BUILDING PHYSICS
RESEARCH AND DEVELOPMENT
1984-88

SP REPORT 1988:51
Building Physics
Borås 1988
ABSTRACT

Research and Development 1984-88

This report presents activities on research and development in the field of Building Physics. The activities include

- thermal insulation
- airtightness
- moisture
- radon
- indoor environment

The results from the research work of the Swedish National Testing Institute are distributed in reports, articles in journals, contributions to conferences and symposia.

This report consists of external publications via articles and contributions to symposia etc. Furthermore many reports have been published booth within and outside the institute. These reports are listed on page 197. Most of them are in Swedish but some are written in English.

Key words: Building Physics, Moisture, Heat insulation, Airtightness, Radon.
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WORKING AREAS

The Energy Technology department at the National Testing Institute is active in a wide range of fields, with the main emphasis on the building side. Energy technology includes Building Physics and Heating, Ventilation and Sanitation.

The work of the Building Physics division is concerned with the characteristics and properties of building materials, building elements and buildings, under the influence of indoor and outdoor climates. This involves mainly skills and expertise within the main sectors of heat transfer, moisture transfer and air movement.

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Work done by the division is concerned partly with energy conservation and efficient energy use in the built environment. To date (1988) over half of the Riksdag's energy conservation objective for the built environment has been achieved, but continued conscious effort in the field of low-energy buildings and components is essential if the entire target is to be achieved. Against the background, too, of the phasing-out of nuclear power generation, coupled with the general environmental debate, continued technological development within the energy conservation sector can be seen to be extremely important. Every kWh saved represents one environmental problem less.

The new low-energy buildings and their components must be matched to each other and to the appropriate heating and ventilating systems. This has sometimes been neglected, resulting in damage or other problems, e.g. moisture damage, high radon levels, poor efficiency of heat exchangers etc. It is important that buildings are seen as active, operating systems, and that building services systems and design features are selected so that they interact in an optimum manner. This requires broad knowledge and experience, not only of building physics, but also of heating and ventilating technology.

It is also important that energy is not conserved at the cost of good indoor environmental standards. We are therefore also involved in methods of measuring or calculating thermal comfort and air quality.

In recent years, the building industry has attached growing importance to durability and long life. There is therefore a greater demand for test and evaluation methods to forecast expected life and maintenance intervals. This is something that involves several units within the National Testing Institute, although it is central for Building Physics, partly because many of the durability aspects relate specifically to properties and characteristics that have an important bearing on energy conservation, and partly because our knowledge of temperature and moisture conditions, is important for all types of durability considerations.

ORGANISATION AND PERSONNEL

Energy Technology consists of seven sections, of which three are concerned with heating, ventilation and sanitation and three with building physics, with the seventh section spanning over both sectors. Tomas Nilsson is head of Energy Technology.

Head of Building Physics, and assistant head of Energy Technology is Per Ingvar Sandberg.

The three sections concerned with building physics are under the leadership of:

- Christer Johansson: Building diagnoses
- Bertil Jonsson: Thermal insulation
- Hans Brolin: Building components
Building Physics employs about 22 persons, of whom half are graduate engineers. Four of the staff hold doctors' degrees.

TECHNICAL EVALUATION

Building materials

This sector is concerned with the thermal insulation properties of building materials and components.

Typical thermal insulating materials are mineral wool, cellular plastics and lightweight concrete. Most of the work on these materials is in the form of manufacturing quality assurance (the VIM scheme, to which virtually all manufacturers and importers of insulating materials subscribe). We measure thermal conductivity, density and air permeability, and carry out site inspections at manufacturers' premises and stores. Such visits are used to monitor the standards of companies' own internal quality assurance procedures.

In the case of loose-fill insulation, which is blown directly into position – nowadays mostly in roof spaces – we also perform installation tests, checking thickness, density, ventilation and so on in the roof space.

Determination of thermal conductivity of mineral wool.
Tests are also performed on new materials to be introduced onto the market or which are being developed. New materials are constantly being developed, and the awareness of the damage caused by chlorinated fluorocarbons (CFC) in recent years has resulted in search for alternative substances for use in the materials in which CFC is today used, or attempts to adapt other materials so that they can be used instead of those based on, or involving the use of CFC.

The thermal insulating properties of foamed plastic pre-formed pipe insulation are also tested at various temperatures. These products are often type-approved, and are subject to manufacturing quality control in a scheme similar to that described for the VIM scheme.

Building elements

This area of activities is concerned with tests of properties such as airtightness, resistance to rain and durability of doors, windows and similar products.
Windows and doors are tested for airtightness, resistance to rain and security against wind loading. Windows with plastic casements and frames require additional tests, necessitated by the special properties and characteristics of plastics, including dimensional stability when exposed to repeated temperature cycling on the outside of the windows. The majority of windows tested are produced by manufacturers belonging to type approval schemes: i.e. P-marking for wooden-framed windows and the type approval scheme for plastic-framed windows operated by the National Board of Physical Planning and Building.

The thermal resistance of building structural elements, e.g. wall elements, doors and windows, is tested in climate chambers by the hot box method. Knowledge of the thermal resistance enables the U-value, which is a measure of the thermal insulating performance of the element, to be calculated. Windows are that part of the building envelope that has the poorest U-value, and so considerable development work is carried out with the aim of improving the design and developing lower-energy-loss materials.

Windows are a particular building element that is tested by several different departments of the National Testing Institute. Acoustic insulation testing by Acoustics, airtightness and thermal resistance testing by Building Physics, testing of mechanical properties by Building Technology and fire resistance testing by Fire Technology (preferably in that order) can well be a typical test program for a window type approval. Hans Brodin is therefore responsible for internal coordination within the National Testing Institute in order to facilitate the internal and external contacts in connection with testing of doors and windows.

The National Testing Institute and the manufacturers have developed rules intended to ensure quality and long life of sealed glazing units, the majority of sealed glazing units produced in Sweden today are P-marked in accordance with these rules. The most important property in this respect is the ageing characteristic, which is tested not only as part of type approval but also subsequently at yearly intervals.

Buildings

The work of this sector involves testing, inspection and investigation of buildings in connection with moisture problems, air quality and ventilation, and also in connection with the quality of workmanship of sealing and thermal insulation.

The quality of workmanship and performance of thermal insulation and sealing are investigated using infra-red cameras. The airtightness of entire buildings or apartments is tested using fans and air flow meters. An extra large fan, with a capacity of 85 000 m³/h, is used for factory premises, department stores etc.
Within the radon sector, we trace radon sources in buildings having high radon decay product levels, and also investigate the reasons for high radon levels in indoor air. Tracing is done using small containers of active carbon, and the entire process can be carried out by post. When investigating the reasons for high radon levels, we make site measurements and inspections and suggest suitable counter-measures in order to reduce radon decay products levels.

As far as investigation of moisture damage is concerned, tests and observations are carried out in accordance with a pre-determined inspection routine developed by us. In order to identify the cause of the damage, it is often necessary to obtain additional information, e.g. analysis of mildew or fungi, the capillary rise of filling materials or computer calculation of expected moisture contents. The report is then used as a basis for suggestions for counter-measures: if possible, a number of alternative measures are suggested.
R&D ACTIVITIES

Research and development in the field of building physics is carried out in project form, with the main emphasis on:

- energy conservation,
- the indoor environment, and
- durability and long-term properties.

These three main sectors are linked to each other. The long-term element of R&D work is intended to maintain levels of expertise and knowledge and, when coupled with specific concentrations of work, to increase such skills and expertise within certain sub-sectors. Typical projects are concered with:

- method development,
- feedback of experience, and
- technological development.

The Energy Conservation sector is concerned with thermal insulation and airtightness in buildings, as well as with low-energy components such as doors and windows. Examples of current or recently concluded projects include preparation of an inventory of test and inspection methods for energy conservation in buildings, the development of new test equipment for inspecting underground piping insulation and a new method of allowing for the effect of moisture on the performance of insulating materials.

The Indoor Environment sector is concerned with such widely differing problems as noise, inadequate lighting, draughts, heat, cold or airborne pollution. If ventilation is inadequate, the effect of airborne pollution will be magnified. The majority of measures employed within the energy sector normally also have some effect on the associated indoor environment, and so the relationship between energy supply, distribution systems and indoor environment constitutes an important area of research.

A project is planned for development and verification of a theoretical model for calculation of comfort at low outdoor temperatures, based on measurements made under different, specified conditions.

R&D work continues, too, within areas such as moisture, mildew and radon, with which the National Testing Institute has long been involved. Investigation of the criteria for the growth of mildew on wood, for example, has been in progress for a long time, with the objective of ultimately being able to formulate criteria for the development of smell of mildew.

Work is also being carried out within the radon sector, primarily concerned with counter-measures. The effect of such counter-measures is verified immediately after applying them, and rechecked about 3-5 years later.
In connection with moisture problems, the effect of various building structural measures is monitored. Additional work is planned in order to be able to specify typical moisture conditions in various parts of buildings. This will enable critical building design features to be examined and modified for the better.

Durability and life of materials and components constitute an increasingly important concept, particularly in relation to annual operating costs. The importance of long-term solutions is emphasised in discussions concerning building standards and new loan rules. Examples of projects within this sector are those concerned with the long-term properties of insulating materials in respect of such aspects as gas migration and moisture, development of methods of age testing of insulated glazing units, functional stability of plastic windows and long-term trials of doors in test buildings in respect of dimensional changes and sealing. A major new effort within this sector relates to a quality assurance system for detached houses, bringing them into the scope of the P-marking scheme.

ADVISORY SERVICES

Participation in standardisation work and other committee activities constitutes an important means of establishing contacts and of being kept informed of, and monitoring decisions that will affect, future activities. Building Physics participates in the work of Swedish (BST), Nordic (INSTA and Nordtest), European (CENT) and international (ISO) standardisation bodies.

The regulatory authority with which we have most contact is the National Board of Physical Planning and Building. We work closely with the Board through both direct contacts with individual project leaders and participation in reference and management groups.

A certain degree of international cooperation also operates through working groups within RILEM and CIB.
Contact persons

Thermal insulating materials: slabs, mats, pipe insulation, loose-fill mineral wool

Bertil Jonsson
Sören Wahlberg

Windows, doors, factory doors, sealed glazing units, plastic windows

Hans Brolin
Mats Tornevall

U-value and thermal resistance of windows, doors, wall elements

Bertil Sjöholm

Moisture and mildew damage

Ingemar Samuelson
Lars Tobin
Ingemar Nilsson
Eva Örtengren

Radon measurement and air change

Ingemar Nilsson
Roland Lofström

Thermal comfort and air quality

Christer Johansson
Annika Ekstrand-Tobin

Insulation and airtightness performance of buildings: U-value, airtightness, thermography, inspection of loose-fill insulation

Ingemar Nilsson
Roland Lofström
Christer Johansson

Measuring of overall building conduction heat loss coefficient

Agneta Olsson-Jonsson

Quality systems for prefabricated houses

Rolf Hilling
Ingemar Nilsson
Per Ingvar Sandberg

Thermal Resistance of a Wet Mineral Fiber Insulation


ABSTRACT: A strategy for assessing the thermal resistance of a wet insulation material has been developed. A computer program has been developed to calculate the effects of moisture flow and phase changes. Laboratory experiments in a guarded hot plate apparatus with moist mineral fiber insulation have been conducted. There was satisfactory agreement between the computer calculations and the experimental results.

The practical thermal resistance of mineral fiber insulation in two applications has been studied using the aforementioned strategy:

1. Insulation with accidental high moisture content caused by leakage, rain penetration, and so on. A typical example is insulation on the exterior of basement walls.
2. Insulation with trapped moisture inside impermeable vapor barriers. This situation is sometimes found in roof insulation.

A conclusion was that phase changes in some cases were important energy transfer mechanisms and therefore must be considered.

KEY WORDS: condensation, fibrous material, guarded hot plate, heat transfer, moisture migration, thermal conductivity, relative humidity, phase change, thermal insulation.

For a long time we have been aware that moisture in thermal insulation affects the insulating ability of the material. However, our knowledge in this area is, in many respects, sparse and contradictory. The reason for this is that many different test methods have been used and the results have sometimes been wrongly interpreted. The thermodynamic processes during a test of a wet material are complicated, and the meaning of the concept of "thermal conductivity of a wet material" is not quite clear.

To get a basis for classifying insulating materials in Sweden, a research project is being carried out at the National Testing Institute. The aim of the project is to review existing information and to propose test procedures.

This paper reports some general aspects of thermal resistance of wet materials and also a more detailed analysis of heat and moisture transfer in wet mineral wool.

Theory and Strategies to Assess Thermal Resistance in Practice

For the following discussion, it is convenient to divide heat flow into three components:

1. Heat flow caused by a temperature gradient in a condition of moisture equilibrium, that is, no moisture transfer. This flow is affected by various mechanisms, among them being the moisture content of the material.

1Head, Division of Building Physics, National Testing Institute, S-501 15 Borås, Sweden.
2. Convective heat transfer by moisture flow. Water vapor and water each carries its own enthalpy. It should be observed that the enthalpy of water vapor differs from the enthalpy of water with the latent heat of vaporization.

3. Heat transfer resulting from phase changes.

Simulation of all these kinds of moisture effects in a test procedure is unrealistic and unnecessary. The effects of Types 2 and 3 depend entirely on the occurrence and size of moisture transfer in the material, and if these effects are allowed during a test, it is difficult to assess a material property or a building component property. There will also be a great risk of overestimating these types of effects.

For these reasons the author has suggested the following strategy:

(a) to determine the effects of Type 1 (thermal conductivity of the wet material) by testing, and

(b) to determine the effects of Types 2 and 3 (effects of moisture flow and phase changes) by calculations or estimations based on experience.

The result of Strategy a is "thermal conductivity of wet material." This is a material property that has to be combined with Strategy b. This combination yields something we may call "thermal resistance of a wet building component." This resistance value, which will represent an average over, say, a year or a heating season, varies not only with the material and its thickness but also with the boundary conditions.

The purpose of the test is primarily to measure the thermal conductivity of the wet material (Type 1 effect). If possible, heat flow due to moisture flow and phase changes (Types 2 and 3) should be negligible during the test. If this is not possible, it is necessary to estimate Type 2 and 3 effects by supplementary measurements and calculations and to correct the test results accordingly.

Calculation of Type 2 and 3 effects is needed in the case of change in moisture content or moisture content distribution. Only net changes during the period studied are of interest. Consequently, daily oscillations, for example, have no effect on the annual mean value as long as the moisture content is the same at the beginning and end of the period. There is, however, one important exception: If moisture migrates in one direction in the vapor phase and then back in the liquid phase, Type 3 effects may be considerable even if no net change in the moisture content occurs. Compare d and e in Fig. 1.

![Diagram](attachment://image.png)

**FIG. 1—Some examples in which moisture effects may have to be taken into consideration.**
Figure 1 illustrates some examples in which Type 2 and 3 effects may have to be taken into consideration:

(a) Drying of the initial moisture content. The moisture content decreases. The heat of vaporization is taken mainly from the inside, which causes an increased heat flow at the wall's inner surface, and the thermal resistance of the wall seems to deteriorate.

(b) Condensation against a cold outer surface. Heat is released in the condensation zone but is then mainly lost to the outside air. A slight rise in temperature at the outer surface will occur, and the thermal resistance seems to be improved.

(c) Periodic moisture flowing between the surfaces in a closed building element. Heat will be liberated and absorbed alternately at the inner and outer surface, and the net effect over several periods is negligible. Daily oscillations, for example, are not of interest when a heating season is studied. During a laboratory test, however, which may last for only a couple of hours and constitute only part of a period, the effects may be significant, and they must be taken into consideration when the test results are evaluated. This is why effects of Type 2 and 3 should be avoided or carefully considered during the test. The effects during the test may be considerable while the effects averaged over a longer period are negligible.

(d) Vapor flow in one direction and liquid flow in the other. During the winter, moisture in a roof construction may be transported upwards in vapor phase by diffusion and back downwards in the liquid phase by capillary suction or the action of gravity. The heat of vaporization is taken mainly from the inside while the heat of condensation is lost to the outside. Although the moisture content is the same, the thermal resistance of the roof is reduced.

(e) The same principle as in Example $d$. Liquid (rain) hits the wall and is absorbed. When the wall dries out again, the heat of vaporization is taken partly from the inside. The thermal resistance of the wall seems to deteriorate.

Thermal Resistance of Wet Mineral Wool

Until recently much of our knowledge in Scandinavia about moisture influence on the thermal conductivity of mineral wool has been based on measurements by Jespersen [7]. He used a stationary method with a hot plate, a cold plate, and heat flow meters on each side of the test specimen. The results for mineral wool are shown in Fig. 2. At about 1% by volume the thermal conductivity rises steeply from $-0.035$ to $-0.065 \text{ W/m} \cdot \text{K}$. It is difficult to find a physical explanation for this sudden increase in thermal conductivity.

The sudden increase can be explained only by phase changes in the material. In that case, the thermal conductivity reported by Jespersen is not a material property but an "apparent thermal conductivity as a function of moisture content according to Jespersen [1]: rock wool, 78 kg/m$^3$; glass wool, 62 kg/m$^3$; expanded cork, 110 kg/m$^3$.

![Thermal conductivity vs. moisture content](image)

FIG. 2—Thermal conductivity as a function of moisture content according to Jespersen [1]: rock wool, 78 kg/m$^3$; glass wool, 62 kg/m$^3$; expanded cork, 110 kg/m$^3$. 
conductivity," which is dependent not only on the moisture content but also on the moisture flow and the boundary conditions.

In Jespersen's tests, the moisture flow causes a heat sink (evaporation) at the warm side and a heat source (condensation) at the cold side. Consequently, the heat flow recorded by the heat flow meters at the test specimen's surfaces is much higher than the Type 1 heat flow in the material.

Apparently many of those who have used Jespersen's results have made the mistake of basing heat flow calculations in mineral wool on measurements carried out with a very special moisture situation that is seldom encountered in practice. This situation requires a permanent supply of moisture at the warm side. In reality, the amount of moisture is limited, and in such permeable materials as mineral wool, the moisture under the influence of a temperature gradient is rapidly concentrated to a thin layer on the cold side. A similar opinion has been expressed by Langlais et al [2] and Thomas et al [3].

The moisture effects of Types 1, 2, and 3 must be separated and the assessment of the thermal resistance handled differently depending on the particular moisture situation. For that reason, a computer program has been developed for studying the thermal resistance under different moisture conditions. The computer model has been verified by comparison with laboratory tests (see Ref 4).

Guarded Hot Plate Measurements on Wet Material

Measurements were made in a guarded hot plate apparatus with a measurement area of 1.0 by 1.0 m. The test arrangement was done according to that shown in Fig. 3. The density of the mineral fiberboard was ~ 250 kg/m².

Between the hot plate and the top piece of mineral fiberboard, a cloth with a known amount of water was placed. A dry cloth was placed between the cold plate and the bottom piece. During testing, the moisture migrated from the top cloth to the bottom cloth.

The heat flow from the hot plate was continuously measured and registered as mean values over 0.5 h. Thermocouples, three on each level, were placed between the mineral fiberboard pieces and on the board surfaces in contact with the cloths. The averages on each level over 3 h were registered.

The heat flow from the hot plate and the boundary temperatures are shown in Fig. 4.

The computer program was used to simulate the same test, and the agreement was found to be good. The difference between the laboratory test and the computer model was less than 0.5 W/m² in heat flow and less than 0.5°C in temperature.

At the end of the test (when a state of moisture equilibrium had been established) the vapor

![Diagram](attachment:image-url)

**FIG. 3—Test configuration.**
concentration was the same in all the board pieces, and the relative humidity (RH) could be calculated:

<table>
<thead>
<tr>
<th>Piece No.</th>
<th>RH</th>
<th>$\lambda_{\text{dry}}$</th>
<th>$\lambda_{\text{end-of-test}}$</th>
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<tr>
<td>1</td>
<td>20 to 30</td>
<td>= 0.040</td>
<td>0.041</td>
</tr>
<tr>
<td>2</td>
<td>30 to 43</td>
<td>= 0.040</td>
<td>0.042</td>
</tr>
<tr>
<td>3</td>
<td>43 to 66</td>
<td>= 0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>4</td>
<td>66 to 100</td>
<td>= 0.040</td>
<td>0.040</td>
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$\lambda =$ thermal conductivity, in watts per metre degrees kelvin.

There is evidently no measurable tendency toward higher thermal conductivity for those pieces with high relative humidity. Moisture effects on Type 1 heat flow are negligible for mineral wool in the hygroscopic range. This experience has also been confirmed in several similar tests.

Accidental High Moisture Content

A mineral fiber insulation that is fully saturated with water will dry out in two stages. During the first stage, which will last for a couple of hours, gravity action will cause a drainage of the material. The rate of draining and the amount of water retained after drainage depends to a great extent on the orientation of the insulation. In a vertical position, the water drains quickly to a water content of 3 to 5% by volume except in the lower 0.1 to 0.2 m, where the material remains saturated [5,6].

During the second stage, which will last from a couple of days to a couple of months, the drying mechanism is vaporization of water and diffusion of water vapor out of the material. If there is an impervious surface layer on the cold side (for example, a vapor retarder) preventing the drying, however, the vapor will condense here. The major part of the moisture will soon be concentrated to a thin layer at the surface.

During the drying (or redistribution) of moisture in the second stage, heat flows and temperatures in the material are affected by phase changes. These must be considered when thermal conductivity design values are assessed.

A typical example of a mineral fiber insulation exposed to accidental high moisture contents is insulation on the outside of basement walls. The concept of mineral fiber as an external insu-
lation and a drainage layer is now well known in many countries [5, 7–9]. Let us use this building component as an illustration of how the aforementioned strategy for determining the thermal resistance of a wet material may be applied.

In 1983, approval of a type of basement wall with an external mineral fiber insulation was due for revision and extension. Up to then, the design value for the thermal conductivity of the mineral fiber had been 0.060 W/m·K. The manufacturer was of the opinion that this value was too high and wanted it reconsidered. Together with the manufacturer, the National Testing Institute analyzed the hygrothermal performance of the insulation with the following results:

1. The insulation is almost continuously subjected to a temperature gradient, and the material is very permeable to vapor diffusion. Consequently, there is a very strong potential for drying.
2. The material is very slightly hygroscopic; at 90% relative humidity, the equilibrium moisture content is less than 0.3% by volume.
3. The normal condition for the material is therefore "almost dry," and moisture effects on Type 1 heat flow are negligible.
4. Type 2 effects (convective heat transfer) can be estimated (see Ref 10) to be less than 0.5% of the total heat flow and may also be neglected.
5. Type 3 effects (phase changes) must be considered. The problem is that there is very little knowledge about accidental wetting by rain, melting snow, or high groundwater level. Lindkvist and Mattsson [11] measured moisture contents in eight houses on one or two occasions. The moisture content was below 0.2% by volume in 35 out of 38 test specimens.

As a design basis, the annual extent of accidental wetting was fixed at ten "light" wettings (ordinary rain) to 0.5% by volume and one "major" wetting (melting snow or heavy rain causing total saturation) to 3.8% by volume. The first figure (0.5%) was based on field measurements [11] and the second (3.8%) on laboratory tests [5, 6].

Assuming a temperature difference of 10°C across the insulation and a thickness of 0.07 m, the heat flow through the warm surface of the insulation was calculated for the two cases of accidental wetting (see Fig. 5). In Fig. 5 the heat flow is expressed by an "apparent thermal conductivity," \( \lambda_a \)

\[
\lambda_a = \frac{q \cdot d}{\Delta \Theta}
\]

FIG. 5—Calculated values of the apparent thermal conductivity as a function of time.
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where

\[ \lambda_a = \text{apparent thermal conductivity, } W/m \cdot K, \]
\[ q = \text{heat flow through the warm surface of the mineral wool, } W/m^2, \]
\[ d = \text{thickness} = 0.07 \text{ m}, \text{ and} \]
\[ \Delta\Theta = \text{temperature difference} = 10^\circ C. \]

The thermal conductivity for the dry material is 0.035 W/m \cdot K.

After the "light" rain, the thermal conductivity is affected for 4 days and the average value of \( \lambda \), during this period is \( -0.046 \) which is 31% above the "dry" value. After the "heavy" rain, \( \lambda \) is affected for 25 days, and the average is \( -0.047, 35\% \) above the dry value. Considering these effects, the annual mean \( \lambda_a \) can be estimated as

\[
\bar{\lambda}_a = \frac{40 \times 1.31 + 25 \times 1.35 + 300 \times 1.00}{365 \times 0.035} = 0.037 \text{ W/m \cdot K}
\]

Consequently, the moisture effects may justify an increase in thermal conductivity (\( \Delta\lambda_{\text{moisture}} \)) of about 0.002 W/m \cdot K. The heat of vaporization, which was taken from the inside, will be recovered in the ground just outside the insulation when the water vapor condenses. This means that the estimate of \( \Delta\lambda_{\text{moisture}} = 0.002 \text{ W/m \cdot K} \) is on the safe side. On the other hand, it may be argued that the mean value should be calculated only for the heating season, which means a slightly higher \( \bar{\lambda}_a \) (\( \Delta\lambda_{\text{moisture}} = 0.003 \)).

Approval of the basement wall type was extended (see Fig. 6). After consideration of scatter in production, moisture, compression from earth pressure, aging, and other factors, the insulation was assigned a design value of 0.042 W/m \cdot K.

FIG. 6—Approved type of basement wall.
Insulation with Trapped Moisture Inside Impermeable Vapor Barriers

In a closed building element, moisture may flow periodically between the surfaces. Heat will be released and absorbed alternately at the inner and outer surface, and the net effect is negligible over several periods. This situation may occur during autumn or spring in roof insulation with a vapor barrier on the inside and a roofing membrane on the outside. Figure 7 shows the calculated heat flow at the inner surface and the apparent thermal conductivity in insulation 0.10 m thick, containing 6% by volume of moisture, with an inside temperature of 20°C and an outside temperature cycling sinusoidally between −10 and +30°C. The average temperature difference is then 10°C, and the dry thermal conductivity is assumed to be 0.035 W/m·K, which means that the average heat flow should be

\[ \bar{q} = \frac{0.035 \times 10}{0.1} = 3.5 \text{ W/m}^2 \]

This is also, as expected, the average of the heat flow calculated in Fig. 7, although there are variations between 10 and −7 W/m².

Two factors influence the heat flow response at the inner surface—effects of phase changes and the thermal diffusivity. To separate these effects, another calculation was carried out with the latent heat of vaporization, \( R = 0 \). The results are shown in Fig. 8. As can be seen from this figure, the moisture acts as a "negative thermal capacity"—the amplitude increases, and the time lag decreases.

The weather conditions with constant cycling will last for only limited periods. In reality a "cycling equilibrium" is never reached. Therefore, further calculations modeling the annual performance of the insulation have been carried out. The following conditions were assumed: thickness, 0.1 m; moisture content, w, 6% by volume; indoor temperature, 20°C; and thermal conductivity, \( \lambda = 0.035 + (0.035/10)w \). This is a moisture effect on Type 1 heat flow, meaning that \( \lambda \) is doubled at 10% by volume moisture content. This correction, which is in accordance with results from Hedlin [12], Bomberg and Shirkilfe [13], and Knab et al [14], seems considerable, but we have to bear in mind that the moisture in mineral wool tends to gather in thin layers and therefore affects only very limited parts of the material. A moisture content of 6% in a 0.1-m-thick insulation may be concentrated in a 6-mm-thick layer.

FIG. 7—Calculated values of the apparent thermal conductivity and heat flow over 24 h.
The external surface temperature has been expressed as a sine function over the year. To this has been added a sine function over the day simulating the daily oscillation

$$\theta_e = 12 + 10 \sin (\omega_2 t) + [6 + 4 \sin (\omega_2 t)] \times \sin (\omega_1 t)$$

where

- $\theta_e$ = external surface temperature, °C,
- $t$ = time, s,
- $\omega_1 = 2\pi/24$ h, and
- $\omega_2 = 2\pi$/year.

The results of the calculation (Fig. 9) are shown as ten-day averages of heat flow as a function of the average temperature difference. The straight line represents the corresponding values for dry insulation. Field tests reported by Hedlin [12] gave similar results (Fig. 10).
FIG. 10—Heat flow versus temperature difference for glass fiber at 6% moisture content by volume (results from field measurements by Hedlin [12]).

The annual mean value of the heat flow in the dry insulation would be 2.8 W/m². The calculated mean value for the moist insulation is around 3.3 W/m², which is ~18% higher than the dry value.

During the summer season vapor diffuses from the outer parts of the insulation and condenses at the inner surface, causing an extra inflow of heat. It is seldom possible to utilize this extra heat, and in many cases the heat may be a disadvantage. It would, therefore, be more correct to restrict the discussion to the period with a net heat flow from inside to outside, that is, the heating season. During this period, $\lambda_s$ is ~0.045 W/m·K, which is ~28% above the dry value. This calculation is made with an arbitrary set of conditions to illustrate the moisture effects, and it is not a proposal for the size of $\Delta\lambda_{\text{moisture}}$.

Conclusions

Two examples have illustrated a suggested strategy for assessing the thermal resistance of wet insulation. These examples have indicated the importance of considering the large-scale and long-term moisture movements in the material. This requires a computer model and knowledge of the moisture boundary conditions and the moisture properties of the material.

Moisture in a mineral fiber insulation is very mobile, and phase changes are therefore often an important energy transfer mechanism.

References


Claes G. Bankvall

Air Movements and the Thermal Performance of the Building Envelope


ABSTRACT: Air movements will influence the thermal performance of the building envelope; to what degree will depend on the pressure situation in and around the structure, the permeability of the different materials, and the airtightness of joints between materials and building elements. In a multilayer structure with a high thermal resistance, different parts have different functions in order to protect against unwanted air flow and ensure airtightness.

Wind protection will give a degree of safety against air flow in the insulation, especially in situations involving large wind loads. Certain areas of the structure may be more sensitive and have a higher need for wind protection than others. In a similar way, the building envelope will be sensitive to air infiltration. The inside—that is, the vapor barrier, inside board, and joints—will greatly influence the air flow and the heat losses from the envelope.

Both types of increased heat losses from the building envelope (that due to air flow along the insulation and that due to air infiltration) will most influence envelopes with high thermal resistance. This type of envelope is typical of today's design in Scandinavia, and the results and discussions are related to this.

KEY WORDS: thermal insulation, air movements, permeability, wind protection, airtightness

Air movements will influence the thermal performance of the building envelope. The thermal insulation is sometimes protected by a special wind protection. This will give the structure a degree of safety against influence from wind. Wind and pressure situations around the envelope are of importance. Certain areas will be more sensitive and have a higher need for wind protection than others.

In a similar way, the building envelope will be sensitive to air infiltration. Infiltration through the envelope was previously a means of ventilating the building. In modern Scandinavian designs, this is not the case. The aim now is to reduce unwanted infiltration as much as possible. The inside—that is, the vapor barrier, board, and joints—will have the most influence on such infiltration.

Figure 1 shows an example of a building envelope. Behind the face wall and underneath the roofing there is an air flow that transports moisture from the structure. The different parts in the design intended to protect against wind (air flow along the insulation) and give the envelope its airtightness are indicated in the figure.

In Scandinavia there are requirements concerning airtightness of buildings and building components such as windows and doors. Wind protection is not quantified in the same manner, but its importance is underlined in the different building codes.

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Air Permeability

An important factor in the design of a modern structure is the airtightness of the building envelope and its joints. The air permeability of a material or a structural part, in combination with a pressure difference, leads to air movement in and through the structure, and consequently influences its thermal performance.

Figure 2 shows how a pressure difference will influence the air flow through different structural parts. The least permeable materials, such as plastic sheeting, are used for the vapor barrier, the main airtightness layer in the building envelope. Nailing a board joint against a crossbar can give fair airtightness, depending on the distance between the nails. A commonly used wind protection in Scandinavia is the asphalt-impregnated porous board. This has a lesser degree of airtightness but is still considered sufficient as wind protection. The face wall gives a certain degree of protection from direct wind. This will depend on the design of inlets and outlets to the air space behind the wall.

The examples in the figure have been based on practical measurements of materials and building elements, but also on theoretical analyses of air flow in different structures [1-4].

Wind on a building envelope will lead to pressure differences and air flow in and around the structure. The actual situation will depend on wind strength, building design, proximity to other buildings, and other factors.

It is therefore difficult to evaluate the true pressure situation for a building. Few field measurements have been done. Some investigations in wind tunnels are available. However, for a rough evaluation of the pressure changes at the outside of a one-family building, Fig. 3 has been
FIG. 2—Air flow through different building components at a 10-Pa pressure difference.

FIG. 3—Estimated pressure changes along the wall surface at varying wind velocities at a one-family house.
constructed. The figure shows that, for a given wind velocity, large pressure changes normally involve only minor parts of the total surface area. At a wind of 10 m/s, up to 50% of the surface area can experience a pressure change of about 20 Pa/m. This diagram can be used for rough evaluations of the importance of protecting thermal insulation from air flow along it in a given situation.

Estimations can also be made of pressure differences over the wall on the windward and leeward sides, based on building code requirements for wind loading in the Swedish building code (Fig. 4). The pressure differences may be somewhat overestimated. Airtightness and the consequences of air infiltration may be evaluated for a pressure difference from inside to outside of about 20 Pa. Experience from field measurements indicates that this is a reasonable value.

Face Wall

The pressure changes behind the face wall will depend on the wind, permeance of the wall, size of the ventilated airspace, and other factors. This is shown in Fig. 5. Two extreme situations are illustrated: one in which the air space has open inlets and outlets and the other in which these are closed. In the diagram, normal permeances for brick and wooden paneling, as measured on Swedish structures, are indicated.

Wind Protection

Air movements in the building envelope behind the face wall will increase the heat losses from the wall section. This may be described as an increase in the \( U \) value of the section (Fig. 6). The \( U \) value is indicated for thermal insulations of 10 and 30-cm thickness. The insulation is a mineral wool with \( \lambda \) value of 0.034 W/°C. Depending on the pressure change outside the insulated space and the wind protection of the insulation, the \( U \) value will increase as indicated in the figure. The unprotected insulation experiences a noticeable increase in \( U \) value, while the

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**FIG. 4—Estimated pressure difference over a wall at varying wind velocities at a one-family house.**
increase for the protected one is very small. Relatively, the most sensitive situations are those with the highest thermal resistance. The basis for these evaluations is presented in Refs 1 and 3.

Wind protection is especially important for those parts of a building in which pressure changes are normally large, such as at corners and eaves. Another situation in which the wind protection is of great importance occurs when the installation of insulation is deficient [5].

Airtightness

Air infiltration increases heat transfer. In many cases this is necessary for the normal ventilation of the building. In modern designs this air leakage means an unwanted increase in heat loss from the building. The airtightness of the building envelope is thus of importance [6].

Most of the air will pass through joints and openings that occur because of the design or installations in the envelope. The inside board and the vapor barrier give the building envelope its airtightness.
The pressure difference across a wall is exemplified in Fig. 7. It can be seen that the vapor barrier has the greatest effect on the pressure drop. When the vapor barrier is missing, the inside board is important. In the “normal” design, the wind protection is of less importance. The increase in heat transfer can be compared with the original $U$ value of the wall. Additional heat transfer will depend on pressure drop, vapor barrier, and, to some extent, wind protection. Figure 8 shows the increased heat transfer as an increase in $U$ value. The basis for this relationship will be found in Refs 1 and 3. With a properly installed vapor barrier, flow through the structure is negligible and is not influenced by the choice of wind protection. Without the vapor barrier, the heat transfer increases markedly. This is even more the case when there are deficiencies in the inside board as well [5].

Air flow through the structure is generally independent of the thermal insulation. Heat transfer through the building envelope will therefore increase independent of the nominal $U$ value. This will most influence structures with high thermal resistance.
FIG. 7—Pressure drop in a crossbar wall with and without a vapor barrier.

FIG. 8—Increase in thermal transmittance due to pressure difference and air flow through the envelope.
Conclusions

When air flows along the thermal insulated space, a special wind protection is useful. This is true for parts of a building where the pressure change is large, such as at corners, or for buildings frequently exposed to strong winds.

The airtightness of the structure depends on the vapor barrier and, to some extent, on the inside board. Air flow through the structure that markedly increases the heat loss is generally due to deficiencies in the vapor barrier and the inside board. Such deficiencies are difficult to compensate for by choice of wind protection.

Both types of increased heat loss from the building envelope, air flow along the insulation and air flow through the insulation, will have the most influence on envelopes with high thermal resistance.

References

Claes G. Bankvall

Thermal Performance of the Building Envelope as Influenced by Workmanship


ABSTRACT: The thermal resistance of the building envelope depends on thermal insulation and design solutions. In practice, however, workmanship may be just as important in the total thermal performance. In the building envelope, certain areas are more susceptible to deficiencies in workmanship than others. This fact should be considered in the design stage.

An ideally installed thermal insulation in a structure will have a well-known thermal resistance. Deviations from this situation will increase the U value. The influence is most important on walls and roofs with low U values, where even small deficiencies may seriously increase the heat loss.

The wind and pressure situation around a building and the air permeability of the structure may lead to air movements in the envelope. This may increase the heat loss. The importance of proper installation of wind protection in an insulated crossbar wall is shown. The increase in U value, especially in combination with deficiencies in the thermal insulation installation, is given. Airtightness of a structure is usually accomplished with a vapor barrier and specially designed joints between different building elements. Large air flows through a wall usually indicate cracks or openings in the vapor barrier and the inside. The increase in heat loss resulting from such flaws is shown. The influence on a building envelope with high thermal resistance is very large.

The results and discussions are related to building envelopes with high thermal resistance and low heat losses. This situation is typical of today's building design in Scandinavia.

KEY WORDS: thermal insulation, building envelope, workmanship, wind protection, airtightness

The thermal resistance of the building envelope depends on the thermal insulation and the building design. In practice, however, the result will be influenced by workmanship. This is obvious for the installation of the insulation, since the thermal resistance of the insulating material is often more than ten times greater than the resistance of the air space that the material fills. Air movements and resulting heat loss through the structure and the insulation will, to a large degree, depend on the vapor barrier, joints, and wind protection. Good workmanship is essential in all these areas. It may be crucial to the thermal resistance experienced in practice.

A sketch of a typical Scandinavian one-family house is shown in Fig. 1. Structural sections with known problems in airtightness and thermal insulation are indicated. There are several reasons for these difficulties. One is susceptibility to strong climatic conditions—for example, high wind loads and pressure differences. Another reason is the difficulty of designing the structure so that its construction can be easily carried out in practice. A third reason may be the building process itself, which makes good workmanship in some areas more difficult. In this paper, the importance of workmanship in three areas will be discussed and exemplified. These areas are the installation of thermal insulation, the application of wind protection, and the airtightness of the structure. For further information on the theoretical analysis and details of measurements, Refs 7–3 should be consulted.

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Thermal Insulation Installation

Ideally, installed thermal insulation normally leads to a well-known thermal resistance and $U$ value. In practice, deviations from this are common.

Deficiencies in the installation can often be attributed to the insulation not completely filling the space to be insulated. Cracks or air spaces may occur around the thermal insulation. The consequences of this are illustrated in Fig. 2. The diagram, based on calculations and laboratory measurements, illustrates deficiencies in an insulated space, where the insulation thickness is intended to be 0.15 m, giving a nominal $U$ value of 0.25 W/m²·°C. The diagram is valid for normal building envelope temperatures [3].

At one of the crossbars there may be an air crack going from the warm to the cold side. This noticeably increases the $U$ value. Also, air spaces at one side of the insulation will increase the $U$ value, but to a lesser degree. The situation giving the largest, and most difficult to assess, increase in $U$ value is a combination of cracks and spaces around the thermal insulation.

These difficulties will be more serious as the nominal thermal resistance of the structure is increased. Even small openings will degrade the thermal performance, especially if conditions are close to those in which natural convection may take place inside a fully insulated space [4]. This is due to the possibility of interaction of air movements in the material and the openings.

Similar deficiencies in other parts of a building envelope—for example, in the roof—will have similar consequences [5, 6].

Wind Protection

The pressure field around the building envelope and the air permeability of the different materials and structural parts may lead to air flow in the structure. Such movements will increase the heat loss from the building [7].

The face wall will give some protection to the insulation in the structure. In this case, the design of the inlets and outlets to the normally ventilated space behind the face wall is of importance because it affects the pressure changes found at the insulated part of the structure. In a careful design for high thermal resistance, a special wind protection is often used for the insulated space (see Fig. 2). A good installation of the wind protection will give a higher thermal resistance to the structure than a poor one [7].

As was pointed out in the previous section, deficiencies in installation of the thermal insulation will influence the $U$ value of the building envelope. It is obvious that the heat loss will increase further if air interchange can take place between the thermal insulation and the outside
air. The wind protection is especially important in such a case. This is illustrated in Fig. 3, which shows measurements on the wall section in Fig. 2. The figure shows the increase in $U$ value with a pressure change of 1 Pa/m in the air space along the insulation [7], for both wind protection and no wind protection conditions, when there is an insulation deficiency in the form of a crack (of the indicated width) in the insulated space. In these measurements, the inside and outside air temperatures were $+20$ and $-15^\circ$C. The insulation was a mineral wool of about 30 kg/m$^3$.

For the asphalt-impregnated porous board, which was carefully installed, the bottom of the marked area in Fig. 3 indicates the result due to the "built-in" crack. The additional increases in $U$ value resulting from the air flow in the outside air space are small (top of the marked area).
For the unprotected thermal insulation, however, these effects, especially combined with installation deficiencies, are very great. They are also difficult to analyze. The situation is relatively more serious for structures with high thermal resistance. The figure shows the importance of good workmanship both for installation of thermal insulation and for application of a wind protection.

**Airtightness**

The airtightness of a multilayer structure is usually designed into the structure by use of a vapor barrier and by specially designed joints between different materials and building elements. If unwanted air infiltration is to be avoided, these measures must be well designed and realized by good workmanship. The importance of the vapor barrier as the main airtightness component has been shown before [7].

Even in modern designs some penetrations will occur in the building envelope. This may be caused by some of the electrical installations. Other problems related to the outside building envelope are openings for windows, doors, ventilation, and so on.

The presence of large air flows through a wall area usually presupposes deficiencies in the vapor barrier and the inside of the wall. This is illustrated in Fig. 4, which shows an example of
deficiencies that occur when mounting an electrical outlet in the building envelope. It is assumed that this outlet will lead to a 1-mm-wide crack around the socket, which goes through the vapor barrier and the inside board. This will allow air infiltration and, depending on the pressure difference between inside and outside [7], will lead to an increase in heat loss from the building. This heat loss per installation can be compared with the original $U$ value of the wall section. The figure shows that both with no wind protection and with conventional wind protection the heat loss is quite large. This additional heat loss is, in most cases, independent of the thermal insulation [7]. The example is intended to illustrate the influence of deficiencies on the main airtightness function of the building envelope.

Conclusion

In practice, workmanship will be just as decisive for the thermal performance of the building envelope as the insulating material and the chosen thermal design. This is especially true for structures with high thermal resistance, that is, low $U$ value.

Three situations are of great importance: the installation of the thermal insulation, its wind protection, and the airtightness of the envelope.

References


Moisture Content and Thermal Conductivity in Soil Insulation

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ABSTRACT

In polystyrene boards used as soil insulation there is a deterioration of the thermal conductivity caused by moisture accumulation and changes in the composition of the cell gas (aging). This study presents results from laboratory measurements of thermal conductivity and moisture content of specimens taken from Scandinavian roads. The actual moisture accumulation is compared to calculated and a simple model for prediction of the thermal conductivity under service conditions is developed.

KEY WORDS

Thermal insulation, soil insulation, polystyrene, moisture accumulation, aging, thermal conductivity.

1. INTRODUCTION

RECENTLY A NUMBER of new polystyrene insulation products have been introduced on the Swedish market. At the same time the authorities have felt the need for methods to compare new and existing materials and to assess design values.

Editor's Note: The complete thermal conductivity expression is W/m²(K/m). W/m²·K is a mathematical reduction as used in SI Units. C and K are equivalent.
The National Road and Traffic Institute in Sweden is carrying out a research project with the aim to compare different materials suited for soil insulation. Some of the measurements in this project have been carried out at the National Testing Institute. This paper deals with these measurements and also presents some further analyses of the results and an attempt to predict the moisture content in service by computer modelling.

2. CALCULATION OF MOISTURE CONTENT

2.1 Method of Calculation

The non-stationary temperature field in the insulation is governed by the equation

\[ q \cdot C_p \cdot \frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \cdot \frac{\partial \Theta}{\partial x} \right) \tag{1} \]

where

- \( q \) = density (kg/m³)
- \( C_p \) = specific heat capacity J/kg · C
- \( \Theta \) = temperature (C)
- \( t \) = time (s)
- \( \lambda \) = thermal conductivity (W/m · C)
- \( x \) = thickness (m)

The moisture content is calculated by a similar equation

\[ \frac{\partial w}{\partial t} = \frac{\partial}{\partial x} \left( \delta \cdot \frac{\partial v}{\partial x} \right) \tag{2} \]

where

- \( w \) = moisture content (kg/m³)
- \( \delta \) = vapour permeability (m²/s)
- \( v \) = vapour content (kg/m³)

In Equation (2) it is assumed that all moisture transfer is due to a gradient in vapour content. This is a reasonable simplification for polystyrene insulation considering that the material is normally used in such a way that it is protected from contact with water and from water pressure. In roads the material is installed on a draining layer and normally protected from precipitation by the asphalt road surface and therefore seldom exposed to free water.
Furthermore, the moisture transfer ability in liquid phase is poor in polystyrene insulation.

A computer program which can calculate temperature and moisture conditions as a function of time in a building material is available. The calculations are unidimensional. Boundary conditions and material properties as described below are used in the calculations.

2.2 Boundary Conditions

The relative humidity on both sides of the insulation is assumed to be 100%. Furthermore the material is not supposed to be subjected to water in liquid phase.

The temperature at the top and bottom surface of a 50 mm insulation has been calculated for a typical road—a test surface in Linköping (Figure 1). The calculation is based on actual ground surface temperature measurements.

2.3 Material Properties

The material properties needed for the calculation are: thermal conductivity, specific heat capacity and vapour permeability as functions of the moisture content and also the relationship between moisture content and relative humidity in the material (hygroscopic sorption curve). For products with mould skin the skin's water vapour resistance must be known.

Extruded polystyrene, $\sim 40$ kg/m$^3$:

Thermal conductivity, $\lambda = 0.030 + 0.0001 \cdot w \, (W/m \cdot C)$ where $w = \text{moisture content (kg/m}^3\text{)}$

Heat capacity, $C = (53 + 4.2 \cdot w) \times 10^3 \, (Ws/m^3 \cdot C)$ (note the unit Ws/m$^3 \cdot C$)
Vapour permeability, $\delta = 0.22 \cdot 10^{-6} \text{ (m}^2/\text{s)}$
Vapour resistance of skin, $z = 35 \cdot 10^3 \text{ (s/m)}$
Sorption curve: \[ \begin{align*}
RH &= w/1.5 \text{ for } w \leq 1.5 \\
RH &= 1.00 \text{ for } w > 1.5
\end{align*} \]

Expanded polystyrene, $\sim 50 \text{ kg/m}^3$:
Thermal conductivity, $\lambda = 0.032 + 0.00013 \cdot w \text{ (W/m} \cdot \text{C)}$
Heat capacity, $C = (70 + 4.2 \cdot w)10^3 \text{ (Ws/m}^3 \cdot \text{C)}$
Vapour permeability, $\delta = 0.3 \cdot 10^{-6} \text{ (m}^2/\text{s)}$
Sorption curve: \[ \begin{align*}
RH &= w/1.5 \text{ for } w \leq 1.5 \\
RH &= 1.00 \text{ for } w > 1.5
\end{align*} \]

2.4 Discussion of Results

Results from calculations indicate that

- the mean moisture content in the insulation increases uniformly with time
- the moisture distribution tends to look like that in Figure 2

The reason that the moisture content continuously increases may be explained by Equation (2). If $\delta$ = constant, we get

\[
\frac{\partial w}{\partial t} = \delta \frac{\partial^2 w}{\partial x^2}
\]  

(3)

Fairly soon the moisture content rises above the hygroscopic range and

**FIGURE 2.** Moisture distribution in extruded and expanded polystyrene.
the relative humidity in the material's pores reaches 100%. The vapour content is now equal to the saturation vapour content, which is a function of the temperature alone. Due to the nonlinear relationship between temperature and saturation vapour content the latter is always slightly curved (convex downwards) even if the temperature profile is linear (Figure 3). The second derivative $\frac{\partial^2 v}{\partial x^2}$ is consequently always positive which means that also $\frac{\partial w}{\partial t}$, moisture increase as a function of time, is positive.

3. LABORATORY MEASUREMENTS OF MOISTURE CONTENT AND THERMAL CONDUCTIVITY

Thermal conductivity measurements were carried out on polystyrene specimens which had served as soil insulation in Swedish roads. The age was between 8 and 16 years. The equipment used was a heat flow meter according to Swedish Standard SS 02 42 11. Mean temperatures during the tests were $-5$ and $+5$ °C respectively and the temperature gradient was chosen to 1 C per cm thickness. Fifteen specimens of extruded and nine of expanded polystyrene were tested. The results are listed in Appendix 1. The moisture content of the specimens was determined by weighing, drying and weighing.

The influence on the heat flow from moisture migration during the test was estimated to be less than 2% and was neglected.

Figure 4 shows the measured values of the thermal conductivity as a function of mean moisture content for fifteen specimens of extruded polystyrene.
Also indicated in the figure is the expression usually found in literature for \( \lambda \) as a function of moisture content:

\[
\lambda = \lambda_{dry} + 0.0001 \cdot w
\]

where

\[
\lambda_{dry} = 0.028 - 0.030 \text{ (W/m \cdot C)}
\]

\( w = \) moisture content (kg/m³)

It is important to note that Figure 4 shows the thermal conductivity as a function of mean moisture content. The moisture distribution in the specimen is also important and the more uneven the distribution the lower the effect on the thermal conductivity.

In addition to the effect of moisture content there is also an effect of aging which contributes to the scattering. The gas composition in the material's pores changes with time and this affects the thermal conductivity. The size of the age effect depends on the material's thickness, age and exposure conditions.

A closer look at the points in Figure 4 shows that the two highest conductivities are those of the oldest specimens (16 years) and the two lowest belong to specimens with a very uneven moisture distribution.
FIGURE 5. Thermal conductivity at +5 °C mean temperature vs. mean moisture content for nine specimens of expanded polystyrene.

Figure 5 shows the measured values of the thermal conductivity for nine specimens of expanded polystyrene. The relationship usually reported in literature is also indicated in the figure.

There are practically no effects of aging in expanded polystyrene but the same observation about the influence of moisture distribution on the ther-
mal conductivity which was made for the extruded material is also valid for the expanded polystyrene.

The measured conductivities at a mean temperature of \(-5\, ^\circ C\) were in average 1.8\% higher than at \(+5\, ^\circ C\) for extruded and 9.0\% higher for expanded polystyrene.

Since the thermal conductivity was also determined for the specimens in dry condition, it is possible to calculate the moisture effect as a function of the moisture content (Figure 6).

4. MOISTURE CONTENT IN FIELD EXPOSED POLYSTYRENE INSULATION

In Appendix 2 results are listed from measurements of moisture content in polystyrene specimens exposed as soil insulation. The results are partly from literature and partly from own measurements. All specimens were taken from test roads in Sweden and Norway. The age varies from 4 to 16 years.

The results are plotted in Figures 7 and 8 for extruded and expanded polystyrene, respectively.

**FIGURE 7.** Mean moisture content vs. age for specimens of extruded polystyrene exposed as soil insulation.
The scattering is moderate for extruded polystyrene considering that the specimens are of different thicknesses and have been exposed in different roads in Scandinavia.

For expanded polystyrene, on the other hand, the scattering is considerably larger. This is probably due to a large variation in material properties (different manufacturers and densities between 18 and 50 kg/m³) and its ability to absorb water in liquid phase when subjected to water pressure. The very high values are from low density materials and maybe also from roads with a badly working drainage and with water in contact with the insulation periodically.

Typical moisture distributions in extruded polystyrene are shown in Figure 9. The values are from a test area in Linköping, but results from other locations are very similar.

**FIGURE 8.** Mean moisture content vs. age for specimens of expanded polystyrene exposed as soil insulation.

**FIGURE 9.** Moisture distribution in extruded polystyrene. Results from test area in Linköping after 8 years' exposure.
The moisture distribution in expanded polystyrene (Figure 10) is not as consistent as in extruded. It is generally more uniform and the highest values may be found at the top side or at the bottom side, whereas the highest values in extruded polystyrene always are found at the bottom side. These differences are more or less expected considering the effects of the mould skin in extruded and the ability to absorb water in expanded polystyrene.
5. COMPUTER MODELLING OF MOISTURE CONTENT

The moisture content and the moisture distribution have been calculated by the computer program mentioned earlier. Boundary conditions and material properties were also chosen as described earlier. For 50 mm extruded polystyrene the result of the calculation is shown in Figure 11 (compare Figure 7).

FIGURE 12. Calculated and measured moisture distribution in 50 mm extruded polystyrene exposed in test surface #25 in Linköping.

FIGURE 13. Calculated (50 mm, density 20 and 50 kg/m$^3$) and measured moisture contents in expanded polystyrene.
FIGURE 14. Calculated moisture distribution in 50 mm expanded polystyrene January 1st after 10 years' exposure.

The agreement between calculated and measured moisture contents is acceptable. The rate of the increase of moisture content seems to be higher in the calculation than in reality.

Also, the calculated moisture distribution agrees fairly well with the measured. Figure 12 shows a comparison for test surface #25 in Linköping, 50 mm extruded polystyrene.

Figure 13 shows calculated moisture contents in expanded polystyrene. The agreement is not very good but the results reflect the great difference between high and low density materials.

The calculated moisture distribution on January 1st after 10 years is indicated in Figure 14 (compare Figure 10).

6. PREDICTION OF THERMAL CONDUCTIVITY OF SOIL INSULATION

In extruded polystyrene, the deterioration of the thermal conductivity is caused by moisture accumulation and changes in the composition of the cell gas (aging).

According to Figure 11, the calculated increase in moisture content for 50 mm insulation may be written

\[ w = 2 + 2.25 \cdot t \]  

(5)
FIGURE 15. Combined effects of age and moisture on thermal conductivity.

FIGURE 16. Estimated thermal conductivity for 50 mm extruded polystyrene compared to measured for 40–60 mm thickness.
where

\[ w = \text{moisture content (kg/m}^3\text{)} \]
\[ t = \text{time (years)} \]

and the effect on the thermal conductivity

\[ \lambda = \lambda_{dry} + 0.0001 \cdot w \] (4)

or

\[ \lambda = \lambda_{dry} + 0.0001 \cdot (2 + 2.25 \cdot t) \] (6)

The effect of aging may be estimated according to Figure 15. The curve is based on information from Dow Chemical. To that effect the effect of moisture is added, and the calculated \( \lambda \) is compared to actual measurements in Figure 16.

In expanded polystyrene there is no aging effect. The moisture effect may be expressed by (see Figure 5)

\[ \lambda = \lambda_{dry} + 0.00013 \cdot w \] (7)

and the increase in moisture content for 50 mm thickness and 50 kg/m\(^3\) density (from Figure 13)

\[ w = 6 \cdot t \]

**FIGURE 17.** Estimated effect of moisture on thermal conductivity for 50 mm, 50 kg/m\(^3\) expanded polystyrene compared to measurements on 60 mm, ~50 kg/m\(^3\) specimens.
which means that

\[ \lambda = \lambda_{dry} + 0.00013 (6 \cdot t) = \lambda_{dry} + 0.00078 \cdot t \]

The effect of moisture as a function of time is compared to measured values in Figure 17.

The comparisons include only a limited number of points but the agreement is good enough to justify a further development of the calculation methods.
### APPENDIX 1

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type of material*</th>
<th>Thickness mm</th>
<th>Density $\bar{\delta}$ kg/m$^3$</th>
<th>Moisture content $\delta^*$ kg/m$^3$</th>
<th>Thermal conductivity W/m · K</th>
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*Type of material: 1 = extruded; 2 = expanded.

** $\delta$, $\mu$ indicates upper and bottom part of the specimen.
## APPENDIX 2 MOISTURE CONTENT IN SOIL INSULATION

### Extruded polystyrene.

<table>
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### Expanded polystyrene.

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BIOGRAPHY

Per Ingvar Sandberg

MOISTURE EFFECTS ON HEAT TRANSFER

Technical report describing the mechanisms by which moisture affects heat transfer and giving the theoretical background for a test method.

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Nomenclature

1. Introduction
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2.4 Total mass transfer
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3 Measurement of thermal conductivity of wet materials
3.1 Generalities
3.2 Derivation of \( \lambda^* \) from measured heat flow
4 Prediction of thermal performances in service conditions
NOMENCLATURE

\[ \begin{align*}
T & = \text{temperature, K} \\
t & = \text{time, s} \\
w & = \text{moisture content mass by volume, kg/m}^3 \\
v & = \text{water vapour concentration, kg/m}^3 \\
g & = \text{density of moisture flow rate, kg/m}^2 \text{ s} \\
\varphi & = \text{density of heat flow, W/m}^2 \\
\lambda^* & = \text{thermal conductivity of wet material, W/m K} \\
h & = \text{specific enthalpy, J/kg} \\
\rho & = \text{density of material, kg/m}^3 \\
C & = \text{heat capacity, J/kg K} \\
L & = \text{latent heat of vaporization, J/kg} \\
d & = \text{thickness, m}
\end{align*} \]

Subscripts

\[ \begin{align*}
\ell & = \text{liquid} \\
v & = \text{vapour} \\
t & = \text{total} \\
m & = \text{measured}
\end{align*} \]
1 INTRODUCTION

The aim of this document is to describe the mechanisms by which moisture affects heat transfer in order to give the theoretical background for a test method providing material properties which allow prediction of thermal performance in presence of moisture.

Although the equations derived here after are as general as possible, examples of use of these equations are given presupposing that measurements would be performed:

- in classic standardized apparatus intended for a stationary method (Guarded Hot Plate or Heat Flow Meter).
- above freezing point.
2 DESCRIPTION OF HEAT AND MASS TRANSFERS

2.1 Qualitative description of mass transfer phenomena in a simple case

Let us consider an homogeneous porous medium with horizontal flat boundaries at constant temperature (fig. 1).

![Diagram](image)

Figure 1

At time $t = 0$, the temperature $T_0$ and the moisture content $\theta_0$ are uniform.

For the sake of simplicity, only vertical unidirectional transfers will be considered. Let us now imagine that at time $t > 0$, the lower boundary temperature is increased to the temperature $T_1 > T_0$.

The difference of temperature applied to the medium will modify the temperature distribution and create a mass transfer in the liquid and the vapour phase.

Those mass transfers result from different mechanisms that we will now describe qualitatively.

2.2 Vapour mass transfer

The temperature increase at the lower boundary induces a vapourization of liquid water close to this boundary and consequently an increase of vapour concentration in this zone. As vapour concentration is lower in cold regions, moisture migrates by a simple diffusion process of water vapour in air, from hot to cold regions.

As it migrates, part of this vapour condensates on the solid matrix of the porous media and also on the existing liquid menisci (fig. 2).
Figure 2

To maintain the thermodynamic equilibrium, condensation at A is followed by evaporation at B.

Vapour therefore migrates towards the cold regions by a succession of "evaporation – condensation – evaporation".

2.3 Liquid mass transfer

The vapour migration leads to a decrease of the water content in the hot regions and therefore to a decrease of capillary pressure, in this zone. This pressure difference induces a liquid phase movement ("suction" effect) in a direction opposite to the vapour flow.

This liquid movement induced by a water content gradient is limited by the capillary pressure increase due to the gradient of temperature which tends to oppose to the liquid migration (fig. 3)
2.4 Total mass transfer

If we note $\varepsilon_v$ and $\varepsilon_l$ the densities of mass flow in vapour and liquid phase, the total mass transfer $\varepsilon_t$ is equal to

$$\varepsilon_t = \varepsilon_v + \varepsilon_l$$  \hspace{1cm} (1)

In a closed system (i.e with a constant moisture content), stationary mass flow is reached when

$$\varepsilon_t = 0 \iff \varepsilon_v = -\varepsilon_l$$  \hspace{1cm} (2)

In other words, stationary mass flow is reached when vapour and liquid transfers are equal and opposite i.e when liquid movement by capillarity is balanced by vapour movement by diffusion.

2.5 Heat transfer equations

As vapour and liquid migrates, they carry their respective enthalpies which leads to an increase of heat transfer.

This heat transport caused by moisture flow is added to the conduction heat transfer described by FOURIER's law giving finally the following expression for the total density of heat flow ($\varphi$)

$$\varphi = -\lambda* \nabla T + (\varepsilon_v h_v + \varepsilon_l h_l)$$  \hspace{1cm} (3)

"CONDUCTION" "BY MOISTURE FLOW"

where $\lambda*$ = thermal conductivity of the wet material - to be explained later

$h_i$ = enthalpy of phase i

$T$ = temperature

The first term in the right-hand part of eq. 3 describes the energy flow caused by a temperature gradient, see fig. 4. It consists of

$\varphi_1$ Conduction in the solid material (1 a) and in the (humid) air in the pores of the material (1 b)

$\varphi_2$ Radiation

$\varphi_3$ Convection in the pores. Note that we assume that convection occurs only locally in the pores and that large-scale convection can be neglected.

$\varphi_4$ Conduction in water bound to the pore walls. The water short-circuits the insulation or acts as parallel resistances which reduces the total thermal resistance.
Evaporation and condensation within a pore or a local area. The moisture moves one way in the vapour phase and then back again in the liquid phase. Note that this is a local process which is caused by temperature differences between the pore walls and takes place even if the moisture gradient is equal to zero. It must not be confused with effects of a large-scale moisture flow or redistribution of the moisture in the material.

\[ \Phi = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 + \Phi_5 = -\lambda^* \nabla T \] (4)

By definition, we will consider \( \lambda^* \) as the thermal conductivity of the wet material – even though it includes other terms than pure conduction.

From this definition, it follows that \( \lambda^* \) can be assumed as a "true material property" only function of moisture content and temperature \( (\lambda^*(w, T)) \). Moisture content \( w \) is defined as the mass of evaporable water divided by volume of material. It is expressed in \( \text{kg/m}^3 \).

It is important to distinguish carefully between moisture effects in service and those in laboratory conditions (during a test).

Simulation of all the complex moisture effects in service conditions during a test is unrealistic and unnecessary. Effects of moisture flow and phase changes depend entirely on the occurrence and magnitude of moisture transfer in the material. If these effects are allowed during the test, it is difficult to assess a material or building component property. There will also be a great risk that these types of effects are overestimated. The main purpose of the test must therefore be to determine \( \lambda^* \) (see next section) which will in turn allow prediction of the thermal performances in service conditions (see section 4).
3 MEASUREMENT OF THERMAL CONDUCTIVITY OF WET MATERIALS

3.1 Generalities

Determination of the thermal conductivity of a material always requires temperature gradients. Normally these will bring about a redistribution of the moisture in the material, which leads to two types of problems:

1. Redistribution of the moisture means that the test is carried out on a material with a changing and unknown moisture distribution.

2. Redistribution of the moisture simultaneously induces heat transfer by moisture flow and phase changes. These effects are unlikely to be of exactly the same extent as the moisture effects in the material in service conditions, which is why these effects should be negligible or well known during the test.

During a test of a wet material the heat flow measured at the surfaces will vary essentially as shown in fig. 5.

An initial phase A, with more or less constant heat flow with conduction, effects of moisture flow and phase changes involved; a transition phase B, and finally a phase, C, with moisture equilibrium.

Existence of a phase A requires moisture content above the hygroscopic range so that the relative humidity in the material's pores remains 100% even if the moisture content is changing. In some instances phase A may not be seen.

![Figure 5: Heat flow during a thermal conductivity test.](image-url)
Let us study the energy balance in a thin layer in the material

![Energy balance diagram](image)

**Figure 6** Energy balance of a thin layer in the material.

\[
- \frac{\partial w}{\partial x} \cdot dx = \rho C \frac{\partial T}{\partial t} \cdot dx + \frac{\partial w_v}{\partial t} \cdot h_v \cdot dx + \frac{\partial w_l}{\partial t} \cdot h_l \cdot dx \quad (5)
\]

where
- \(\varphi\) = density of heat flow, W/m²
- \(\rho\) = density of the material, kg/m³
- \(C\) = heat capacity of the material, J/kg K
- \(h_v, h_l\) = specific enthalpy of vapour and liquid resp., J/kg

Equation 5 describes that inflow – outflow = accumulation by temperature and moisture.

The rate of change of moisture content is for the liquid and vapour phases respectively:

\[
\frac{\partial w_l}{\partial t} = \frac{\partial \varphi}{\partial x} + \frac{\partial w_{v\rightarrow l}}{\partial t} \quad (6)
\]

\[
\frac{\partial w_v}{\partial t} = - \frac{\partial \varphi}{\partial x} - \frac{\partial w_{v\rightarrow l}}{\partial t} \quad (7)
\]

where \(\frac{\partial w_{v\rightarrow l}}{\partial t}\) = rate of transfer (phase change) from vapour to liquid.
According to our assumptions, we have thermally stationary conditions which means that

\[
\frac{\partial T}{\partial t} = 0
\]  

(8)

Then, using equations (6) and (7), we get

\[
- \frac{\partial \phi}{\partial x} \cdot dx = h_v \cdot dx \left( \frac{\partial g_v}{\partial x} - \frac{\partial w_{v\rightarrow g}}{\partial t} \right) + h_l \cdot dx \left( \frac{\partial g_l}{\partial x} + \frac{\partial w_{v\rightarrow g}}{\partial t} \right)
\]

(9)

\[
\frac{\partial \phi}{\partial x} = h_v \cdot \frac{\partial g_v}{\partial x} - h_l \cdot \frac{\partial g_l}{\partial x} + (h_v - h_l) \frac{\partial w_{v\rightarrow g}}{\partial t}
\]

or

\[
\frac{\partial \phi}{\partial x} = h_v \cdot \frac{\partial g_v}{\partial x} - h_l \cdot \frac{\partial g_l}{\partial x} + L \cdot \frac{\partial w_{v\rightarrow g}}{\partial t}
\]

(10)

(11)

where \( L \) = latent heat of vaporization, \( J/kg \) \( L = h_v - h_l \).

At the surface of the material in contact with the measuring apparatus \((x = 0 \text{ and } x = d)\):

\[
\frac{\partial g_g}{\partial x} \cdot dx = 0
\]

(12)

\[
\frac{\partial g_v}{\partial x} \cdot dx = 0
\]

(13)

\[
\phi + \frac{\partial \phi}{\partial x} \cdot dx = \varphi_m
\]

(14)

where \( \varphi_m \) = heat flow, measured in the apparatus, \( W/m^2 \).

Using eq (12), (13) and (14), we obtain

\[
\varphi_m - \phi = -h_v \cdot g_v + h_l \cdot g_l + L \frac{\partial w_{v\rightarrow g}}{\partial t} \cdot dx
\]

(15)

A condition for the existence of a phase A is that the vapour concentration in the material does not change with time

\[
\frac{\partial w_v}{\partial t} = 0
\]

(16)

which means that (from eq. 7)

\[
- \frac{\partial g_v}{\partial x} = \frac{\partial w_{v\rightarrow g}}{\partial t}
\]

(17)

1320b
or expressed in words: The vapour is transformed into liquid as soon as it reaches the surface.

The heat flow, $\varphi$, expressed in terms of temperature gradient and moisture flow is (see eq. (3)):

$$\varphi = -\lambda^* \frac{\partial T}{\partial x} - \varepsilon_v h_v$$

(18)

Equation (15) may then be written, using eq. (17), (13) and (18):

$$\varphi_m = -\lambda^* \frac{\partial T}{\partial x} + \varepsilon_v \cdot L$$

(19)

3.2 Derivation of $\lambda^*$ from measured heat flow

We need to relate the measured heat flow to the property we want to measure: $\lambda^*(\omega)$. We can derive from energy balances such relationships during the equilibrium phases (A) and (C).

3.2.1 Phase (A)

Measurements during phase A requires a uniform or almost uniform moisture distribution allowing us to consider the temperature distribution linear in the specimen. Otherwise $\varphi T$ at the surfaces has to be determined by measurements or estimations, compare 3.2.2.1.

From 3.1 we have

$$\varphi_m = \lambda^* \varphi T + \varepsilon_v \cdot L$$

(20)

To derive $\lambda^*$ from the measured heat flow, we must

- either evaluate $\varepsilon_v$
- or have conditions for which the term $\varepsilon_v \cdot L$ is negligible

3.2.1.1 Evaluation of $\varepsilon_v$

From Fick's law we have in phase (A)

$$\varepsilon_v = -\delta_v \cdot \text{grad} v_s$$

(21)

where $\delta_v$ = the moisture permeability of the material

$v_s$ = saturation vapour concentration

$\delta_v$ can be measured using ISO.... allowing the derivation of $\varepsilon_v$ from eq. (21) and finally $\lambda^*$ from eq (20).
3.2.1.2 Cases for which \( \delta \gamma \cdot L \) is small

A case of interest is the case for which

\[
L \, \delta \gamma \text{grad } v_s \ll \lambda^* \text{grad } T
\]

For instance at 10 °C, with

\[
\text{grad } v_s = \frac{\partial v}{\partial T}, \quad \text{grad } T = 0.6 \cdot 10^{-3} \cdot \text{grad } T
\]

and supposing that the requirement for neglecting \( \delta \gamma \cdot L \) is that \( \delta \gamma \cdot L \) is less than 3 \% of \( \lambda^* \text{grad } T \) it gives

\[
L \cdot \delta \gamma \cdot 0.6 \cdot 10^{-3} \cdot \text{grad } T < 0.03 \cdot \lambda^* \text{grad } T
\]

and finally

\[
\delta \gamma < 200 \cdot 10^{-7} \cdot \lambda^* = \delta_{cr}
\]

Note that this condition is independent of "grad T"! From this follows that working at low temperature gradients is not automatically a solution for obtaining a negligible \( \delta \gamma \cdot L \).

Table 1 shows values of \( \delta_{cr} \) calculated for a number of building materials.

**Table 1 \( \lambda^* \), \( \delta \gamma \) and \( \delta_{cr} \) for building materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>( \lambda^* ) W/(m.K)</th>
<th>( \delta_{cr} ) ( \times 10^{-7} )m²/s</th>
<th>( \delta \gamma ) ( \times 10^{-7} )m²/s</th>
<th>( \delta \gamma \cdot L ) may be neglected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polystyrene</td>
<td>0.035</td>
<td>7</td>
<td>5–10</td>
<td>yes/no</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.035</td>
<td>7</td>
<td>100–200</td>
<td>no</td>
</tr>
<tr>
<td>Aerated concrete</td>
<td>0.14</td>
<td>28</td>
<td>30–60</td>
<td>no?</td>
</tr>
<tr>
<td>Ordinary concrete</td>
<td>1.7</td>
<td>340</td>
<td>3–7</td>
<td>yes</td>
</tr>
<tr>
<td>Brick</td>
<td>0.60</td>
<td>120</td>
<td>30–50</td>
<td>yes</td>
</tr>
<tr>
<td>Wood</td>
<td>0.14</td>
<td>28</td>
<td>2–4</td>
<td>yes</td>
</tr>
<tr>
<td>Wood–wool slab</td>
<td>0.08</td>
<td>16</td>
<td>50–90</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 1 shows that in many cases, \( \lambda^* \) can be readily derived from the measurement of heat flow during phase (A) using

\[
\varphi_m = \lambda^* \frac{\partial T}{\partial x}
\]
3.2.2 Phase (C)

In phase (C) both heat and mass flows are stationary, meaning that

\[
\frac{dT}{dt} = \frac{dw}{dt} = \frac{dw_q}{dt} = 0
\]

\[g_v + g_l = 0\]  \(27\)

Eq. (19) is still valid

\[\varphi_m = -\lambda^* \frac{dT}{dx} + g_v \cdot L\]  \(19\)

In practice liquid flow will generally be limited to a portion of the sample creating a zone which must be handled differently from the zone in which we don't have any liquid flow. To illustrate this we can make the following sketch.

![Diagram of Zones](image)

Figure 7 Phase (C), Zone 1 and 2, without and with liquid flow.

To solve the equations for \(\lambda^*\), we have to know \(x_2\) and \(g_v\). In theory, zone 2 is the portion of the material where the moisture content is above the critical moisture content (\(w_{cr}\)). We define \(w_{cr}\) as the moisture content below which no moisture transfer in liquid phase takes place. The determination of \(\lambda^*\) therefore requires measurement of the moisture distribution. Two cases are possible

- moisture content never exceeds \(w_{cr}\)
- moisture content exceeds \(w_{cr}\) in a zone of thickness \(x_2\)

3.2.2.1 No liquid movement \((w < w_{cr})\)

In this case we end up with

\[\varphi_m = \lambda^* VT\]  \(28\)
Having in mind that \( \lambda^* \) is a function of \( w \) and that in phase (C), \( w \) is a function of \( x \), we can integrate the last equation only if we know both the moisture and temperature distributions.

If only moisture distribution can be measured, then approximate solutions are possible such as the following.

If we consider the sample as \( n \) slices of equal thickness \( e \) and of known and uniform moisture content \( w_i \) (determined for example by cutting and weighing), and assuming (which appears to be true in most cases) that we have a linear variation of \( \lambda^* \) with moisture content \( w \) and negligible variation of \( \lambda^* \) with temperature

\[
\lambda^* (w) = a \, w_i + \lambda^* o
\]  
(29)

with

\[
a = \text{constant}
\]

\[
\lambda^* o = \text{thermal conductivity of dry sample}
\]

we can write the total resistance of the sample as the sum of individual resistances and then

\[
\varphi_m = \frac{T_{\text{hot}} - T_{\text{cold}}}{e \sum \frac{1}{i \, a \, w_i + \lambda^*} \, \lambda^*}
\]  
(30)

The only unknown of this last equation is \( a \) and it can therefore be used to determine the variation of \( \lambda^* \) with moisture content.

3.2.2.2 Liquid movement (\( w \geq w_{cr} \) in zone 2)

In zone 1, we have no liquid movement and

\[\varphi_m = \lambda^* \, VT\]  
(31)

We are back to case 3.2.2.1 which has been treated previously.

In zone 2, we have

\[\varphi = \lambda^* \, VT + e_v \cdot L\]  
(19)

It is necessary to know the temperature distribution, at least the temperature at the border between zone 1 and 2.

We are then back to case 3.2.1 treated previously.
PREDICTION OF THERMAL PERFORMANCES IN SERVICE CONDITIONS

To predict thermal performances in service conditions, we need equations describing heat and mass transfers. The derivation of these equations is beyond the scope of this document and can be found for instance in [1] (see also bibliography).

We end up with a system of 2 equations describing conservation of mass and energy. This system is valid assuming a certain number of hypothesis among which:

- The solid matrix of the porous medium is homogeneous, isotropic and non deformable
- Absence of chemical reactions and of interaction between phases
- The total pressure of the gaseous phase is constant and uniform
- Gaseous phase obeys the laws of ideal gases
- The work of external forces of diffusion and compression and kinetic energy are negligible.

We so obtain:

\[
\frac{\partial w}{\partial t} = - \frac{\partial \xi}{\partial x} \tag{32}
\]

\[- \rho \cdot c^* \frac{\partial \xi}{\partial t} = \lambda^* \frac{\partial^2 \rho}{\partial x^2} + \xi_v \frac{\partial h_v}{\partial x} + \xi_l \frac{\partial h_l}{\partial x} + L \frac{\partial \xi_v}{\partial x} \tag{33}
\]

where

- \( w \) = moisture content \( \text{kg/m}^3 \)
- \( \xi \) = density of total moisture flow rate \( \text{kg/m}^2\text{s} \)
- \( \xi_v \) = density of total vapour flow rate \( \text{kg/m}^2\text{s} \)
- \( \xi_l \) = density of total liquid flow rate \( \text{kg/m}^2\text{s} \)
- \( T \) = temperature \( \text{K} \)
- \( h_v, l \) = respectively vapour and liquid specific enthalpy \( \text{J/kg} \)
- \( L \) = latent heat of vapourization \( \text{J/kg} \)
- \( \lambda^* \) = thermal conductivity of wet material (see definition in § 2) \( \text{W/m K} \)
- \( c^* \) = heat capacity of wet material \( \text{J/kg K} \)
The meaning of the different terms in the right hand side of the energy conservation equation is as follows:

1. conduction term
2. heat transfer due to mass flows
3. phase changes

It shows again that the property we want to measure to characterize the material is $\lambda^*$, while effects (2) and (3) may be variable depending on conditions of use, the sum of the 3 terms characterizing the material in a given system.

Knowing $\gamma_y$ and $\gamma_l$, one can solve the set of equations to find the evolution of temperature and moisture distributions with time.

Then knowing surface temperature and surface coefficient of heat transfer ($\alpha$), the heat flow on the surface can be found from

$$\varphi = \alpha (T_{air} - T_{surface})$$  \hspace{1cm} (34)

References

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PI/0012  Contribution to ASTM-symposium, Dec 1987

DETERIORATION OF THERMAL INSULATION PROPERTIES
OF EXTRUDED POLYSTYRENE.

CLASSIFICATION AND QUALITY CONTROL SYSTEM IN SWEDEN.

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ABSTRACT

In the process of assessing design values for thermal conductivity of insulating materials, knowledge of the time-dependent deterioration of the insulation performance is important. Extruded polystyrene is affected by changes in the composition of the gas mixture in the cells (normally referred to as "ageing") and in some applications by moisture accumulation, both mechanisms resulting in a higher thermal conductivity.

In the Swedish quality control system the determination of thermal conductivity is carried out 90 days after manufacture. Part of the ageing has then already taken place and the rest of the ageing during the life span of a building is taken care of by a specified addition ($\Delta \lambda_a$) to the laboratory value in the assessment of the design value. The more of the ageing that takes place before the determination of the thermal conductivity the more accurate the design value will be. Different ways of accelerating the ageing have therefore been discussed and the paper describes a method of acceleration by cutting the specimens into thin slices. It is shown that, by making use of this method, no extra addition allowing for the ageing under service conditions is needed, i.e. $\Delta \lambda_a = 0$.

The paper also deals with moisture accumulation in soil insulation and inverted roofs. The moisture corrections ($\Delta \lambda_m$) in the classification system are given. A method for acceleration of the moisture pick-up and correlation to in situ measurements as well as a theoretical model for
predicting moisture accumulation is described. Finally effects of moisture on thermal conductivity is discussed.

**KEYWORDS:** Thermal conductivity, ageing, moisture, extruded polystyrene, classification, quality control

**BACKGROUND**

The current Swedish system for classification of thermal insulation materials was introduced in the middle of the 60's. Since then a far-reaching development has taken place but the rules have not yet been adapted to these changes.

A new classification system has therefore been worked out with the aim to guarantee impartial rules for all insulation materials. The new system will probably be adopted by the end of 1987. This paper describes how the new system will handle the adverse effects of moisture and change in gas composition on the thermal conductivity in extruded polystyrene (XPS).

The thermal conductivity, applicable in practice (design value), is in principle calculated according to:

\[ \lambda_p = \lambda_{10} + \Delta \lambda_s + \Delta \lambda_m + \Delta \lambda_1 + \Delta \lambda_a \]

where

\[ \lambda_p \] = practical thermal conductivity
\[ \lambda_{10} \] = laboratory measurement on dry material at 10°C mean temperature
\[ \Delta \lambda_s \] = correction for dispersion in the manufacturing process
\[ \Delta \lambda_m \] = correction for moisture
\[ \Delta \lambda_1 \] = correction for air movements in the material
\[ \Delta \lambda_a \] = correction for ageing

In addition to these material corrections, there are also corrections of the thermal transmittance of building elements (\( \Delta U \)) for environmental factors and workmanship.

**CHANGE OF GAS COMPOSITION IN THE CELLS**

**Assessment of \( \Delta \lambda_a \) in the classification system.**

After manufacture, extruded polystyrene contains a certain amount of chlorofluorocarbon (denoted CFC) in the cells. CFC has a lower thermal conductivity (\( \lambda \)) than air and the presence of CFC is favourable for the material's \( \lambda \)-value.
Gradually, however, air diffuses into the material and CFC diffuses slowly out of the material. The composition of the gas mixture will change and the thermal conductivity will rise. This process is usually referred to as "ageing".

A difficult problem in a classification system is to predict the deterioration of the thermal conductivity during the service life of the building. To be able to do that it is necessary to know the duration and exposure conditions during the period between manufacture and the determination of $\lambda_{10}$. There is obviously a relation between what has happened before the test of $\lambda_{10}$ and the further deterioration of the thermal conductivity, $\Delta\lambda_a'$, see fig 1. This fact has in some cases been overlooked and classification systems have been operating with identical values of $\Delta\lambda_a$ but different rules for the conditioning of test specimens.

As regards the length of the period between manufacture and test of $\lambda_{10}$, there are two conflicting wishes. On the one hand, measurements should be made as soon as possible after manufacture so that indications regarding defects in manufacture may be obtained; on the other hand enough time should be allowed for the major part of the ageing to have taken place, so that the extrapolated value $\Delta\lambda_a$ is sufficiently small to be reliable. Both alternatives should presumably be applied, the internal control of the manufacturer being carried out on fresh material, and the supervisory control of the testing institute being applied to aged material.

**Acceleration methods**

The wish to achieve as much ageing as possible during a short period of time makes one considering possibilities to accelerate the ageing process. An accelerated laboratory method may be an acceptable solution provided that one

- is able to establish an acceleration factor which correlates time in laboratory with time in service
- ensures that the acceleration does not result in effects that would not be found in practice

When solving diffusion problems, we often make use of a non-dimensional "time", the Fourier number:

$$Fo = (D \cdot t)/d^2$$

where $D$ = gas diffusivity, $m^2/s$
$t$ = time, $s$
$d$ = thickness of material, $m$

The gas diffusivity may be concentration-dependent.
The value of the Fourier number indicates how far a diffusion process has advanced. An acceleration can consequently be achieved by increasing $D$ or by decreasing $d$.

A rise in temperature will cause an increased gas diffusivity and this fact is used in many countries to accelerate the ageing. Unfortunately the different gases involved, react differently to an increased temperature. The diffusivity and consequently the magnitude of acceleration for the different diffusion processes will therefore vary and the gas composition achieved will never be equal to the composition during natural ageing. The second condition for a sound acceleration method as mentioned above is not fulfilled.

In Sweden we have investigated the technique of accelerating the ageing by cutting the material to small thicknesses. This should be a powerful means of acceleration since the rate of ageing should be proportional to $1/d^2$; compare the expression for $F_0$ above.

Fig 2 shows an example of thermal conductivity vs time for XPS specimens, which have been stored in laboratory in three thicknesses: 10, 30 and 50 mm. The 50 mm slab had mould skin on both sides and the other two no skin. If the time scale for the 30 and 50 mm materials are recalculated according to

$$t_0 = t \cdot (0.01/d)^2$$

where $t_0 =$ equivalent time
$t =$ (real) time (= time for the 10 mm material)
$d =$ thickness of material (m)

all the data points should, according to theory, fall on one curve. This is almost true, compare fig 3.

Experience has shown that the mould skin has the effect of retarding the diffusion and roughly corresponds to 0.01 m material. The thickness of the 50 mm slab was consequently set to 0.07 m in the formula above.

The acceleration factor can be calculated according to

$\text{acceleration factor} = (d_{\text{service}}/d_{\text{lab}})^2$

where $d_{\text{service}} =$ thickness under service conditions
$d_{\text{lab}} =$ thickness during laboratory conditioning

There are no effects of the acceleration we can think of, deviating from the natural behaviour, except that a layer of cells at each surface is destroyed by slicing the sample. The influence of this is probably small.
Conditioning rules and $\Delta \lambda_a$

The rules laid down in the Swedish classification system prescribe conditioning of the material at 10 mm thickness for 91 days in an atmosphere of 20°C and 50% relative humidity before determining $\lambda_{10}$. By conditioning the material according to these rules, the thermal conductivity attained is the same as that of 100 mm thick sheets after 25 years and no correction for ageing is needed.

For sheets less than 100 mm thick, the method gives too low values of the thermal conductivity, while for sheets more than 100 mm thick the value measured is too high. The calculated deviation from correct value (25-year value) is given in fig 4 according to Isberg [1]. If an error of 5% can be allowed, the method can be applied to extruded poly-styrene of 50-200 mm thickness. If the mould skin is retained on the sheets in practice, the method can be applied down to 30 mm thick sheets. This means that it is applicable to all thicknesses encountered in practice and no correction for ageing is needed, $\Delta \lambda_a = 0$.

For products with other surface layers than mould skin, special rules depending on the diffusion resistance of the surface layer, are applicable.

The principle of acceleration by cutting to thin thicknesses is also studied in an ISO working group on "Effects of Ageing on Thermal Properties" and a method is under preparation.

Moisture Accumulation

$\Delta \lambda_m$ in the classification system

Moisture accumulation in the material will cause an increase of the thermal conductivity. In the proposed classification system, the moisture correction, $\Delta \lambda_m$, depends on the field of application for the material. Six different moisture environments are defined:

1. Internal use; in equilibrium with 30-70 % relative humidity (RH)
2. External use, protected from precipitation; in equilibrium with with 70-98 % RH
3. External use, unprotected; periodically in equilibrium with 100 % RH
4. External insulation on building elements below ground level, e.g. external basement insulation
5. Soil insulation, ground on both sides
6. Inverted roofs
For extruded polystyrene in categories (1) - (4), $\Delta \lambda_m = 0$. In category (5) $\Delta \lambda_m = 0.004 \text{ W/mK}$ and (6) $\Delta \lambda_m = 0.001 - 0.008 \text{ W/mK}$ depending on the construction. For inverted roofs there is - in addition to a $\Delta \lambda_m$ - also a correction of the thermal transmittance $\Delta U = 0.00 - 0.04 \text{ W/m}^2\text{K}$ to allow for the effects of rain water movements in the joints and between insulation and roofing membrane. Lower values of $\Delta \lambda_m$, than these nominal values of the corrections, may be accepted if the manufacturer can show that the material performs better than what is settled in the rules.

Both laboratory methods, in which the natural moisture accumulation is accelerated, and calculation methods, simulating the natural behaviour, can be used to predict moisture accumulation under service conditions and form a basis for the assessment of $\Delta \lambda_m$.

**Accelerated moisture accumulation**

A more detailed analysis of moisture transfer in extruded polystyrene shows that an increase in temperature level and temperature gradient would accelerate the moisture accumulation. This is achieved in a method, originally developed by the Norweigan Road Research Laboratory. In this apparatus the material is exposed to an atmosphere of $+60^\circ\text{C}$ and 100 % RH on the warm and $+10^\circ\text{C}$ and 100 % RH on the cold side. The method is primarily suitable for acceleration of the moisture accumulation in soil insulation (category 5), but may also yield valuable knowledge for the inverted roof application (category 6).

Results from laboratory tests on 50 mm XPS show a moisture accumulation rate in the laboratory apparatus which is 60-70 times the value found in specimens which have been exposed to natural conditions in Scandinavian test roads. For more details see Sandberg [2]. The acceleration factor 60-70 applies to the mean moisture content. It may be important to point out that normally there is a considerable difference in moisture distribution between laboratory and service conditions. In this respect the acceleration method is not quite reliable and the discrepancy may have to be taken into consideration when the moisture effects are evaluated.

**Calculation of moisture accumulation**

A computer program solving the non-stationary temperature and moisture field has been developed at the National Testing Institute. The moisture content is calculated by
\frac{\partial w}{\partial t} = \delta \frac{\partial}{\partial x} (\delta \cdot \partial v / \partial x)

where \( w \) = moisture content, kg/m\(^3\)
\( \delta \) = water vapour permeability, m\(^2\)/s
\( t \) = time, s
\( v \) = water vapour content (vapour concentration), kg/m\(^3\)

In this equation it is assumed that all moisture transfer is due to a gradient in vapour content. This is a reasonable simplification for XPS considering that the moisture transfer ability in liquid phase is poor.

The material properties needed for the calculation are: thermal conductivity, specific heat capacity and vapour permeability as functions of moisture content, and also the relationship between moisture content and relative humidity in the material (hygroscopic sorption curve). For products with mould skin, the skin’s vapour resistance has to be known. Results from computer modelling show a reasonably good agreement between calculated and measured moisture contents and distributions in soil insulation, see fig 5. The scatter in the measured values depends probably primarily on variations in material properties (e.g. vapour resistance of mould skin) and different relative humidities in the ground at different locations.

An example from a calculation of an inverted roof is given in fig 6. The results, showing that the lower slab has the highest moisture content, are confirmed by field measurements in Sweden and Norway, see for example Petersson [3], Nilsson [4] and NBI [5]. The results also indicate the crucial effect of a water film between the upper and lower slab. Results from field measurements are essentially in agreement with the calculated alternative with a water film between the slabs.

**Moisture effects on heat transfer**

The moisture content itself is seldom of primary interest, no matter how it is estimated: by experience, by laboratory acceleration or by computer modelling. More important are the effects of moisture on the material’s performance; in this paper the effects on the heat transfer.

Generally there are two effects of moisture on heat transfer:

- one which is related to the presence of moisture in the material, and
- one which is related to moisture movements and phase changes.
The latter effect can normally be neglected in XPS since the material is fairly impermeable and the moisture transfer slow. Note, however, the effect mentioned above of moving rain water in inverted roofs, which must be considered.

The effect of moisture in the materials pores may be regarded as an addition to the thermal conductivity of the dry material. This addition is normally assumed to be a linear function of the moisture content.

\[ \Delta \lambda_m = K \cdot w \]

where \( K \) = constant

\( w \) = moisture content, kg/m\(^3\)

Typical values of \( K \) found in literature are ~0.0001 for XPS. Our own test results are the same although there is some scattering.

The value of \( K \) is only slightly dependent on the moisture distribution. In most cases when the thermal conductivity is determined, only the mean moisture content and not the distribution is known. This is in many cases acceptable. A material with a distribution where, for example, all the moisture is concentrated to 25% of the material's thickness, has a thermal resistance which is only about 5% higher than the same material with an even moisture distribution.

REFERENCES


Fig 1. Outline of relationship thermal conductivity vs time during laboratory conditioning and service life

Fig 2. Thermal conductivity vs time in laboratory conditions for three thicknesses of XPS
Fig 3. Thermal conductivity vs time in laboratory conditions for three thicknesses of XPS. The time scale for each thickness is recalculated to "equivalent time", see text.

Fig 4. Calculated deviation from the correct 25 year value if tests for all product thicknesses are made on 10 mm thick test specimens, stored for 3 months.
Fig 5. Mean moisture content vs age for specimens of XPS exposed to natural ageing in Scandinavian roads. The straight line indicates results from computer calculations.

Fig 6. Calculated moisture contents in the upper and lower slab of XPS on an inverted roof. Two alternatives: with and without water film between the slabs.
THERMAL TRANSFERENCE MEASUREMENTS ON CULVERT PIPES

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SUMMARY

This paper presents the results of a comparative study of available test methods for steady state thermal transfer properties of horizontal culvert pipes. The results of a theoretical study of the heat transfer in the systems are discussed. An alternative test method suitable for SP's type of testing work is formulated based on these results.

The method now under development has considerable advantages regarding practical aspects and the technique of measurement. The apparatus is described at the current stage of development, as well as some test experience. Conclusively the future test program is discussed.

1 INTRODUCTION

Up to now heat loss estimations and rentability calculations of district heating systems mainly concerned the installations used by the energy producer and the individual consumer. Pipe heat loss measurements are limited to an overall post-installation thermography of the network. The heat loss per meter of pipe (expressed as thermal transference (T), W/mK) is however of as great an importance as the rentability of the installations involved.

On the other hand, there do exist Swedish and international regulations co-ordinating the quality control of culvert pipes. A specific, practical test method for the steady state thermal transfer properties of horizontal culvert pipes is not described, however. This physical property is only related to the DIN 52613 standard. DIN 52613 may be useful regarding pipe insulation thermal properties but is certainly not the optimal test method for culvert pipes - as will be shown below.
RELEVANT STANDARDS

There exist a number of standards or descriptions concerning the steady state heat transfer properties of pipe insulation. These principles are most applicable to the case of culvert pipes. The relevant standards are:

ASTM C335-79, describing a calibrated or calculated end apparatus and a guarded end apparatus.
DIN 52613, describing a guarded end apparatus and a calculated end apparatus (according to van Rinsum's work at the beginning of this century).
NORDTEST NT VVS 014, describing a guarded end apparatus. An ISO-standard is in preparation (ISO/DP 8497).

The result is expressed as a $T$-value in ASTM and NT. DIN expresses the results as a $\lambda$-value, which is less relevant when concerning culvert pipes.

EXISTING APPARATUS

The standards mentioned resulted in three different types of test methods.

Germany: a literal application of the DIN 52613 principles results in a calculated end apparatus (CEA), figure 3a. A combination of DIN 52613 and the ASTM guarded end alternative results in a hybrid guarded end apparatus (HEA), figure 3b.

Sweden: at Chalmer's Technical University (CTH), a completely guarded end apparatus (GEA) has been developed recently, figure 3c.

These apparatus all have disadvantages. Some concern purely practical aspects, others concern the technique of measurement and the end cap correction.

The GEA fulfils the requirements of a purely radial flow through the metering area, but a lot of preparatory work is involved. The culvert pipe is crosscut, the guard sections are prepared consisting of two parts each, thermopiles are installed, the different sections are glued to one another, the guard areas are separated from the metering area, the heating pipe is installed and centred. This is hardly acceptable from the economical point of view for a testing institute such as SP.

The HEA requires the same amount of preparatory work. Moreover, from the point of view of the technique of measurement the way of controlling the balance between guard and metering section is rather ambiguous. This makes it necessary to correct the results because the imbalance between the heat pipe's metering and guard section is not known.
Figure 3a, b, c: The principles of three test methods for the thermal transfer properties of culvert pipes: (a) calculated end apparatus (CEA); (b) hybrid end apparatus (HEA); (c) guarded end apparatus (GEA).

The CEA is purer in its kind than the HEA. Less preparatory work is involved, but long specimens (up to 3 m) are used. The handling of the heating pipe becomes difficult. The correction used assumes that there only is a minimal gap between the steel pipe and the heating pipe thus, demanding different heating pipes for each specimen diameter. Moreover, the correction as described in DIN 52613 might be criticized from the purely theoretical point of view for short specimens.
THEORETICAL ANALYSIS

In order to find a test method acceptable by SP from the point of view of specimen preparation and technique of measurement, the problem was tackled theoretically. Conduction, convection and radiation were studied separately for a culvert.

Conduction was studied using a finite element method program (FEMP).
Radiative heat transfer was studied using a simplified resistance network including end caps, heating pipe, an annular element of the culvert (width dx), remaining part of the culvert. The model included one dimensional conduction through the culvert pipe.
The study of convective heat transfer dealt only with literature on cylindrical systems.

Because of the complexity of heat transfer in the system discussed, mainly qualitative conclusions were drawn:

1. The lateral flow in the steel pipe causes a temperature drop towards the end caps which is concentrated for 90 to 95% in a 0.3 m area near the caps. This is independent of the ratio between the culvert's inner diameter and the heating pipe's diameter (d2/d1). The leakage through the caps (i.e. as percentage of the radial flow through the specimen) increases however proportionally to d2.

2. The convective heat transfer from the heating pipe to the culvert's steel pipe is proportional to d2/d1. The less d2, the less important the convection. The convective heat transfer is only slightly dependent on the temperature difference between air and steel pipe. Its effect on the temperature drop near the caps is minor. More important is to avoid any leakage between the metering area and the guard areas.

3. Conductive heat transfer in the air between the heating pipe and culvert's steel pipe increases the temperature drop on the steel pipe.

4. Radiation from the heating pipe reduces the temperature drop. This effect is proportional to d2/d1 and also strongly depends on the caps' temperature if they are black bodies (ε=1). If the caps are highly reflective (ε=0) the effect is independent of d2/d1.

5. The geometric form of the caps, apart from the thickness, is not important.

6. The lower the ratio between the caps' λ-value and the λ-value of the culvert's insulation the less the temperature drop.

7. A high end cap temperature (forced) reduces the temperature drop or even changes its sign. This is also achieved when the heating pipe perforates the caps partially or completely.
(8) The temperature drop is reduced if the steel pipe is not in contact with the caps; cross cutting the steel pipe has the same effect and concentrates the temperature drop in the outer (guard) part.

5 CONCLUSIONS AND FUTURE RESEARCH

Different systems may be proposed based on the above considerations: the GEA as developed at CTH, an apparatus with a non-cross cut specimen and heating pipe with double guard sections. More interesting are the alternatives without heating pipe \(\frac{d2}{dl} = \text{minimal} = 1.0\). If, moreover, the physical guard sections are eliminated, the specimen preparation is reduced to a minimum. The following principles were chosen:

(1) The culvert's steel pipe becomes the heating pipe.
(2) High density PUR caps are used, the current is fed at the caps using brass shoes which are in perfect contact with the steel pipe; a resistance wire on the shoes is used to compensate for end losses.
(3) The power is controlled by the inside surface temperature; the end cap power by the temperature difference between pipe middle and caps.
(4) The current is measured at the entrance; the voltage is measured between two (or more) points; the distance between these points defines the specimen's length.

Up to now the method has been developed using a Ø114 culvert pipe. The tests showed excellent possibilities of controlling the inside surface temperature (110 °C) and the temperature drop towards the caps (approximately 0.1 °C).

Next stage in the development includes testing on larger diameters. A detailed error analysis will be made in order to make a more direct comparison between the GEA and DIN 52613. Conclusively comparative measurements will be made.

ACKNOWLEDGEMENTS

The author is very grateful to Sven Bohlin for his past, present and future help during the development of the test method.

REFERENCES

Staelens, P. A test method for steady state heat transfer properties of horizontal culverts. SP report to be published (with complete references).
HOT-BOX MEASUREMENTS - CURRENT STATUS

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SUMMARY

Both in Sweden and abroad standards regulate the Hot Box (HB) measurement conditions and discuss the consequent accuracy. It is shown that SP's Guarded Hot Bot (GHB) fulfills Swedish Standard (SS) and ISO proposal (ISO/DP) requirements. The overall accuracy is estimated for two high thermal resistance specimens. It is instanced that some of the requirements may be difficult to fulfil. The causes are discussed. Conclusively SP's R&D program is presented.

1 INTRODUCTION

The HB method is used to determine the thermal resistance of building components. The primary purpose is to measure the conductive heat transfer properties of the specimen which is usually vertically installed. Secondary purposes can be to study air movements cavities and their effect on the thermal resistance, the risk of surface condensation etc.

Two types of HB are frequently used:  
The guarded HB (GHB) using a metering chamber in the indoor climate chamber, thus creating a guard zone between the metering area and the edges of the indoor climate chamber.  
The calibrated HB (CHB) without guard zone; the CHB has therefore to be calibrated for the losses towards the laboratory. This has to be done for the complete range of relevant thermal resistances.

Relevant standards and regulations are:  
SS 02 42 12 (corresponding with NT Build 119, DS 1121 in Denmark and NS 3161 in Norway): specifies HB measurements on opaque specimens.  
SS 02 42 13 (corresponding with NT Build 301): concerns windows.  
ISO/DP 8990 discusses HB measurements on opaque specimens.  
An addendum to this ISO proposal discussing a more detailed error analysis has recently been prepared as well.
The documents named above describe the use of the GHB and CHB in a most general way. The relevant problems concerning the technique of measurement are discussed equally generally and error limits are given for the different parameters. The SS 02 42 12/13 and ISO/DP 8990 demands are summarized in table 2a together with SP's GHB limits. The table shows that SP's GHB fulfills the requirements.

Table 2a: SS and ISO/DP demands together with data on SP's GHB.

* Calibrated values; the calibration covers the complete system, from sensor to logging/display.
** Merely because of the frequent manipulation.

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>SS 02 42 12</th>
<th>ISO/DP 8990</th>
<th>SP'S GHB</th>
</tr>
</thead>
<tbody>
<tr>
<td>overall error</td>
<td>±10 %</td>
<td>±5 %</td>
<td></td>
</tr>
<tr>
<td>temperature difference</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>indoor chamber</td>
<td>+10 °C</td>
<td>+10 °C</td>
<td>+25 °C</td>
</tr>
<tr>
<td>environmental chamber</td>
<td>-</td>
<td></td>
<td>-5 °C</td>
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<tr>
<td>temperature stability</td>
<td></td>
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</tr>
<tr>
<td>metering chamber</td>
<td>±0.3 °C</td>
<td>±0.3 °C</td>
<td>±0.1 °C</td>
</tr>
<tr>
<td>indoor chamber</td>
<td>±0.3 °C</td>
<td>±0.3 °C</td>
<td>±0.2 °C</td>
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<tr>
<td>environmental chamber</td>
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<td>±0.3 °C</td>
<td>±0.5 °C</td>
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<tr>
<td>accuracy on</td>
<td></td>
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<tr>
<td>power, $\Phi_T$</td>
<td>±2 %</td>
<td>&lt;1 % $\Phi_1$</td>
<td>±0.2 %*</td>
</tr>
<tr>
<td>area</td>
<td>±2 %</td>
<td></td>
<td>±1 %</td>
</tr>
<tr>
<td>absolute temperatures</td>
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<td>±0.1 °C*</td>
</tr>
<tr>
<td>differential temperatures</td>
<td>±0.3 °C</td>
<td>±0.3 °C</td>
<td>±0.1 °C*</td>
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<tr>
<td>temperature gradient</td>
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<td>&lt;2°C/m/&lt;0.6°C</td>
<td>&lt;1°C/m/&lt;0.5°C</td>
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<td>&lt;0.25 mm</td>
<td>0.4 mm**</td>
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<td>&lt;0.5 % $\Phi_1$</td>
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<td></td>
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<tr>
<td>thermal resistance</td>
<td>&gt;1 °Cm²/W</td>
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<td>5 °Cm²/W</td>
</tr>
<tr>
<td>imbalance</td>
<td></td>
<td></td>
<td>&lt;±0.05 °C</td>
</tr>
<tr>
<td>gasket</td>
<td></td>
<td>&lt;20 mm</td>
<td>=10 mm</td>
</tr>
<tr>
<td>thermopile (m²/junction)</td>
<td></td>
<td>0.25</td>
<td>&lt;0.25</td>
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<tr>
<td>mask ($\Phi_2 = \text{two dim. effekt}$)</td>
<td>&lt;0.5 % $\Phi_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>type</td>
<td></td>
<td></td>
<td>EPS, without load bearing elements</td>
</tr>
<tr>
<td>thickness, accuracy</td>
<td></td>
<td></td>
<td>&lt;±0.5 mm</td>
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<tr>
<td>surface coefficients</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>metering chamber ($m_1$)</td>
<td></td>
<td>U is measured</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>or calculated</td>
<td>(0.12 windows)</td>
</tr>
<tr>
<td>environ. chamber ($m_0$)</td>
<td></td>
<td>using $m_1 + m_0 = 0.1 &lt; V &lt; 0.1 m/s$</td>
<td>0.06</td>
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<tr>
<td></td>
<td></td>
<td>0.25 m²°C/W and</td>
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<tr>
<td></td>
<td></td>
<td>a measured $R$</td>
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</table>
3 ACCURACY OF HOT BOX MEASUREMENTS

Using table 2a the overall error ($\delta U$) is estimated for two different types of specimen (table 3a):
Case (1) 200 mm expanded polystyrene (EPS), without mask
Case (2) 120 mm EPS with a 200 mm EPS mask covering 25% of the metering area.

$\lambda$-value for EPS = 0.040 W/m²°C

Further data (taken from SP's larger metering chamber):
metering area: 2.731 m², chamber's total area: ≈5 m², its thermal resistance: 5 m²·°C/W.
All heat flows used in the estimate are one dimensional flows calculated for the given conditions.

This shows that:
(1) SP's GHB fulfils SS 02 42 12 requirements with large margin.
(2) SP's GHB fulfils the ISO/DP 8990 requirements.
(3) $\Delta\phi_3 < 0.05 \phi_1$ is a severe requirement for metering chambers with low thermal resistance (<2.5 m²·°C/W).
(4) A good accuracy of the power measurement (via calibration) increases the overall accuracy considerably.
(5) The overall accuracy increases when measuring differential temperatures.
(6) The error is underestimated because $\phi_2$ (as well as $\phi_3$) was taken zero in the example. $\phi_2$ or $\phi_3$ can be used as controlling parameter for the metering chamber's imbalance. It is difficult to eliminate both however. On the other hand $\phi_2$ and $\phi_3$ (and also $\Delta\phi_3$) can be reduced by way of calibration.
(7) There exist less favourable specimens than the ones used in the estimate, the ISO/DP requirements then may seem hard to fulfil.
Table 3a: An estimate of $\delta U$ for SP's GHB as well as according to SS 02 42 12 for two specimens (1), (2) and two temperature differences $\Delta \Theta$: 30 °C (a), 10 °C (b).

$\phi_T$=total electr. power, $\phi_1$=flow through specimen, $\phi_M$=flow through mask, $\phi_3$=flow through metering chamber (assumed 0), $\Delta$=absolute error [W], $\delta$=relative error [%]

$|\Delta \phi_1| = |\Delta \phi_M| + |\Delta \phi_T| + |\Delta \phi_3|$, $|\delta U| = |\delta \phi_1| + |\delta \phi_3| + |\delta \Delta \Theta|

<table>
<thead>
<tr>
<th>Case (1)</th>
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<tbody>
<tr>
<td></td>
<td>SS</td>
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<tr>
<td>$\phi_T$</td>
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<td>\delta \phi_T</td>
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<td>$</td>
<td>\Delta \phi_T</td>
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<td>\Delta \phi_3/\phi_1</td>
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<td>\delta \phi_1</td>
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<td>\delta U</td>
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<tr>
<td>$\phi_T$</td>
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CONSIDERATIONS

(1) Nordic round-robin tests carried out in the past showed differences between 5 % and 10 %.

(2) The calibration of the temperature sensors only is not a guarantee for relevant surface temperatures. The way of applying the sensors to the surfaces, their position and the relevance of the mean temperature are probably much more important.

(3) Surface coefficients affect the measurements considerably when it concerns low resistance specimens. Their value is not known exactly and they are not constants for the specimen surface. These problems are related to surface temperature measurements and to the type of boundary conditions in the chambers.

(4) Insufficient guardning causes a heat flow between the metering area and the guard area (GHB). This problem also is related to a difference in surface coefficient between the metering area and the guard area.

(5) Moisture transport through the specimen and re-arrangement of the initial moisture content in the specimen affect the results considerably. The stable 3 hrs period may turn out to be a quasi-stable situation when the measurement is continued. Proper conditioning thus is very important.
(6) Inhomogeneities such as thermal bridges and three-dimensional elements affect the results indirectly because of the influence the surface temperatures, the surface coefficients, leak flows, the heat flow at the edge between mask and specimen, the stability of the air temperature in the indoor and metering chamber. Measuring on windows causes analogue problems. The total heat flow (\( \Phi_T, \Phi_I \)) becomes however rather large, affecting the total error positively.

(7) The GHB (CHB) boundary conditions differ considerably from those in a Guarded Hot Plate (GHP). In a GHP there are no surface resistances as in a HB. The transient period is different as well. This causes a substantial difference between \( \lambda \)-value measurements and HB measurements on homogeneous insulation specimens (up to 5%). This often is eliminated by calibrating the HB.

(8) The way the results are interpreted is as consequential as the measurement itself, especially when discussing glazing units. HB measurements take into account the aluminium profiles at the edges (contrary to certain types of GHP measurements). The way these are accounted for depends strongly on the way of installing the specimen in the mask. The convective heat transfer in the glazing unit is different from horizontal GHB tests as well.

5

CONCLUSIONS - SP'S R&D PROGRAM

A number of important aspects affecting HB measurements are currently not discussed properly in standards, solely because they have not been investigated yet. It is the task of each laboratory using the HB method to tackle those problems. There exists already some specific research programs.

At SP a complete and general (error) analysis will be worked out. The first step has already been completed, namely a check against the governing regulations. The next step will be a study of the specific boundary conditions in a HB. These must be compared with the GHP boundary conditions and the boundary conditions in the field. The third step includes a mathematical model of the leak flows and the way they are affected by surface coefficient variations. Step four should include an extension for non homogeneous specimens. Window and glazing unit U-value measurements will be studied and comparative GHP measurements will be made.

REFERENCES

ISO TC 163 SC1/WG1 workgroup documents, unpublished.
Thermal Bridges: A Non-Computerized Calculation Procedure

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ABSTRACT

This study presents a non-computerized calculation procedure for steady state two-dimensional conductive heat losses through thermal bridges. The heat flow is divided into distinct flow paths based on physical considerations. A resistance is derived analytically for each flow path. These resistances are combined into a network. The network simulates the construction. Calculating the total resistance of the network gives the thermal resistance of the construction. The algorithm is compared with a finite forward difference method. The relative error on the linear thermal transmittance of the thermal bridges calculated does not exceed 10%. The absolute error on the mean surface temperature is approximately 1°C and independent of the type of construction. The minimum inside surface temperature can be estimated in only a few cases; the absolute error is approximately 0.5°C. The algorithm is developed mainly for designers. Its simplicity and the possibility it offers for quick and accurate control calculations makes it an ideal design tool. It can be programmed in Lotus for specific applications of a designer. It is ideal for prevention of condensation, more so than predicting heat loss (or gain).

KEY WORDS

Thermal bridge, linear thermal transmittance, numerical, analytical, flow path, resistance, network.

Reprinted from JOURNAL OF THERMAL INSULATION Volume 10—January 1987
INTRODUCTION AND DEFINITIONS

This study is part of the comprehensive discussion on calculation procedures for heat losses through thermal bridges for standardization purposes. The background of these discussions is twofold.

From the daily building practice, one gathers that building elements with low thermal qualities are commonly used in otherwise well insulated building envelopes; older houses are, for example, not designed to meet today’s energy efficiency requirements and newly designed buildings often contain thermal bridges.

From the mathematical and physical point of view, heat transfer problems are described rather accurately, taking into account a lot of parameters, or are solved approximately, by use of empirical formulae containing coefficients, depending on the construction considered.

The former approach results in complex mathematical problems that only can be solved by use of a computer. The latter results in a poor accuracy and small field of application. Both approaches have in common that they are not user-friendly and that the user does not acquire any understanding of the phenomena he is dealing with.

Thermal bridges are defined in this study as each part in a construction with a locally increased heat loss or a decreased inside surface temperature. Since these phenomena are also ascertained with outer wall corner constructions, these are defined as thermal bridges, too. Thermal bridges are two- or three-dimensional.

All thermal bridges discussed in this study are two-dimensional, i.e., linear construction parts. The calculation of the overall heat loss of a building is simplified by introducing a linear thermal transmittance for linear thermal bridges.

**FIGURE 1.** The part of the total linear heat loss which goes through the thermal bridge (1) is directly proportional to the linear thermal transmittance of the thermal bridge ($P_{tr}$-value). The area of the main construction is arbitrarily chosen to $1 \times 1 \text{ m}^2$ because this always is larger than $1 \times b$, m$^2$. 
The total heat loss of a thermal bridge is the linear thermal transmittance multiplied with the length of the construction element.

The concept linear thermal transmittance used in this study is related to the total heat loss through the thermal bridge and is denoted $P_{TB}$. It is defined as the difference between the total linear heat loss and the linear heat loss through the homogeneous parts of the main construction (Figure 1). Advantages of this definition over other definitions are:

- The definition is applicable in the case of asymmetric constructions.
- It is equally valid in the case of corner constructions; other definitions often result in negative $P_{TB}$-values.
- The concept is related to the inside area or the cross section of the thermal bridge; this is very convenient when calculating the overall heat loss of buildings. In the case of projecting corners and windows, however, the $P_{TB}$-value is not related to any area at all.

The calculation of the linear thermal transmittance of a thermal bridge includes two types of heat transfer calculations:

- an usual one-dimensional calculation of the heat flow through the homogeneous parts of the building component
- a two-dimensional method for the calculation of the total heat loss, taking into account the interdependence of the thermal bridge and the main construction

Because of the latter type of calculation, it is important to determine the influence of a thermal bridge on the heat flow and temperature field in the surrounding main construction. This influence is a disturbance of the one-dimensional flow and temperature field. Its area is therefore defined as "disturbed area," denoted $b_1$ (Peter Staelens, 1986 [1]).

**SIMPLIFIED METHODS FOR TWO-DIMENSIONAL CASES**

Calculation methods for thermal bridges may be divided into two groups: one-dimensional, simple methods and more-dimensional methods. The latter group includes a large range of methods: modified one-dimensional methods, two-dimensional methods—such as the one here presented—and complicated two-and three-dimensional computer methods. Only the non-computerized methods are discussed because precisely these are topics within national and international standardization working groups on thermal bridges.

The one-dimensional steady state heat flow calculation is often used to evaluate simple two-dimensional cases. This results in a $U$-value method and a $\lambda$-value method.

The $U$-value method calculates a surface averaged $U$-value for the con-
struction. The thermal bridge is considered being coupled in parallel with the main construction. This results in a large difference between the flow through the homogeneous part and the flow through the thermal bridge. A slightly changed version of this method is used in the British standard (CIBS guide, A3) and Norwegian standard (NS 3031).

The $\lambda$-value method applies a similar principle: for each distinguishable homogeneous layer a mean $\lambda$-value ($\bar{\lambda}$) is calculated. The thermal transmittance is calculated as in the $U$-value method with the new mean $\lambda$-values and their respective thicknesses ($d'_i$). The thickness $d'_i$ is determined by the relative situation of the layers in the homogeneous part and in the thermal bridge.

The $\lambda$-value method gives a constant density of heat flow rate because the thermal bridge is spread over the construction. This method is used in the German standard (DIN 418, Teil 1,2,3) and the Swedish Building Code (SBN 80).

Berthier (1973) [2] and Verhoeven (1978) [3] discuss a more refined method which consists of empirical expressions. The constants in the expressions depend on the type of main construction. The links between the construction, the expressions and the constants are made by use of experiments or computer calculations. The Dutch standard (NEN 1068) is based on this method. The French standard (R Th K-77) and the Belgian standard (NBN B62-002,003) are based on similar principles.

Other methods of this type more recently developed are quite complicated, but give better results. Against the simple methods, these methods evaluate the variation of the surface temperature on the location of the thermal bridge rather accurately (Erhorn and Tammes (1983), [4]). They do not, however, give any understanding of the problem.

A second type of more refined methods are the network methods. The user is not provided with thoroughly tested formulae but with an algorithm. Each step of the computation is given, and since these methods are built up stepwise the user acquires insight into the physics of the problem.

Finn O. Buø et al. (1981), [5] present a semi-analytical algorithm. The construction is divided in primary zones separated by an infinite insulation. The temperature field and the heat flows are calculated easily under these conditions. In the second step the insulating partitions are omitted. By use of the continuity conditions for the temperature on the zones’ boundaries, and by use of the law of conservation of energy in the thermal bridge, a second set of heat flows and a second temperature field are calculated semi-analytically. The superposition of both gives the final temperature and heat flow field. The algorithm gives good results but it is not always clear to the user what he actually is doing. In a more user-friendly version of this method (Finn O. Buø, unpublished) a network is set up explicitly. The con-
Continuity conditions are replaced by highly conductive elements. The place and length of these links are gathered from what is learnt from the first version. Executing the method by hand takes too long. This means that the method has to be implemented on a computer.

Gudni Johannesson et al. (1981), [6] developed a method for calculating the heat loss through steel structures. This method is a semi-analytical method. The construction is divided into cells. For each of the cells, heat flow paths are introduced and evaluated as to their resistance. The scheme of heat flow paths thus results in a network of resistances coupled in series or in parallel. This method is used in the Swedish standard on steel structures (SS 024 230). Heat flows are estimated accurately. Surface temperatures are estimated less accurately. Unlike the previous method this is a hand calculation method.

This algorithm is the basis of this study.

THE ALGORITHM

The continuous heat flow field is reduced to a number of main—i.e., characteristic—flow paths:

- Firstly, the transversal flow paths—generally three—are introduced. For symmetry reasons, one of the flow paths coincides with the dimensional symmetry line.
- Secondly, and according to the physics of the problem, the transversal paths are linked with lateral paths. The lateral paths are situated in the outer leaves of the construction.

The flow through the insulation is considered purely transversal. Two exceptions are made:

- The insulation is applied on a building element with only a lateral flow, for example, a floorslab between two rooms with equal equivalent air temperature. The flow through the insulation is inherently coupled to the lateral flow in the construction element.
- The insulation has the function as inner leaf in a construction with a thermal bridge (corners not included). In this case both a lateral and transversal flow are considered.

The way proposed is not the only way of doing so, but it gives in most cases, good results, it is simple and in principle valid for all kinds of constructions (Peter Staelsens 1986, [1]).

The flow scheme is made more concrete by introducing three types of flow paths:

- the flow between two parallel surfaces (not necessarily of the same area)
- the flow between two perpendicular surfaces
• The flow in highly conductive rods. This refers to steel structures where it is difficult to tell apart the lateral and the transversal flow in the elements.

These flow paths are easily defined in the flow scheme.

In order to calculate the thermal resistance of the flow paths, material and dimensional data are needed. These data are acquired by defining nodes for each flow path and by constructing cells (Figure 2).

Nodes are the places in the scheme where several paths meet or intersect. One node represents the inside ambient air and one node represents the out-

**FIGURE 2.** Nodes and cells determined by the main flow paths for a symmetric planar construction with thermal bridge.

- A. The computer calculated heat flow field and the simplified version according to the algorithm; the flow paths are indicated 1,2,..5a,5b,..8.
- B. The cell and the nodes for path 2.
- C. The cell and the nodes for path 5a and 5b.
- D. The cells and the nodes for the paths 6,7,8.
- E. The resulting resistance network. The resistance are denoted \( R_1,..,R_8 \). (Table 1.) \( R_1, R_2, R_3, R_8, R_7, R_8 \) are the cases 1 and 2 or a combination of them; \( R_4 \) and \( R_5 \) are represented by case 4.
side ambient air. Cells are constructed in such a way that the nodes are situated on the boundaries. This allows the cells to overlap one another. Cells have two or three nodes. The nodes are situated in the middle of the cell’s surfaces. This is not evident as to the lateral flow: Finn O. Buφ (1981), [6] demonstrates that the main point of the type of lateral flow used in this algorithm is situated at a distance of 0.4 times the layer’s thickness from the symmetry line or from the insulation. Using 0.5, however, is simpler and the error is negligible.

The resistances for the different flow paths are given in Table 1. Surface coefficients are constants for each cell. The cells are considered homogeneous and isotropic.

The assumptions regarding transversal flow paths are:

- The boundaries parallel to the flow are very well insulated \((R = \infty)\); in this way the influence of the neighbouring cells is neglected, no matter how small the cell is.
- The surfaces perpendicular to the heat flow are isothermal.

The assumptions regarding the lateral flow paths are:

- One of the long sides has an infinite insulation.
- The short side is isothermal.
- The cell is infinitely long; the ratio \(D(\text{or } H)/L\) is very small. This means, in practice, \(D(\text{or } H) < 0.2 \text{ m}\).
- When two sides border the ambient air, the cell is split in two parts: its dimensional symmetry line replaces the infinite insulation.

Extra assumptions as to the partially insulated cells are:

- It always concerns a symmetric cell.
- The flow through the non-insulated part and through the insulated part of the cell are coupled in series.

The heat flow in steel profiles is tackled in a similar way (Gudni Johannesson 1981 [6] and Table 2). The assumptions are:

- The steel elements are rods.
- The elements are surrounded by an infinite insulation.
- The flow through the elements and the rest of the structure are coupled in parallel.

The flow scheme is completed with the resistances. The total resistance of the network is the simulation of the heat loss in the construction:

- The resistances stand for the material fields.
- The nodes coincide with the surfaces of the material fields.

Resistances which are coupled in series represent one flow path. Therefore, they are considered as one resistance. They were split in the beginning.
Table 1. The cells with dimensions and material parameters for the resistances used in the heat flow scheme of a heavy construction (as instanced in Figure 2).

<table>
<thead>
<tr>
<th>TRANSVERSAL</th>
<th>LATERAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RECTANGULAR CELL</strong></td>
<td><strong>NOT INSULATED</strong></td>
</tr>
<tr>
<td>[ R_{//} = \frac{d}{\lambda \cdot A} ]</td>
<td>[ R_{\perp} = \sqrt{\frac{0.4 \cdot \frac{A}{hD}}{\lambda}} - \frac{1}{h \cdot A} ]</td>
</tr>
<tr>
<td><strong>SURFACE RESISTANCE</strong></td>
<td><strong>HOMogeneously INSULATED</strong></td>
</tr>
<tr>
<td>[ R_s = \frac{1}{h \cdot A} ]</td>
<td>[ R_{\perp} = \sqrt{0.4 + \frac{\lambda \cdot R_{s,eq}}{D}} - \frac{1}{h \cdot A} ]</td>
</tr>
<tr>
<td>[ R_{s,eq} = \frac{1}{h} + \frac{D_p}{\lambda_p} ]</td>
<td><strong>PARTIALLY INSULATED</strong></td>
</tr>
<tr>
<td><strong>TRAPEZOID CELL</strong></td>
<td><strong>PARTIALLY INSULATED</strong></td>
</tr>
<tr>
<td>[ R_{//} = \frac{d}{\lambda} \cdot \left[ \frac{2}{A_1 + A_2} \right] ]</td>
<td>[ R_{\perp} = \sqrt{\frac{H \cdot d}{\lambda \cdot H \cdot B}} - \frac{1}{h \cdot A} ]</td>
</tr>
<tr>
<td>[ B = F(\lambda, \lambda_p, L, L', H, dp) ]</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. The resistances used when calculating the heat loss through steel constructions.

<table>
<thead>
<tr>
<th>FLANGES IN PLANE CONSTRUCTION</th>
<th>WELDED PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2L = A$</td>
<td>$\beta = \sqrt{\frac{h}{\lambda \cdot t}}$</td>
</tr>
<tr>
<td></td>
<td>$R_1 = \frac{\beta}{2 \cdot h \cdot \tanh \left( \frac{\beta A}{2} \right)} - \frac{1}{h \cdot A}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I - PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta = \sqrt{\frac{h}{\lambda \cdot t}}$</td>
</tr>
<tr>
<td>$R_2 = \frac{\beta}{2 \cdot h \cdot (\beta \cdot l + \tanh (\beta (L - l)))} - \frac{1}{h \cdot A}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LATERAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{12} = \frac{1}{2R_1} + \frac{1}{2R_2}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CIRCULAR FLANGE - BOLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_3 = \frac{1}{2 \cdot \pi \cdot \lambda \cdot t \cdot F(\beta r_1, \beta r_2)} - \frac{n}{A \cdot h}$</td>
</tr>
<tr>
<td>$A = \pi (r^2_2 - r^2_1)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RECTANGULAR FLANGE - BOLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_7 = \frac{l \ln \left( \frac{l}{r} \right)}{2 \cdot \pi \cdot \lambda \cdot t}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$r$ - PROFILE WITH EXTRA INSULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_6 = \frac{1}{1 \cdot \lambda \cdot \left( \frac{h}{\lambda} + \frac{2}{\pi} \right)}$</td>
</tr>
</tbody>
</table>

(continued)
### Table 2. (continued)

<table>
<thead>
<tr>
<th>TRANSVERSAL</th>
<th>HOMOGENEOUS WALL PART</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td>$ R_B = \frac{d}{\lambda \cdot A} $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SURFACE RESISTANCES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image2" alt="Diagram" /></td>
<td>$ R_i = \frac{1}{A \cdot h_i} $  $ R_e = \frac{1}{A \cdot h_e} $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WAIST OF A SCREW</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td>$ R_5 = \frac{H}{\lambda \cdot \pi \cdot r^2} $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WEB OF A PROFILE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4" alt="Diagram" /></td>
<td>$ R_4 = \frac{H}{\lambda \cdot t \cdot b} $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WELDED (REINFORCED) PROFILE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td>$ \beta = \sqrt{\frac{h}{\lambda \cdot t}} $  $ \beta' = \sqrt{\frac{h}{\lambda \cdot t'}} $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LATERAL CORNER CONSTRUCTIONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image6" alt="Diagram" /></td>
<td>$ R_{10} = 2 \left[ \frac{1}{R_1(\beta', L')} + \frac{1}{2hL'} + \frac{1}{R_1(\beta, L) + \frac{1}{2hL}} \right]^{-1} - \frac{1}{h(L + L')} $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FLANGES OF A T-PROFILE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image7" alt="Diagram" /></td>
<td>$ R_9 = 2 \left[ \frac{1}{R_2(\beta, L, l') + \frac{1}{2hl'} + \frac{1}{R_2(\beta, L, l) + \frac{1}{2hl}}} \right]^{-1} - \frac{1}{h(L + L')} $</td>
</tr>
</tbody>
</table>
for the sake of simplicity, because only then each of the resistances was related to a homogeneous material field.

The primary network is reduced stepwise to an equivalent set of series and parallel couplings by use of four simple operations. This is precisely what makes it possible to calculate the heat loss using a pocket calculator only.

- Series and parallel couplings are replaced by their equivalent.
- Star couplings of three resistances are replaced by triangular couplings and vice versa (Peter Staelens 1986 [1]).

The linear thermal transmittance becomes:

$$P_{TB} = \left( \frac{1}{R_{TOT}} \cdot \frac{1}{A_{TOT}} - \sum_k U_{HOM,k} \right) \cdot L$$  \hspace{2cm} (1)

**FIGURE 3.** Estimation of the minimum surface temperature.
A. $\theta_{min}$ is located on the construction; the relevant node temperature is indicated in the network ($\theta_{node} = \theta_3$).
B. Relevant material properties and dimensions.
C. Simplified relation between $\theta_3$, $\theta_{min}$ and $\theta_i$. 
with

\[ L = 1 \text{ m} \]
\[ A_{\text{tor}} = 1 \text{ m}^2 \]

Average surface temperatures can be calculated in each node by solving the network explicitly.

The minimum or maximum value of the construction's surface temperature cannot be calculated because it is not related to one specific node. The minimum inside surface temperature is, however, approximated by relating it linearly to the equivalent air temperature at the inside and the temperature of the nearest node in the construction (\( \Theta_3 \)). The parameters in Figure 3 are:

- the surface coefficient at the inside
- A distance \( d (m) \) determined as the mean value of \( d_x \) and \( d_y \cdot d_{x(y)} \) is the distance in the \( x(y) \) direction between the node (\( \Theta_3 \)) and the point considered (\( \Theta_{\text{min}} \)).
- The thermal conductivity of the material between the nodes (\( \Theta_3' \)) and (\( \Theta_{\text{min}} \)). The cell considered has to be homogeneous because it is not the physical distance which is used.

\[
\Theta_i - \Theta_{\text{min}} = \frac{R_{si}}{R_{si} + \frac{d}{\lambda}} \cdot (\Theta_i - \Theta_s)
\]

\[
\left(1 - \frac{R_6'}{R_{\text{tor}}} - \frac{(R_6' + R_7) \cdot (R_{\text{tor}} - R_1' - R_6')}{R_{\text{tor}} \cdot (R_6' + R_7 + R_6')}\right)
\]

(2)

**RESULTS AND DISCUSSION**

Because physical considerations are the basis of the network, the algorithm results in different networks for different constructions.

This gives the possibility of taking into account edges or lintels on floor slabs, multi-layer wall leaves and constructions with a pronounced thermal bridge (the main wall is provided with an insulation with \( R > 2.5 \text{ K} \cdot \text{m}^2/\text{W} \)) or building parts with a poorly insulated main construction (thermal resistance of the main construction is of the same magnitude as the thermal bridge's thermal resistance); homogeneous corner constructions can be calculated as well as corner constructions with a column or containing both a homogeneous wall part and a cavity wall part.

The different networks may always be related to a general network or pattern network. The algorithm offers the possibility of constructing new networks not yet discussed.

No matter how many links are introduced, the network still is a rough
scheme. In the case of steel structures this problem is partially solved by introducing more complex resistances. This is not possible when it concerns heavy constructions. As a consequence small elements with a low or high thermal conductivity cannot be simulated.

Cavities are treated as material fields with equivalent properties. For small cavities an overall resistance may be used.

The algorithm differs from computerized methods in mainly three elements:

- The cells are large, mostly rectangular cells, which cover a material field completely and which may overlap one another.
- The relation between the cells is not a simplification of the differential equation, but consists of "macroscopic" flow paths based on physical considerations. Their resistance is calculated analytically without relating the cell considered to the neighbouring cells.
- The results from the algorithm are average values for each material field.

Only surface temperatures can be calculated. No information is acquired on what happens in the cells. The temperature in a point can only be approximated.

The algorithm is much more comprehensible than computerized numerical methods because the problem is split into part-problems and each part-problem is solved on its own. The flexibility of the algorithm is as large as that of computerized methods; instead of introducing a new grid, the heat flow scheme is slightly changed or only one of the resistances has to be replaced.

The results of the algorithm are compared with the results of a forward difference method (ACA-STAT) implemented on a NORD 10 computer (A.-C. Andersson, 1982 [7]). The criteria used are:

- the relative difference \( \delta \) between the computer calculated \( P_{tn} \)-value and the \( P_{tn} \)-values calculated by use of the algorithm
- the relative difference \( \delta^* \) between the computer calculated \( U \)-value of a building component of an arbitrary chosen area containing a thermal bridge on its symmetry axis (the area is chosen to \( 1 \times 1 \) m\(^2\) and the thermal transmittance is denoted \( U_{str} \)-value) and the value calculated by use of the algorithm.

For all calculated constructions \( \delta \) was less than 5% when using the network which applies to the physics of the problem. Under the same assumptions \( \delta^* \) was less than 10%, if the heat loss through the thermal bridge is larger than 30% of the total heat loss (Figure 4).

Symmetric constructions are evaluated by use of half the network. Most asymmetric constructions can be evaluated as two independent symmetric
FIGURE 4. The relative difference $\delta$ resp. $\delta^*$ between the numerically calculated $P_{\text{red}}$ resp. $U_{\text{arb}}$-values and the values resulting from the algorithm. The diagram for $\delta$ includes 164 cases; the diagram for $\delta^*$ includes 205 cases.

FIGURE 5. The relative difference $\delta'$ between the $U_{\text{arb}}$-value calculated by use of the general method and the $U_{\text{arb}}$-value calculated by use of the simplified method. The diagram covers 80 cases.
halves without loss of accuracy (Figure 5). This is called the simplified method—versus the general method. An accurate estimate of the overall heat loss in this way, however, does not guarantee an accurate estimate of the heat flow through each of the parts.

In all other cases, a good estimate of the total heat loss implies a good estimate of the part flows.

The maximum difference between the computer calculated mean surface temperature and the results of the algorithm is less than 1°C.

The minimum inside surface temperature is overestimated when it concerns steel structures. In all other cases there is no such trend. The difference with computer results is about 0.5°C. The calculation of the minimum surface temperature becomes too complicated in case of asymmetric constructions, but is not impossible.

CONCLUSIONS

The algorithm presented gives very good results in comparison with computerized numerical method. It may be defined as a semi-numerical or semi-analytical method.

The method can be executed using a hand held calculator only. The execution time varies between 5 and 15 minutes per network. The number of operations needed is about two (symmetric constructions) to eight (more complicated asymmetric constructions). In simple cases the algorithm is faster than and as accurate as computerized numerical methods.

The user sees what happens in the construction because he deals with large cells and mean values. The parts in the construction determining the heat loss are easily defined. Changes in material properties are immediately translated into effects on the overall heat loss.

The method thus is a design tool.

It also offers the possibility of taking into account thermal bridges when calculating the overall heat loss of buildings. In this case a programmed version may be useful.

ACKNOWLEDGEMENT

This project was financially supported by way of grants from the Swedish Institute and the Åke and Greta Lisshed's Foundation.

REFERENCES

2. Bertheir, J. "Thermal Points or Thermal Bridges," a Building Research Station


**BIOGRAPHY**

Peter Staelens is research engineer at the Division for Building Physics of the Swedish National Testing Institute, Borås. He is involved in research in the field of thermal insulation, principally related to measuring methods on pipe-insulation and culverts, and the Hot Box method. He is a former research assistant at the Division for Building Technology of the Lund Institute of Technology, Lund, Sweden. His work was focused on heat loss calculation methods. He is a graduate (1984) of the Leuven Catholic University, Leuven, Belgium with an M.Sc. in architectural engineering.
ADDITIONAL INSULATION ON ROOFS
Measurements on a school-building in Boxholm

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Ph.D
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Building Physics
P.O. Box 857, S-501 15 Borås

SUMMARY

15 different roofs on a school-building in Boxholm have been insulated on the outside with 120 mm mineral wool directly on top of the old roofing. Measurements have been done on moisture content both in the old roof and in the new insulation. The following results are of interest.

- The moisture content in the old roof is constant from summer to winter after the insulation. Earlier the moisture content varied.

- The moisture content in the new insulation material is depending on the weather when the work was done. It is hard to dry out built-in moisture.

- The 120 mm extra insulation gives a good insulation value for the roof as a whole.

1 BACKGROUND

Low sloped ventilated roofs or parallel roofs are common constructions. These roofs that were built during the 60:s and in the beginning of the 70:s have bad insulation value and their air spaces have small dimensions. Today these roofs have to be re-insulated and the roofing on the top has to be retrofitted.

This study concerns additional insulation laid directly on the top of the roofing and a new roofing on top of the insulation. In order to get a good insulation value of the roof the air space has to be sealed. This, however, should not be done until the roof is completely dry. To be sure that it dries out, the roof normally has to be insulated first and the ventilation space left open during another summer-period.

This way of insulating roofs has earlier been studied in Copenhagen. Results from this study are very positive and therefore some experiments also have been done in Sweden, but not in the same scale.
Among these experimental houses is the Stenbocksskolan in Boxholm. On this school there are different buildings with totally 15 different roofs. All the roofs are insulated on the top with 100 + 20 mm mineral wool. When the insulation was laid on the roofs the measurements devices were installed in different levels of the roof in order to measure the variations in the moisture content in the old air space, in the old wooden panel and in the new insulation. The different measuring points are shown in figure 1 a.

Fig. 1 a Measurings have been done on different levels in the roof. 0) in the old insulation material, 1) in the air space, 2) in the old roof panel and 3) in the new insulation material.

The measurings have been done with the help of temperature and relative humidity probes and with resistant measurings in wood. The results show that the old roof has dried out. There is still some variation from winter to summer specially as long as the air space is open but there are no high moisture values in the old roof. There is, however, some variation in the moisture content in the new insulation. This probably depends on the amount of water that was built in in the roof. If it was rainy weather when the roof was insulated, the rainwater that was built in has to dry very slowly because of the tight roofings on the top and the bottom. This is also shown in the measurings of the relative humidity where many measuring points show 100 % relative humidity in the insulation.

To control the amount of moisture some specimens have been cut out. The total amount of moisture in the insulation, however, was small, only some 100 g/m² roof area. This is a neglectible amount of moisture and will not cause an immediate damage or insulation decrease, but if the roof has this high relative humidity during a long time it may
accelerate the ageing of the glued mineral wool and this may result that the mineral wool will be soft and changes its dimensions by time.

In figure 1 b the moisture content in the upper part of the insulations is shown. The figure shows all the measurements in the different roofs in Boxholm. The roofs are insulated during the autumn 1982 and ventilation space is sealed two years later.

![Fig. 1 b](image)

The moisture content in the old roof panel is shown in figure 1 c. The figure shows all the values from the roofs in Boxholm.

![Fig. 1 c](image)
The moisture content from the measuring points in the airspace is shown in figure 1 d.

Fig 1 d

2 CONCLUSIONS

The values from all the roofs in Boxholm show that the moisture content decreases as soon as the roofs are insulated on the outside. This is an expected effect because the old roof is getting warmer after the insulation and therefore the wooden panel can dry out. Even if indoor air with high water vapour concentration should flow up in the construction, the wooden panel will be more dry after than before the outside insulation.
LOOSE FILL INSULATION IN 433 HOUSES: EXPERIENCE FROM POST-INSTALLATION QUALITY CONTROL INSPECTION

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S-501 15 BORAS

SUMMARY

Since 1983, the Swedish National Testing Institute has carried out sample checks of the quality of loose fill insulation work in roof spaces. The results of this inspection are as follows:

- Loose fill insulation is particularly suitable for use in confined spaces and where a large number of pipes and ducts are run in the roof space.

- Glass fibre insulation has the highest level of incidence of faults due to insufficient density.

- Mineral wool and cellulose insulations exhibit the highest levels of faults due to insufficient thickness.

- Ventilation of the roof space has been insufficient or totally lacking in about 20% of the cases inspected.

- About 10% of the installations inspected exhibited damage due to being walked on or loaded.

- Loose fill insulation can easily be displaced by draughts in the roof.

BACKGROUND

Since 1983, a type approval process has been operated in Sweden for the use of loose fill insulation on horizontal or slightly inclined roof spaces that can be inspected. Inspection in accordance with §12:12 of the Swedish Building Standards is required if type approval is to be valid.

This report summary describes the results of sample inspection of such insulation work.
2 INSPECTION PROCEDURES

Sample inspection has consisted of:

- General (overall) checking: checking to see that the working instructions relating to such aspects as ventilation, walkways, edging strips, seals etc. that must be followed for compliance with type approval actually have been followed.

- Measurement of thickness.

- Measurement of density.

3 RESULTS OF INSPECTION

The inspectors have looked for insufficient density, inadequate thickness or shortcomings in the quality of the work. The percentage breakdown of such cases is shown in Table 3a. The figures are based on a total of 433 houses inspected between 1984 and 1986.

The table shows both overall results for all types of insulation and a breakdown of results related to type of insulation: glass fibre, mineral wool and cellulose. Fractionated paper fibres and cellulose fibres are regarded as belonging to the group of cellulose insulation.

Table 3a  Percentage distribution of faults found in insulation work between 1984-1986.

<table>
<thead>
<tr>
<th></th>
<th>Insulating material</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Mineral wool</td>
<td>Glass fibre</td>
<td>Cellulose</td>
<td></td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Insufficient density</td>
<td>15</td>
<td>12</td>
<td>27</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Inadequate thickness</td>
<td>24</td>
<td>34</td>
<td>11</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>No ventilation</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Insufficient ventilation</td>
<td>10</td>
<td>12</td>
<td>7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Shortcomings in ventilation arrangements</td>
<td>21</td>
<td>19</td>
<td>29</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Walkways partly or entirely missing</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Edgings too low or of wrong material</td>
<td>5</td>
<td>1</td>
<td>9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Inadequate prior cleaning</td>
<td>7</td>
<td>10</td>
<td>6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Unsatisfactory seals</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

| Number of buildings inspected | 433 | 128 | 191 | 114 |
4 COMMENTS ON THE RESULTS

4.1 Density

Minimum density limits are specified in the type approval procedure.

It can be seen from table 3a that glass fibre insulation exhibits the highest incidence of faults involving insufficient density. During 1986, the minimum density limit was increased from 14 kg/m$^3$ to 16 kg/m$^3$, and the statistics for 1986 show a reduction in the number of such cases.

The cellulose-based types of insulation have not suffered from any cases of insufficient density at all, while mineral wool insulation occupies a half-way position.

4.2 Thickness

The majority of cases of inadequate thickness relate to mineral wool and cellulose insulation. Cellulose-based insulation tends to exhibit greater settlement than other types of insulation, which therefore needs to be compensated for by a settlement allowance when laying. This allowance was raised from 10–15 % to 20–30 % in 1986, resulting in a reduction in the number of cases of inadequate thickness found.

The incidence of such cases for mineral wool insulation cannot be explained in the same way, as mineral wool insulation does not suffer from significant post-installation settlement.

4.3 Ventilation

The application of additional insulation to roof spaces will result in a reduction in temperature in the roof space and an increase in relative humidity. It is therefore important that the roof space is properly ventilated. Figure 4.3a shows one way of providing satisfactory ventilation at the eaves.
It is also important that the ceiling structure is airtight relative to the heated space below, so that warm air does not leak through into the roof space through gaps around pipes or ducts etc.

Inspection has shown that about 20% of faults relate to unsatisfactory provision of ventilation gaps or to a complete lack of ventilation. In six cases, this has caused serious moisture damage to the outer roof in the form of mildew and changes in the shape of the timber structure. These cases were found by inspection carried out between 0 and 12 months after installation. More cases of moisture damage resulting from lack of ventilation would probably have been found if inspection had been carried out later.

Inadequate ventilation has been found in about 20% of the cases. Many of these cases relate to newly-built houses. Wind deflectors have been too short, allowing the insulation to blow away, or improperly secured to that they have fallen on to the insulation.

It is most important that finishing of the insulation at the eaves is properly airtight. Figure 4.3b shows a poor arrangement at the eaves, allowing air to blow in beneath the original insulation and completely negating the effect of the insulation.
4.4 Walkways

Loose fill insulation is sensitive to loading and to being walked on, so walkways should be constructed across it to openings in the roof and to water or ventilation equipment needing occasional attention.

About 10% of the cases inspected showed signs of damage due to the insulation being walked on or loaded by furniture etc., with the damaged area of insulation covering between 5% and 90% of the total ceiling area.

In the case of newly-built houses, most of the cases of damage caused by being walked on were due to the fact that the insulation was laid too early, before all building work on the roof and installation of ventilating equipment etc. in the roof space had been completed.
4.5 Edging strips

Edging strips must be constructed around access hatches and heating and ventilating openings. Most of the cases of faults found have been related to edgings around access openings made of unsuitable materials such as foamed plastic, fibreboard or cardboard, or being too low.

4.6 Cleaning prior to laying insulation

Before starting to lay insulation, the ceiling structure must be cleaned. Cases of inadequate cleaning prior to laying have related to the presence of pieces of plastic, studding, tile etc. left on the top surface of the ceiling and simply covered with insulation.

4.7 Seals

As pointed out above in §4.3, it is important that the ceiling structure is draughtproof. Faults found in this respect have related to penetrations for ventilating ducts and pipes, as well as to the lack of sealing strips around access hatches.

4.8 Other points

Loose fill insulation fills out spaces very well, and is particularly suitable for use in confined spaces and where there are a lot of ducts, pipes etc. in the roof space.

Loose fill insulation, and particularly low-density insulation, is sensitive to draughts, i.e. to being blown about. Of the 433 houses inspected, cases of movement of the insulation were found in 18.

The reasons for redistribution were:

- Insufficient distance between the top of the wind deflector and the insulation.

- Failure of the wind deflectors to cover the full width between the roof trusses.

- Wind deflectors coming loose and falling down on to the insulation.
- Laying the insulation at too early a stage of building work, before the eaves were clad.

In a few cases, although the termination of the insulation at the eaves had been quite correctly made (see Figure 4.8a), the insulation had still blown away. Eddies form behind the edge beam, and wind deflectors should also be mounted here in particularly exposed situations.
THERMAL PERFORMANCE OF LOOSE FILL INSULATION ON THE FLOOR OF AN ATTIC

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SUMMARY

Thermal performance of loose fill insulation at an attic has been monitored together with the performance of an insulation of expanded polystyrene foam. The average thermal conductivity for a 17 day period has been determined and compared to laboratory measurements. The field measurements show a higher conductivity for loose fill insulation than measured in a heat flow meter apparatus.

Comparing the thermal performance of the two insulation materials shows a similar response to climate changes. There is no signs of a greater sensitivity for loose fill material to climate variations.

1. BACKGROUND

Thermal conductivity of thermal insulation material is normally determined at laboratories by use of the heat flow meter (HFM) apparatus or guarded hot plate (GHP) apparatus. At laboratory tests natural convection is restricted in several ways.

Studies of the in situ performance of loose fill insulation installed on an attic floor may tell us if the thermal performance of such a material is overestimated at laboratory tests.

If another thermal insulation with low air permeability is installed on the same attic floor as a reference, a study in parallel may point out differences in their thermal performance. If the thermal resistance of loose fill insulation is dependent of external climate, it might be shown in this study.
2. TEST PERFORMANCE

2.1. General

Two different kinds of thermal insulation were installed February 1987 on the attic floor of a three storey building situated in Dalshöfs, Sweden.

This report covers the thermal performance of the attic insulation monitored from 4th to 20th March 1987. Measurements will continue during the summer 1987.

2.2. Test arrangement

The attic had a concrete floor (10m x 40m) that was covered with 300 mm thick loose fill insulation of fibre-glass. On one side of the attic two rafter bays close to each other were chosen for the test performance. The floor area in each bay was 1.2m x 5.0m.

The first bay was insulated with 25 + 300 mm of expanded polystyrene foam insulation board (EPS) with the area 1.0m x 4.2m. The insulation board was on its sides surrounded by loose fill materia at same height. Heat flux transducers were mounted in the lower 25 mm board. Studies of thermal performance regards to the upper 300 mm board. Density of EPS was 20 kg/m3.

The second bay was insulated with 25 mm EPS + 268 mm loose fill insulation (LF) of fibre-glass. Density was 25 kg/m3. Heat flux transducers were mounted in the EPS board under the loose fill insulation. Thermal performance regards to the LF material only.

2.3 Measuring equipment

Temperatures were measured by use of thermocouples (Copper-Constantan). As environmental temperature was measured the temperature on the surface of a piece of EPS (400mm x 400mm) fixed 100 mm above insulation so it was facing the ceiling.

Heat flux transducers were made of 25 mm thick EPS (400mm x 400 mm) with a thermopile of 8 elements. All transducers had been calibrated in a HFM apparatus.

Consecutive measurements were made every 15th second by a data acquisition system. Average was calculated and stored every 30th minute. Once a day, the data were automatically collected by telephone.
2.4 Monitored data

For each bay were measured at three points: the heat flow on the warm side and temperature at three levels. The air temperature and the environmental temperature in the attic space were measured in only one point.

3. RESULTS

3.1 Basic parameters

Heat flux density \((Q)\) on the warm side of insulation is shown in fig 3.1 a for a period of 17 days. Along with the heat flux density is shown the environmental temperature \((T_{env})\) and the insulation's surface temperature on the warm side \((T_{si})\).

3.2 Thermal resistance - long time average

Fig 3.2 a shows the successively calculated average of the thermal resistance \((R)\). The thermal resistance includes here boundary layer resistance at external surface \((1/h,ext)\).

The average is after a few days converging close to the final value. The average for the whole period is shown in table 3.2 a.

<table>
<thead>
<tr>
<th>Material</th>
<th>(R + (1/h,ext))</th>
<th>m²·°C/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>6.70</td>
<td></td>
</tr>
<tr>
<td>EPS</td>
<td>9.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1/h,ext) = 0.12</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Fluctuations in thermal resistance

Momentarily values of thermal resistance are in fig 3.3 a plotted together with the average for the period. This plot shows fluctuations with a 24 hour period, caused by dayly fluctuations of environmental temperature. Heat flux response is moderated and delayed by the heat capacity of the insulation material. The time delay is approximately 1.5 hour for LF and 3 hours for EPS.
Average of thermal resistance for 24-hour periods has been continuously calculated and is in fig 3.3 b compared with the average for the whole period.

The figure shows only small fluctuations from the mean value for both insulations. There is no indication found that the thermal resistance is more sensitive to climate variations for LF than for EPS.

3.4 Comparison to laboratory tests

Thermal conductivity has been calculated from the average thermal resistance during the measurement period. In table 3.4 a these values are compared to expected when similar insulation materials are tested in HFM apparatus.

Table 3.4 a - Thermal conductivity

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Measured</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS (20 kg/m³)</td>
<td>0.032</td>
<td>0.033-0.034 m²°C/W</td>
</tr>
<tr>
<td>LF (25 kg/m³)</td>
<td>0.041</td>
<td>0.034-0.036 m²°C/W</td>
</tr>
</tbody>
</table>

Measured conductivity for the loose fill insulation is significantly higher than expected. This might be caused by natural convection in the loose fill material.
EPS AND LOOSE FILL ON ATTIC FLOOR

Fig 3.1 a

THERMAL RESISTANCE

Fig 3.2 a
PERMANENT DEFORMATIONS IN PLASTIC WINDOWS

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Borås, Sweden

SUMMARY

Field studies of 10-20 years old plastic windows in central Europe showed average bowing of the profiles in magnitudes ranging from 1 to 4 mm depending on window construction, surface colour and which direction the windows are facing.

A temperature cycling test has been included in the Swedish certification programme for plastic windows. It has also been used to study the influence of different methods of mounting the window in the wall. A mounting method which allowed the thermal movements to take place more freely than the traditional mounting method seemed to be favourable.

1 INTRODUCTION

When a window is exposed to different temperatures on its two sides, a bending movement will occur in the frame and casement due to the linear expansion of the material. Since the mean expansion coefficient is much higher for plastic materials than for most other building materials (80·10^-6/°C for PVC compared to 12·10^-6/°C for steel) the effect on plastic windows can be substantial. Through relaxation of the stresses in the material at warmer temperatures there will in time be permanent deformations. If their size becomes too large the functional properties of the window can deteriorate, e.g. air- and raintightness and manoeuvrability.

A few years ago windows made of plastic materials were very rare in Sweden, but they are now introduced in increasing numbers. For this reason an investigation concerning suitable requirements for plastic windows was started in cooperation with the other Scandinavian countries. Special attention was paid to the functional performance of the windows at cold temperatures and after repeated temperature changes. As a part of this work a field study was made of old plastic windows in central Europe.
A field study was conducted on windows in Germany and Switzerland which had been exposed to natural climate for 7 to 22 years.

The deflections of the frames and casements of 23 windows were measured using a measuring device as shown in Figure 1.

![Diagram of measuring device]

**Figure 1.** Device used for measurements of the deflection of window profiles.

The measured windows included windows in different sizes and different colours from six different manufacturers. The group also included windows with and without metal reinforcement in the plastic profiles. In spite of the many variables some conclusions can be drawn from the results. See table 1.

**Table 1. Deflection of casement profiles. Mean values (mm)**

<table>
<thead>
<tr>
<th>Group of windows</th>
<th>Deflections (mm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows with metal reinforcement in the profiles</td>
<td>0.8</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Windows without metal reinforcement</td>
<td>1.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Windows without metal reinforcement, dark colours</td>
<td>2.0</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Group of windows</td>
<td>Deflections (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Top piece</td>
<td>Bottom piece</td>
<td></td>
</tr>
<tr>
<td>Windows without metal reinforcement. Light colours. Facing north</td>
<td>±0</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Windows without metal reinforcement. Light colours. Facing south</td>
<td>0.8</td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>

The plus sign indicates deflection towards the interior and the minus sign deflection towards the exterior.

The figures show clearly that the solar radiation has a great influence. The bottom pieces show much bigger deflections than the top pieces as do the windows facing south compared to those facing north. Higher surface temperatures of dark coloured windows lead to bigger deflections of the profiles.

It is also clear from the figures that metal reinforcement of the profiles has a favourable effect on the thermal stability of the windows.

3 TEST METHOD

The field studies had shown that deflections could appear in plastic windows to such an extent as to impair the functional properties of the window. The climatic stability is important in Sweden where the temperature difference between summer and winter is high and where the requirements for air tightness are high because of the cold winter. Therefore a temperature cycling test was included in the Swedish certification programme.

During this test the window is mounted in a partition wall between two climatic chambers. On the exterior side of the window the air temperature is varied between -30 and +60 °C in daily cycles. On the interior side the air temperature is kept constant at +23 °C. The duration of the test is 45 days.

After the test the window shall fulfil the requirements for air tightness. The leakage through the window must not exceed 10 m³/m².h at an air pressure difference across the window of 700 Pa.

It is not unusual that windows fail in this test but usually the window can be approved after the manufacturer has adjusted the hinges or changed the weather strip. It
has however so far not been possible for a window without metal reinforcement to pass the test.

The average deflection of the casement with metal reinforcement after this test has been 1.1 mm with no difference between the top and bottom pieces. This value is of the same magnitude as those obtained at the field studies.

4

FIELD STUDIES IN NORTHERN SWEDEN

Four plastic windows of a type that has passed the temperature cycling test have been mounted in a building north of the polar circle and are inspected regularly. After four years' exposure the deflections of the casement average only 0.3 mm. It can thus be assumed that window constructions that pass the temperature cycling test will show a good thermal stability in practice for a very long time.

5

DIFFERENT METHODS OF MOUNTING

The temperature cycling test has also been used to study the influence of different methods of mounting the window in the wall. Two windows of the same make, type and size were mounted in the partition wall between the two climatic chambers.

One of the windows was mounted with the traditional method which means that the frame is quite rigidly fastened to the wall. The other window was mounted with a Scandinavian mounting method where the window is allowed to move more freely. The positions of the setting blocks are shown in Figure 2.

Figure 2. Positions of the setting blocks used for mounting the window frame in the wall.
The changes of the angles of the corners of the window frame were studied through careful measurements of the sides in right-angled triangles. The biggest difference of the values between the two windows was obtained in the upper corner at the lock side (indicated in Figure 2).

An angle in this corner that was originally 90° had after the 45 days of temperature cycles changed to 89.61° at the traditionally mounted window and to 90.02° at the window that was mounted with the Scandinavian method.

The more acute angle of the corner in the traditionally mounted window indicates that this corner has been subjected to a higher stress than the corresponding corner in the other window. The results thus seem to indicate that the Scandinavian mounting method is more favourable and probably decreases the risk of cracks in the welded corner joints.

REFERENCES

DIMENSIONAL STABILITY OF ENTRANCE DOORS EXPOSED TO NATURAL CLIMATE

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SUMMARY

Entrance doors, exposed to different climatic conditions on each side, are distorted by forces resulting from the effects of temperature and moisture, which tend to bow the doors. This, in turn, affects the performance of the doors, e.g. their airtightness and ease of closing.

In order to investigate these points, we have tested a number of different types of doors in the climate chamber at the Swedish National Testing Institute. The same types of doors have also been installed in a test building outside the laboratory, in order to provide reference data when exposed to natural conditions.

1 DIMENSIONAL STABILITY

An entrance door, exposed to different climates on each side, is affected by changes in the dimensions of its materials resulting from the effects of temperature and moisture, which influence its performance, e.g. its airtightness and its ease of closing.

As the movements in the surface layers on each side of the door are of differing magnitude, the door will be bowed. This will result in alteration of the width of the gap between the frame and the door. The airtightness of the door and its ease of closing will then be determined by the ability of the sealing strips to compensate for dimensional changes, their resistance to deformation and their sealing performance.

2 LABORATORY TESTS

A method of testing doors under varying climatic conditions has recently been adopted by Nordtest (NT Build 234). The test doors are installed in a wall separating two climate chambers, in which conditions are as shown in table 2a.

During the test described here the Nordtest method was used except that the temperature on the cold side of the door was reduced only to -10 °C on the 29th day. The test was also continued after the 29th day for a further thirteen weeks with a temperature of +3 °C on the cold side.
Table 2a  Climatic conditions during the laboratory tests.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Climate - cold side</th>
<th>Climate - warm side</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 days</td>
<td>$+3 \pm 2 , ^\circ{C}$</td>
<td>$+23 \pm 2 , ^\circ{C}$</td>
</tr>
<tr>
<td></td>
<td>$85 % \pm 5 % \text{ RH}$</td>
<td>$30 % \pm 5 % \text{ RH}$</td>
</tr>
<tr>
<td>1 day</td>
<td>$-20 \pm 2 , ^\circ{C}$</td>
<td>$+23 \pm 2 , ^\circ{C}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$30 % \pm 5 % \text{ RH}$</td>
</tr>
</tbody>
</table>

2.1  Results

As an example of the results obtained, consider the two doors shown in Figure 2.1a. Figure 2.1b shows the mean value of bowing of the doors at the latch side and hinge side. It can be seen that door E, which contains a thicker layer of aluminium than does door B, reacts considerably more to temperature drops. On the other hand, the aluminium sheet in door E resists the effects of moisture considerably better than the aluminium film in door B. For door B, bowing during to the effect of moisture was equal to bowing caused by temperature difference after only about a week while it took about 60 days for door E to reach the same state.

![Diagram of door sections](image)

Figure 2.1a Sections through two of the doors in the trials.

Bowing, mm

![Graph showing bowing over time](image)

Figure 2.1b Bowing of the doors shown in Figure 2.1a. Bowing is positive when the door is convex on the outside.
Five different doors have been installed in the north and south walls of a test building close to the laboratory in Borås to study their behaviour under natural climatic conditions. Conditions inside the test building simulate a natural indoor climate through heating and humidifying. Four of the door types are the same as those tested in the laboratory.

3.1 Results

3.1.1 Bowing

Figure 3.1a shows the daily mean values of bowing on the lock side for door types B and E in the southern wall of the test building from June 1982 until May 1983. Details of insolation, air temperature and relative humidity are also shown.

Figure 3.1a Daily mean values of climate and bowing of doors.
Figure 3.1b Climate and bowing of doors during a 24-hour period in August.

Door E has been more stable than door B as far as daily mean values of deflection are concerned. However, it reacts very much more rapidly to temperature changes, as can be seen from Figure 3.1b, which shows the bowing effect over a period of 24 hours in August. It can be seen that door E has reacted immediately every time the sun has gone behind a cloud or come out again. The reason for this is that the door contains a relatively thick piece of aluminium sheet, close to the surface, and that the surface was black.

Table 3.1a is a summary of the test results. It shows the maximum and minimum daily mean values of boxing in the test building and the bowing measured during the laboratory trials. The maximum values of bowing are those observed when the doors have been most convex (or least concave) towards the exterior and the minimum values relate to the most concave (or least convex) value towards the exterior.
It is clear that the doors on the north of the building have tended to bow more in absolute terms (outwardly convex). On the other hand, there has been the greatest change in bowing in the doors in the south wall. The reason for this is probably that the external surface of these doors dries out more during the summer. The opposing movement caused by moisture is therefore less in the winter, when temperature-induced bowing tends to make the doors concave on the outside.

Table 3.1a A summary of bowing and air leakage of doors.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Exposure</th>
<th>Bowing, mm (daily mean values)</th>
<th>Air leakage, m³/h at 50 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max. value</td>
<td>Min. value</td>
</tr>
<tr>
<td>A</td>
<td>North</td>
<td>4.2</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>3.7</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>2.6</td>
<td>-1.3</td>
</tr>
<tr>
<td>B</td>
<td>North</td>
<td>6.8</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>5.8</td>
<td>-1.0</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>C</td>
<td>North</td>
<td>5.6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>4.0</td>
<td>-3.0</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>North</td>
<td>5.9</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>3.4</td>
<td>-3.5</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>2.0</td>
<td>-2.2</td>
</tr>
<tr>
<td>E</td>
<td>North</td>
<td>2.8</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>-1.0</td>
<td>-4.8</td>
</tr>
<tr>
<td></td>
<td>Laboratory</td>
<td>2.1</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

The bowing deflection during the laboratory trials agree well with values from the north wall of the test building. However, the laboratory trials have underestimated the maximum convex bowing likely to be encountered, although this may be due to termination of the laboratory trials before bowing was fully developed (see Figure 3.1b), while the doors in the test building had been in position for a year before measurements were made.

3.1.2 Air leakage

The air leakage rates of the doors at 50 Pa pressure difference are also shown in Table 3.1a. It is clear that the air leakage around the doors can vary quite considerably, and that the greatest rates of leakage tend to be around the south-facing doors.
Healthy Buildings '88
Stockholm, Sweden 1988

MOISTURE IN BUILDINGS

How to keep buildings dry enough to keep them healthy

Ingemar Samuelson
Swedish National Testing Institute

Abstract

This paper describes our greater awareness of the factors involved in deciding whether a given indoor environment is regarded as good or bad. Many of the mechanisms that create a bad environment require, or are exacerbated by, the presence of moisture, either in the structure or in the air. The most important measure in creating a good internal environment is therefore to ensure that moisture does not get to where it should not be. The paper describes means of preventing this, and describes the importance of ventilation, partly as a means of preventing moisture access or attack and partly as a complement to other measures.

Background

Hitherto, a good indoor environment has been concerned only with thermal comfort. Its criteria have been temperatures, draughts and operative temperature. However, in recent years, various other problems have come to the fore, such as indoor air pollution, odour, noise and other irritants, often associated with problems in the form of tiredness, headaches and other physical symptoms. Sometimes it has been possible to trace the cause: in recent years problems have been identified that were previously non-existent, or of which we were not aware. The release of formaldehyde, odour from mildew and self-leveling floor compounds are examples of such mechanisms, as is the emission of radon from building materials and the ground.

Inadequate or incorrect ventilation often contributes to increasing the concentration of pollutants and making problems noticed.

In order to ensure a good indoor climate, the most important first step is to eliminate or reduce the emission of pollutants to the indoor air. This can then be followed by planning for good ventilation.

The presence of moisture is an important prerequisite for the decomposition of the majority of materials, and thus also for the emission of pollutants to the indoor air. Moisture accelerates ageing processes and reduces life. The majority of forms of damage to buildings, i.e., not merely problems associated with the indoor environment, are probably caused by moisture. This is very disturbing, particularly when taken together with the fact that practising
engineers and designers know little about moisture transport mechanisms or moisture calculations. They may be thoroughly familiar with the design of static systems, but they are less familiar with building physics calculations.

Knowledge of moisture conditions in and around structural features is necessary in order to be able to make a correct assessment of the risk of future damage. Proper design of structural features, selection of the right materials that can be relied on even in the long term not to become a source of hazardous emissions, and sensible use of the building ensure that it will be healthy from the start and also remain so.

Sources of moisture

When designing a structural feature in terms of its ability to withstand or protect against moisture, consideration must be given to the following factors.

Precipitation in the form of rain or snow tends to fall on the roof, which must be able to carry away large quantities of water without leaking. Driving rain, i.e. rain in combination with wind, strikes also vertical surfaces of the building. Exterior walls must be capable of withstanding this loading, as must windows and doors.

Surface water on the ground can flow towards the building and damage the foundations if the ground slopes the wrong way. In order to prevent this, the ground should slope away from the building: if this is not possible, the structure must be designed to withstand water pressure.

Water in the ground can be drawn up towards the building by capillary action in various materials. Such moisture migration can be prevented by protecting the foundations by a layer of gravel that breaks the capillary link up to the foundations themselves. Moisture also migrates in the form of diffusion from damp ground. In the long term, this can result in the same level of moisture in and around the foundations as caused by capillary attraction, unless special measures are taken to prevent it.

Locally, leakage of water from pipes and internal systems can result in heavy moisture loadings. Visible routing of pipes and careful positioning of apparatus can reduce the risk of such damage.

Moisture incorporated in structural materials at the time of building must be allowed to dry out. As far as possible, such drying out should take place before the building is completed. As it is often not possible to dry out all moisture in this way, the structural design should be such that moisture can continue to dry out after completion.

Moisture carried in the indoor air can create condensation in the interior of the structural elements, partly through diffusion from the interior towards the exterior and partly by convection. In this context, convection refers to the transport of moisture in air currents. Moisture convection can cause damage if warm, moist indoor air flows through the structure and, on its way, comes into contact with cold surfaces upon which condensation occurs.
The design of moisture-resistant structural features

The following principles for design and use of structural features in buildings should be applied, not only in new buildings but also when rebuilding parts of existing buildings. Compliance with them will ensure that buildings remain dry.

A. Prevent moisture from reaching parts of the building by employing:
   - impermeable layers
   - layers intended to carry away water
   - drainage
   - capillary breaks
   - temperature elevation.

The use of impermeable layers must be suited to applications and conditions. Correctly used, an impermeable layer will result in a dryer structure than a similar structure without such a layer. On the other hand, a structure incorporating an incorrectly applied or employed impermeable layer will instead tend to trap moisture that would otherwise have dried out and become considerably damper inside. Any impermeable layer should prevent the undesired transport of moisture without causing unnecessary risks.

Water must be led away. This applies, of course, primarily to the roof, which is exposed to rain and snow, and where water should not be allowed to remain standing for longer periods. However, it also applies to window sills, drip plates over doors and windows and at joints between parts of the building.

Water in the ground must not be allowed to flow towards the foundation structure, but must be drained away.

It may be necessary to incorporate a capillary-breaking layer of gravel in order to prevent groundwater from being drawn up and to maintain the structure permanently dry. It is also generally good practice to prevent capillary transport between moist concrete and wood: a damp-proof course of building felt or some other membrane should always be incorporated there.

By raising the temperature of a structural element or part of a building, conditions are made less favourable for the transport or water vapour from moist areas. Temperatures can be raised either through active heating or by the addition of thermal insulation.
B. Heat parts of a building

A part of a building can more easily be protected against the damaging effects of moisture if its temperature is elevated. This can be done actively by means of a heating cable or hot pipes, as is often done around the perimeter of a slab floor in order to prevent damage and to ensure that the floor is warm. It can also be done by the application of external insulation to the structure. By insulating the exterior of that part of the building that is sensitive to moisture, its temperature will be raised closer to that of the indoor temperature, which should normally prevent damage from arising. This will extend the life of the structure and reduce the risk of emissions.

Heating of buildings and parts of buildings should be constant and continuous. Intermittent heating always involves increased risk of damage. As intermittently heated structures sometimes have temperature gradients in one direction and sometimes in the other, moisture can migrate upwards, e.g. from warm, moist ground. In a basement or cellar, floor heating should remain on throughout the year, so that even in summer condensation in the floor is prevented, with its otherwise associated risks of odour, corrosion and other deterioration.

C. Provide ventilation where moisture can occur

In many cases, ventilation can be employed to ensure that roofs, walls and floors are kept dry. By ventilating away moisture, building elements can be maintained dry, while even if moisture should get into them, it can dry out before damage is caused. Ventilation often provides additional security against damage.

Normally, we attempt to design ventilation systems so that the air is moved by wind pressure or thermal forces, although in difficult-to-ventilate spaces, where ventilation is essential, such as under low roofs or beneath floors, it may be necessary to resort to fans.

In such applications, the ventilation system should be designed so that damage caused by convection is avoided. In ventilated areas, the air should always move from a lower temperature to a higher temperature area. In a ventilated underfloor space, the air should be drawn in along or through the exterior wall and towards the centre of the building, from where it is then evacuated. Travelling in this direction, the air can pick up an increasing quantity of moisture. If it flowed in the opposite direction, from a higher temperature to a lower temperature, there would be a risk of condensation being formed as the air was cooled.

D. Use the building properly

This means making sure that the building is properly ventilated, i.e. with fans and extractions arranged in kitchens, laundry rooms and bathrooms and in other areas where moisture can be generated or released. The occupants of the building should also understand the importance of ventilation and temperature in controlling relative humidity indoors.
The design of healthy buildings

Materials and structural features of healthy buildings should be designed as follows:

1. Use materials of which both the present and future properties are known. The materials should not themselves emit pollutants or contribute to other materials or structural or design features becoming unhealthy.

2. Design structural features and combine materials in such a manner that problems cannot arise. Build dry.

3. Design the ventilation system so that all spaces are correctly ventilated. Check the performance of the ventilation system at the time of installation and when the system has been in operation for about a year or so. Draw up clear and easily-understood operating and maintenance instructions.

A building that has been designed and constructed with these guidelines in mind will be a healthy building. However, this does not necessarily mean that the indoor environment will be healthy: the activities carried on in the building can release pollutants as can the interior finishes, fittings and equipment.

Testing and evaluation

New designs should be tested and evaluated in terms of their safety to health and performance in respect of, and in relation to, moisture. Methods of calculation provide an important aid: calculations can be used to check the moisture status of a structural feature under normal circumstances with the assumption of a standard climate on both sides. Conditions with extremes of indoor and outdoor climates can then also be checked to assess the performance of different designs relative to each other.

Laboratory testing of structural elements can expose them either to standard climate on both sides or to extreme climates. Moisture variations in real structures can be investigated and compared with the theoretical values.

Test buildings are used to investigate the behaviour of design and structural features in natural outdoor climates. Indoor climates can be varied as required, establishing either a standard climate or more extreme values.

In the case of full-scale trials, i.e. investigations of existing buildings etc., trial conditions are more or less restricted to those actually encountered indoors and outdoors.
Contribution to the CIB W40 Borås meeting 1987

MOISTURE CONDITIONS AND MOULD ODOUR IN 146 SINGLE HOUSES

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ABSTRACT

The moisture content in the ground construction has been investigated in 24 houses. The houses have been selected among 146 houses with odour problems and some of the houses have been rebuilt. One measure among others was to ventilate the air space in the floor in order to create an underpressure which prevents the odour from coming up to the room. In most cases the odour problem was solved by this measure.

The problem

In the beginning of the 1970's 359 one-family houses were built in Uddevalla on the west coast of Sweden. Some years later mould odour occurred in 146 houses of these. Some of the houses had severe problems while in other houses the odour was observable only by the owner. However, a lot of people have investigated the odour in the houses and it is out of question that all these 146 houses have more or less problems.
Fig. 1 The area with the 359 houses.
The construction

The ground construction in the houses is concrete slabs with overlaying insulation. The construction is shown in figure 2.

![Diagram showing ground and wall construction with wooden panel, wall element, impregnated wood pieces, chip board, mineral wool, and studs.]

Fig. 2 The ground- and wall construction.

Mould growth

Mould growth is possible under the following conditions

- temperature above 0 °C
- relative humidity above 70-75 %
- presence of fungi spores
- oxygen
- wood or other material where fungi can grow

These conditions are present in the ground construction of the houses and there was a discussion if moisture could move into the construction according to one or more of the mechanisms described in figure 3.
Fig. 3 Some possible explanations of why the construction has a moisture content that allows mould growth and odour.

The three most possible transport mechanisms were moisture from the ground, condensation and built-in moisture.

Measures

The following measures were all used in the houses. Some houses had only one measure done other had two or more.

- improved drainage
- ventilation by underpressure in the construction

Fig. 5

- ozontreatment to take away the odour
- rebuilding the floor in some rooms.

Temperature and moisture measurements were done in 20 houses where the floor construction was rebuilt. Furthermore the same type of measurements were done in four reference houses without odour problems.

Results

The two tables show the results from measurements in one house with odour and another without odour (reference house). It is obvious that the moisture conditions in the two houses are about the same.

The floor construction was ventilated in most houses after they were rebuilt. The aim of this measure was to prevent the odour from coming up to the house. The result of this measure was controlled in an inquiry to the house owners. From 107 answers the result was that 72 were completely content, 28 noticed a slight odour and 7 had other complaints.
Table 1
MEASUREMENT IN HOUSE WITH ODOUR
Day of measuring: 1984-12-10

<table>
<thead>
<tr>
<th>Measuring point</th>
<th>Temperature °C</th>
<th>Relative Humidity %</th>
<th>Vapour content g/m³</th>
<th>Notes</th>
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</thead>
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<tr>
<td>1</td>
<td>11,7</td>
<td>80</td>
<td>8,4</td>
<td>on the slab</td>
</tr>
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<td>2</td>
<td>10,3</td>
<td>95</td>
<td>9,1</td>
<td>under the slab</td>
</tr>
<tr>
<td>2</td>
<td>13,8</td>
<td>84</td>
<td>10,0</td>
<td>on the slab</td>
</tr>
<tr>
<td>3</td>
<td>12,9</td>
<td>96</td>
<td>10,7</td>
<td>under the slab</td>
</tr>
<tr>
<td>3</td>
<td>13,8</td>
<td>63</td>
<td>7,5</td>
<td>on the slab</td>
</tr>
<tr>
<td>4</td>
<td>13,0</td>
<td>96</td>
<td>10,8</td>
<td>under the slab</td>
</tr>
<tr>
<td>4</td>
<td>11,3</td>
<td>90</td>
<td>9,1</td>
<td>on the slab</td>
</tr>
<tr>
<td>4</td>
<td>8,8</td>
<td>97</td>
<td>8,4</td>
<td>under the slab</td>
</tr>
<tr>
<td>Indoor</td>
<td>20,8</td>
<td>53</td>
<td>9,5</td>
<td>Additional moisture</td>
</tr>
<tr>
<td>Outside</td>
<td>6,0</td>
<td>74</td>
<td>5,4</td>
<td>4,1 g/m³</td>
</tr>
</tbody>
</table>
### Table 2

**MEASUREMENT (REFERENCE HOUSE)**

Day of measuring: 1985-10-24

<table>
<thead>
<tr>
<th>Measuring point</th>
<th>Temperature °C</th>
<th>Relative humidity %</th>
<th>Vapour content g/m³</th>
<th>Notes</th>
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<td>95</td>
<td>12.8</td>
<td>on the slab under the slab</td>
</tr>
<tr>
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<td>15.0</td>
<td>100</td>
<td>12.8</td>
<td>on the slab under the slab</td>
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<td>77</td>
<td>10.6</td>
<td>on the slab under the slab</td>
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<td>16.2</td>
<td>96</td>
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<td>on the slab under the slab</td>
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<td>3</td>
<td>16.2</td>
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<td>on the slab</td>
</tr>
<tr>
<td>Indoor</td>
<td>20.8</td>
<td>62</td>
<td>11.2</td>
<td>Additional moisture 4.3 g/m³</td>
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<tr>
<td>Outside</td>
<td>9.0</td>
<td>78</td>
<td>6.9</td>
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</table>
ACTIONs AGAINST MOISTuRE PROBLEMS AND MOuLD DAMAGE

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SUMMARY

This paper presents a SP-project evaluating different kinds of measures against moisture and mould problems. The drawn conclusions are based on measurement results acquired up to now. Final conclusions of the study will be presented in a later BFR-report.

The project is financed by grants of BFR.

1 INTRODUCTION

Since the beginning of the 1970's moisture damage of house foundations has increased conspicuously. A number of methods for coping with these problems have been tried out. Some of these have given good results, others had no effect at all. Theoretically, many methods are correct but they fail because they are not carried out carefully enough. Other methods are doubtful because they will not give any essential improvement. During recent years many methods have been presented for the solution of moisture problems, odours and mould. Up to now, no all comprising follow-up or evaluation of these methods has been carried out. On the other hand questions from property owners and managers regarding suitable actions and their reliability have become quite frequent.

2 DESCRIPTION OF THE PROJECT

The follow-up and evaluation of measures taken in a damaged house are carried out in three steps:

- The moisture conditions are determined as well as the extent of the damage before the action.
- Measurements are made during a period of at least one year after implementation of the action.
- The measurement results are evaluated in relation to the theoretically expected results.
The results of the various actions taken will be compiled in a report. In this report the different methods will be accounted for in the following manner:

- The object and its problems
- Investigations carried out and its conclusions
- Actions introduced
- The theory and the purpose of the actions
- The results of the follow-up measurements
- Evaluation of the method

Not all types of methods to solve moisture and mould problems have been evaluated because of economical limits.

3 POSSIBLE MEASURES AGAINST MOISTURE AND MOULD DAMAGES

Fourteen different types of moisture and mould damages have been studied up to now.

- Pressure ventilation under the base slab (Tyréns method).

The method is evaluated in three single unit dwellings and in a sports hall. So far the results vary slightly. In the single unit dwellings with light clinker foundation the method appears to give a positive result in about a year. In the sports hall the result is yet quite doubtful.

The effect of the measure taken has been improved to some extent by increasing the pressure ventilation under the slab.

![Diagram of pressure ventilation system](image_url)

Fig. 3 a

- Negative pressure ventilation with and without additional drainage.

The method is evaluated in three single unit dwellings built on a gravel bed. After one year of measurements the results are negative.
Fig. 3 b

- Deep drainage of the ground slab.

The method is evaluated in about ten single unit dwellings. The results depend on the nature of the foundation which partially explains the differing results.

Fig. 3 c

- Injection in the lower part of external cellar walls in order to prevent capillary suction up through the walls.

The method is studied in two houses with basements external cellar walls of lightweight concrete with capillary suction problems. It should be pointed out that the injecting fluid contains water that also will moisten the walls.

Just over a year after implementation of the action the moisture content can be seen to be lower than it was before the actions were carried out.

Fig. 3 d
- Balanced ventilation under the base slab.

Measurements are carried out at two single unit dwellings. In one of the houses where measure had been taken for about a year ago one can see positive results. No evaluation has been made of the measurements in the other house.

![Fig. 3 e](image)

- Negative pressure ventilation of a framework wall against an external cellar wall to prevent unpleasant odors to reach the inside air.

Two single unit dwellings have been studied. The method appears to give the intended result after about a year. Evaluation should be continued, however, during another year before drawing final conclusion.

![Fig. 3 f](image)
- Negative pressure ventilation of stud work on the base slab.

This method has been evaluated earlier in several houses. This project also includes own measurements on two additional single unit dwellings. So far the results of these later measurements are relatively good.

![Diagram: Air-tight seal](image-url)

Fig. 3 g

The evaluation of the following methods is in progress:

- Heating of external wall sills with heating coils.
- Ventilation in the air gap under a moisture barrier on the base slab.
- Moisture barrier on the upper surface of the base slab.
- Ventilation of external wall sills.
- Ventilation of the stud work on the base slab with the AVS method.
- Negative pressure ventilation of the crawl space under the building.

4 CONCLUSIONS.

It is very difficult to guarantee the result of an action taken because in many cases the construction is not always known in detail. On the other hand it is very important that the measures are carried out in a proper way.

This reliability of an action is sometimes affected by the fact that one is trying to change the function of an existing building part, using no more measures than necessary.
MOULD GROWTH ON WOOD

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BUILDING PHYSICS in the NORDIC COUNTRIES
Symposium in Lund, August 24-26, 1987

SUMMARY

A number of houses in Sweden have been damaged by mould growth. It has been learned by experience that such infections may occur in a climate where the humidity is constantly higher than 75% RH. However, in many constructions the RH level exceeds far beyond this limit without resulting in mould growth. In two research projects, the mould growth on wood blocks has been studied under controlled conditions at constant humidity (65, 75, 85, 95% RH, respectively). Initially, the wood blocks were placed in storehouses at sawmills for getting a "natural contamination" of spores from moulds. The results show that mould growth increased with increasing RH within the interval 75 - 95% RH and that it also increased in course of time. Moreover, it was obvious that the growth varied depending on where the wood blocks had been stored for contamination. The local, environmental conditions at the sawmills seem to influence stored wood in such a way that the wood will get mouldy or not when it afterwards get exposed to humidity between 75 and 95% RH. Other factors studied seem to be of less importance for the disposition of unpreserved wood to get mouldy.

INTRODUCTION

Mould-infected houses has been a problem in Sweden for at least 15 years. The infections appear on organic building material, like wood, when this is exposed to high humidity. Damages caused by moulds are frequently found in closed constructions, where a high humidity may last for a time which is long enough to allow mould growth. Thus, the infection is not initially observed by the eye but by the odour evolved from the growth. Further, liquid water is not a necessary moisture requirement and a relative humidity above 75% seems to be enough. The existence of mould growth on preserved wood makes the situation still more difficult to control. The biological background is simple. Dead, organic material normally starts to get mouldy when it is exposed to moisture. Fungal spores are present in the air everywhere, even if the frequency varies in course of a year. This makes practically all surfaces contaminated with spores and those which contain sufficient nourishment will be disposed for mould growth.

During the last decades new building material and new constructions have constantly been introduced to the market. Moreover, the handling with wood before it has been put in constructions, has changed. Even if we know about the basic principles for mould growth, we do not know enough to balance the damages caused in the present industrialized production of houses, where narrow margins is said to be a necessity.
We know by experience that mould growth is possible when the RH level exceeds 75 %, but we also know that no growth occurs in many constructions of the same kind as the mouldy ones, despite that the humidity is higher than this level. This directs our attention to the quality of the wooden material, which now been studied at the National Testing Institute (Borås).

Our starting-point was to imitate an important part of the history of commercial wooden material, in a laboratory scale. Blocks of wood where placed in storehouses at different sawmills and left there for exposure to environmental condition. Afterwards, the wood blocks were placed in humidity boxes (constant RH = 65, 75, 85, 95 % resp.) to imitate the situation in a closed construction and the mould growth was registered at regular intervals. Both natural and impregnated wood were tested in the same way.

This report is based on the results from two research projects (Hallenberg & Gilert, 1986, 1987).

MATERIAL AND METHODS

In the first project the wood blocks were selected from material sent to the National Testing Institute for ordinary firmness testing. Wood from pine (Pinus silvestris) and spruce (Picea abies), both fast-grown and slow-grown, were used. These blocks (about 200x50x30 mm) were placed in storehouses at 4 different sawmills to get exposed to the environmental conditions present there (including contamination by spores). After seven months exposure the wood blocks were gathered up to the institute where they were easily dried at room temperature. They were then placed in separate boxes with a regulated air flow of constant humidity (room temperature). Altogether 96 boxes divided into 4 RH levels (65, 75, 85, 95 % RH) were used.

At regular intervals pieces were taken from these blocks for mycological analysis. The first analysis were made just before the blocks were placed into the humidity boxes, the last after 14 months. The method used in these analysis is in principle a direct observation in the microscope (400 X magnification) of scraped off pieces from the wood surface. The frequency of fungal structures (hyphae, spores, fruitbodies) is calculated from these observations. An essential point is the frequency of hyphae, as their growth must be connected with conditions present at the wood surface.

The method for making this kind of mycological analysis has been developed by the mycologists working in connection with the National Testing Institute and is in detail described in Omér & Samuelson (1982) and Hallenberg & Gilert (1986). It is based on experience from a great number of investigations concerning damages caused by mould growth in houses.

The second project followed the same routine, but here the history of the wood blocks was better known. The material was obtained from a research project at the Department of Forest Products (Swedish University of Agricultural Sciences) regarding decay in window joinery. The wood blocks came from mature trees of pine and spruce, felled in Häreringland and Småland (central and southern part of Sweden). Both winter
felled and summer felled (ponded and non-ponded) timber were used. Further, one part of the sawn up boards was kiln dried, another part was laid out for air-drying.

A number of the wood blocks were treated with wood preservatives: CCA, CCB (pressure preservatives), Mitrol PQ, Järnia Träolja (superficial brushing; the last mentioned preservative lacks anti-fungal agents).

Two sets of wood blocks were placed in the storehouses of two sawmills. These sawmills had also been used in the first project and the exposure there had great, respectively little influence on the subsequent mould growth. After being exposed for environmental conditions during three months (September - November, 1985) the blocks were gathered up and treated in the same way as in the first project. However, this time the equipment for humidity boxes had been improved and it's capacity increased to 352 boxes.

RESULTS

From the first project the following conclusions could be drawn:

* Mould growth increased with increasing humidity within the interval 75 - 95 % RH. No growth was recorded at 65 % RH.

* Mould growth increased in course of time.

* Mould growth varied depending on where the wood blocks were stored during the exposure period at the sawmills. For example, when the blocks had been stored at one particular sawmill in southwestern Sweden (here called V1), mould growth was recorded when the RH-level was 75 % or higher. Wood blocks stored at another sawmill (here called Ö2) only got mouldy at 95 % RH. No growth was recorded at 75 or 85 % RH even after 14 months exposure to this humidity.

In the second project the mould growth was related to a number of factors, including exposure to environmental conditions at V1 and Ö2. An index has been calculated in order to visualize the degree of mould growth. This index is a number between 0 (no growth recorded) and 10 (rich growth in all samples) and is given for each RH-level (A = 65, B = 75, C = 85, D = 95 % RH). The index is calculated as a mean value of mould growth, for the total number of samples which share a common factor. These factors are related to the history of the wood blocks or the place where it has been stored. Further, the degree of mould growth is also included in the calculation of the index. After the index-figures (below), the number of samples is given (in brackets), upon which the index is based.

1. Wood blocks not treated with any preservative.

1.1. Wood blocks stored at V1 versus Ö2.

Index: V1 B 0,5 C 4,5 D 8,6 (16)
Ö2 B 0,3 C 0,7 D 6,0 (18)

The big difference recorded in the first project between these two sawmills was repeated. It is quite obvious that the environmental condi-
tions at V1 strongly favours mould growth on the exposed wood blocks when compared with Ö2. This factor is the most important one found here for non-treated wood. The influence is so strong that it has been desirable to give an additional index for the restricted number of blocks stored at Ö2, separately (below).

1.2. Pine compared with spruce

Index: Pine  B 0,1  C 2,3  D 8,1 (16)
        Spruce  B 0,6  C 2,5  D 6,4 (14)
        Pine–Ö2 B 0,2  C 1,3  D 7,1 (8)
        Spruce–Ö2 B 0,0  C 0,0  D 5,7 (7)

Judging from the material studied here, pine has a higher disposition to get mould growth than spruce. However, these differences are equalized when the wood blocks from V1 are included in the comparison.

1.3. Pine heartwood compared with pine sapwood.

Index: Heartwood  B 0,0  C 1,3  D 5,8 (4)
        Sapwood  B 0,0  C 3,9  D 8,9 (6)
        Heartwood–Ö2 B 0,0  C 0,0  D 1,7 (2)
        Sapwood–Ö2 B 0,0  C 3,3  D 7,8 (3)

Pine heartwood is more resistant to mould growth than sapwood, which was already known (see for instance Henningsson, 1984).

1.4. Timber from Hälsingland versus Småland.

Index: Småland  B 0,2  C 2,1  D 6,8 (16)
        Hälsingland B 0,5  C 2,7  D 8,0 (14)
        Småland–Ö2 B 0,0  C 0,4  D 5,4 (8)
        Hälsingland–Ö2 B 0,2  C 1,0  D 6,7 (7)

Contrary to traditional ideas it seems to be a slightly higher resistance towards mould growth on wood from southern Sweden (Småland) compared with central Sweden (Hälsingland). The difference is, however, very small.

1.5. Kiln dried versus air-dried wood.

Index: Kiln dried, pine  B 0,0  C 4,2  D 7,5 (4)
        Air-dried, pine  B 0,0  C 1,9  D 7,8 (6)
        Kiln dried, spruce B 0,0  C 2,5  D 5,4 (4)
        Air-dried, spruce B 0,0  C 3,8  D 8,3 (4)

Slightly higher resistance towards mould growth in airdried pine compared with kiln dried. The situation seems to be the opposite one in spruce.

Other comparisons made (winter felled versus summer felled, ponded versus non-ponded timber) did not result in any noticeably differences.

2. Wood blocks treated with different preservatives.

Index: CCA  B 0,0  C 0,0  D 1,8 (11)
        CCB  B 0,0  C 0,0  D 0,2 (10)
        Mitrol PQ B 0,0  C 0,8  D 2,9 (8)
        Järnia Träölja B 0,5  C 1,9  D 6,7 (14)
        Non-treated B 0,4  C 2,4  D 7,3 (34)

The pressure preservatives tested (CCA, CCB) seem to be very effective.
Mitrol PQ also had a good preservative effect but this was quite restricted to the brushed areas. Järnia Träolja had no anti-fungal effect. Henningsson (1984) made similar observations.

DISCUSSION

The results presented here are based on a limited number of tested samples. Therefore, no further statistical testing has been undertaken. On the other hand, the purpose has been to find indications on which factors that may influence the wood blocks to get mouldy. In further studies a representative material should be used, but for a restricted number of factors. When comparing the results with the situation in mould-infected houses it is important to stress that such comparisons can only be made with closed constructions and not with material which is exposed to outdoor situations. Further, the temperature in the humidity boxes were about 23°C, while normally much lower in mouldy constructions. Consequently, the mould growth is faster in the boxes.

The major result from these two projects is the discovery that environmental factors during storage seem to be important for the disposition of wood to get mouldy. In future research these environmental conditions should be analyzed in detail. One factor which has been discussed is the contamination of spores at the sawmills. The quantity and composition of air-borne spores were measured at the two sawmills (V1 and Ö2). Even if the quantity was higher in V1 than Ö2, there may as well be other environmental factors which are of high importance.

Another important result is the resistance towards mould infections, by pressure preservatives. Sometimes, however, mould growth is recorded from preserved wood in closed constructions. It now seems probably that such infections have occurred only when exposed to 100% RH.

ACKNOWLEDGEMENT

Financial support has been given by the National Testing Institute and the Swedish Council for Building Research.

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RADON IN RESIDENTIAL BUILDINGS - EXAMPLES OF DIFFERENT TYPES OF STRUCTURAL COUNTER-MEASURES

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Abstract

Many buildings in Sweden have a high radon concentration in the indoor air. To deal with this problem it is necessary to locate the radon source, to suggest proper counter-measures and to check that intended reduction in radon daughter levels has been achieved.

This paper describes a technique for investigation of buildings with high radon levels including a check of the building materials and measurements of radon/ radon daughter concentration and air change rate.

Principles for different counter-measures in new and existing buildings and results from actual cases are given.

Finally, the importance of a check that the intended reduction in radon concentration is achieved as well as the long run effectiveness of different counter-measures is discussed.

**

Many residential buildings in Sweden suffer from high radon levels in their indoor air. Radon can be released from building materials, the ground and water. Of these sources, radon from the ground is the most difficult to deal with.

In a joint research project with Allmänna Ingenjörsbyråns in Solna, the Swedish National Testing Institute has investigated the efficacy of various types of counter-measures intended to reduce radon levels in buildings. Over 100 buildings have been monitored, with measurements of radon levels before and after application of the counter-measures and also after a further interval of about 3-5 years. Comprehensive measurements have been made of radon and radon decay product (radon daughter) levels, air change rates, air flows in ventilation ducts and so on in about 15 of the buildings.

The following counter-measures have been evaluated:

- Negative pressure ventilation beneath the foundation slab.
- Positive pressure ventilation beneath the foundation slab.
- Negative pressure ventilation in ground structures.
- Sealing of leaks.
- Increased ventilation.
- Ventilation of underfloor crawl spaces.

These counter-measures have been applied to buildings in which radon has originated from the ground. Where the radon originates from building materials, the effect of increased ventilation and replacement of radon-releasing materials has been investigated.

The following guidelines should be applied when a building is being treated to reduce high radon decay product levels:

- The counter-measures must not result in other problems such as moisture condensation in the structure of the building.
- They must not be too complicated - occupants must be able to understand how the system works.
- The cost of the counter-measures should be as low as possible.
- The counter-measure must suit the design and structure of the building.
- The work will be considerably simplified if the sources of leakage are known.

The counter-measures must be durable, and not simply work for only a year or two.

Results

Comments are given below on some of the counter measures.

Negative pressure ventilation beneath the foundation slab

The principle of this method involves establishing a pressure difference across the foundation slab, intended to oppose the negative pressure induced inside the building by chimney effect. See Figure 1.

![Diagram of negative pressure ventilation](image)

**Figure 1.** Operating principle of negative pressure ventilation beneath the foundation slab. Note that the fan should be installed outside the building.
The requirements that should be fulfilled in order to apply negative pressure ventilation are:

- Duct penetrations through the slab must be airtight (right).
- Success of the method depends on the permeability of the ground, i.e. it is not suitable for use where the material beneath the foundation slab is airtight.

- The properties of the material beneath the slab must be known (see previous point).
- The system must be quiet in operation, both indoors and outdoors.
- The moisture production indoors must be low (corresponding 1-2 g/m²).

The fans used for this application create a pressure drop of about 300 Pa with an air flow rate of 30-40 m³/h. However, this does not necessarily mean that they have had to operate at maximum speed in all applications, as it is the pressure pattern across the foundation slab that is decisive. The ducts used should be made of plastic.

Figure 2 presents the results of negative pressure ventilation counter-measures.

![Bar chart showing radon decay product levels](image)

Figure 2. Column 1 indicates the radon decay product level in the houses before counter-measures, Column 2 immediately after and Column 3 as measured 3-5 years after original application. The values shown are averages for about thirty houses.
It can be seen from Figure 2 that, after 3-5 years, the radon decay product level has risen slightly in comparison with the level achieved immediately after application of the countermeasure. However, the increase is not large, and so the countermeasure can be regarded as being of lasting effect. In some cases, the radon decay product level had risen to the original pre-improvement level after some years. This has been caused by the fans either stopping or having been disconnected: the latter when the occupier felt that the equipment was too noisy.

The drawbacks of negative pressure ventilation beneath the slab are:

- Noise from fans and ducts.
- A risk of elevated radon decay product levels from leaks in the system.
- Susceptibility to interruption (fans stopping).
- A risk of cold floors.

The advantages of the method are:

- Cheap to install.
- Easy to install.
- No special components required.
- No risk of condensation problems.

Positive pressure ventilation beneath the foundation slab

The principle of this method depends on blowing ventilation exhaust air from the building down beneath the foundation slab, thus diluting the radon level in the ground.

![Diagram of positive pressure ventilation](image)

Ground radon

Figure 3. Operating principle of positive pressure ventilation beneath the foundation slab.
The requirements on such installations are largely the same as those for negative pressure ventilation, possibly with the exception that those relating to noise should be more stringent, as the fan in a positive pressure ventilation system is installed indoors.

Figure 4 shows performance results from counter-measures based on positive pressure ventilation.

![Graph showing radon decay product levels before and after counter-measures](image)

Figure 4. Column 1 indicates the radon decay product level in the houses before counter-measures and Column 2 immediately after application. The values shown are averages for about seven houses.

The reason for the lack of measurements taken 3-5 years after application of the original strategy is simply that this method was developed relatively recently. However, the results have been monitored in some houses after 3-5 years, and have shown that radon decay product levels have not changed from those applying immediately after the work was first carried out. This can indicate that the method still works 3-5 years after original application.

The drawbacks of positive pressure ventilation are:

- It is a relatively unproven method.
- Moisture beneath the slab can be made to migrate from the centre to the periphery. This is particularly the case towards the end of the winter, at which time the peripheral footing is at its coldest.
- It is sensitive to interruption (the fans stopping).
- The method is not suitable for use in terrace houses, linked houses or semi-detached houses - in such cases, there is a risk of assisting radon to penetrate into the houses.
The advantages of the method are:

- The ground beneath the centre of the foundation slab is dried.
- It is easy to install.
- No special components are required.
- It is cheap to install.
- Floors become warmer.

Which of these methods of ventilating the ground and changing the pressure pattern in it beneath foundation slabs is best? Comparisons have been made by applying both systems to a particular building and measuring the resulting radon decay product levels. It can be seen from the results in Table 5 that the radon decay product levels are approximately the same for both methods. If anything, they might be slightly lower with the positive pressure ventilation method, although this could be accounted for simply by high winds at the time when the tests were being carried out. This would result in somewhat lower radon decay product levels as the air change rate would increase. However, based on the results of this one test only, it is not possible to draw any conclusion concerning any difference between the two methods.

![Graphs showing radon decay product levels](image)

**Figure 5.** Radon decay product levels in a residential building with negative pressure and positive pressure ventilation of the ground beneath the foundation slab. The rising characteristic at the beginning of each of the two tests shows measurements made while the fans were stopped (5-10 hours), while the falling characteristic shows decay product levels with the fans running.
Ventilation in ground floor structure

The operating principle of this method involves creating a lower pressure beneath the floor than in the rest of the building, preventing ground radon from entering the building. The method has been successfully applied in many houses suffering from mildew. The operating principle is shown in Figure 6.

![Diagram of ventilation system](image)

**Figure 6. Operating principle of the ventilation.**

The requirements to be met in connection with this method are:

- The floor must be suitable for ventilation, i.e. a floating floor (consisting from the bottom and up of concrete, foamed plastic insulation slabs, chipboard and surfacing) cannot be ventilated.
- The negative pressure beneath the floor must be maintained even when the ventilation exhaust air fans in the rest of the house are operating at maximum speed.
- A negative pressure must be maintained beneath the entire floor.
- Ducts and fans must be airtight.
- The building must be airtight where the exterior walls join the foundations - if not, there is a risk of inducing exterior air and cooling the floor (right).

Figure 7 shows the results from ventilating a ground floor structure.
Figure 7. Column 1 indicates the radon decay product level in the houses before counter-measures, Column 2 immediately after and Column 3 as measured 3-5 years after original application. The values shown are averages for about eight houses.

It can be seen from Figure 7 that the method has a lasting effect, as there has been no great change in the radon decay product levels from immediately after application to a period 3-5 years later.

The benefit of ventilating a ground floor is that the floor becomes drier and warmer. Disadvantages are that the air flow rates beneath the floor are difficult to control, and that the ventilation system in the rest of the house is affected. This means that, for example, in houses having only natural ventilation, the exhaust air ducts may become supply air ducts. For this reason, houses to be treated by this method should incorporate mechanical exhaust ventilation.

Sealing

This is the simplest and cheapest means of tackling high radon decay product levels. However, if it is to be successful, the source of inward leakage must be known. Common leaks through foundation slab are around floor drains and cable or pipe penetrations, although settlement cracks may also provide a means of ingress.

Figure 8 shows how sealing should be applied around a floor drain. A silicone sealant should not be used: instead, a non-hardening mastic is preferable.
Figure 8. Method of sealing a floor drain.

The results from sealing are shown in Figure 9.

Figure 9. Column 1 indicates the radon decay product level in the houses before counter-measures, Column 2 immediately after and Column 3 as measured 3-5 years after original application. The values shown are averages for about ten houses.

It can be seen from Figure 9 that radon decay product levels have not changed when monitored 3-5 years after application, indicating that the method can be regarded as of lasting effect.
Summary

In the majority of cases, the follow-up measurements made in houses suffering from high radon levels have shown that the counter-measures are of lasting effect. However, how often the decay product levels need to be checked in order to establish permanency of improvement is open to discussion.

The counter-measures described in this paper have demonstrated that they are also suitable for application to buildings having very high radon decay product levels. When applying them, it helps if the points of ingress are known, as this enables suitable counter-measures to be selected, based on the structural details of the building and where the radon leaks are.
METHODS TO DEAL WITH THE PROBLEM OF RADON IN BUILDINGS

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SUMMARY

The objective of the study has been to check whether the counter-measures are still as effective as at the time when they were first applied. Various methods of dealing with the problem of radon in buildings have been investigated: in principle, all known methods were included in the review. The results that we obtained indicate that most of the counter-measures are still operating as intended. The results also show that it is possible to provide suitable counter-measures for buildings with very high radon decay product levels.

1 THE EXTENT OF THE STUDY

On behalf of the Swedish Council for Building Research, the Swedish National Testing Institute and Allmänna Ingenjörsbyrån in Solna (a firm of consultants) have evaluated the various measures adopted to deal with the problem of radon in buildings. Most of the problem buildings have suffered from influx of radon from the ground on which they are built. The counter-measures were applied 2-5 years before the review was carried out, and in the majority of cases measurements were available of radon decay product levels before and immediately after carrying out the work.

A total of 150 buildings has been included in the investigation, which has been carried out between two and five years after applying the counter-measures. In the majority of the houses, radon decay product levels have been checked using tracer film, while radon levels, radon decay product levels, air change rates and air flows in ventilation ducts have been measured in about a dozen houses in order to check the performance of some particular counter-measure.

Radon decay product levels had also been measured in the same way immediately before and after applying the counter-measures. As a result, conditions in these houses are very well documented.
The investigation has concentrated on buildings receiving radon from the ground. Some houses are also built from materials emitting radon.

The following types of counter-measures have been checked:

- Sealing the foundation slab (mainly with respect to the entry of services and drains).
- Pressure reduction beneath suspended floors.
- Ventilation of crawl spaces.
- Sub and over pressure ventilation of the capillary-breaking layer beneath the foundation slab.
- Increased indoor ventilation.

2 RESULTS

2.1 Sealing of foundation slabs

Leakage through the foundation slab or raft occurs in some buildings: such leakage is often around penetrations through the slab. If these points can be located, it is relatively simple and inexpensive to prevent ground radon from entering the building.

Buildings in which radon influx has been dealt with in this way have shown approximately the same radon decay product levels at the time of our subsequent visit as immediately after implementation of the method. In other words, this method of dealing with the problem still works effectively some years after implementation.

2.2 Exhaust ventilation beneath suspended floors

The principle of this method involves using fans to maintain a lower pressure beneath the floor and above the ground than in the building above, thus preventing ground radon from entering the building. The same method is also used in houses suffering from attack by mildew. Our subsequent checking indicated that there was no change in radon decay product levels relative to that measured after application of the method. However, it must be noted that this method of dealing with the problem has not been used in very many houses, and so there is no great fund of experience on which to draw.
2.3 Ventilation of crawl spaces

Houses built with crawl spaces beneath the ground floor suffer more often from high radon decay product levels than is generally realized. The reason is that the indoor pressure is lower than in the crawl space, causing air to be drawn in from the crawl space through gaps in the floor. One way of reducing radon decay product levels is to modify the pressure conditions so that the pressure in the crawl space is lower than in the house.

The majority of houses included in our investigation still exhibited low radon decay product levels, although levels had increased in a few houses since applying the counter-measure. This was probably due to a reduction in the capacity of the crawl space fans, with the result that pressure conditions were no longer the same as when the work was originally carried out.

Trials have also been carried out involving maintenance of over pressure in the crawl space. In five houses it was found that this resulted in a substantial reduction in radon levels in both the crawl space and the house. However, in one house the method was anything but successful, resulting in an increase in radon level in the house. It must be pointed out that this was only a trial, and that over pressure in the crawl space has not been applied as a permanent counter-measure.

2.4 Sub and over pressure ventilation of the capillary-breaking layer beneath the foundation slab

By using fans to maintain a sub pressure in the capillary-breaking layer beneath the foundation slab, radon can be prevented from penetrating into the building. This particular counter-measure has been applied to the greatest number of house (about 100), and so considerable experience is available.

Indoor radon decay product levels fell by about 90% immediately after application of this counter-measure, but were found to have increased slightly at the time of carrying out our subsequent checks. The reason for this is probably due to a deterioration in fan performance, with a resulting rise in sub pressure beneath the foundation slab. In a few houses the fans were found to have stopped entirely.

The results show that this method works quite well, although the problem for the house occupier is to know when fan capacity has dropped. Another difficulty is to
ensure that the material underneath the foundation slab has approximately the same permeability for air at all points, in order to be certain that all of it is properly ventilated.

Trials have also been conducted in some cases with arranging for fans to blow air from the house into the material underneath the foundation slab. The objective of this is to dilute the radon concentration beneath the slab, thus resulting in a corresponding reduction in indoor radon level. Results from this experiment are not consistent: in some cases, indoor radon levels have risen, while in others they have fallen. However, other consultants report good results from this method.

2.5 Increased indoor ventilation

Increasing the indoor air change rate is the commonest and most effective way of reducing high radon decay product levels caused by radon from building materials. This method can also be suitable for buildings suffering from only a small influx of ground radon. However, a necessary prerequisite is that the air change rate should be as little below atmospheric pressure as possible.

This counter-measure has been applied in about ten houses. Before application, indoor radiation levels were about 800–1100 Bq/m$^3$, falling to below 100 Bq/m$^3$ in most of the houses after application. Our subsequent monitoring revealed that radon decay product levels were still low, with one exception. In this house, the air change rate appeared to have dropped due to clogged filters in the ventilation system. In other words, it is important that the occupiers should maintain the ventilation systems.

2.6 Decoration with PVC wallpaper

This measure was applied in one house with radon-emitting structural materials. The impervious PVC wallpaper prevented radon from entering the house.

Before improvement, the radon decay product level was about 400 Bq/m$^3$, falling to about 200 Bq/m$^3$ afterwards. By the time that our checks were made, it had again risen to 400 Bq/m$^3$, indicating, for example, that the seams between the sheets of wallpaper were no longer impermeable.
Continuous measurement of radon levels over a period of a week indicated that very high levels occurred at irregular intervals. This indicates that the house was receiving additional input from ground radon, which had not previously been suspected. It is not therefore possible to say categorically whether the observed increase was due to failure of the seams of the wallpaper or to natural variation of radon decay product levels resulting from influx of ground radon at certain times. This illustrates the difficulty in deciding on the correct counter-measure to be applied.

3 CONCLUSIONS

One house had a level of over 35 000 Bq/m³ in the basement before improvement. After improvement, the maximum level of activity was 200 Bq/m³ in the basement, and this reduced level was still maintained over three years after applying the counter-measures.

The study show also:

- sealing of foundation slabs is also in long run a very effective counter-measures,
- its very important that ventilation systems are well maintained.

We have also monitored a number of different methods used in new building work and intended to prevent the diffusion of ground radon into buildings. Drain pipes have been laid in the capillary-breaking layer beneath the house before building. In some cases, fans have also been connected to these drains. The results indicate that houses can be built on ground with high radon release rates.
Healthy buildings with a sound indoor environment

Part of the business of the National Testing Institute is to monitor the development of damage and its effects on the indoor environment of buildings. The advice given to project planners is:

- Choose materials with known properties.
- Avoid problems in the design and in the material combination.
- Plan for the right level of ventilation in all areas.

The National Testing Institute works with questions relating to the indoor environment both in conjunction with such matters as investigation of damage, inspection of emissions from different materials, design of ventilation in buildings and in the planning of new constructions. The Testing Institute is often commissioned to evaluate the effects of measures adopted to counteract an unhealthy indoor environment.

Most of the problems which the Institute deals with relate to chemical pollutants or smells in the indoor environment, damage caused by damp or mould, and ventilation problems. These problems are often intimately related to one another. For instance, an examination of ventilation problems may lead to investigations of formaldehyde emissions from particle board, emissions of plasticizer from PVC flooring materials and mould in timber structures.

Healthy buildings

A healthy building offers good thermal comfort and suitable lighting. The building suffers from no noise and no pollutants. Unfortunately, not all buildings are healthy. A number of problems have arisen in recent years. It may be smell from mould and self-levelling screed which it is believed lead to tiredness, headaches and other sources of discomfort. It may also be completely new substances which have not been used before or have not been pinpointed as a problem source. The emission of formaldehyde, smells from building materials and radon emission from materials and ground are examples of just a few such sources.

The Testing Institute is in regular contact with the private sector, particularly in the field of ventilation. Materials and designs are inspected, and new products and designs are assessed and tested in the development stage. The knowledge gained from such activities, together with the experience of any number of damage claim investigations, constitutes the basis of the activities of the National Institute of Testing with regard to the indoor environment.

Sick buildings

Inefficient or faulty ventilation is often the reason why a concentration of pollutants accumulates in a building. There are also cases in which people living or working in a building become ill without it being possible to find the cause of the complaint. Such buildings are usually called sick buildings.

Emissions into the indoor air

The most important measure to be adopted for solving problems in the indoor environment is to reduce the emission of pollutants into the indoor air. Accordingly, planning for adequate ventilation is a key aspect.

There are two ways in which emissions can take place into the indoor air. They may come from materials which themselves emit pollutants. Examples of this are radon from blue aerated concrete, formaldehyde from certain types of particle board and plasticizer emissions from PVC.

But the emissions may also come from materials that emit pollutants in contact with other materials, or in an unsuitable design. One example of this is self-levelling screed which, in a damp alkaline environment, emits ammonia.

In both cases, the National Testing Institute has devoted a great deal of work aimed at clarifying the relationship between emissions and problems in the indoor environment.

What can be done?

If a building is to become healthy, it is vital to plan and construct the building in a certain way. But even so, this does not guarantee that the indoor environment will be healthy. The activities conducted in the building, the interior fixtures and fittings may also emit pollutants.

Some advice to planners:

- Select materials whose present and future properties are known.
- Design the structure and combine materials so that no problems can arise.
- Plan the ventilation so that every room and every space receives the correct degree of ventilation. Check the efficiency of the ventilation both on installation and after one year's operation. Draw up simple operational and maintenance instructions.

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Translation reprint of article from the magazine BYGGFORSKNING (BUILDING RESEARCH) No 3:1988
PERFORMANCE REQUIREMENTS APPLICABLE TO INSTRUMENTS FOR MEASURING INSULATION PERFORMANCE AND AIRTIGHTNESS IN BUILDINGS

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SUMMARY

The results showed that there were few instruments that were capable of measuring surface temperatures with the resolution, accuracy and repeatability necessary for use with present-day designs.

The results were even more depressing for the instruments intended to measure coefficient of thermal transmittance. Advertisements often claim that these instruments can find shortcomings in thermal insulation, which is simply not the case. For an instrument to have any value at all, it must be able to read values down to tenths of a W/m², as the heat flow through present-day structures is not large, even at high temperature differences.

When tracing air leakage, it was found that instruments that measure infra-red radiation need to brought right up to joints if they are not to miss a leak. This is due to the fact that it can be difficult to align them exactly on, say, a joint between floor and wall from a distance of a few metres.

1 THE EXTENT OF THE STUDY

The objective of this project has been to check whether the instruments available on the market today are capable of being used to measure insulation standards and airtightness of newly-built buildings. About 25 instruments, ranging from the simple to the sophisticated, were borrowed from various instrument manufacturers and suppliers. The results of the tests carried out are presented in a report, No. SP-RAPP 1984:32 (in Swedish), entitled "Measurement of Insulation Performance and Airtightness".

The instruments were divided up into the following groups: surface temperature, thermal resistance or coefficient of thermal transmittance and leakage. Their repeatability and ease of use were checked, and their general utility was assessed on the basis of their use in or with present-day buildings.
SURFACE TEMPERATURES

2.1 Performance requirements for temperature-measuring instruments

As modern houses are very well insulated, temperature differences between sound parts and areas of faulty insulation are small. Figure 2.1a shows, for a temperature difference of 20 °C, by how much the surface temperature is reduced when the coefficient of thermal transmittance is poorer than expected.

![Graph showing reduction in surface temperature](image)

Figure 2.1a The diagram above shows the reduction in surface temperature when U-value deteriorates. Internal surface thermal insulation has been assumed to be 0.2 m²°C/W.

It can be seen from the diagram above that the surface temperature of well-insulated structures does not alter very much, even with quite substantial lack of insulation. This means that such instruments must be capable of meeting the following requirements:

- Temperature indication in tenths of a degree (°C)
- Very high levels of accuracy and repeatability.
2.2 Results from checking instruments intended to measure surface temperature

Of the total of 13 instruments tested, eight displayed temperatures with a resolution of 0.1 °C. Four displayed temperatures in whole degrees, which meant that they could not be used to measure temperatures in well-insulated buildings. One instrument displayed W/m².

Bearing in mind the fact that accuracy of measurement, general applicability, repeatability and the ability to determine the extent of a defect were all important, there were only a few instruments (thermvision cameras) that could be regarded as fulfilling the necessary performance criteria. These instruments allow the surface temperatures of two surfaces to be displayed as isotherms. However, actually to measure the temperatures required the use of a second instrument, which can be a disadvantage.

The final assessment is that simple instruments are not capable of meeting the necessary requirements. Even quite large faults in insulation require advanced instruments if they are to be located with reasonable accuracy.

3 THERMAL RESISTANCE OR COEFFICIENT OF THERMAL TRANSMITTANCE

3.1 Performance requirements for instruments intended to measure thermal resistance or coefficient of thermal transmittance

Even when driven by large temperature differences between interior and exterior, the heat flow through well-insulated building structures is not large. Figure 3.1a shows the magnitude of heat flow for various types of structures with different amounts of insulation for a given temperature difference.

It can be seen from the diagram that, with a temperature difference of 20 °C, the heat flow increases by 2 W/m² for each 10 % increase in U-value. The first effect of this is therefore a requirement that any instrument used should display heat flow to a resolution of 0.1 W/m² if it is to be of any reasonable use in determining the U-value.

A second requirement is that the person using the instrument should be aware of the variations in heat flow through a building element. It is seldom or never that climatic conditions are constant over a sufficiently long time before measurement to allow the heat flow to reach equilibrium. The user of "instantaneous" instruments must
therefore be extremely cautious when stating a measured "instantaneous" U-value. One way of improving the accuracy obtained from such instruments is to make a series of readings over a longer period.

Temperature difference

3.2 Results from checking instruments intended to measure thermal resistance or coefficient of thermal transmittance

Of the total of six instruments tested, only one could be regarded as usable. It records heat flow continuously over a period of several days, printing out integrated values on a paper strip, normally at three-hourly intervals.

Of the remaining five instruments, four could not be regarded as anything other than poor. Many measured values, for example, differed by 50-100% from the calculated U-value, in spite of the fact that the tests were conducted under the best possible conditions. A climate chamber was used, in which steady-state conditions had been maintained for 2-3 days before the tests. It might be possible to develop one of the instruments to a level at which it becomes usable.
4.1 Results from checking instruments intended to trace air leakage

A total of 13 instruments was checked on a test wall incorporating built-in air leaks (the leaks were along the junction of the test wall with the climate chamber). Several persons with considerable experience of making such measurements were asked to trace the leaks: before starting, they did not know where the leaks were.

Nine of the instruments worked by measuring the infra-red radiation from the surface. Not all of the leaks were detected when using them at a distance from the surface, although all were detected when using the instruments close up against the joint. The difficulty when attempting to measure some distance away from the leak was to sight the instrument exactly on the joint, except in the case of those instruments that display the surfaces on a screen, with which there was no difficulty in tracing the leaks.

All the leaks were detected using the air velocity meters. These are probably also the most reliable instruments for this purpose, as the results cannot be misinterpreted. With the infra-red instruments, there is a risk of misinterpreting natural cooling in the joint resulting from a cold bridge as a leak.
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