation flow rate. Test period 3 represents the case with continuous air infiltration from the attic airspace through the ceiling into indoor air.

All the test roofs had ventilation openings on the eaves for ventilation of the space between the roofing and the underlay. The opening, as well as the ventilation space, was 50 mm wide. This ventilation was independent for each roof section. Depending on the test period, the roofs had (slightly) different ventilation principles that are presented in Table 1.

In test period 1, there was no air leakage between indoor air and the roof structures. In the upper ventilation cavity, additional ventilation was arranged for two of the steel plate roofs through small openings at the ridge. These ridge openings connected the upper ventilation airspace with the outdoor air through small holes (eight ϕ 20 mm holes through 50 mm wood), and they represented the low ventilation caused by a leaky air ridge or possible openings on the gables of a house. Only one sealed roof section with a steel plate covering had totally airtight roofing and only eaves-to-eaves ventilation (Figure 2).

EXPERIMENTS WITH EQUAL MOISTURE LOADS

In test period 1, about equal moisture load was caused for each roof section by using water vessels. The results from these experiments have already been presented in detail in earlier papers (Ojanen 1999, 2000). The moisture sources used in these tests were water vessels that were open from above to the attic airspace (Figure 3). The water flow into the attic space of each roof section could be monitored and controlled. The target moisture load into each roof section was 1 g/(h m^2) (per ceiling area), which can be considered relatively high but still a realistic moisture load from the indoor air to the roof (Janssens and Hens 1998). It corresponds to that caused by continuous 0.10 L/s m^2 air-leakage flow from indoor air transporting +3 g/m^3 moisture increase into the attic space.

Thermal Performance

Figure 4 presents the measured outdoor air and attic airspace temperatures in a reference and a sealed roof with concrete tile roofing during a short winter period. The temperature in the reference roof followed the changes in the outdoor air temperature more closely than the sealed roof. When the outdoor air temperature was constant or decreased, the temperature in the sealed roof attic space was typically higher than in the reference roof, but when the outdoor air temperature increased, the sealed roofs remained colder than the reference roofs for a few hours.

The thermal performance was characterized by the relative heat losses through the roof sections. In the analysis, the thermal resistance between the indoor air and the upper surface of the thermal insulation was assumed to be the same in each roof section and the thermal resistance above this surface could be improved (increased) by the sealed roof system. Using this assumption and the measured temperature difference over the thermal insulation layer, the heat flows could be determined and approximations for other insulation thicknesses could be solved. Table 2 presents the relative reduction in heat losses due to a sealed roof system during the

TABLE 1
Roof Cases During Experiments with Equal Moisture Load in Each Roof Section in Test Period 1 (Top) and During Experiments with Air Leakage Flows in Test Periods 2 and 3 (Bottom)

Case	Underlay	Roofing layer	Ventilation of attic space	Ventilation between roofing and underlay
Reference, concrete tile	Reinforced plastic foil	Concrete tile	Eaves (+ridge)	Eaves + brick joints
Reference, steel plate	Reinforced plastic foil	Steel plate	Eaves (+ridge)	Eaves (+limited ridge)
Sealed, concrete tile	Highly vapor-permeable foil	Concrete tile	No ventilation	Eaves + brick joints
Sealed, steel plate	Highly vapor-permeable foil	Steel plate	No ventilation	Eaves (+limited ridge)
Sealed, steel plate e-e	Highly vapor-permeable foil	Steel plate	No ventilation	Eaves to eaves (closed ridge)

Case	Underlay	Roofing layer	Ventilation of attic space	Ventilation between roofing and underlay
Reference, concrete tile	Reinforced plastic foil	Concrete tile	Eaves	Eaves + brick joints
Reference, steel plate	Reinforced plastic foil	Steel plate	Eaves	Eaves
Sealed, non-ideal	Highly vapor-permeable foil	Concrete tile	Leakage cracks (d = 1 mm) on eaves (L = 1,2 m)	Eaves + brick joints
Sealed, no leakage	Highly vapor-permeable foil	Steel plate	No ventilation	Eaves
Sealed, ideal	Highly vapor-permeable foil	Steel plate	No ventilation	Eaves

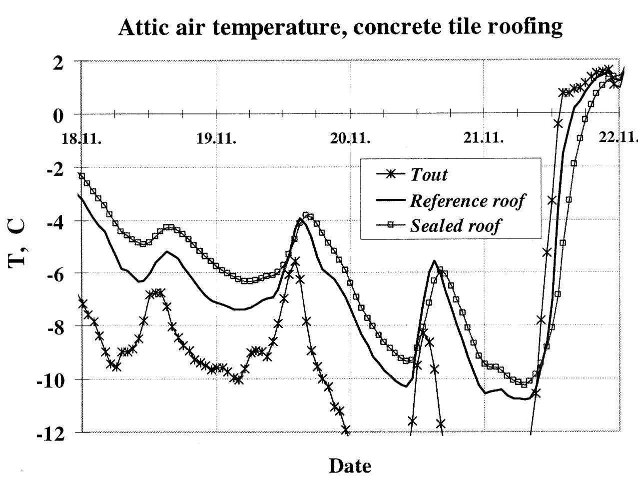

Figure 4 *Measured outdoor air and attic airspace temperatures in reference and sealed roofs.*

TABLE 2
Relative Savings in the Heat Losses Due to the Sealed-Roof System in Finnish Climatic Conditions in Cases with Airtight Ceilings (Conductive Heat Losses Only)

Insulation thickness (mm)	Reduction in heat losses due to sealed roof system		
	Concrete tile	Steel plate	Steel plate (e-e)
300	1.9%	2.2%	3.1%
250*	2.2%	2.6%	3.7%
200	2.8%	3.2%	4.6%
150	3.6%	4.2%	6.0%
100	5.2%	6.0%	8.5%
50	9.3%	10.7%	14.8%

* Measured case

heating season. With 250-mm-thick glass-wool insulation, the reduction in heat losses was about 2% to 4% when applying the sealed roof system compared to a conventionally ventilated reference roof.

In this case, the roofs had a perfectly airtight air barrier at the inside surface of the structure and the savings in the heat losses are based only on the increase of the thermal resistance between the upper surface of the thermal insulation layer and the outdoor air. In the case with strong airflow in the thermal insulation, or air leakage through the ceiling, the presented approach could not be applied and the effect of a sealed system on the total heat losses would be different.

Measured Moisture Performance

The moisture contents were measured at four points in each roof section at about one-week intervals. The local maximum of these four points in each measuring time represents the maximum moisture risk in each roof section, and these maximum values are presented in the following discussion as the main result of the moisture experiments.

Moisture Distribution. The measured moisture content distribution in roofs depended on the roof structure and on the case. The distributions are presented by using the difference between the measured local maximum and minimum values in each roof. Figure 5 presents these moisture content differences for one sealed roof and one reference roof that both had steel-plate roofing. Roofs with concrete tile roofing had about the same performance. Typically, the moisture contents were higher on the north side than on the south side. During test period 1, which had no air leakage through the ceiling, the moisture content distribution (difference between local maximum and minimum) was significantly higher in the reference roof than in the sealed roof. The average moisture content scattering during the first one-year-long measuring period was 1.5% (weight) in the reference roof and 0.9% (weight) in the sealed roof. The lowest moisture content scattering in the sealed roof was detected during the cold winter period. The nonventilated airspace in the attic provided more uniform conditions than the roof with a ventilated attic.

In cases with air leakage through the ceiling, the moisture content scattering was about the same for reference and sealed roofs. The average values were 1.5% and 1.4% (weight) during exfiltration and 1.0% and 0.9% (weight) during infiltration for reference and sealed roofs, respectively.

Maximum Moisture Contents. Figure 6 presents the measured moisture content of the critical part of the five roof sections studied (i.e., the wooden roof truss in the attic airspace). The values present the measured maximum local moisture content of the roof truss (maximum of the four

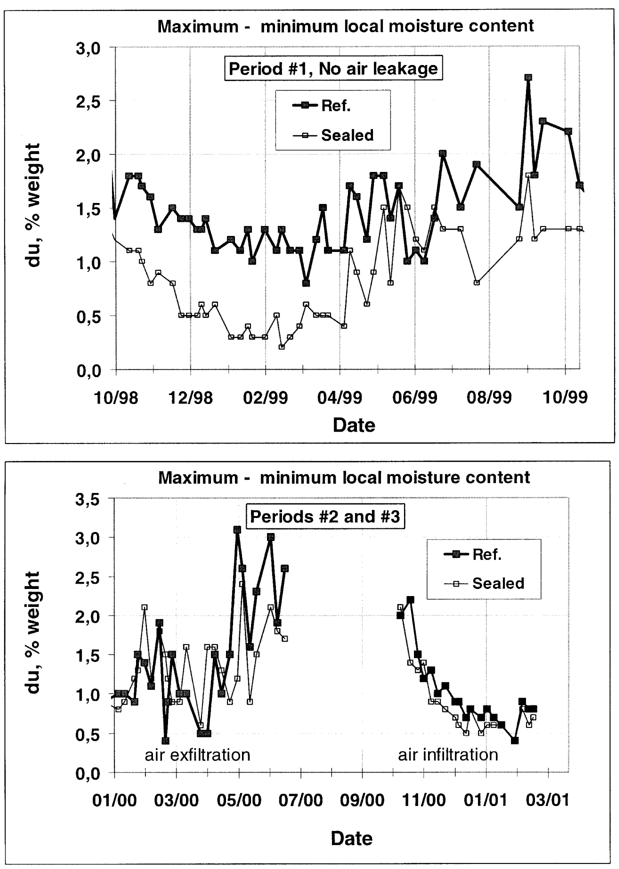

Figure 5 *Maximum measured local moisture content difference (maximum–minimum of four measuring points in the wooden roof truss in each roof [Figure 3]) in reference and sealed roofs during different test periods.*

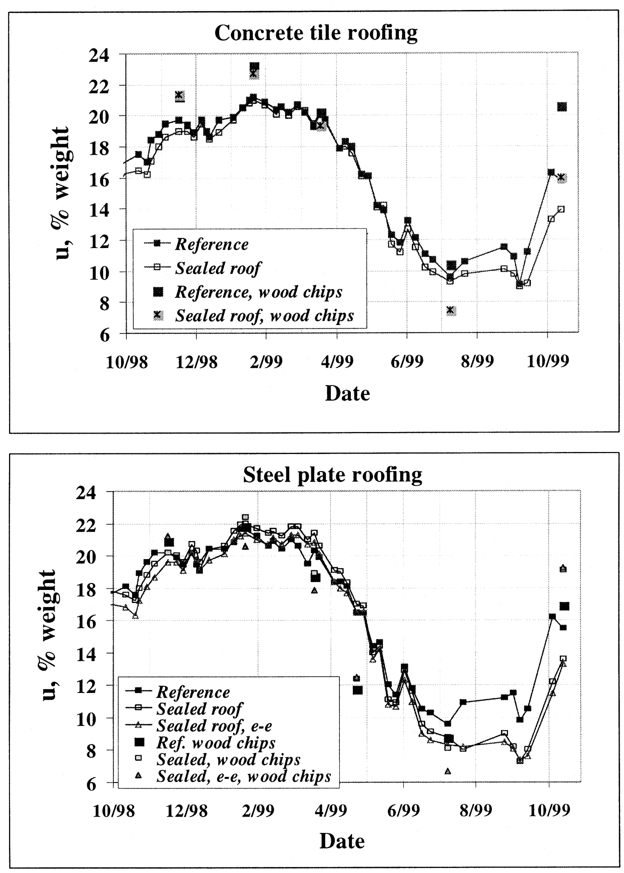

Figure 6 *Measured maximum moisture content of the wooden roof truss in the attic airspace. Lines represent electric measurements and single points the results from wood chip weighing. Concrete tile roofing above and steel plate roofing below.*

measuring points in each roof section), which represents the highest risk in the moisture performance. The overall moisture performance was very similar for all the roof sections. During the winter, the sealed steel roof with eave-to-eave ventilation had a temporary 1.5% (weight) higher moisture content than the reference roof, but at the end of the test period the moisture contents were about 2% (weight) lower in the sealed roofs than in the reference roofs. The drying efficiency during springtime was at least as good with the sealed roofs as with the reference roofs.

Evaluation of the Measurement Confidence. The possible error in electric moisture content measurements is higher than the measured difference. Taking into account that the sensors were calibrated and that the average moisture content represents the same tendency as the presented maximum values (maximum local moisture content of the four measuring points in each roof section), the results, especially the differences between the cases, are more reliable than what the absolute accuracy of the electric measurement indicates.

The electric measurements represent the moisture content of the wood truss from the surface to about 15 mm depth, whereas the weight measurements represent only about 2-mm-thick surface conditions of the timber layer. Therefore, the weight measurements react faster to the changes in the surrounding conditions than the electric measurements, which have more delay. For example, the weighing method shows higher moisture content during the winter (for the surface layer of the wood) and lower values during the drying period in the spring (surface layer dries out first), which could be expected. Due to the different reaction times of the measurements, the order of the moisture content levels between different cases could also be different when determined by weighing or electric measurements. These measurements still show relatively good agreement in the overall moisture performance of the roof systems studied.

Moisture Performance. The experimental studies show that in Finnish climatic conditions, the sealed roof system has as good a moisture performance as a conventionally ventilated roof construction when the internal moisture load to the roof is relatively high (about 1 g/[h m^2]). In a sealed roof system, the moisture load coming from indoor air can dry out as well as in a conventional roof construction with a ventilated attic and, in summer conditions, the sealed roofs showed even better drying efficiency.

EXPERIMENTS WITH AIR LEAKAGE

In this case, the air leakage through the structures was arranged by using similar airflow openings through the air/vapor barrier of the ceiling of each roof section (Figure 3). The air leakage openings were 50 mm diameter pipes (one through each roof section) that included a calibrated orifice plate having a 23 mm diameter opening. These pipes connected the indoor air with the lower part of the thermal insulation layer, allowing airflow through the air and vapor barrier of the roof. The same measuring system was used both in exfiltration and infiltration experiments. This instrumentation allowed continuous monitoring of the airflow leakage rates through each roof structure.

The airflow rate through each roof section depends on the total air pressure difference between indoors and outdoors and on the airflow resistance of the roof structures including the orifice pipes. The pressure difference was the same for each roof section. The main difference in roof structures was the underlay system that was either ventilated or sealed. The sealed underlay system causes higher flow resistance than what the reference roofs have and the leakage airflow rates should also be lower.

The roof cases studied are presented in Table 1. Four of the roof sections had air leakage between indoor air and the structure, and one (sealed roof) was airtight. Both of the sealed roofs with steel plate roofing had only eave-to-eave ventilation. Small holes representing some gable openings (as in test period 1) were not present. In these studies, only one sealed roof system was really sealed with airtight joints. The other sealed roof was non-ideal and the purpose was to study a more realistic case with possible leakage flows. This leakage through the underlay system was caused by two cracks along the wind barrier on both sides of the roof. These cracks were about 1.5 mm wide and 1.2 m long (the width of the roof section). The roof structures and air leakage openings were mainly the same in cases where air exfiltration or infiltration were studied.

Some small changes were done for test period 3. In test period 2, the only material layer between the outdoor air and attic airspace by the eaves was the vertical part of the porous wood fiberboard wind barrier. This part of the wind barrier board was about 0.5 m high; it was partly in contact with the thermal insulation and partly above the insulation, and it was sealed with the underlay from the top of the board. In the test period with infiltration (test period 3), the sealed ideal structure was improved so that these vertical parts of the wind barrier by the attic space were covered using the vapor-permeable underlay foil. This gives a better idea of the ideally sealed underlay system, when the total airflow resistance of the sealed system depends only on the underlay foil but not on the other material layers.

Another improvement was done in the heat flow measuring system. All the roofs were equipped with heat flux meters covering the whole roof area. These heat flux meters were made of 25-mm-thick hard mineral wool boards (60 kg/m^3, 0.6 by 1.2 m) that had five thermocouples each. The thermal conductivity of these boards was measured using heat flux meter apparatus, and the thermocouples were calibrated separately. Each roof had ten such heat flux meter boards below the actual thermal insulation and above the PE vapor barrier. The total thickness of the thermal insulation layer in these air infiltration experiments was 275 mm.

The purpose of this improvement was to avoid the errors caused by the previous method to determine heat flux distribution by using the temperature difference over the whole thermal insulation layer. When there was airflow in the insulation layer, this method could result in false heat flux values. The measuring system using these built-in heat flux meters that cover the whole ceiling area eliminates this source of error.

Heat Losses During Air Leakage

The thermal performance of the roof/ceiling structures during air leakage was analyzed by determining the transmission (conduction) heat losses through the ceiling area and the ventilation heat losses due to the air leakage through the ceiling of each roof section. In this analysis, the assumption was that the required air change of the room space was taken care of by a ventilation system and that the heat losses caused by air leakage were considered additional and undesirable. The overall heat losses for each test roof section were determined as a sum of these heat losses, and they were presented as heat flux values solved per ceiling area (W/m^2):

$$q_{,tot} = q_{,c} + q_{,air} \tag{1}$$

where $q_{,tot}$ is the total heat flux for the roof section, $q_{,c}$ is the measured average heat flux through the ceiling area, and $q_{,air}$ is the ventilation heat losses defined in Equation 2.

$$q_{,air} = V\rho_a c_p \Delta T / A \tag{2}$$

where V is the leakage airflow rate through the ceiling (m^3/s), ρ_a is the thickness of the air (kg/m^3), c_p is the specific heat of the air (J/kg K), and A is the ceiling area (about 7.2 m^2 in each roof section). The temperature difference term ΔT is defined as follows:

$\Delta T = T_{in} - T_{out}$, in cases with air exfiltration, and
$\Delta T = T_{in} - T_{air,in}$, in cases with air infiltration,

where T_{in} is the indoor air temperature, T_{out} is the outdoor air temperature, and $T_{air,in}$ is the temperature of the air flowing into the room space during infiltration.

The definition of the ventilation losses takes into account the heat recovery from conductive heat losses to infiltrating air. Without heat recovery, the temperature of the air flowing into the room would be that of the outdoor air. During infiltration, the colder outdoor air cools down the structure and increases the conductive heat losses. During air exfiltration, the heat recovery has an effect only on conductive heat losses that are reduced.

The effectiveness (ε) of the heat recovery is defined as

$$\varepsilon = \frac{T_{air,in} - T_{out}}{T_{in} - T_{out}}. \tag{3}$$

The thermal performance of different roof structures was presented by comparing their conduction, ventilation, and overall heat losses. The ratio between the overall heat losses of the sealed roof and that of the reference roof ($q_{,tot,sealed}/q_{,tot,reference}$) shows the effect of the sealed roof system on the total heat losses. With ratio < 1, the sealed roof system has lower heat losses than the reference roof. When the comparison is made with a roof having an airtight ceiling (no air leakage), the ratio ($q_{,tot}/q_{,tot,no\ leakage}$) shows how the (uncontrolled) air leakage increases the heat losses in each case. These figures are studied more in detail in the following sections where the research findings are analyzed.

The overall thermal performance of an air-leaking structure is about the same for cases with air infiltration and exfiltration. With a similar air leakage flow route through the structure, the heat recovery effect during air infiltration and exfiltration is almost the same (Ojanen and Kohonen 1989). This means that the sum of conduction and ventilation (air leakage) heat losses through the wall is the same with the same airflow rate and does not depend on the direction of the leakage airflow. During infiltration, the conductive heat losses increase and ventilation losses decrease due to the heat recovery and, during air exfiltration, the conductive heat losses are reduced due to the warm airflow through the structure. In both the cases, the total heat losses approach the ventilation losses when the airflow rate increases.

The thermal performance analysis is presented only for those tests (air infiltration) where the improved heat flux meter system was used when determining the conductive heat losses.

Indoor Air Leakage Flow

Air leakage from indoors to outdoors through a structure (air exfiltration) may cause severe moisture loads to the structure in cold climates. During air exfiltration, the warm and humid indoor air may cause moisture accumulation or even condensation when it flows along or through colder material layers.

In the field tests, the total pressure difference between indoor and outdoor air was kept at 20 Pa (indoor overpressure), and it was the same for each roof section. During the measuring period (from January 5 to April 20, 2000), average leakage airflow rates through the reference roofs were 1.99 to 2.0 L/s; through the sealed non-ideal roof, 1.96 L/s; and through the sealed ideal roof, 1.83 L/s. The ideally sealed underlay system could decrease the air leakage flow rate by only about 8%. In the non-ideal case—about 1.5 mm wide and 1.2 m long—air cracks on both eave sides of the roof nearly cut off all the additional airflow resistance from the sealed underlay system (1.5% to 2% lower air leakage flow rate). One reason for the relative low effect of the underlay system on the air leakage flow rate in the ideally sealed roof was the additional leakage through the approximately 0.25-m-high (above the top surface of the thermal insulation layer) vertical parts of the wind barrier (porous wood fiberboard) that formed part of the sealed roof and was connected to the underlay foil. This part was improved before test period 3.

Moisture Performance. Figure 7 presents the measured maximum local moisture content in the wooden roof truss in the attic airspace during air exfiltration.

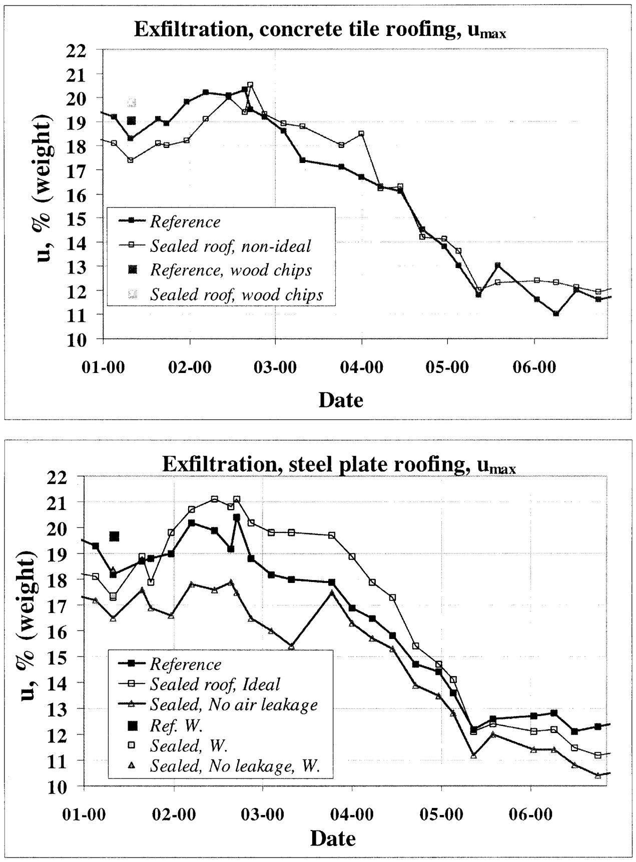

Figure 7 *Measured maximum moisture contents of the wooden roof truss in the attic airspace during indoor air leakage through the roof. Lines represent electric measurements and single points the results from wood chip weighing. Concrete tile roofing above and steel plate roofing below.*

The maximum local moisture contents during the experimental period were, in both the reference roofs and non-ideal sealed roof, about 20.5% (weight), 21% (weight) in the sealed ideal roof, and about 18% (weight) in the sealed roof without indoor air leakage.

The sealed non-ideal roof had about the same moisture performance as the reference roofs, which was expected because the roof was actually ventilated below the underlay by the air leakage through the cracks on both eaves. The air leakage flow rates through the reference and sealed non-ideal roof cases were also similar, which shows that the airflow resistance of the non-ideal underlay system was about the same as that of the ventilated roof.

The sealed ideal roof had a 2% (weight) higher local maximum moisture content than the reference roof during the winter period. The sealed roof dried out so fast that, at the beginning of May, the moisture contents were at the same level as those in the reference roof. Before the middle of April, the moisture content level decreased below 17% (weight), which corresponds to relative humidity conditions below 80%. This moisture level is considered to be the lowest level that may cause mold growth under suitable temperature conditions (Viitanen 1996). The temperatures were low during the peak moisture period. The average daily outdoor temperature exceeded 0°C in early April and it was about 10°C at the beginning of May. At the end of the experiments, in June, the sealed roof had 0.5% to 1% (weight) lower moisture content level than the reference roofs.

The slightly higher temporary maximum moisture content level during the cold period is not expected to cause moisture problems. Also, the drying of the sealed roof system was at least as fast as that of the reference roof and the end moisture contents were at the same level. Therefore, the moisture performance of the sealed roof is as good as that of a typical roof structure even when the moisture load is caused by indoor air exfiltration into the roof.

Air Infiltration

In this case, the internal moisture load to the roof was almost negligible and the main interest in this case was in the thermal performance of the roofs.

Moisture Performance. Due to continuous air infiltration, there was no convective moisture load into the roof from the indoor air, and the net water vapor diffusion through the opening and the vapor barrier should also be insignificant. Thus, only the outdoor moisture load has an effect on the moisture performance of the roofs, and the predicted moisture levels of the roof sections are lower than in the cases having additional moisture sources, such as water vessels or air exfiltration as in the other experimental cases. The measured maximum local moisture content in the wooden roof truss in the attic airspace of each roof section during air infiltration is presented in Figure 8.

The moisture performance was about the same for all the roof sections, even though the initial moisture content level was different in each case. Due to air infiltration, the temperature of the thermal insulation, and the airspace above it, may be closer to the outdoor temperature than in other experimentally studied cases. This may have caused the slightly higher moisture content levels in the attic space. The local maximum moisture content was 20% in both the reference cases—about 21% (weight)—which is slightly higher than what was measured in the exfiltration case. It seems that when the temperature of the attic airspace is close to that of the outdoor air, the moisture content also approaches the conditions of the outdoor air that has high relative humidity level during the cold season. In this case, the temperature level had an even greater effect on the moisture level of the roof than what the internal moisture loads had in the air exfiltration case.

Thermal Performance during Infiltration. During air infiltration through the ceiling, the outdoor air typically warms up due to heat recovery from warm material layers. The inflowing air warms up and the structure cools down locally by the airflow route. The cooling of the structure means that the conductive heat losses increase, but at the same time the ventilation heat losses decrease from what they were if the inflowing air was at the outdoor air temperature. The heat recovery effect depends on the airflow rate and route. In these experiments, the airflow route was limited to the surrounding area of the air opening in about the middle of each roof section.

Figure 9 presents the average measured heat flux distribution in each roof section during air infiltration. The figure presents only the average conductive heat losses for the period of October 15, 2000, to January 8, 2001. The infiltrating air cools down the roof and increases the local heat losses as the air warms up due to the heat recovery effect. The convective heat losses caused by air leakage were solved using the measured airflow rate and the temperature difference between the inflowing and indoor air.

The measured heat flows, temperatures, and leakage airflow rates are presented in Table 3. The values presented are the average values for the period of October 15, 2000, to January 8, 2001, during which the indoor and outdoor average temperatures were +22.9ºC and +4.4°C, respectively.

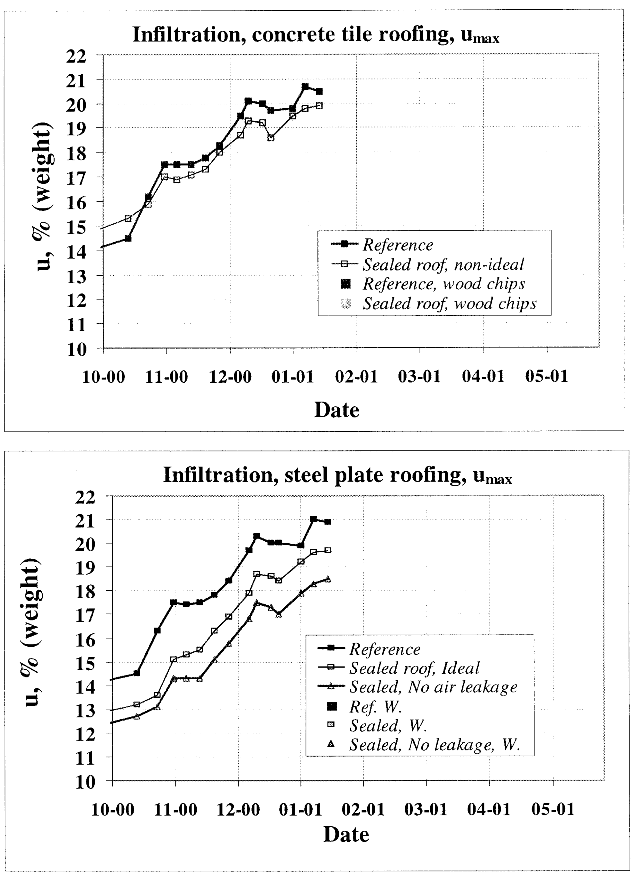

Figure 8 *Measured maximum moisture content of the wooden roof truss in the attic airspace during air infiltration. Lines represent electric measurements and single points the results from wood chip weighing. Concrete tile roofing above and steel plate roofing below.*

When analyzing the effect of a sealed roof system on the heat losses, the sealed roof results should be compared with the reference case that has a similar air leakage path. The case with no air leakage always has the lowest heat losses and the general aim is to build airtight structures without any leakage. However, some leakage paths are typical in real structures. Comparison with a non leaking ceiling shows how sensitive the thermal performance is to air leakage. Comparison with a reference roof shows the benefit of a sealed underlay system in reducing the heat losses.

The first part of Table 3 (on top) presents the conductive heat losses and their relative values when compared to the case with no air leakage through the ceiling and with the reference case having the highest average conductive heat losses. Lower air leakage flow in the ideally sealed roof means decreased cooling effect during cold periods and, thus, the conductive heat losses were 17% lower than in a reference roof.

The middle section of Table 3 presents the air leakage flow rates through the roofs, temperatures of the infiltrating air, and the absolute and relative heat losses caused by the cool airflow into the room. The convection-caused heat losses are presented as nominal values solved per roof area (W/m^2) to enable simple comparison with the average conductive heat losses.

The ideal sealed roof had about a 15% lower leakage airflow rate than the reference roof even though the flow paths and pressure differences were the same in both cases.

The heat recovery effect of the infiltrating air, defined as in Equation 3, depends on the airflow rate. A lower airflow rate means a better heat recovery effect and a higher infiltrating air temperature. In the reference and non-ideal sealed roof cases that had about the same flow rate, the inflowing air tempera-

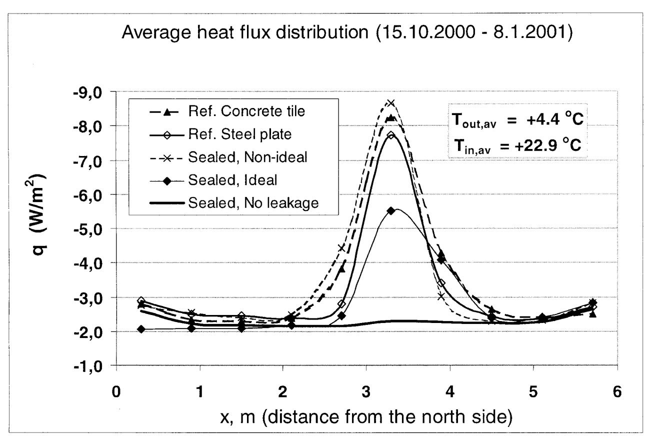

Figure 9 *Measured average conductive heat flux distributions through the experimentally studied roof sections during air infiltration. Numerical values presented in Table 3.*

TABLE 3
Summary of the Thermal Performance of Roof Sections During Air Infiltration Experiments
Measured Average Values During October 15, 2000, to January 8, 2001. Average Indoor and Outdoor Temperatures were +22.9ºC and +4.4ºC. Conductive Heat Losses are Presented on the Top, Convective Heat Losses in the Middle, and Total Heat Losses on the Bottom Table.

Case	Conductive heat flux, q, W/m^2	q / q (no leakage)	q / q (ref. max)
Ref. concrete tile	3.37	1.46	1.000
Ref. steel plate	3.17	1.38	0.940
Sealed, Non-ideal	3.37	1.47	1.002
Sealed, Ideal	2.80	1.22	0.832
Sealed, No leakage	2.30	1.00	0.683

Case	Leakage air flow rate (L/s)	$V/ V_{ref, max}$	$T_{,air\ in}$ (°C)	$q_{,air}$ (W/m^2)	$q_{,air}$ / q (ref. max)
Ref. concrete tile	1.84	0.983	9.26	4.35	0.984
Ref. steel plate	1.88	1.000	9.27	4.42	1.000
Sealed, non-ideal	1.81	0.964	8.90	4.38	0.990
Sealed, ideal	1.60	0.852	11.67	3.10	0.702
Sealed, no leakage	0.00	0	-	-	-

Case	Total heat flux, $q_{,tot}$ (W/m^2)	$q_{,tot}$ / $q_{,tot}$ (no leakage)	$q_{,tot}$ / $q_{,tot}$ (ref. max)
Ref. concrete tile	7.72	3.35	1.000
Ref. steel plate	7.59	3.30	0.983
Sealed, non-ideal	7.75	3.37	1.004
Sealed, ideal	5.91	2.57	0.765
Sealed, no leakage	2.30	1.00	0.298

ture was in the range of 8.9ºC to 9.3ºC and the effectiveness of the heat recovery was about 25%. In the ideal sealed roof case, the average inflowing air temperature was 11.7ºC, corresponding to nearly 40% heat recovery effect. Due to the higher infiltrating air temperature and lower airflow rate, the convective heat losses in the ideal sealed roof were 30% lower than in the reference case.

The last part of the table presents the absolute and relative total heat losses (sum of conductive and convective heat losses) of each roof case. In the measured case, the ideal sealed underlay system caused about a 17% savings in conductive heat losses, a 30% savings in ventilation heat losses due to air leakage, and the overall savings were 23%.

Reduction of air leakage flows due to the sealed underlay system causes significant savings in heat losses. If the roof structure was perfectly airtight, the effect of the sealed roof would be limited to decreasing the convective heat losses from the cold surface of the thermal insulation layer, and the maximum effect would only be about 4% with a 250 mm insulation thickness (Table 2).

The non-ideal sealed roof was not really sealed, but the air leakage flow rate, as well as the conductive and convective heat losses, were in the same range as those measured for the reference roofs. This shows how even relatively small leakage cracks (1.5 mm wide and 1.2 m long cracks on a 12-mm-thick porous wood fiberboard wind barrier on the eaves) through the sealed system that the underlay and wind barrier of the wall forms, may change the thermal performance of a sealed roof to correspond to that of a ventilated reference roof. The relation between the area of the ventilation opening of the cracks and that of the roof was, in this case, only 0.05%. This shows how small leakage openings can induce ventilation in the structure. It also emphasizes the importance of planning the structural details and the need for good workmanship when applying a sealed underlay system, in order to have the system as airtight as possible and that the system may cause reduction in heat losses.

APPLICABILITY OF SEALED COLD-ROOF SYSTEM IN COLD CLIMATES

The sealed cold roof underlay system is meant to protect the roof against wind-caused convection and to produce additional flow resistance to reduce air leakage through the roof. The following conclusions are based on the results of the experimentally studied cases.

The sealed system can improve the thermal performance of the roof. The savings in heat losses are at the level of 2% to 4% when the ceiling is perfectly airtight and the thermal insulation layer is about 250 mm thick. A perfectly airtight ceiling structure has no air leakage losses and it represents an optimal implementation of the building envelope. Structures may typically have some air leakage openings and, in that case, the sealed underlay system can form an additional air barrier layer that reduces the leakage flow rates and the uncontrolled ventilation heat losses through the roof area.

In the experiments under winter conditions in Finland, the ideally installed sealed underlay system could reduce the leakage airflow rate by 15% when compared to a similarly ventilated roof solution (reference case), having a similar air leakage opening through the ceiling. The measured result is the average of a nearly three-month period with 20 Pa pressure difference between indoor and outdoor air (indoor underpressure). In this case, the infiltrating air cooled down the structure and increased the conductive heat losses. Due to the lower leakage flow rate in the sealed roof system, the reduction of conductive heat losses was 17% when compared to the reference case. Also, due to the lower air leakage flow rate, the heat recovery effect during air infiltration improved, which still reduced the ventilation heat losses. The reduction in ventilation heat losses (due to air leakage) was about 30% in the sealed roof case when compared to the reference case. The savings of the overall heat losses through the sealed roof, when compared to a typical ventilated roof, was 23% during the measuring period and in the measured conditions. The requirement is that the sealed system form an additional air resistance layer and thus reduce the air leakage flow rate through the ceiling.

As a summary, the sealed roof has better thermal performance than the reference roof with ventilated attic space. When the ceiling is airtight, the effect of the sealed system on the heat losses is relatively low—< 4% in the experimental case. The effect on heat losses may be significant when the sealed system reduces unwanted air leakage flows through the roof. The possible energy savings depend strongly on the pressure conditions (pressure difference over the building envelope) and on the implementation of the sealed underlay system. The requirement is that the sealed underlay system be ideal (i.e., all the joints are sealed and there are no extra leakage cracks through the sealed underlay system). Air cracks on both sides of the roof, having a total area of 0.05% of that of the ceiling, could cut down nearly all of the thermal benefit of the sealed roof system. This means that the structural details and workmanship have an important role in the thermal performance of the sealed underlay system. If the sealed system is non-ideal and has air leaks, the thermal performance approaches that of a reference case.

According to the measurements during three heating seasons in Finnish climatic conditions with different moisture loads, the moisture performance of the sealed system is as good as that of a typical roof having ventilation on both sides of the underlay. The requirement for such good moisture performance is that the underlay material have a very low vapor diffusion resistance—the material used in the tests had vapor permeance value (corresponding to thickness of still air) Sd < 0.02 m. During the summer period, the sealed roof typically had lower moisture content levels than the reference roof, which improves the moisture safety. When the starting level is lower, the maximum moisture content during the winter accumulation period will probably also be at a lower level. Possible non-idealities (air leakage) in the sealed underlay system do not affect the moisture performance of the roof.

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