1.2 THERMAL DESIGN

INTRODUCTION

Thermal design is concerned with the flow of both heat and water vapour through the roof construction, and the effect of these on the performance of the roof and on the various components in the roofing system. The designer has two separate areas for consideration: the amount of thermal insulation required to control heat loss and the amount of insulation required to control condensation.

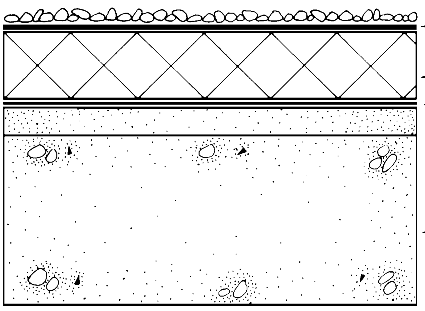
All materials used in roof construction possess thermal insulating properties to varying degrees and, in certain cases, such as woodwool slabs or aerated concrete units the deck component alone can provide significant thermal insulation.

Generally however, a separate insulation layer will be required usually in the form of a rigid board insulation above the deck, or a fibrous quilt immediately above the ceiling.

Roof constructions can normally be categorised as either warm roofs or cold roofs, depending on the position of the principal thermal insulation layer in relation to the deck.

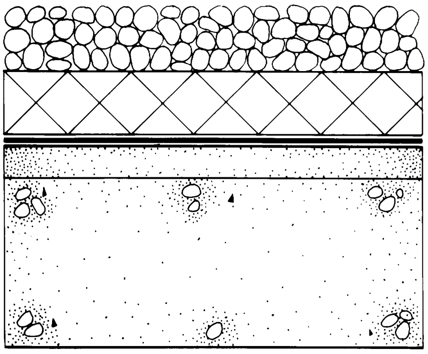
WARM ROOF

Warm roof or warm deck construction has the principal thermal insulation placed above the structural deck.



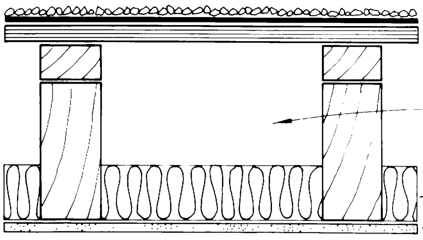
INVERTED ROOF

Inverted roof construction is a form of warm roof where the principal thermal insulation is placed above the waterproof covering. This system is also referred to as a protected membrane or upside-down roof.



COLD ROOF

Cold roof or cold deck construction has the principal thermal insulation layer below the structural deck and the concept is usually concerned with roof structures which include an independent ceiling enclosing an air space between the deck and ceiling.



HYBRID ROOF

Not all roof constructions will fall within the warm or cold categories and the concept can be misleading if the exceptions are not recognised. Some structural decks are themselves composed of insulating materials, for example woodwool, and it is difficult to place the final roof construction into a warm roof or cold roof category.

Cases also arise where insulation is added above the deck in addition to insulation at ceiling level, and again it is difficult to categorise the construction. These exceptions are sometimes called hybrid roofs.

THERMAL PROPERTIES

The rate of flow of heat through a roof is determined by the thermal conductivity of the elements making up the roof system. Regulations set out mandatory standards for the thermal transmittance or U-value of the roof. The associated terms and methods of calculation are as follows:

THERMAL CONDUCTIVITY (λ)

Thermal conductivity or lambda-value (λ) is a measure of the rate at which heat will flow through a material when a difference exists between the temperatures of its surfaces. It is expressed in W/mK.

For example, cork insulation with a λ-value of 0.042W/mK will allow more heat to pass through than the same thickness of polyurethane foam insulation which has a λ-value in the order of 0.023W/mK. A good insulant therefore has a low λ-value. Note that K refers to temperature in degrees Kelvin. K is equivalent to °C.

THERMAL RESISTANCE (R)

As the thickness of a material increases, its resistance to heat flow increases in direct proportion and can be calculated as:

$$R = \frac{t}{\lambda} \quad \text{Thermal resistance}$$

Where t is the thickness in metres and λ the thermal conductivity. The thermal resistance (R) is expressed in m^2K/W.

For example, the thermal resistance of 40mm of polyurethane insulation board ($\lambda = 0.023 W/mK$) is:

$$\frac{t}{\lambda} = \frac{0.04}{0.023} = 1.74 m^2K/W$$

Similarly, for 40mm mineral wool slab ($\lambda = 0.036 W/mK$)

$$\frac{t}{\lambda} = \frac{0.04}{0.036} = 1.11 m^2K/W$$

At an exposed surface, the resistance to heat transfer by radiation and convection can also be regarded as thermal resistance, generally termed surface resistance. The surface resistance value depends on the emissivity of the surface, the direction of the flow of heat and additionally, for the external surface, on the degree of exposure. A standard value of $0.14 m^2K/W$ is taken as the total combined internal and external surface resistance for roofs. The individual values are normally taken to be $0.04 m^2K/W$ for the external surface resistance and $0.10 m^2K/W$ for the internal surface resistance.

The thermal resistance of airspaces depends on the size and ventilation of the cavity, the direction of the flow of heat, and on the emissivity of the surfaces of the cavity. For unventilated cavities, with an upward heat flow, the following values should be used:

Cavities with high surface emissivity $R = 0.17 m^2K/W$

Cavities with low surface emissivity $R = 0.35 m^2K/W$

High emissivity should be assumed unless the airspace is lined with aluminium foil.

The total thermal resistance (R) of a roofing system is the summation of all the individual thermal resistances, taking into account the resistance of all the components of the roof including surface resistance and the resistance of cavities.

THERMAL TRANSMITTANCE (U-value)

The thermal transmittance or U-value of the roof is defined as the quantity of heat that flows through unit area in unit time, per unit difference in temperature. It is expressed in W/m^2K and is the reciprocal of the total thermal resistance of the roof:

$$U = \frac{1}{R} \ W/m^2K$$

The U-value provides an easy method of assessment of the heat loss through the building structure and is not only required by the heating engineer in his calculations for heating systems, but also allows the designer to compare thermal performances of alternative roof constructions. The smaller the U-value, the better the insulation.

The actual heat loss through a roof is calculated by multiplying the U-value by the roof area and then by the difference between the internal and external temperatures. Multiply this by the cost of fuel per watt to give the cost of the heat loss.

U-VALUE CALCULATION METHOD

The U-value is obtained from the total thermal resistance (R) of the roof structure which is calculated from the individual thermal resistance of each component of the roof.

$$U = \frac{1}{R_{si} + R_{so} + R_{cav} + R_1 + R_2 + R_3 \text{ etc}} \ W/m^2K$$

where Rsi = internal surface resistance
Rso = external surface resistance
Rcav = resistance of any cavity from standard thermal resistance values.
R1, R2, R3 etc = thermal resistance of material, calculated from t/λ where t is the thickness of material and λ the thermal conductivity of the material.

A number of calculated examples are given in Appendix A1, together with standard thermal properties of materials used in roof construction, see Appendix A2, table A1. The thermal properties are those adopted by the Flat Roofing Contractors Advisory Board or CIBSE Guide A3 1988 and are generally accepted within the roofing industry.

For roofs incorporating rooflights or areas with different thermal properties, it is permissible in heat loss calculations to take a mean or average U-value. Similarly when the thickness of insulation varies the average thickness may be used to calculate the U-value.

$$\frac{\text{Area A x U-value of area A}}{\text{Total area}} + \frac{\text{Area B x U-value of Area B}}{\text{Total area}}$$

= Mean U-value for total roof

Note that average U-values or average thickness should not be used for consideration of condensation risk.

BUILDING REGULATIONS

The various UK Building Regulations define acceptable levels of heat loss from buildings by requiring maximum U-values for walls and roofs.

The revised Building Regulations England and Wales 1991, which are in force from 1 July 1995, specify in general terms a maximum U-value of $0.35 W/m^2K$ for flat roofs of dwellings and $0.45 W/m^2K$ for most other heated buildings.

The Building Standards (Scotland) Regulations are expected to follow similar lines when published.

The Building Research Establishment Report "Thermal insulation: avoiding risks" 1994 edition, gives guidance on good practice in the application of insulation. Emphasis is placed on the need for continuity of insulation to avoid thermal bridging, in particular at the junction of a flat roof with an internal wall.

Detailing should bring the insulation of the roof in contact with the insulation in the wall, using connecting strips of insulation if necessary. At brick parapets or abutments the skirting should be insulated or formed on a line of insulating blockwork in lieu of brickwork.

Whilst the BRE report is not strictly a part of the Building Regulations, compliance with the report should satisfy the regulations in respect of thermal bridging.

There is no substitute for working direct from the Building Regulations and approved documents but the following indicates the broad principles to be followed for flat roofs.

The Building Regulations give three alternative methods of approach, an Elemental method, a Calculation method and an Energy Use method.

DWELLINGS

The required U-value for flat roofs of dwellings using the elemental method is $0.35 W/m^2K$. Warm roof construction with no rooflights has no thermal bridging other than at details, and $0.35 W/m^2K$ will prove satisfactory. When rooflights are included the most attractive solution will probably be to leave the opaque part of the roof at $0.35 W/m^2K$, double glaze the rooflights, and ensure they are taken into account in the overall allowance for windows and doors of a house.

Cold roof construction is always best avoided, but if used, an allowance must be made for thermal bridging at joists in accordance with the regulations.

BUILDINGS OTHER THAN DWELLINGS

For buildings other than dwellings the required U-value for flat roofs by the elemental method is $0.45 W/m^2K$. Rooflights are allowed up to 20% of the roof area provided that the average U-value of all rooflights, windows and doors is not more than $3.3 W/m^2K$.

Table 8 in approved document L1 gives alternative percentages of roof area for average U-values of openings which differ from $3.3 W/m^2K$.

For all buildings the overall U-value must make allowance for thermal bridges. These should not arise if the insulation over the roof is fully continuous but will arise if the insulation is discontinuous such as insulation between joists in a cold roof construction.

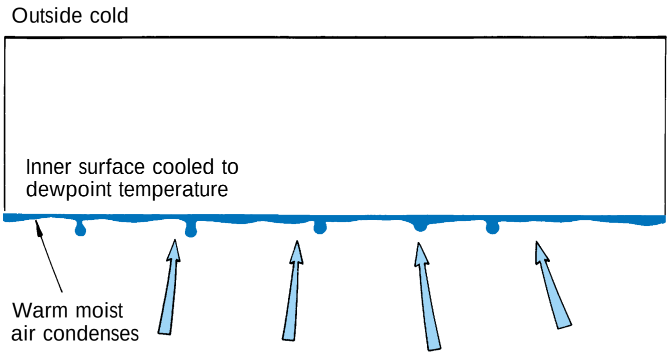
CONDENSATION

Moisture producing activities take place in most buildings. Some manufacturing processes clearly release a large amount of water vapour into the internal air. Bathrooms, kitchens, laundries and swimming pools are also sources of high humidity and the combustion products of gas, oil and paraffin are rich in water vapour.

Air has a limited capacity for carrying water vapour and when it can take up no more, it is said to be fully saturated. The moisture vapour in air exerts a pressure, as does any gas, and this is known as the vapour pressure. The ratio between the vapour pressure of moisture in the air and the saturated vapour pressure at the same temperature is termed the relative humidity (RH) and is expressed as a percentage.

The temperature at which the air becomes fully saturated with moisture, ie 100% RH, is called the dew point. When warm moist air meets a cold surface it is cooled, and if its temperature drops below the dew point it will give up moisture in the form of surface condensation.

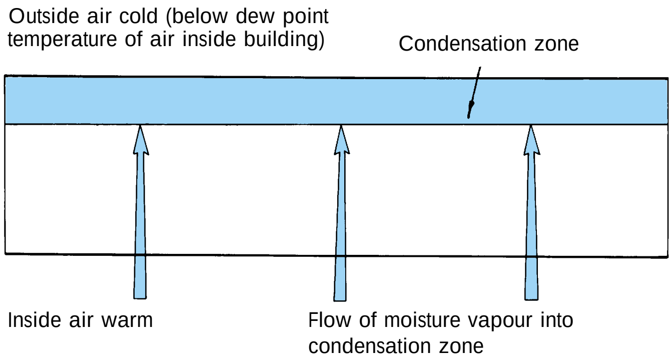
The air in a building normally contains more water vapour than the external air and so has a higher vapour pressure. This creates a vapour drive from the areas of high pressure to areas of low pressure and therefore the water vapour will try to escape by all available routes to the low pressure conditions outside the building.

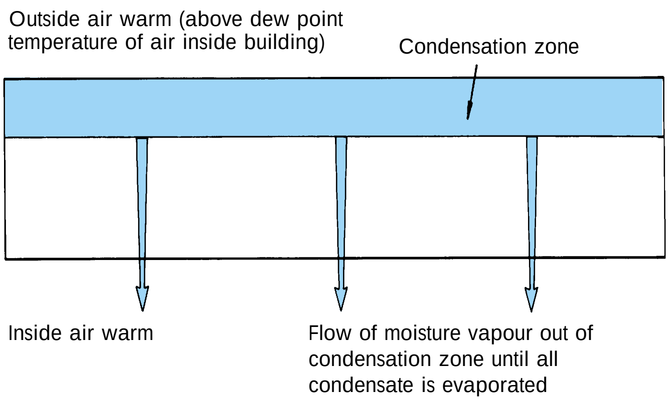


Surface condensation

Moisture vapour is also present in all the permeable materials of a building, including the roof construction and, as the vapour pressure inside a building is continually changing, there is a constant flow of water vapour in and out of the roofing materials. The movement continues until the vapour pressure in the materials is in equilibrium with the vapour pressure inside the building.

In cold weather the temperature under the waterproofing will fall and can create a zone in the roof structure where the temperatures are below the dew point. Moisture will condense in this zone to form interstitial condensation. When interstitial condensation is occurring, the vapour pressure in the relatively cold condensation zone will be less than the vapour pressure inside the building and the resulting pressure difference causes a vapour drive into the zone of condensation.





In warmer weather the temperature of the roof materials will not fall below the dew point. No interstitial condensation will occur and any remaining condensate will dry out by evaporation. During evaporation, the vapour pressure in the relatively warm zone will rise above the vapour pressure inside the building and moisture vapour will be driven out of the roofing materials.

The flow of water vapour through the roof takes place slowly and continuous periods of condensation are necessary before interstitial condensation becomes a problem. Normally the periods of condensation will be relatively short and the condensate will dry out again without causing any harm.

Continual wetting of materials due to condensation can, if not controlled, lead to fungal growth, decay in structural timbers and the accelerated corrosion of metal components and fixings. There is also the risk that insulation boards containing organic fibres can decay from the growth of fungus, lose their strength and suffer a reduction in their insulating efficiency. These effects may be taking place within the structure but with no visible indication of problems appearing at the ceiling level.

SURFACE CONDENSATION

The overall level of thermal insulation has a direct influence on the likelihood of surface condensation below the soffit of a roof deck or ceiling. If sufficient thermal insulation is provided to keep the ceiling or soffit temperature above dewpoint, surface condensation will not occur.

In order to check for surface condensation, it is necessary to calculate the ceiling or soffit surface temperature and the dewpoint temperature, for the prevailing internal temperature and relative humidity. A comparison of these temperatures will then indicate whether surface condensation will occur. Calculation procedures are set out in Appendix A2.

As an alternative to the calculation, tables 1.6 and 1.7 show the internal relative humidity and temperatures at which surface condensation will occur on the underside of a roof construction for a specified U-value and at an external temperature of -5°C and -10°C. A high emissivity internal surface is assumed.

The tables indicate that for the insulation values normally specified, the relative humidity at which surface condensation occurs is well in excess of normal working conditions.

When the U-value varies across the roof because of the use of tapered insulation or insulating screed to falls, the condensation risk must be calculated at the point of maximum U-value. The average U-value is only used for heat loss calculation.

It should be noted than an increased danger of surface condensation arises on cold water pipes which are positioned between the ceiling and the deck. Such pipes need to be insulated and wrapped with a moisture resistant material to act as a vapour check.

The thermal mass of the structure also has a bearing on the likelihood of condensation. In general, roofs may be of heavy construction, such as a dense concrete slab and screed, or of lightweight materials, such as metal decking and insulation boards. Whilst each may be designed to the same U-value, the heavy structure has a high thermal mass and will therefore heat up or cool down slowly, while the reverse is true of lightweight, low thermal mass systems. The heating system must therefore be suited to the construction. High thermal mass combined with intermittent heating is more likely to lead to surface condensation in cold weather, as the internal air temperature will increase much faster than the internal surface temperature, which may remain below the dewpoint for long periods.

Internal %RH at which surface condensation will occur on the underside of the roof construction

TABLE 1.6 External Temperature -5°C

U-Value W/m^2K	Internal Temperature °C															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0.25	96	96	96	96	96	96	96	95	95	95	95	95	95	95	95	95
0.35	95	95	95	95	94	94	94	94	94	94	93	93	93	93	93	93
0.45	94	94	94	94	94	93	93	93	93	93	93	92	92	92	92	92
0.60	92	92	91	91	91	91	90	90	90	90	89	89	89	89	88	88
0.70	91	90	90	90	89	89	89	89	88	88	88	87	87	87	87	86
1.00	87	87	86	86	85	85	85	84	84	83	83	83	82	82	81	81
1.50	82	81	80	80	79	79	78	77	77	76	76	75	75	74	74	73
2.00	76	76	75	74	73	72	72	71	70	70	69	68	68	67	66	66

TABLE 1.7 External Temperature -10°C

U-Value W/m^2K	Internal Temperature °C															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0.25	96	95	95	95	95	95	95	95	95	95	94	94	94	94	94	94
0.35	94	94	94	93	93	93	93	93	93	93	92	92	92	92	92	92
0.45	93	93	93	93	92	92	92	92	92	92	91	91	91	91	91	91
0.60	90	90	90	89	89	89	89	88	88	88	88	87	87	87	87	87
0.70	89	88	88	88	88	87	87	87	86	86	86	86	85	85	85	85
1.00	84	84	84	83	83	82	82	82	81	81	80	80	80	79	79	79
1.50	78	77	77	76	75	75	74	74	73	73	72	72	71	71	70	70
2.00	72	71	70	69	69	68	67	67	66	65	65	64	63	63	62	62

INTERSTITIAL CONDENSATION

WARM ROOFS

Under certain conditions too much vapour will rise into a warm roof system and it will prove necessary to protect the components, in particular the thermal insulation, from excessive interstitial condensation. A suitable vapour control layer will be required.

Movement of moisture through a warm roof is mostly by diffusion and, as diffusion rates are fairly easy to predict, the moisture movements and moisture gain in the roof materials can be calculated by moisture gain analysis. This involves an assessment of the resistance to diffusion of moisture vapour for all the materials of the roof system including an allowance for gaps between the insulation material and penetrations in the vapour control layer if present.

The resistance to diffusion is used to calculate the moisture vapour flow into and through the system with a final calculation of the weight of water which collects as condensate in the system during a typical severe cold spell in winter. The weight of water which can reasonably be expected to dry out in a typical spell of summer weather is also determined.

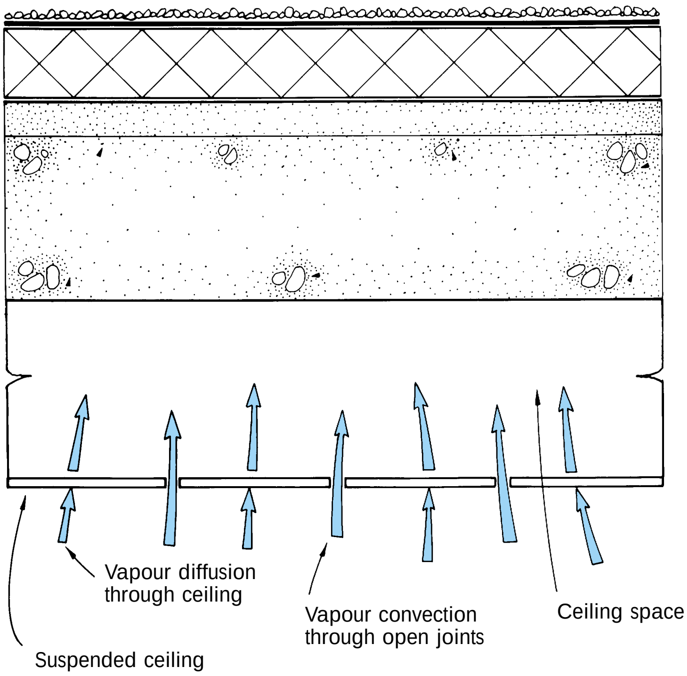
The analysis then checks that the water collection in the winter spell does not exceed certain stated limits. It also checks that no more than a trivial amount of moisture remains in the system after the drying conditions in summer. It should be appreciated that these calculations are by their nature arbitrary, and represent a prediction of extreme circumstances in one year. There is no likelihood of a build-up of moisture of the same severity year after year, because the calculation assumes adverse conditions which will not be repeated in the succeeding years.

Moisture gain analysis enables the designer to decide whether or not a vapour control layer is necessary, whether sufficient thermal insulation has been allowed for, and whether it is suitably positioned with regard to ceiling spaces, vapour control layers and other components of the roof construction.

An example of moisture gain analysis is given in Appendix A2 and the results of the analysis for typical warm roof constructions are given in the Vapour Control Design Guide, Section 1.3.

A warm roof system will be designed to avoid the need for ventilation of closed air spaces, and this aspect may be checked by calculation to ensure that air spaces do not present a surface condensation risk or conditions sufficiently humid to support mould or fungus growth in timber products. Such a space is usually between the structural deck and a suspended ceiling. Suspended ceilings usually contain joints which allow a measure of convection through them, and it will be prudent to assume convection is taking place from the inside of the building into the ceiling space.

The space forms a large reservoir for moisture vapour which is kept continuously and speedily replenished by convection and the amount of condensation which can take place will be far greater than that indicated by calculation based on diffusion alone. The flow of air into the ceiling space can be assumed to be sufficient to give the same moisture content, and consequently the same vapour pressure above the ceiling as below. The temperature in the



ceiling space will however, be lower than the internal temperature due to the insulating effect of the ceiling and it is important to demonstrate that no condensation occurs in the ceiling space, even for short periods of time.

Surface condensation in the ceiling space is most likely to occur on the soffit of the deck, and will depend on the amount of insulation above the surface compared with the insulation below. This is commonly referred to as the balance of insulation and can be checked by reference to tables 1.11 and 1.12 in the Vapour Control Design Guide, Section 1.3.

If the check shows a risk of condensation under the roof deck, the insulation on top of the roof deck should be increased or the insulation of the ceiling should be reduced in order to achieve a satisfactory balance of insulation.

The passage of water vapour through the ceiling into the ceiling space is sometimes prevented by the installation of a plenum system in the ceiling space, which increases the pressure inside the space by powered ventilation to ensure that it exceeds the pressure inside the building. The movement of air from the ceiling space will then be through the ceiling and into the building below and will prevent air from inside the building reaching the ceiling space.

INVERTED ROOFS

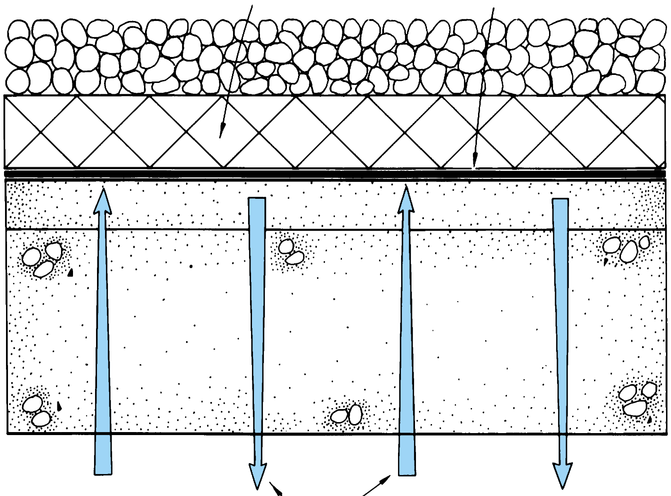
Moisture movements in the insulation layer of an inverted roof are virtually unaffected by internal conditions. Below the level of the waterproofing, moisture vapour from inside the building will flow in and out of the roof components as a result of humidity changes inside the building. But the temperature in the roof components will be maintained above the dew point, and interstitial condensation will not occur.

There is a possibility of surface condensation on the underside of the deck due to the flow of cold rainwater below the insulation. A method of checking for this is to assume a temperature of 0°C at the waterproofing level and carry out the surface condensation check calculation as given in Appendix A2.

Internal %RH at which surface condensation will occur on the underside of an inverted roof

TABLE 1.8

Resistance below insulation m^2K/W	Internal Temperature °C															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0.15	51	49	47	45	43	41	40	38	37	35	34	33	32	31	29	28
0.30	72	70	69	67	66	65	64	63	62	60	59	58	57	56	55	55
0.45	80	79	78	77	76	75	74	73	72	72	71	70	69	68	68	67
0.60	84	84	83	82	81	81	80	79	79	78	77	77	76	75	75	74
0.75	87	87	86	85	85	84	84	83	82	82	81	81	80	80	79	79
0.90	89	89	88	88	87	87	86	86	85	85	84	84	83	83	82	82



As an alternative to the calculation, table 1.8 shows the internal relative humidity and temperatures at which surface condensation will occur on the underside of an inverted roof construction. To use the table, calculate the total thermal resistance of the construction below the insulation and read off the relevant temperature and allowable relative humidity.

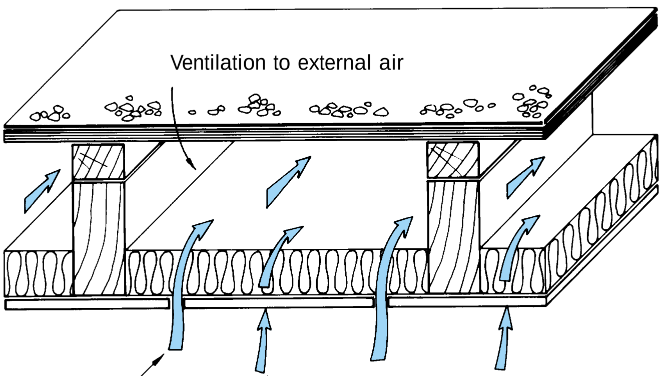
COLD ROOFS

Cold roofs usually include a ceiling space which is also cold as it has little or no insulation above it. Unless it is ventilated, the ceiling space or cavity acts as a reservoir for water vapour, held ready to condense when the temperature drops.

A cold roof will always suffer the risk of condensation in the ceiling space if the ceiling construction allows moisture vapour from inside the building to pass into the cavity by diffusion or convection through open joints, and if cavity ventilation is not provided.

A typical pattern of moisture movement in a cold roof is for penetration of moisture vapour to the cavity by the combined effects of diffusion, convection and air leakage through joints, followed by dispersal of the moisture vapour by means of ventilation to the external air.

For natural ventilation to be useful, there must be an adequate open area on each side of the cavity and there should be a free path for the flow of air in between. If this is not possible a cold roof construction should be abandoned.



Natural cross-ventilation depends on the wind speed, but the air is often static at the time that ventilation is most needed, during long periods of still, cold weather. Wind induced ventilation is not the only mechanism of vapour escape, however, as the vapour pressure in the ceiling space will produce a vapour drive through the openings. The stack effect from rising warm air will also drive the air to the outside.

BUILDING REGULATIONS

In the Building Standards (Scotland) Regulations, the Scottish Office considers that cold roofs should not be endorsed for the climatic conditions in Scotland. Although the Regulations do not prevent the use of cold roof constructions, warm roof constructions are recommended.

The Building Regulations England and Wales require permanent ventilation of a cold roof space by means of a continuous opening along two opposite roof edges with an unrestricted path for ventilation between the two edges. For a cold roof below a 15° pitch, continuous vent openings of 25mm are required and the space between insulation and underside of roof deck must be 50mm minimum. Where the roof span exceeds 10m, increased ventilation openings may be required totalling 0.6% of the roof area. For a cold roof above 15° pitch where the ceiling follows the line of the deck, the above applies. With a flat ceiling the minimum opening at the bottom of the slope is 10mm and the minimum at the top of the slope is 5mm. Variations of ventilation design is allowed providing the equivalent open area of ventilation is maintained.

Meshes will prove necessary to cover the ventilation openings to prevent entry of birds and insects.

Note that under severe wind conditions the airflow will be enough to disturb loose insulation and a breather membrane may be required on top of the insulation in order to keep it stable. In reality a cold roof construction is a cumbersome and rather uncertain form of design and a warm roof will prove more satisfactory in the vast majority of cases.

SUMMARY

DESIGN PRINCIPLES FOR MOISTURE CONTROL

Whatever the type of roof construction - warm, cold, or hybrid - there are three basic design rules for moisture control:

- All warm roof constructions which allow moisture movement by diffusion alone can be analysed by calculation to determine whether excessive interstitial condensation is likely. If necessary, adjustments can then be made to produce a design which is satisfactory.
- All warm roof constructions which allow an element of convection in addition to diffusion can be checked by calculation to determine whether surface condensation is likely in any spaces where air may be circulated by convection.
- All cold roof construction requires ventilation in accordance with Building Regulations, but in reality is best avoided.