TPF informs No. 7

VAPOUR CONTROL LAYERS (VCL) IN ROOFS

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Information pamphlet No. 7
Published April 1996

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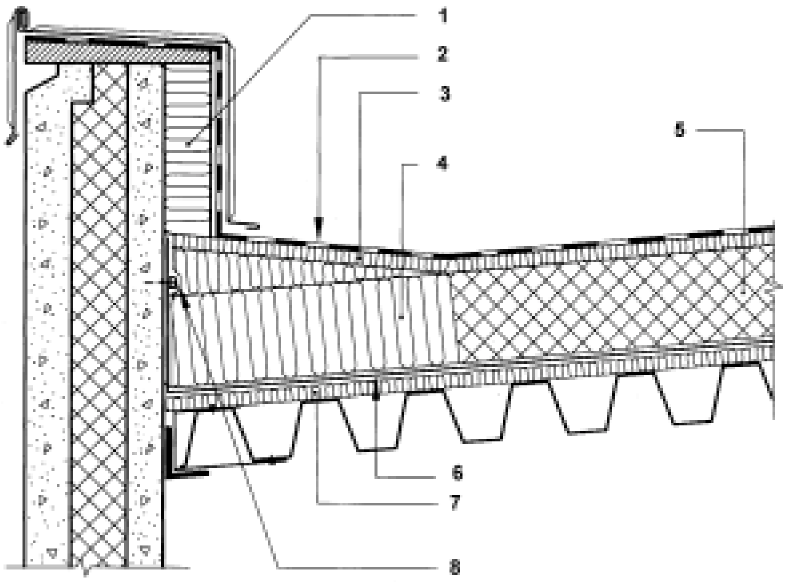

1 Insulation/cold bridge break
2 Roof waterproofing
3 Non combustible insulation
4 Non combustible insulation
5 Combustible/non combustible insulation
6 Vapour control layer (VCL)
7 Non combustible insulation or panel K1-A as support for VCL
8 Batten for tightening of VCL

SCOPE

Norwegian Roofing Research Group (TPF) and Norwegian Building Research Institute (NBI) have published this information pamphlet.

It covers the use of vapour control layers (VCL) in compact as well as ventilated roofs whether flat or pitched.

What is TPF?

The Norwegian Roofing Research Group (TPF) is an association of manufacturers of roofing materials such as flexible membranes and insulation, installers and associated trades.

The aim of TPF is to cover the need of the members for research, when developing insulation and roofing systems, and to publish information regarding the correct use of these products.

Firms connected to TPF
Producers of insulating materials:
A/S Rockwool, Oslo

Producers of roofing materials and have contracting departments:
Icopal A/S, Fjellhamar
Isola as, Eidanger
Protan A/S, Drammen

Roofing companies:
Hesselbergtak A/S, Oslo
Ing. Per E Jørnsen A/S, Drammen
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Tingstad A/S, Oslo
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INTRODUCTION

This pamphlet about vapour control layers (VCL) in roofs published by Norwegian Roofing Research Group (TPF) has been prepared according to an assignment contract by Norwegian Building Research Institute (NBI). The term roof in this context covers both ventilated and compact configurations, flat and pitched.

The aim has been to collect all relevant knowledge about the subject and publish recommendations about the selection of type and design details for the use of VCL in roofs. The reason for this is the great number of reported damages caused by moisture where incorrect use and design detailing of the VCL was the primary cause.

The first section of the pamphlet contains background information, while the last two chapters are about recommendations and design guidance. The form in chapter 7 shows a simplified method for “design” of VCL to be used in cases where more sophisticated approaches are unnecessary.

The Research Council of Norway (NFR), TPF and NBI have funded the research work in parts. Some of the results from the joint project have been made accessible in cooperation with the project team of the research project “Moisture in building materials and structure” as well as with the team in the “Pitched roofs” project sponsored by Statsbygg (The Directorate of Public Construction and Property).

We are of the opinion that there are basically two paths to follow in order to choose the right type and design detailing for VCL.

A) A choice based on experience to obtain satisfactory safety is shown in chapter 7. Chapter 8 shows in addition some practical design detailing.

B) A choice can also be based on detailed moisture technical calculation and evaluation for each individual building where among other factors the local climate is also accounted for. One of the ways to do this is on the basis of calculations using the data program MATCH as shown in Chapter 6. The results of such a calculation of the moisture transfer by diffusion and of the drying out potential of the construction is to be compared with the total moisture transfer and a possible damage profile.

2. MOISTURE MECHANICS

Protection against moisture damage requires a certain level of knowledge about the mechanics of moisture. Moisture mechanics is the study of how building materials absorb, transport and emit moisture. Several material properties are dependent upon the moisture content:

- Changes in the level of moisture content (MC) of materials may result in changes in volume which may cause twisting, deformations, expansion and formation of cracks in the constructions
- High level of moisture content gives rise to the formation of rot in wood and wood based materials. A moist environment gives rise to corrosion of metals
- Exposure to moisture may cause changes in colour and appearance of many materials
- The thermal resistance of materials is usually reduced with increasing moisture content

2.1 Relative and absolute moisture content of air

The ability of the air to absorb moisture in the form of water vapour is dependent on the temperature. At a given temperature the air can only contain a certain amount of water vapour. The water vapour pressure in air with maximum water content is called saturated vapour pressure (SVP). If air at SVP is supplied with more humidity or if the temperature is lowered it will cause a decrease in SVP and excess water vapour will condense out. Table 2.1 gives the saturation vapour pressure for a range of air temperatures.

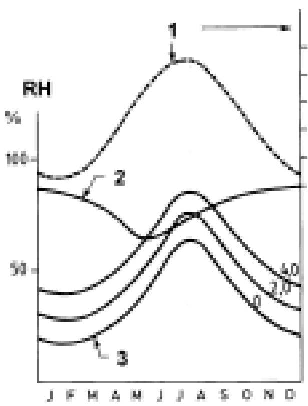
The moisture content in air can be stated as the relative humidity (RH), which expresses the moisture content as a percentage of the SVP at the specified temperature. The moisture content can also be expressed in absolute terms usually in grams per m^3 of air or as a partial pressure in Pa (N/m^2).

Table 2.1
Saturation vapour pressure (SVP) and moisture content (MC) for air temperatures between 30°C and − 30°C (for temperatures below freezing the saturation pressure referred to is just above the surface of ice)

Temp °C	SVP N/m^2	MC g/m^3	Temp °C	SVP N/m^2	MC g/m^3	Temp °C	SVP N/m^2	MC g/m^3
30	4245	30.36	10	1228	9.40	–10	260	2.14
29	4005	28.78	9	1147	8.83	–11	238	1.97
28	3780	27.24	8	1072	8.28	–12	225	1.81
27	3565	25.80	7	1001	7.76	–13	199	1.66
26	3360	24.40	6	935	7.27	–14	181	1.52
25	3170	23.04	5	872	6.80	–15	166	1.39
24	2985	21.80	4	813	6.37	–16	151	1.27
23	2815	20.60	3	757	5.96	–17	137	1.16
22	2640	19.45	2	705	5.57	–18	125	1.06
21	2485	18.35	1	656	5.20	–19	114	0.97
20	2335	17.29	0	611	4.84	–20	104	0.88
19	2195	16.33	–1	563	4.48	–21	94	0.80
18	2060	15.40	–2	517	4.13	–22	85	0.73
17	1935	14.50	–3	475	3.82	–23	78	0.67
16	1818	13.65	–4	437	3.52	–24	71	0.61
15	1703	12.82	–5	402	3.24	–25	64	0.55
14	1596	12.09	–6	368	2.99	–26	58	0.50
13	1496	11.37	–7	338	2.75	–27	52	0.46
12	1400	10.68	–8	310	2.53	–28	47	0.41
11	1311	10.03	–9	284	2.33	–29	42	0.38
						–30	37	0.34

2.2 Exterior and interior air moisture content

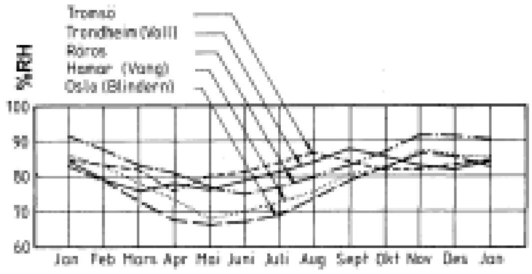
The relative moisture content in the air varies during the year as well as through the day. Figure 2.2 shows an example of average exterior and interior temperature and moisture content.



1 Exterior temperature
2 Exterior RH
3 Interior RH

Figure 2.2
Variation in air temperature and humidity through the year.

It can be seen from the graphs that the relative humidity is much lower indoors in the winter than outdoors, but the large difference in saturation pressure between warm interior air and cold exterior air causes the interior air to contain far more water vapour than exterior air.

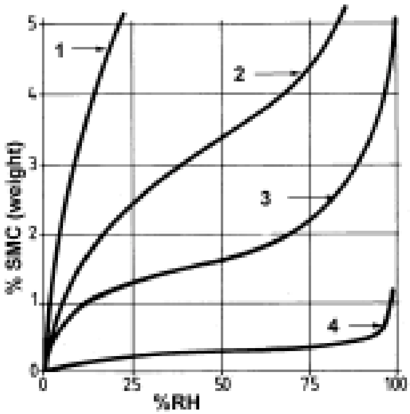


Typical variation in exterior RH

2.3 Equilibrium and relative MC

Hygroscopic materials can pick up quite a lot of moisture directly from the air. Wood can pick up about 27 – 30% by weight, which is in the order of 150 kg water per m^3. A material stored in an environment with constant air temperature and relative MC (RH) obtains after a given time a steady state. This moisture content where there is no further changes is called the equilibrium moisture content (EMC). Figure 2.3 shows examples of some EMC curves, also called sorption curves.

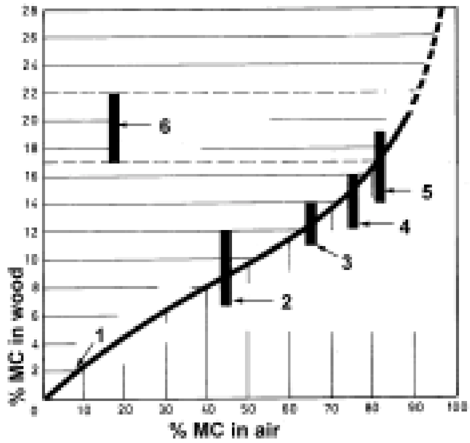
Sorption curves for a material may vary depending whether drying out or wetting up obtains the steady state. If there is wetting up the curve is named adsorption curve, while at drying out it is named desorption curve.



1 Wood
2 Aerated concrete
3 Concrete C 25
4 Masonry

Figure 2.3
Example of sorption curves at wetting up for four well-known materials.

Two materials in contact will with time obtain the same level of relative air moisture content (% RM) in the pores although the moisture content by weight may be different.



1 Balanced MC at 15°C
2 Furniture
3 Windows, external door
4 Load bearing structures
5 External wood cladding
6 Dry wood in external air

Figure 2.4
Wood EMC stored in air with respect to humidity and temperature. Typical levels of moisture content in wood in relation to use are marked.

2.4 Vapour diffusion and convection

The transport of moisture within a material and within a structure may be carried out in both the vapour phase as well as in the liquid phase (capillary transport). In connection with computation of the risk of condensation within or on the surface of building materials it is mainly transport in the vapour phase that is of interest.

This transport in the vapour phase can take place by two processes, convection and diffusion as follows:

- *Moisture convection*, which implies the transport of water vapour with streams of air. Convection of moisture within a structure is dependant of the air tightness and pressure difference across the structure.

- *Diffusion*, which implies the movement of water molecules through the material in the direction of decreasing vapour pressure. This means it is the absolute moisture content in the air or the vapour pressure that decides which way the diffusion goes and not differences in the relative moisture content.

See NBI Design Sheet 421.132 for more details about how moisture transport by convection or diffusion can be calculated.

The most common definitions are:

- *Water vapour permeability* (δ_p), referred to as "permeability" in what follows, is water vapour transport through a material in kg/msPa or rather as $kg/m^2s(Pa/m)$.

- *Water vapour permeance* (w_p) is water vapour transport through a material (layer) with a given thickness d_g in m (kg/m^2sPa). The permeance $w_p = \delta_p / d_g$.

- *Water vapour resistance* (Z_p) is a measure of the vapour tightness for a material (layer) with a given thickness (m^2sPa/kg). The resistance, calculated from the permeability and actual thickness (d in m) of the material is $Z_p = d/\delta_p$ or $1/w_p$
  Example:
  Permeability for wood particleboard is $\delta_p = 3.8 \times 10^{-12}$ kg/msPa.
  Water vapour resistance for a 12 mm board is: $Z_p = 0.012/3.8 \times 10^{-12} = 3.2 \times 10^9$ m^2sPa/kg.

3. INTERIOR ENVIRONMENT

3.1 Interior air vapour content

The air moisture content in a building varies with the time of the year, the use of the building and ventilation. It is therefore important to know the environmental condition of the building in order to assess properly the moisture condition in the roof construction.

The greater the moisture content in the interior air the greater is the amount of moisture that might be transported up into the roof and the greater is the risk for condensation within the roof construction.

This is valid for both diffusion and convection.

Measurements in the actual building can give information about interior moisture content. If the ventilation is insufficient the interior air of the building may have very high moisture content.

Moisture production

The production of moisture may come from a variety of sources like perspiration and breathing of humans and animals, washing-up, washing and drying of clothes, bathing and showering, cleaning, making food as well as from plants. Indoor swimming pool and aquarium may increase the production of moisture. Sometimes humidifiers are used to increase moisture.

The moisture production varies of course in time and space, but a distribution takes place due mainly to convection and the moisture capacity of materials.

According to an investigation carried out in Sweden small living houses have an average moisture production of 9.8 ± 0.5 kg/24 hrs and an apartment in a high-rise building of 5.8 ± 0.5 kg/24 hrs.

Added moisture

Added moisture is the difference (positive is increase) in vapour content between interior and exterior air.

Vapour content in interior air is dependant on the vapour content of exterior air, the interior production of moisture and the rate of ventilation.

$v_i = v_e + v_\Delta$ or $v_\Delta = G/Q$

where

v_i = Vapour content in interior air in kg/m^3
v_e = Vapour content in exterior air in kg/m^3
v_Δ = Added moisture in kg/m^3
G = The production of moisture in kg/24 hrs
Q = The rate of ventilation in m^3/24 hrs

3.2 Interior air pressure

When there is a difference in interior and exterior air pressure, the air flows through ventilation gaps and other openings in the building envelope.

The pressure differences may be created by various factors such as wind, the ventilation system or temperature differences. See figure 3.2 taken from the NBI hand book "Building with wood"

The wind creates an outside suction on the leeward side and a pressure on the windward side of a building. Size and location of the openings in the exterior envelope will decide whether the interior pressure turns out to be positive or negative. NS 3479 chapter 4.2.5 says more about that.

Large portions of a roof may experience positive pressure on the inside independent of the wind direction because of the thermal buoyancy inside the building.

At the neutral zone of the building the pressure difference is zero because of the temperature differences. The distribution of the leakages decides the location of the neutral zone. If all leakages are located in the lower part there will be a positive pressure in the upper part of the building.

A mechanical ventilation system with fans creates a pressure difference between exterior and interior air. The pressure differences created in this way may vary by more than 10 Pa depending upon how the system is regulated with a positive, balanced or negative pressure.

The maximum interior positive pressure because of the chimney effect may vary with temperature, volume, and distribution of leakages and the height of the building. As a rule of the thumb you may say that there is a pressure increase due to thermal buoyancy of 1 Pa per m height in areas of average low temperatures.

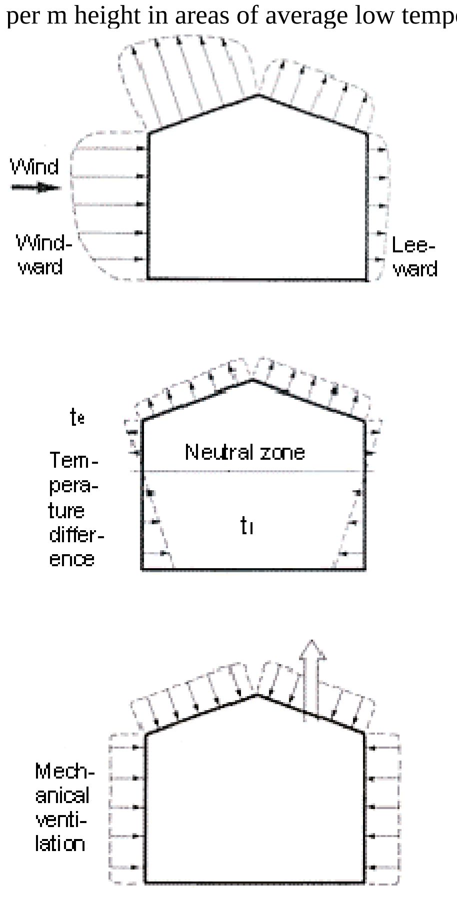


Figure 3.2
Pressure differences at exterior envelope due to wind, thermal buoyancy and mechanical ventilation. The location of the neutral zone is based on even distribution of leakages.

4. ROOF CONFIGURATION

The choice and build of the roof construction shall satisfy the Building Regulation. These are the four main points to observe:

- Building elements and structure shall have such a design that moisture should not penetrate into or through to give rise to moisture damage or any other inconveniences.
- The external envelope shall have such a design that water from precipitation is drained away.
- All structures containing materials that can be damaged by moisture shall have such a design that all entrapped moisture should have a possibility of drying out.
- Materials and structure shall at the time of closing in be sufficiently dry in order not to initiate the growth of micro-organisms, degrading of organic substances and increased emission of gasses.

For the structure to comply with the first of these conditions it requires to some extent air tightness as well as resistance against vapour penetration.

Air tightness
It is always necessary to have air-tightness in an insulated roof structure

- against penetration of air from outside to inside
- against escape of air from inside to outside
- against penetration of wind into the insulation

Sufficient air tightness can be obtained by:

- load bearing structure of insitu cast concrete
- membrane roof waterproofing with tight details
- interior membrane in form of airtight VCL with tight joints and connection to adjacent walls.

Water vapour resistance
A certain amount of vapour resistance on the warm side of the insulation is usually necessary. This is in order to prevent penetration of moisture by diffusion. In roof structures with potential for attack of rotting there is usually the need for permeability on the cold side of the insulation. This is to enable the moisture to escape on the cold side.

4.1 Compact roof

In a compact roof the layers of materials lay in direct contact with each other without any form of cavity or ventilation. In such roofs the waterproofing membrane may function as an air-tightening barrier. However this is usually not the case at parapet and penetrations. The VCL layer, if properly installed, is usually the layer that is most reliable regarding air tightness of the construction.

Compact roofs will usually have two more or less vapour tight layers, the VCL and the waterproofing membrane. Materials containing wood should not be used in between these layers because entrapped moisture may cause formation of rot and fungi.

Compact roofs are considered to be warm roofs where melting of snow will take place. Such roofs should as a main rule have interior outlets to avoid melting water to form ice on cold areas and cause damage.

4.2 Ventilated roofs

A ventilated roof has a ventilated space between the thermal insulation and the roof waterproofing for the passage of exterior air. This air should facilitate the transport of moisture from the structure without reduction of the thermal resistance. The ventilation should result in low temperature in the membrane to reduce the melting of snow. A good condition for drying out is an important characteristic for a ventilated roof.

4.3 Entrapped moisture

Building materials such as insitu cast concrete and wood in a new building posses excess moisture (so-called entrapped moisture), which have to dry out before the EMC in relation to the interior condition of the building is reached. The drying out is a process that may take some time and cause a series of practical problems. It is important to identify these moisture conditions in relation to the choice of materials and the effectiveness of the drying out mechanism. Entrapped moisture in compact roof constructions with materials containing wood should be avoided.

Compact roofs with mineral wool on concrete and membrane with bitumen or polymeric sheet contain no organic materials that can be damaged by moisture. Insitu cast concrete may however contain a large amount of water, which may evaporate and reduce the thermal resistance if allowed to condense within the insulation. Placing a VCL directly on the concrete will stop this massive transport upwards. The water will then dry out inwards over a longer period of time. Experience has showed this to be true.

4.4 Damage

NBI has numerous reports of damage by moisture in its files. Moisture as direct water penetration from the outside or as condensation from inside is the dominating causes. The use of wood or materials containing wood in construction exposed to moisture may cause considerable damage by rot during just a few years.

The process of rotting may progress with accelerating speed because of the production of water.
Other damage caused by moisture may be dripping, fungus (bad smell), corrosion and excessive heat transfer.

The workmanship of installing the VCL is important in relation to the moisture control of the entire building. Almost as important as good tightness against precipitation is the effectiveness of drying out of a ventilated roof. Control of interior pressure conditions is also an important factor if you want to reduce damages by moisture in a building.

4.5 Rot and fungus

The most important factor for the growth of fungus is the amount of water available. The individual organisms have clear limits for how dry or wet it may be before growing takes place. The growth stops when the conditions are too dry. Some species die as soon as it becomes too dry for growth, while others survive drying out for years.

In order that fungus spores should start growing in wood the temperature in most cases have to be above 10°C and free water must be present. If the wood is infected in the first place it only requires + 5°C and wood moisture content of 20 % (RH = 85%) for the growth to resume. The damage may be considerable if the ideal condition exists for a prolonged period of time. Mould may occur in the same manner on surfaces exposed to moisture over some time corresponding to 75 % RH for wood based materials and 85 % for mineral wool.

Rot fungus is specialized in breaking down cellulose and/or lignin. To live fungus needs wood or products made from wood (paper). Mould experienced in buildings has a great ability to find nourishment from a large variety of materials such as; rubber, polish, painting, food, paper, plastic and derivatives of wood.

The problems in connection with rot in buildings might be related to aesthetics, health or collapse of the structure. Mould on the other hand might be related to problems associated with aesthetics, health and bad odour.

5. VAPOUR CONTROL LAYERS

5.1 Function

The vapour control layer (VCL) has several functions. The VCL shall deter moisture from passing from the interior and out into walls and roof by diffusion or convection, moisture that with time may cause damage. The VCL shall also prevent excessive heat loss and annoying draughts due to air leakage. To do so all joints and connections must be airtight.

5.2 Requirements to VCL

Test methods and requirements for PE sheets used as VCL can be found from Product Norm 8000 “PE sheet as VCL in buildings” issued by Norwegian Plastics Association. This norm refers to mechanical properties, durability and required material quality. Flexibility, toughness and strength are important properties for ease of installation. Product Norm 8000 is only valid for PE sheets, but could serve as a guide when selecting VCL made of other materials.

A VCL should not have lower water vapour resistance than $50x10^9 m^2s$ Pa/kg. When designing a construction susceptible to rot the total vapour resistance on the warm side of the thermal insulation should at least be in the order of 5 to 10 times greater than the resistance on the cold side.

In compact roofs without materials susceptible to rot and where the interior vapour pressure is reasonably low the roof may be designed in the usual way with VCL of PE sheet or alternatively with a sheet which facilitates drying out to the interior during the summer season.

In buildings with high interior vapour pressure the roof VCL must be of high quality. To enable the roof construction to dry out a ventilated configuration should be evaluated.

Roof on cold stores where the interior temperature is lower than the exterior the whole year, the VCL should be located on the outside and preferably combined with the roof water proofing membrane with good vapour resistance. Because of the stable conditions the gradient of the vapour pressure always runs from the outside to the inside and never offers the possibility for drying out. VCL on the inside is not required but a layer to secure air tightness is preferable.

Air tightness
In the Norwegian Building Regulation, chapter 53, a requirement for the total air tightness for the whole building is given. Total passage of air through plain surfaces with joints shall be lower than a certain level. In order to facilitate required total tightness the passage of air through a VCL should not be greater than 0.002 m^3/m^2hPa.

In practise it is the joints and the penetrations that are decisive for the air tightness. A VCL should therefore be delivered in large widths in order to minimize the number of joints during installation.

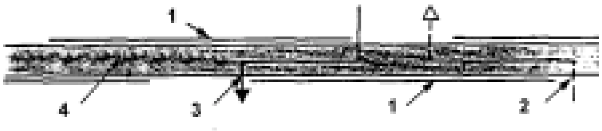
Table 5.2
Water vapour resistance for some types of VCL materials

Material	**Thickness** mm	**Water vapour resistance at 35-75 % RH** x 10^9 m^2sPa/kg
Polyethylene (PE)	0.15	360
Polyethylene (PE)	0.20	450
Aluminium foil on strong paper		240
Polyvinyl chloride (PVC-P)	1.0	70
Butyl (IIR)	0.5	900
Bitumen with core of polyester felt	2	700
Hygrodiode	0.5	100

5.3 Types of VCL
Polyethylene (PE) is today the dominant material used as VCL. The sheets may be produced in thickness up to 0.2 mm in various widths and lengths. A minimum thickness of 0.15 mm is recommended to minimize damages during installation.

Other types
In compact roofs it may be relevant using VCL of other materials. The most common is made of bitumen felt with core of glass- or polyester fibre, polymeric sheets of PVC or rubber made of butyl.
VCL with high mechanical resistance, which facilitates welded joints and can function as a temporary roof waterproofing is often called Roof VCL (RVCL).

Hygrodiode
This is a type of VCL developed to increase the potential for the construction to dry out. The principle of how the Hygrodiode function is shown in figure 5.3. In the warm period when the sun shines on the outer surface the moisture moves inwards and condenses on the Hygrodiode. The water is led through the synthetic felt by capillarity and eventually evaporates to the adjacent room. Since the air tightness is moderate the Hygrodiode should be used with caution in buildings with high interior air pressure or high RH. On the other hand since the drying out function is excellent this is a good alternative if the roof gets sufficient heating from the sun.



1 Plastic film
2 Diffusion in winter
3 Capillary suction in summer
4 Synthetic felt

Fig 5.3 The principles of function for Hygrodiode

5.4 VCL punctured by roofing fasteners

The air tightness of VCL was investigated by NBI in 1992. A laboratory test was developed to measure the tightness of joints and the VCL after being punctured by fasteners for roof waterproofing.
The air leakage caused by incorrect installation was marked greater than when the fasteners were properly installed. The sideways sliding of drills and self-tapping screws should be avoided. Fasteners that do not obtain proper grip should be left in place and additional fasteners installed.

For buildings with a potential high interior RH like swimming pools, wet industry, laundries, wood driers etc., NBI discourage the use of mechanical fasteners for membranes in compact roofs unless special precaution is observed. Small installation errors may in buildings of this kind lead to serious moisture problems. Other roof configurations should be considered such as ballasted systems.

Figure 8.4 in chapter 8 shows one possible design for such instances (not in risk class R4), preferably in connection with a ventilated roof waterproofing.

5.5 Jointing of VCL

In order to obtain sufficient air tightness all joints must be carefully executed. This can be done in several ways. Air tightness is best obtained using fully bonded joints where the VCL is placed on an even surface without intricate details.

Joint with overlay only
Investigation has shown a relatively high air leakage in joints with overlay only. There is no unambiguous relationship between the width of overlay and the air leakage. This type of joint should only be used in connection with the recommended interior environmental category. When using this type of joint the VCL must lay on an even surface, the overlay should be 200 mm and loaded with insulation on top exerting a pressure on the layers. This type of jointing must not be used in buildings with high air pressure and/or high RH.

Tape
The use of tape is acceptable if used as tightening in an overlap joint. Any transfer of forces must not take place. The durability must be documented. A successful use of tape is very much dependant of the conditions during installation.

Mastic sealants, sealant stripping
Sealants may be used in an overlap joint. It is important that it sticks to the material used. Double sided EPDM sealant stripping is also available.

Welding
Hot air welding of PE sheets is possible and renders good air tightness when used properly. The welding technique is inconvenient in use and hence not commonly used.

6. CALCULATION OF THE DRYING OUT POTENTIAL FOR DIFFERENT ROOF CONFIGURATIONS

Whether a construction has acceptable design from a moisture point of view or not can be assessed in different ways, mainly according to the accuracy of the method:

a) compare estimated vapour pressure and estimated saturation pressure across the construction
b) compare estimated moisture accumulation and estimated drying out by diffusion (Glaser method)
c) perform a dynamic analysis of the moisture transport through the construction during one or more years using data programs.

NBI has carried out a number of calculations for compact roofs. With reference to Project Report N3796 the following conclusions can be drawn:

- To omit VCL from a construction that does not possess sufficient tightness gives unwanted moisture concentration.
- To omit VCL from an in-situ placed concrete deck allows the moisture to penetrate outwards and accumulate by condensation.
- Continuous VCL may slow down the drying out of entrapped moisture. Entrapped moisture should be as low as possible.
- The difference in practice between 0.15 mm PE and say 0.8 mm PVC is in most cases negligible although the VCL made of PE has about 5 times higher vapour resistance.
- The Hygrodiode may give a marked increase in the drying out potential of the construction.
- The progress of drying out is to a small extent dependant on the thickness or type of insulation.
- Light coloured external surfaces render slower drying out inwards than dark surfaces.
- Bitumen felts have higher resistance than PVC sheets and offer less potential for drying out.
- Pitched roofs facing south offer better drying out inwards than flat roofs or roofs facing north.
- Norwegian west coast climate offers less possibility for drying out than inland climate.

7.0 SELECTION OF VCL BASED ON EXPERIENCE TO OBTAIN SUFFICIENT SAFETY

The choice of VCL configuration in a building must be based on an overall evaluation containing:

- Interior moisture content and temperature
- Interior air pressure under the roof
- Type of load bearing system
- Exterior climate

Ventilated and compact roofs are two alternative roof configurations. Correctly built both should give satisfactory buildings. The correct use of VCL is more important in a ventilated roof than a compact roof.

Ventilated pitched roof contains usually wood based materials. The following should therefore be carefully monitored; internal VCL and external windbarrier, all forms for penetrations and joints are carefully planned and possible to install and that the ventilation is functioning as planned.

Compact roofs should not contain materials susceptible to rotting unless based on an advanced and specific evaluation of the moisture condition.

In the following a method is given to estimate the total "risk class" based on the overall evaluation indicated above. First step is to find the exposure score relevant to each of the four categories of exposure. The risk class is then found by adding the individual exposure scores. The VCL configuration needed is found on the basis of the risk class given.

The method is relevant for compact roofs as well as for ventilated roofs:

- Find exposure score on a scale from 0-10 for each category of exposure according to Table 7.2.
- Find total exposure score by adding E1-E4.
- Find risk class. 5 grades are available from moderate (R0) to high (R4).
- Select VCL configuration according to Table 7.3

In most cases the form given in Tables 7.2 and 7.3 should be self explanatory or possibly supported by the examples of calculation. Exposure score for interior climate may be established as follows:

a) Estimate the moisture content of interior air on the basis of expected temperature and RH at design winter conditions. As a guide Table 2.1 and Figure 2.2 can be used. Interior RH may be difficult to estimate and this method might be somewhat inaccurate.

b) Estimate the interior air MC as a sum of the exterior air MC and expected additional moisture (see clause 3.1) for the relevant category of building. Table 7.1 may be an additional support. This table, based partly on investigation and partly on estimates, shows interior MC as a function of the lowest monthly average exterior air temperature (see Table 7.4) and additional moisture.

Table 7.1
Interior air MC as a function of lowest monthly average exterior air temperature (from Table 7.4), additional moisture and building category.

Building category \ Lowest monthly ext. air temperature	ΔMC g/m³	Interior air MC g/m³ 0 °C	–5 °C	–10 °C
No additional MC	0	4.5	3	2
Office, dry interior climate	2	6.5	5	4
School, shops, hospitals, nursing homes and flats with dry climate	4	8.5	7	6
Assembly room and dwelling with moist environment	6	10.5	9	8
Shower rooms and moist industry	9	13.5	12	11
Swimming pools with de-moistening and moist industry	12	16.5	15	14
Swimming pools without de-moistening and wet industry	≥13	>15	>15	>15

Comments:

NBI recommends installing VCL in risk class R0 as well (the use of the building may change).

VCL of PE sheet can be used in most ordinary buildings. Tight joints and connections must be used in risk class R2 while in R1 it is sufficient with loose overlap joints.

Some buildings require extra tough VCL in the roof, in this connection named Roof VCL. This is a membrane VCL with good mechanical properties, which offers the possibility for welded joints and connections.

Roof VCL should be used in:

- Printing works, laundries and other wet industry
- Swimming pools and changing room sections in sport halls
- In buildings with overpressure ventilation
- Other buildings with exceptionally high RH.

Table 7.2 Form for selection of VCL configuration

E1 Interior environment		**E2 Interior air pressure**		**E3 Construction**		**E4 Exterior clima**
Scale of expected total MC in interior air		Scale of expected interior air pressure under the roof		Scale of the inbuilt tightness of the construction		Scale of the expecte temperature condition
Estimated on the basis of interior temperature and RH at design winter conditions for the building. Use Table 2.1 and figure 2.2. Alternatively the interior air MC can be taken from Table 7.1 directly.		The neutral axis is determined with respect to form and locations of openings and leakages. From this level add 1 Pa for every m up to the roof level. Pressure caused by the ventilation system is added and you end up with the pressure under the ceiling.		Insitu cast concrete constructions is tight and is given 0 on the exposure scale if dry. Wet concrete is given the same classification as steel structures. Steel structures are considered as open. Several penetrations in the roof give one additional mark.		Lowest exterior air average temperature design winter conditi site in question See Table 7.4
Scale: 1- 10		Scale: 1- 10		Scale: 1- 10		Scale: 1- 10
MC in g/m^3	p	Int. air pressure in Pa	p	Tightness of construction	p	Mont. av. temp. in °C
< 4	0	< 0	0	Insitu concrete, dry	0	> 0
4 - 8	2	0 - 2	2	Prefab. concrete, dry	2	0 to - 5
8 - 15	5	2 - 5	5	Wood/steel, wet concrete	5	- 5 to - 10
> 15	10	> 5	10	Wood/steel + penetration	10	< - 10

Table 7.3 Risk class and requirements to VCL

Risk class	**Total marks**	**Requirements to VCL**
R0	$\Sigma E \leq 5$	None (NB! Future change of use and unforeseen factors favours recommendation to install a VCL)
R1	$5 < \Sigma E < 12$	0.2 mm PE sheet with 200 mm loose laid joints
R2	$12 \leq \Sigma E < 22$	0.2 mm PE sheet with 200 mm tight joints and connections (batten, tape, mastic sealant)
R3	$22 \leq \Sigma E < 32$	a) Roof VCL of bitumen felt of category U2 NS 3530 fully bonded joints and tight connections b) Roof VCL of 0.8 mm PVC sheet (or equivalent) with bonded/welded joints and tight connections
R4	$\Sigma E \geq 32$	a) Roof VCL of bitumen felt of category U2 NS 3530 fully bonded joints and tight connections b) Roof VCL of 0.8 mm PVC sheet (or equivalent) with bonded joints and tight connections + 0.15 mm PE sheet loose laid and with loose overlaps in order to obtain sufficient vapour resistance. NB! For $\Sigma E \geq 32$ it is not recommended to use mechanical fasteners for the roof waterproofing.

Table 7.4 Lowest monthly average temperatures for some Meteorological stations in ℃.

Station		**Station**		**Station**	
Finnmark County		Trondheim – Voll	- 3.4	Lyngør	- 1.1
Alta-Elvebakken	- 8.3	Selbu	- 4.2	***Telemark County***	
Ingøy	- 2.7	Berkåk	- 6.5	Gvarv	- 6.5
Kistrand	- 6.5	Røros	-11.2	Dalen i Telemark	- 5.0
Mehamn	- 4.9	***Møre og Romsdal County***		Vefall i Drangedal	- 5.4
Tana	- 9.9	Kristiansund N	0.9	Jomfruland	- 2.0
Rustefjelbma	- 11.2	Ørsta	- 0.8	Tveitsund	- 4.2
Vardø	- 5.2	Tafjord	0.1	***Buskerud County***	
Vadsø	- 6.9	Runde	2.1	Eggemoen	- 7.8
Ekkerøy	- 6.3	Ålesund	2.1	Buskerud	- 7.7
Kirkenes	- 9.8	Ona	2.1	Modum	- 6.9
Karasjokk	- 14.8	Gjermundnes	- 0.3	Nesbyen II	-10.9
Kautokeino	- 14.4	Åndalsnes	- 1.0	Geilo	- 9.1
Siccajavre	- 14.3	Molde	- 0.9	Dagali	- 8.2
Troms County		Sunndal	- 4.5	Lyngdal i Numedal	- 7.1
Sandøy i Senja	- 1.8	Tingvoll	- 2.2	Svene	- 8.3
Gibostad	- 4.0	***Sogn og Fjordane County***		Kongsberg III	- 6.7
Bardufoss	- 9.0	Myrdal	- 6.4	***Oppland County***	
Sommarøya i Senja	- 1.9	Vangsnes	- 0.3	Fokstua	-10.4
Dividalen	- 9.0	Balestrand	0.1	Dombås	- 9.0
Skibotn	- 5.8	Fjærland	- 3.6	Vågåmo	- 9.6
Tromsø	- 4.0	Lærdal-Tønjum	- 2.7	Vinstra	-10.8
Torsvåg Fyr	- 1.2	Leikanger	- 0.6	Vollen i Slidre	-10.6
Nordland County		Luster Sanatorium	- 4.2	Lillehammer II	- 9.0
Nordli III	- 10.0	Fortun	- 5.1	Østre Toten	- 7.0
Majavatn	- 6.9	Førde i Sunnfjord	- 2.2	***Hedmark County***	
Brønnøysund	- 0.8	Kinn	1.9	Tynset II	-12.8
Hattfjelldal	- 10.1	Brandsøy	1.2	Alvdal	-11.2
Skålvær	- 0.4	Nordfjordeid	- 1.3	Drevsjø	-11.1
Mo i Rana	- 6.4	Oppstryn	- 1.8	Koppang-Øyset	-11.2
Myken	0.4	***Hordaland County***		Rena	-10.5
Glomfjord	- 1.4	Indre Matre	0.7	Ytre Rendal	- 8.6
Rognan	- 7.4	Svandalsflona	- 7.2	Trysil	-10.1
Bodø	- 2.4	Ullensvang	- 0.7	Kise på Hedmark	- 6.8
Fauske	- 4.0	Kvamskogen	- 3.4	Hamar	- 8.1
Grøtøy	- 0.9	Slirå	-10.0	Flisa	- 8.4
Bjørnefjell	- 10.6	Voss II	- 5.0	Vinger	- 7.3
Narvik	- 4.2	Bergen	1.3	Skotterud	- 6.8
Offersøy	- 2.5	Syfteland	- 0.8	***Akershus County***	
Skrova	- 0.9	Modalen	- 2.4	Gardermoen	- 6.9
Svolvær	- 1.8	***Rogaland County***		Hvam	- 6.8
Røst	0.7	Klepp	0.2	Fornebu	- 4.6
Eggum	- 0.7	Sola	0.4	Asker	- 5.2
Bø i Vesterålen	- 1.5	Stavanger	0.8	Ås	- 5.2
Andenes	- 1.5	Sauda	- 2.4	***Oslo County***	
Nord-Trøndelag County		Skudesnes II	1.3	Tryvasshøgda	- 5.6
Meråker	- 5.1	Utsira Fyr	1.6	Oslo-Blindern	- 4.7
Værnes	- 3.4	***Vest-Agder County***		***Østfold County***	
Ytterøy	- 2.7	Kristiansand S	- 1.3	Rygge	- 4.7
Steinkjær	- 3.9	Kjevik	- 1.9	Råde-Tomb	- 4.1
Kjevli i Snåsa	- 6.4	Oksøy	- 0.3	Kalnes	- 4.1
Namsos	- 3.0	Mandal II	- 1.1	Råde	- 4.1
Høylandet	- 7.3	Konsmo	- 2.6	Brekke Sluse	- 4.5
Grong	- 5.1	Lista Fyr	0.3	***Vestfold County***	
Nordøyan	0.1	Tonstad	- 2.1	Horten	- 3.2

Sør-Trøndelag County		***Aust-Agder County***		Stokke	- 4.2
Vallersund	- 0.4	Grimstad	- 1.0	Eidsberg	- 4.8
Ørland	- 0.8	Byglandsfjord II	- 3.7		

Calculation example 1

A) Apartment building in Oslo, 4th floor, prefabricated concrete structure with minimum penetrations in the roof area. VCL is supposed to be used, but what are the requirements?

Interior environment: E1 = 2 p
The design winter condition gives:

- Interior temperature + 23°C
- Interior RH is 35 % from fig 2.2 for January/February
- Expected total interior air MC is about 7 g/m^3. (Table 2.1: 23°C → 20.6 g/m^3 at RH = 100% ⇒ 7 g/m^3 at RH = 35%)

Alternatively use Table 7.1 and 7.4:
Lowest monthly average ~ –5°C/residence with low moisture production ⇒ MC ~ 7 g/m^3

Interior pressure: E2 = 5 p
Four floors gives about 12 m high building. Suppose even distribution of leakages over all floors, but floor dividers are tight and the neutral axis is higher than half of the height, say 8 m above ground.

The pressure under the roof caused by thermal buoyancy of air is about 4 Pa.
Addition caused by ventilation will be 0 (This may of course vary depending on the running of the system)

Construction: E3 = 2 p
Prefabricated concrete construction → 2 p
Since there are only a few penetrations it is estimated not to raise the score by one.

Exterior climate: E4 = 2 p
Table 7.3 gives for Oslo lowest month. average –4.7°C

Total exposure points:
ΣE = 2 + 5 + 2 + 2 = 11 p
Which gives risk class R1.

The VCL can be:
0.2 mm PE sheet with 200 mm with loose laid overlap

B) Same apartment located in Bergen:

Interior environment: E1 = 5 p
The design winter condition gives:

- Interior temperature + 23°C
- Interior RH is 40 % from fig 2.2 for January/February
- Expected total interior air MC is about 8-9 g/m^3. (Table 2.1: 23°C → 20.6 g/m^3 at RH = 100% ⇒ 8.2 g/m^3 at RH = 40%)

Alternatively use Table 7.1 and 7.4:
Lowest monthly average ~ –0°C/residence with low moisture production ⇒ MC ~ 8.5 g/m^3

Interior pressure: E2 = 5 p
Same as for A)

Construction: E3 = 2 p
Same as for A)

Exterior climate: E4 = 0 p
Table 7.3 gives for Bergen lowest month. average +1.5°C

Total exposure points:
ΣE = 5 + 5 + 2 + 0 = 12 p.
Which gives risk class R2.

0.2 mm PE sheet can be used as VCL. Tight joints and penetrations with clamping and polymeric tape or mastic sealant are recommended.

Calculation example 2

Swimming hall in Tromsø, 8 m to the rooftop, steel construction in the roof, few penetrations.
Ventilation system designed to give max 55% RH at interior temp of 30°C.
What are the requirements to VCL?

Interior environment: E1 = 10 p
Table 2.1 gives MC of 30.4 g/m^3 at RH = 100% ⇒ 16.7 g/m^3 at RH = 55%)

Alternatively use Table 7.1 and 7.4:
Lowest monthly average is ~ −4°C. Use column −5°C in table 7.1 for swimming pools with dehumidifier.
This gives MC ~ 15 g/m^3

Interior pressure: E2 = 10 p
Assume the leakages to be located at windows 2-3 m above floor level. This gives internal pressure under the roof $p = 0.43x (t_i - t_e) x \Delta h = 0.043x(30 - (-5)) x 5 = 7.5$ Pa.
Low pressure in ventilation system should not be accounted for unless specific control is established.

Construction: E3 = 10 p
Steel structures possess low self-tightness. Even few penetrations may render large leakages. This building should rather be given an additional point because of the risk of leakages at penetrations.

Exterior climate: E4 = 2 p
Table 7.3 gives for Tromsø lowest monthly average −3.5°C

Total exposure points:
ΣE = 10 + 10 + 10 + 2 = 32 p.
The VCL should be designed for risk class R4.

Risk class R3 is obtainable if the following measures are taken:
- Tight control of the ventilation system to maintain RH ≤ 50 % at winter conditions
- Maintain low pressure conditions
- Reduce penetrations to a minimum

8.0 DESIGN DETAILS

For a configuration to function properly the following must be observed:

- Proper design and planning of construction progress to make is possible to end up with an airtight VCL.
- Build in additional safety against leakages even if there should be an increase in cost.
- Use of materials and system that reduces the risk of entrapped moisture (precipitation, moist materials)

Leakages will occur where there is no natural tightness in the structure itself such as:

- At connection roof/wall
- At penetrations
- Around electrical boxes when submerged
- At connections to main load bearing system, columns and windows
- At open overlap joints in VCL
- At shifts in roof- and wall surface
- At connections between different constructions
- When overlap joints are pressed against grooved lining boards

The figure on the front page and figures in the following section shows how to obtain an airtight construction:

- Locate the main load bearing system, columns and beams in its entirety, inside the building. These vital parts will thus be situated in a stable interior climate. Thermal insulation and VCL can be installed continuous, uninterrupted by the main structure.
- Use preferably 0.2 mm VCL sheets not < 0.15 mm
- Consider VCL more as an air-tightening layer. Where possible the joints should be provided with a clamping board nailed every 150 mm.
- The VCL should be designed to be installed on smooth surfaces avoiding complicated joints requiring splitting of the sheet.
- Provide continuity of the VCL from wall to roof.
- Avoid puncturing of the VCL. Install cables, armature and pipes visibly on the room side and not through the VCL.

The following figures show examples on how the connection between roof, wall and other details may be designed to give satisfactory sealing.

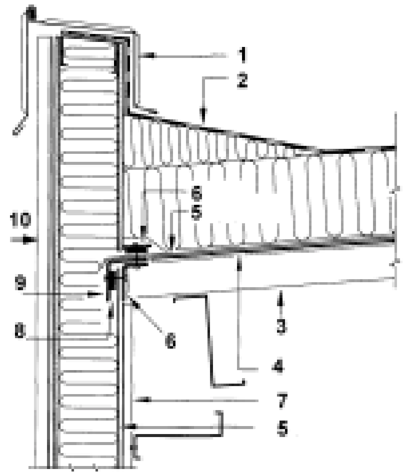


Figure 8.1
Shows possible tracking and clamping of the VCL where profiled steel sheets are brought up against inner parapet face.

1	Metal coping	6	Batten profile
2	Roof waterproofing	7	Interior wall lining
3	Load carrier/steel sheet	8	Mastic tape
4	Fire safe panel (K1-A)	9	Angle profile
5	VCL	10	Exterior wall lining

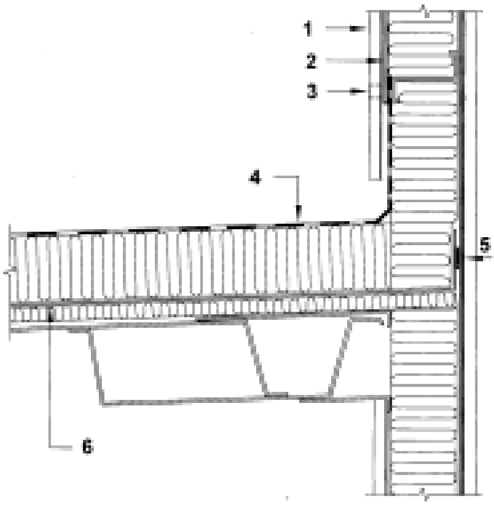


Figure 8.2
Shows possible feed track and clamping of VCL at joints between roof and high wall. It is important to obtain continuity between the VCL in the lower roof and the wall above.

1	Exterior cladding	4	Roof waterproofing
2	Wind break	5	Mastic tape
3	Profiled tightening strip	6	VCL

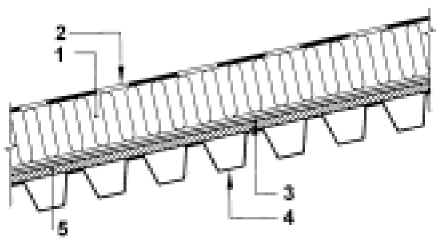


Figure 8.3
VCL with overlap joints installed directly on a profiled support is rarely tight. Use a hard support; hard mineral wool or panel K1-A (Where appropriate wood based panels). The VCL should not have a position higher than a _ up the total insulation thickness

1	Insulation	2	Roof waterproofing
3	VCL	4	Corrugated sheet deck
5	The support should be even. Hard insulation or fire safe panel (K1-A).		

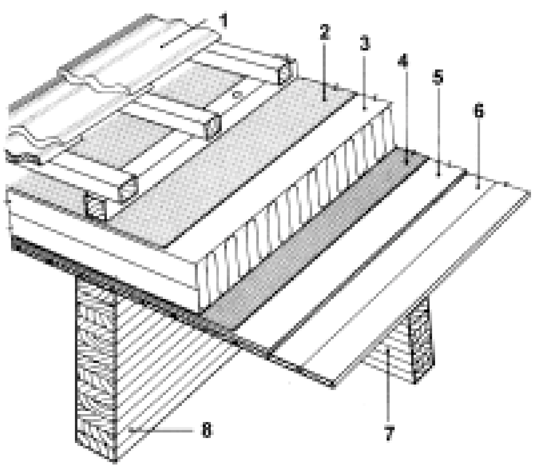
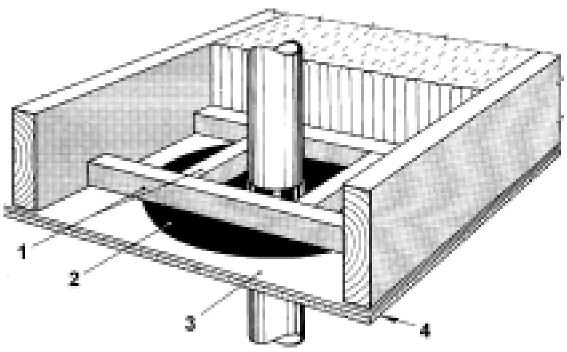


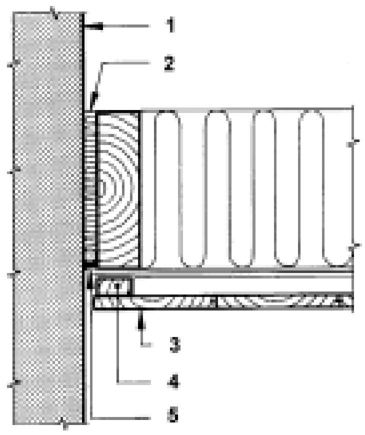
Figure 8.4
Pitched wooden roof with exterior insulation and exposed roof waterproofing. On top of the load bearing structure is the combined ceiling and roofing support. On top of this is a Roof VCL. This should function as a temporary roof waterproofing. The insulation must have high compressive resistance. The permanent roof waterproofing is either ventilated or compact. Wind uplift resistance is most conveniently obtained by using mechanical fasteners.

1	Roof waterproofing	5	Gypsum panel
2	Drainage layer	6	Wood panel
3	Insulation	7	Joist
4	Roof VCL	8	Beam



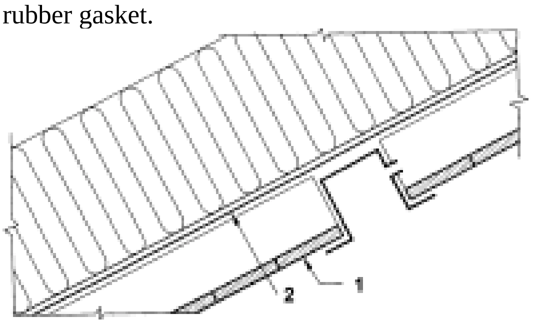
1 Timber stud
2 Rubber gasket
3 VCL
4 Gypsum panel

Figure 8.5 Tightening of VCL around penetrations using a rubber gasket.



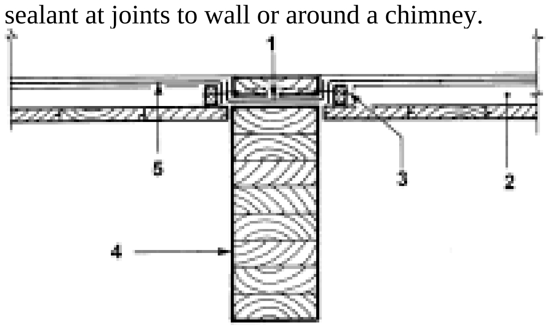
1 Chimney
2 Mineral wool
3 Ceiling panel
4 Clamping board
5 Mastic sealant

Figure 8.6 Tightening using mineral wool and mastic sealant at joints to wall or around a chimney.



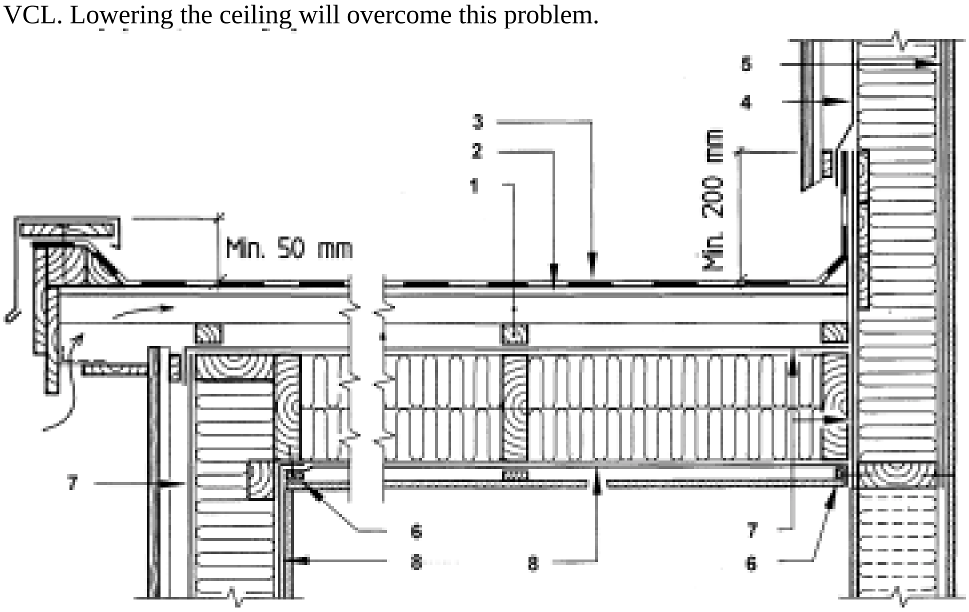
1 Ceiling
2 New tight VCL

Figure 8.7 Large air leakages can occur through and around electrical connection boxes that punctures the VCL. Lowering the ceiling will overcome this problem.



1 Strip of PE membrane
2 Joist
3 Batten
4 Beam
5 VCL

Figure 8.8 Jointing of VCL over beam



1 Furring strips
2 Support for roof membrane
3 Roof membrane
4 Wind break
5 VCL
6 Batten
7 Wind break
8 VCL

Figure 8.9 Connection between roof with pitched ceiling and gable walls.
Design of VCL, windbreak and roofing membrane.