Thermography

Testing of the Thermal Insulation and Airtightness of Buildings

Bertil Pettersson
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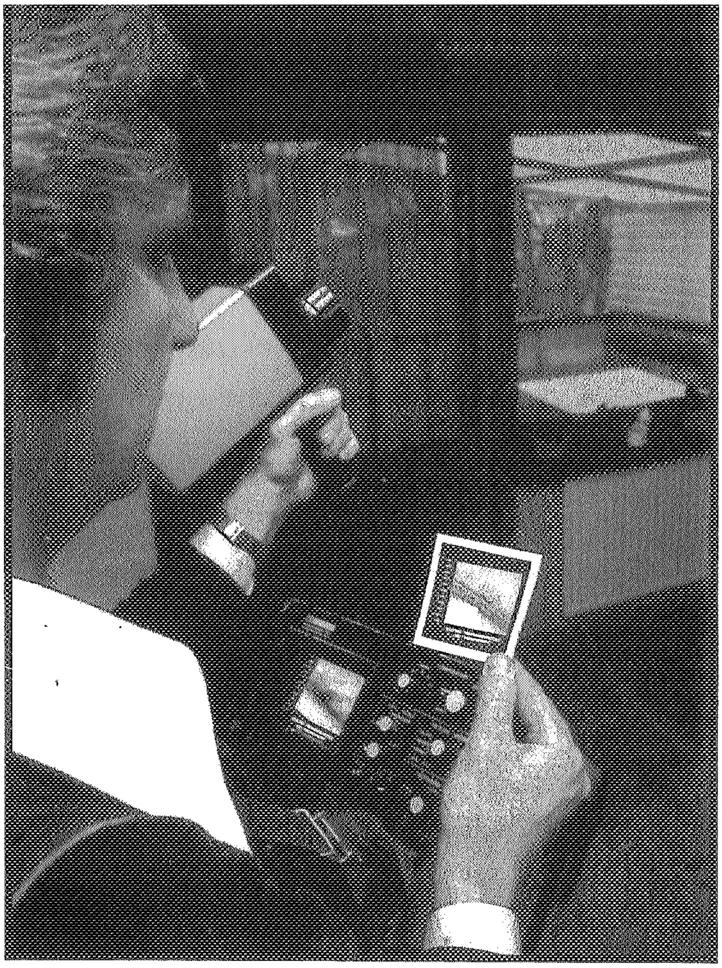

Swedish Council for Building Research

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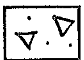
Contents

Symbols

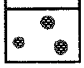
	Energy consumption	kWh
E	Energy flux per unit area	W/m^2
ΔI	Difference in isotherm units between two isotherm markings	
M	Thermal resistance of the structure	$m^2 \cdot K/W$
M_{tot}	Total thermal resistance	$m^2 \cdot K/W$
m_i	Surface thermal resistance on the inside of the structure	$m^2 \cdot K/W$
m_u	Surface thermal resistance on the outside of the structure	$m^2 \cdot K/W$
α	Surface coefficient of heat transfer	$W/(m^2 \cdot K)$
$\alpha_i = 1/m_i$	Surface coefficient of heat transfer on the inside of the structure	$W/(m^2 \cdot K)$
$\alpha_u = 1/m_u$	Surface coefficient of heat transfer on the outside fo the structure	$W/(m^2 \cdot K)$
k	Thermal transmittance	$W/(m^2 \cdot K)$ alt. $W/(m^2 \cdot {}^\circ C)$
p_i	Air pressure on the inside of the wall	Pa
p_u	Air pressure on the outside of the wall	Pa
$\Delta p = p_i - p_u$	Difference in air pressure, indoors–outdoors	Pa
p	Static pressure	Pa
q	Density of heat flow rate	W/m^2
T	Thermodynamic temperature	K
t	Celsius temperature	°C
t_{ref}	Reference temperature	°C
t_i	Indoor temperature	°C

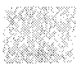
t_{vi}	Surface temperature on the inside of the structure	°C
t_u	Outdoor temperature	°C
t_{vu}	Surface temperature on the outside of the structure	°C
Δt	Temperature difference corresponding to the isotherm difference on the thermogram	°C
λ	Wavelength (radiation)	μm
C_s	Radiation constant for a black body	5,67 W/(m^2 · K)
c	Velocity of light	$3 \cdot 10^8$ m/s
g	Acceleration of gravity	9,81 m/s^2
h	Planck constant	$6{,}63 \cdot 10^{-34}$ Ws^2
k	Boltzmann constant	$1{,}38 \cdot 10^{-23}$ Ws/K
σ	Stefan & Boltzmann constant	$5{,}67 \cdot 10^{-8}$ W/(m^2·K^4)
α	Absorptance	1
τ	Transmittance	1
ρ	Reflectance	1
ϵ	Emittance	1
ρ	Density	kg/m^3
v	Velocity of wind	m/s
c	Specific heat capacity	J/(kg · K)

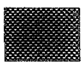
 Heat camera

 Concrete

 Lightweight concrete

 Lightweight-aggregate concrete

 Thermal insulation

 Defect marking

1 Introduction

1.1 General

There has been an increasing demand in recent years for low energy constructions. Owing to developments in the energy sector, and the demands for a satisfactory indoor climate, increasing attention must be paid both to the thermal insulation and airtightness performance of a building, and to the efficiency of its heating and ventilation system.

In edition No. 3 of Swedish Building Code, SBN 1975, The Swedish Nadional Board of Physical Planning and Building introduced new rules and regulations concerning economic management of energy in buildings, which implies that buildings are required to be airtight and to have a high degree of insulation. As regards workmanship and inspection, more stringent requirements have also been introduced concerning testing and checking by means of both laboratory and field measurements. There is a great need for suitable test methods whereby the thermal insulation and airtightness of buildings can be checked.

In buildings which are airtight and have a high degree of insulation, a low standard of insulation and airtightness may have a considerable influence on losses of energy. Defects in the thermal insulation and airtightness of a building will not only cause heating and maintenance costs to be excessive, but will also be instrumental in creating an unsatisfactory indoor climate.

At present, there are no reliable data available concerning the cost, in terms of an increase in annual energy consumption, of defects in insulation and airtightness. However, the results of a number of investigations indicate that such defects are very common even in recently constructed dwellings, and that these have a great influence on energy consumption.

The degree of insulation in a building is usually given in the form of a thermal resistance or a thermal transmittance (k-value) for the different parts of the building. However, the values of thermal resistance which are quoted seldom constitute a true measure of the transmission losses in a building. Movement of air through inadequately sealed joints and connections, and incorrect placing of insulation material, often give rise to appreciable deviations from the values on which design is based and which are expected in the completed construction.

Compliance of individual materials and building components with their specified properties is verified by tests in the laboratory. In order to ascertain that the intended insulation and airtightness of a building are really achieved, it is necessary to perform tests and checks in the completed building.

In the past few years, investigations have been performed in Sweden with the aim of developing a method for routine checking of the insulation and airtightness of buildings by means of thermography. With the aid of this method, the temperature distribution over a surface (in actual fact, the emission of thermal radiation from this) can be determined and reproduced.

In its structural application, thermography is used for the study of the temperature variations along the surfaces of the building structure. Under certain conditions, variations in the thermal resistance of the structure give rise to temperature variations over its surfaces. The leakage of cold (or warm) air through the construction also has an effect on the distribution of surface temperature. This makes possible the location and mapping of defects in insulation, thermal bridges and points of air leakage in the constructional elements which enclose the building.

The method of thermography does not directly give the thermal resistance or airtightness of the construction. In cases where the thermal resistance or airtightness are to be quantified, additional measurements must be made. When thermography is applied to buildings, certain conditions relating to the distribution of temperatures and pressures over the construction must be satisfied.

Appreciable variations in the amount of detail, shapes and contrast in the thermogram may arise when certain parameters are changed. A sound knowledge of the properties of materials and structures, the effect of climate and measuring techniques is therefore essential for a detailed analysis and interpretation of the thermogram. The assessment of the results of measurement imposes special demands on the competence and experience of the staff performing the measurements. One of the accepted qualifications is the authorisation given by the Swedish National Testing Institute.

The fundamental conditions underlying the thermography of buildings were previously the subject of investigation by the Swedish National Testing Institute. Some of this work was reported in a publication by the Swedish Council for Building Research, Paljak & Pettersson (1972). This publication, which mainly refers to measurements made in the laboratory, proposes rules for the interpretation of thermograms. The investigations described in this report were mainly made in situ, i.e. in completed buildings. They deal in greater detail with the parameters concerned, measuring conditions, the interpretation procedure, etc, and give practical examples of thermography and of systematic defects in the thermal insulation and airtightness of buildings.

1.2 Arrangement

The object of this publication is to give an account of the usability and reliability of the IR camera for the location and mapping of defects in insulation and airtightness in completed buildings, and to lay down a suitable procedure for the routine application of the method of thermography.

Chapter 1 gives an introduction of the method. Chapter 2 deals in general terms with energy consumption and energy requirements, and with the testing and checking of buildings. An outline description is given of the different methods available for verification of the state of insulation and airtightness of buildings. This chapter concludes with an assessment of the effect which effective control and testing is likely to have on the insulation and airtightness of buildings.

Chapter 3 discusses the influence of various parameters on the thermography of buildings. A brief description is given of the principle of operation of the infrared camera. The chapter examines thermal radiation and the way in which the emissivity, reflection and transmission characteristics of a surface influence the ability of the infrared camera to reproduce correctly the temperature of this surface. The relationship between surface temperatures and thermal resistance is discussed, and an account is given of the way in which variations in conditions, such as wind, surface resistance, temperature and insolation, influence the appearance of the thermogram.

The requirements which must be satisfied when buildings are subjected to thermography are specified in Chapter 4. Rules are given for the interpretation of thermograms, and the use of comparative thermograms, and examples are shown. The importance of correct camera setting for the quality of the thermograms is touched upon. This chapter also deals with the reliability of this method, i.e. the possibility of locating and determining with satisfactory accuracy defects in the insulation and airtightness of a building. Examples are given of the verification of defects indicated by thermography.

In Chapter 5, examples are given of comparative thermograms for common defects in insulation and airtightness. The purpose of these comparative thermograms is to facilitate the interpretation and assessment of thermograms in the field.

Chapter 6 gives examples of actual cases where certain constructions and components were examined.

Chapter 7 gives examples of the effectiveness of improvements made to remedy certain types of defects in insulation and airtightness.

Systematic defects in the thermal insulation and airtightness of buildings, for certain types of constructions, are described in Chapter 8. The investigation comprises about 400 projects, corresponding to about 3000 dwellings in single-family houses and blocks of flats. The geographical distribution of the projects covers the whole country.

Details of experience gained regarding structural design, materials and workmanship are given in Chapter 9. Recommendations are given concerning the preparations to be made prior to measurement, and a suitable procedure is indicated for the thermography of buildings. Chapter 10 gives a brief history of the application of thermography in buildings.

2 Energy consumption and testing

2.1 Energy consumption in Sweden

Over the period 1953–1973, total energy consumption in Sweden rose by 5–6% annually. The "oils crisis", which caused essential changes in conditions governing the consumption of oil in industrialised countries, occurred in 1973. Limitations in the supply of cheap and readily available energy became evident. There was a temporary drop in energy consumption in 1974, but consumption again rose after this. Compared with that prevailing before 1973, there is no tendency for the rate of increase in energy consumption after 1975 to drop. According to The National Central Bureau of Statistics (SCB), the total energy supply in Sweden in 1978 amounted to about 440 TWh (440.10^9 kWh).

According to the energy policy resolution adopted by the Parliament in 1975, the rate of increase in total energy consumption must be limited to an average of 2% annually up to 1985, while from the beginning of the 1990s there must be no increase at all in energy consumption. As far as the housing sector is concerned, this energy policy goal implies a planned drop in consumption by an average of 0.9% annually over the period 1975–85, in spite of the fact that the total housing stock is expected to increase.

Energy consumption is usually divided into three sectors: industry, communications and others. The distribution over these sectors has been broadly the same during the past few years. About 40% of energy is consumed by industry, about 20% by communications, and about 40% by the "others" sector.

In this latter sector, most of the energy is used for purposes of comfort, i.e. heating, ventilation, lighting etc in dwellings and other premises such as nursing homes, hospitals, offices, schools and holiday houses.

Since almost one half of the energy consumed in Sweden is used for comfort purposes in the "others" sector, this sector is of great interest when measures to save energy are being considered. An approximate breakdown of energy consumption in dwellings is about 54% in single-family houses and about 46% in blocks of flats.

2.2 Energy consumption in a building

The energy losses in a building can be broadly divided into the following headings:

- Transmission losses through the surfaces enclosing the building
- Ventilation, which consists of an intentional portion by means of ventilation equipment, etc and an unintentional portion which occurs through points of leakage in the building.

In addition to the above, energy is also used for water heating, household appliances, etc, which energy may to a certain extent be utilised in heating the building.

In the major investigations concerning the energy sector, estimates have been made of the annual losses of energy in existing buildings. The following figures have been quoted (SOU 1977:56):

Dwellings	Single-family houses and blocks of flats	≈ 100 TWh/year
Other premises	Industrial	≈ 25 TWh/year
	Others	≈ 50 TWh/year

FIG. 1 shows an example of energy consumption in a single-family house insulated according to a normal standard in Sweden at the beginning of the 1970s. An air change rate of 0.8 per hour has been assumed for ventilation.

FIG. 2 shows an example of energy consumption in a similar single-family house provided with insulation in accordance with the new requirements laid down in Swedish Building Code 1975 (SBN 1975) /16/. As will be seen, there has been an appreciable increase in the degree of insulation. An air change rate of 0.5 per hour has been assumed for ventilation.

Transmission losses are determined theoretically by the thermal resistance of k-value of the different parts of the building. In designing the thermal resistance of a construction, the aim is to achieve the desired indoor climate in the best possible way with regard to the given outdoor climate. This also necessitates some form of climatic installation, for instance heating and ventilation equipment.

The transmission and ventilation losses given in FIG. 1 and 2 are valid for construction free of defects. Experience has shown that defective installation of insulation, windproofing and joint sealants often give rise to considerable deviations from the expected energy consumption in a building.

In order that an optimum degree of insulation and airtightness may be achieved in practice, it is essential that

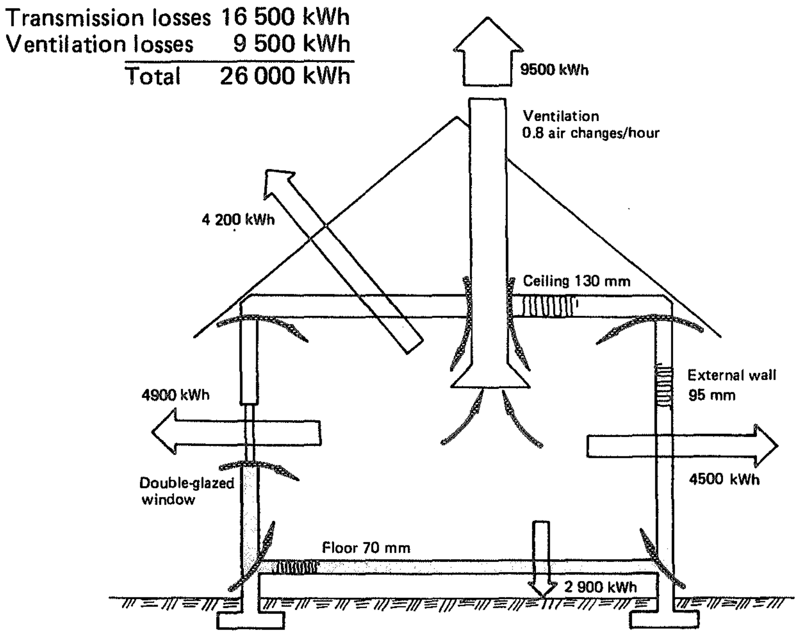


Fig. 1. Ventilation and transmission losses in a single-family house of 125 m^2 area, insulated in accordance with normal standard in Sweden at the beginning of the 1970s.

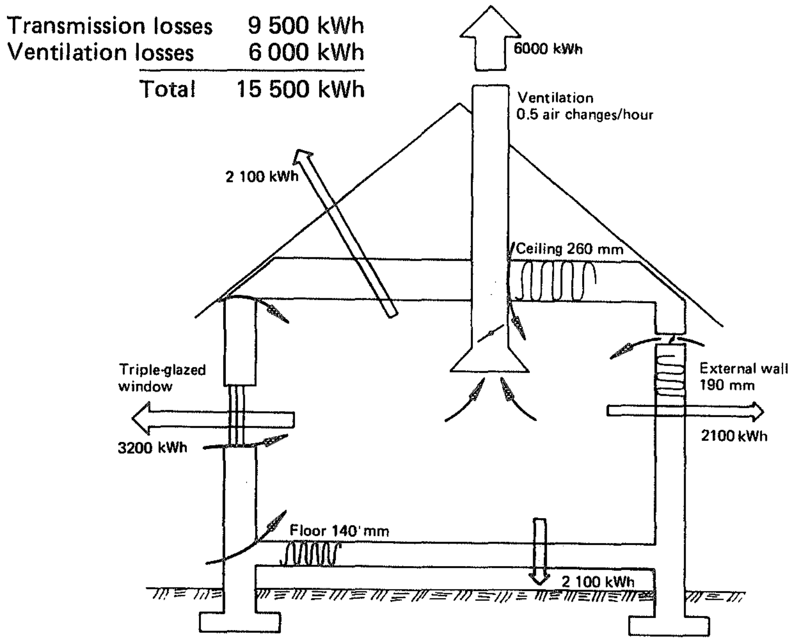


Fig. 2. Ventilation and transmission losses in a single-family house of 125 m^2 area, insulated in accordance with the requirements laid down in SBN 1975.

the correct design rules be used and that the estimates made concerning the cost of energy and the rises in this be correct. What is of decisive importance, however, is that the intended insulation and airtightness performance should be achieved. This is influenced by the design, the choice of materials and the standard of workmanship. In constructions provided with a high degree of insulation and airtightness, this is especially important since defects in such constructions have a greater relative effect than those in constructions with a lower degree of insulation and airtightness.

2.3 Requirements and guidelines according to SBN 1975

2.3.1 Thermal insulation and airtightness

Swedish Building Code, SBN 1975, lays down certain general requirements concerning the thermal insulation and airtightness of residential buildings. Section 33:1 reads:

"A building which is to be maintained at a temperature above that outdoors shall be thermally insulated and tightened to the movement of air to such an extent that no hygienic inconvenience will arise, and that the emission of heat and movement of air through the surfaces enclosing the building are limited so as to conform to the requirement concerning economical management of energy."

The following is prescribed with regard to the airtightness of building elements (Section 33:3):

"Building elements enclosing premises which are to be maintained at a temperature above that outdoors, and the connections between these elements, are to be constructed in such a way that undue movement of air through these is prevented."

The following is prescribed with regard to design (Section 33:4):

"Building elements provided with thermal insulation, and the connection between such elements, shall be designed in such a way that no movement of air, which unduly reduces their thermal insulation capacity, occurs inside these elements. The construction shall further be designed in such a way that the materials comprised in the construction do not attain a moisture content which impairs the performance and durability of the construction. In addition, the construction shall be designed in such a way that undue thermal bridges are not formed."

In the Building Codes, these requirements are supplemented by the specification of highest permissible values of permeability and the k-value for both building elements and the complete building.

2.3.2 Testing and checking

One consequence of the stringent demands imposed on a construction from the energy consumption standpoint is that testing and checking have become essential requirements in order that the expected performance may be secured.

Section 33:5 of SBN 1975 lays down the following with regard to workmanship and supervision:

"Building elements provided with thermal insulation shall be constructed and erected in accordance with approved documents and under the supervision of the responsible site supervisor. It is the duty of the responsible site supervisor to check, by inspecting the insulation and joints, etc., in the construction, that workmanship is satisfactory.

The airtightness of a completed construction shall be checked by means of random tests. Special checks concerning the thermal insulation and airtightness of the completed construction shall be made in cases where doubt arises regarding the standard of workmanship and the Building Committee considers that such checks are warranted."

In the Commentary to Swedish Building Code, 1977:3, Economical management of energy, etc., Section 33:5K lays down the following with regard to special checks concerning the airtightness and thermal insulation of buildings:

"Special checks concerning thermal insulation and airtightness shall be made where there is reason to suspect that the standard of workmanship with regard to thermal insulation capacity of airtightness is unsatisfactory. One such reason may be that satisfactory results are not obtained in the course of ordinary airtightness checks in accordance with the above; tests over and above those originally intended may in such a case be prescribed by the Building Committee.

One other reason may be that, in the course of inspection, insulation or airtightness are found to be below standard.

Special tests regarding airtightness shall be carried out using the method and procedure specified for the ordinary airtightness test according to the above.

Movement of air through the construction may be traced by means of an infrared camera.

Special checks with regard to thermal insulation may be carried out by one of the following methods:

a) Assessment of the state of thermal insulation by thermography with an infrared camera.
b) Measurement of the thermal insulation capacity of the sections concerned by determination of thermal resistance.
c) Dismantling of the construction at the sections concerned, and visual inspection of the standard of installation of thermal insulation."

2.4 The effect of testing and checking

The performance of thermal insulation and the degree of airtightness in a completed building may be difficult to predict. During the erection of the various components and building elements on the site, operations occur which can have a very great effect on the final results. The effect of transport, handling and storage on the site, as well as that of workmanship, cannot be estimated in advance. In order that the intended performance may be attained in practice, verification by testing and checking in the completed building is essential.

The insulation techniques of today have reduced the theoretical heat requirement below that previously necessary. This implies, however, that defects of a relatively minor nature – but situated in critical positions – for instance, inadequately sealed joints or faults in placing the insulation material, may have considerable consequences from the points of view of both heat requirements and comfort. Verification tests by means of e.g. thermography have been found valuable from the points of view of designers and constructors and also building owners, property managers and the users.

As far as *the designer* is concerned, it is essential that the performance of different types of constructions should be known, so that these may be designed with regard to both workmanship and performance requirements. The designer must also know how different materials and material combinations work in practice. Effective testing and control, as well as the feedback of data, can lead to the desired development in this field.

Increased testing and control is essential from the point of view of *the constructor,* in order that he may be sure that the constructions conform to an expected performance laid down in official specifications and the contract documents. The constructor must be informed at an early stage of the construction of any changes which must be made in order that systematic defects may be avoided. During the construction stage, checks must therefore be made in the dwellings first completed in a series. These checks must then be repeated as production continues. Systematic defects can be avoided, and unnecessary costs and problems prevented, in this way. These checks are beneficial for both the producer and the user.

From the point of view of *the building owner and the property manager,* it is important that buildings should be subjected to checks with regard to thermal economy, maintenance (damage due to moisture or moisture movement), and the comfort of the occupants (for instance, cool surfaces and movements of air in the occupation zone).

As far as *the user* is concerned, it is important that the completed product should meet the requirements laid down with regard to the thermal insulation and airtightness of the building. For an individual, the purchase of a house entails a considerable economic commitment, and it is therefore of great importance to him that any defects in construction which may occur should not have serious economic consequences or give rise to hygienic inconvenience.

In accordance with the inspection procedure employed up to now, the buyer is entitled to be present when the final inspection is made (on occupation of the property and at the guarantee inspection which takes place one to two years after final inspection). These inspections are made by an independent inspector. Assessment of the thermal insulation and airtightness of a building by means of visual inspection is very difficult, and these inspections therefore chiefly relate to obvious faults and cosmetic defects. It is quite possible for extensive concealed defects in workmanship to remain undetected, with serious consequences for the user.

The effect due to testing and control of the thermal insulation of a building is both physiological and economical in character.

The physiological perception of the climatic environment indoors is of a very individual nature. It varies because the thermal balance and temperature perception of the human body are different from person to person. The perception of climate depends on both the temperature of the room air and the temperatures of surrounding surfaces. The velocity and humidity of the room air are also significant. From the physiological point of view, the sensation of a draught is due to local cooling of the surface of the body caused by

- excessive air movements in the occupation zone with a normal air temperature,
- normal air movements in the occupation zone with an abnormally low temperature,
- a large exchange of radiant heat with a cold surface.

It is difficult to assess quantitatively the effect due to testing and checking the thermal insulation and airtightness of a building. However, the following has been found in the course of these investigations.

In a number of cases, it was found that the cost of measures to remedy defects in insulation and airtightness may be as much as Skr. 3000–5000 per house or even more, if the defect is not discovered until after the house has been completed and the occupants have moved in. Testing and checking should be carried out at the beginning of a construction stage. This should be such in scope that systematic defects can be detected and put right at an early stage. Examples have proved that the cost of measures and alterations can be cut to a very low level. Random tests in a number of single-family houses or dwellings in a group of buildings can have an appreciable effect without all the units having to be subjected to test. In cases where thermography has been specified in the contract documents as a control measure, an appreciable improvement in workmanship has been noticeable in comparison with the usual situation.

Investigations have shown that defects found in the thermal insulation and airtightness of buildings in many cases give rise to heat losses 20–30% higher than those expected. Determination of energy consumption before and after remedial measures in relatively large estates of single-family houses and in blocks of flats has also given the same results. It is probable that the above figures are not representative for buildings in general, since the investigation material cannot be said to be typical of the entire housing stock. At a conservative estimate, however, effective testing and checking of the thermal insulation and airtightness of buildings may cut energy consumption by minimum about 10%.

The investigations have also shown that an increase in energy consumption connected with defects is often due to the occupants raising the indoor temperature by a degree or two above the normal in order to compensate for the effect of an unpleasant radiation of heat towards cool surfaces, or for undue air movements in the room.

2.5 Methods and apparatus for checking the insulation and airtightness of buildings

Properties	Thermography	Meas. of surface (air) temp	Radiation measurement	Heat flow measurement	Tracer gas method	Pressure method	Air velocity measurement	Smoke test	Soap bubble method	Dismantling	Examination of drawings
Thermal resistance	1	1	1	2	–	–	–	–	–	1	1
Standard of insulation	2	1	1	1	–	–	–	–	–	2	–
Airtightness (according to SBN 1975)	1	–	–	–	0	2	0	0	–	0	0
Standard of airtightness	2	1	1	–	1	1	1	1	1	1	–
Degree of ventilation	–	–	–	–	2	0	0	0	–	–	–
Air movements inside construction	2	1	1	–	–	0	1	0	–	0	0
Movements in room air	–	–	–	–	–	–	2	1	–	–	–
Surface temperature	2	2	2	–	–	–	–	–	–	–	–
Air temperature	–	2	–	–	–	–	–	–	–	–	–

Suitability is graded as follows: 2 Suitable (recommended); 1 Less suitable (can give an idea of property in question); 0 Unsuitable; – Not usable

Table 1. Summary of methods which can be used for verification of the insulation and airtightness of buildings.

Defects in the thermal insulation and airtightness of buildings will be manifested by abnormally high heating costs and an unsatisfactory indoor climate.

The methods which can be used for the verification of the quantities which influence energy losses and the climate in a building are set out in TABLE 1. With the exception of the soap bubble method, these methods have been tested in this investigation.

A. Measurement of surface temperature

1. Thermography

Instrument	Infrared camera, surface temperature recording instrument, manometer and air velocity recording instrument.
Measuring accuracy	± 0.5 °C or ± 10% of the measured temperature difference.
Principle	Recording of thermal radiation within the 2.0–5.6 μm wavelength region. Measurement and reproduction of the distribution of radiation over a surface.
Method	The distribution of thermal resistance and the standard of workmanship relating to insulation and airtightness are assessed by a reproduction and mapping of the surface temperature distribution. (Swedish Standard SIS 02 42 10.)
Field of application	Completed buildings; building elements, joints, connections between precast units and junctions.

Advantages:
The method is quick and provides a clear picture of the temperature distribution due to the radiation emitted from a surface of large dimensions.

Measurements can be made on inaccessible surfaces. During measurement, there is no interference due to contact between measuring instrument and the object.

A picture is obtained of the insulation and airtightness performance of the construction.

With the aid of the infrared camera, defects in insulation, points of air leakage and thermal bridges in the construction can be located and mapped. The method is educational. The results of thermography are suitable for use in the feedback of experience.

(Excellent supplement to measurements of thermal resistance and airtightness according to B and C.)

Limitations:
The method is qualitative and does not give direct values of the thermal resistance or airtightness.

The method necessitates that certain conditions concerning temperatures and pressures over the construction should be satisfied.

The method necessitates the exercise of judgment, and staff must therefore be competent and experienced.

2. Surface thermometer

Instrument	Rapid thermometer. Electrical instrument incorporating a thermocouple or resistance sensor.
Measuring accuracy	± 0.5 °C
Principle	The instrument (sensor) is placed in contact with the surface in question, whereupon the temperature is measured at a certain point.
Method	By measurement and mapping of the surface temperature, the thermal resistance and standard of insulation are roughly assessed.
Field of application	Building elements, joints between precast units, connections.

Advantages:
Measurement is made at certain definite points, and the actual temperature of the surface is determined at these points. Areas of defective thermal insulation capacity can be located. The method is relatively simple.

Limitations:
Location of defects in insulation and points of air leakage in an entire building is very time consuming.

Owing to contact between sensor and surface, the surface temperature field is liable to interference. The method necessitates certain temperature and pressure conditions. Normally, only major defects in insulation are detected.

Competence and experience are needed for the assessment of the results.

3. Instrument sensitive to infrared radiation

Instrument	Radiation pyrometer
Measuring accuracy	± 1 °C.
Principle	Measurement of thermal radiation emitted from the surface. Reading depends on the emissivity and temperature of the object.
Method	The thermal resistance and the standard of insulation and airtightness are roughly assessed by measurement of the surface temperature.
Field of application	Building elements, joints between precast units, and connections.

Advantages:
Measurement is made at certain points where the temperature of the surface can be determined.

Measurement of several points over a certain surface can be made from one position. There is no interference due to contact between instrument and the surface. Surfaces which are difficult to get at can be subjected to measurement. Areas of defective thermal insulation capacity can be located.

Limitations:
Insufficient accuracy for determination of absolute temperatures. Unreliable in certain cases. The radiation characteristics of the surface must be taken into account.

Necessitates certain temperature and pressure conditions. Staff must have competence and experience for the assessment of the results. Normally, only major defects in insulation can be detected.

B. Determination of thermal resistance and k-value

1.

Instrument	Heat flow meter, temperature sensor and recording equipment.
Measuring accuracy	± 10% of the measured value.
Principle	The heat flow through the construction is measured.
Method	The thermal resistance is determined by simultaneous measurement of the temperature difference over the construction and the (unidimensional) heat flow through this under stationary conditions.
Field of application	Building elements.

Advantages:
The measurement gives values of the thermal resistance or thermal transmittance of the wall at certain sections. Relatively high measuring accuracy.

Limitations:
Conditions during measurement must conform to special requirements. Readings are obtained only at sections of limited extent. Time consuming to make measurements in an entire building. Unsuitable for location of defects in insulation.

The method requires competent and experienced staff.

When supplemented by thermography, sections of defective thermal insulation capacity are pinpointed. Thermography can be employed for the correct positioning of the points of measurement.

2.

Instrument	Mobile hot box, temperature sensor and recording equipment.
Measuring accurracy	± 10% of the measured value.
Principle	Measurement of heat flow through the construction over a section of large dimensions which may include thermal bridges. The open side of the hot box is placed against the surface to be measured. The temperature in the box is made the same as that outside. The power suppled thus passes through the test surface.
Method	The thermal resistance is determined by simultaneous measurement of surface temperatures over the construction and the heat flow through this under stationary conditions. (This method has not yet been developed fully for use in the field.)
Field of application	Building elements, joints between precast units.

Advantages:
The measurement gives a quantitative value of the thermal resistance or k-value of the wall over a certain section which may contain thermal bridges. Relatively high measuring accuracy.

Limitations:
The measurement conditions must conform to special requirements. Time consuming to make measurements in an entire building. Not suitable for location of defects in insulation and points of air leakage.

This method is normally more suited to laboratory use.

C. Testing and checking the airtightness of a building

1. The tracer gas method

Instrument	Gas analyser.
Measuring accuracy	–
Principle	The number of air changes per time unit in a room (building) is determined by measurement of the variation in the concentration of tracer gas with time.
Method	Assessment of the airtightness and energy losses in a building by determination of the degree of ventilation under different conditions.
Field of application	Completed building (definite volumes).

Advantages:
The measurement provides values of the degree of ventilation in the building under actual conditions. Continuous measurements can give values of the annual ventilation losses in the building.

Limitations:
The method does not provide information concerning points of air leakage. The measurement is a result of interaction between the points of leakage in the building and the weather situation at the time of measurement. Movements of air inside the construction cannot be verified. Not suitable as a routine method for quality control of the airtightness of a building. Slow in an airtight building.

2. The pressure method

Instrument	Speed regulated fan with a tube for measurement of air flow. Micromanometer for measurement of pressure.
Measuring accuracy	± 6% of the measured value.
Principle	Determination of air flow Q at a pressure drop of 50 Pa over the construction. The number of air changes is determined from the relationship. $n = \frac{Q}{V}$, where V is the volume of the building.
Method	Assessment of the airtightness of the building by determination of the flow of air through the surfaces enclosing the building at a pressure drop of 50 Pa over the construction.
Field of application	Completed building. (Definite volumes, not too large in size.)

Advantages:
Simple apparatus for small volumes (< 700 m^3). The method is rapid and unambiguous, and provides a value of the building at the applied pressure.

Measurement is normally independent of weather at the time of measurement. The method is suitable for use, for instance, in quality control of the airtightness of buildings, comparisons between buildings, and for code requirements.

Limitations:
Measurement provides no information concerning true air leakage under operational conditions. No information is given as to position of air leakage. Air movements inside the construction cannot be detected. For large volumes, bulky apparatus is required.

3. Measurement of air velocity.

Instrument	Hot-wire anemometer type instrument for measurement of air velocity.
Measuring accuracy	± 0.2 m/s within the range 0.2–10 m/s.
Principle	In the hot-wire anemometer, the cooling effect of air on a heated wire is used as a measure of air velocity. Measurement is carried out near the surface of the construction where air movements indicate leakage of air through the construction.
Method	Assessment of the airtightness of a building by measurement of air velocity near the surface of the construction.
Field of application	Joints, connections between precast units, junctions (e.g. at eaves, floors, windows, etc).

Advantages:
The measurement provides a value of air velocity at the point of leakage. Leakage of air right through the construction can be detected. The instrument is easily handled. Points of leakage can be located.

Limitations:
Time consuming to locate points of air leakage in an entire building. The measurement gives no information concerning the quantities of air leaking through the construction. Air movements inside the construction cannot be detected. A certain pressure difference (5–10 Pa) is required across the construction. Using only this measurement as the basis, it can be difficult to decide what remedial measure is necessary. Low reproducibility.

4. Smoke tests

Instrument	Smoke pistol.
Principle	Assessment of air velocity by observation of the movements of puffs of smoke. When a search is made for points of air leakage in a building, movements of the smoke at the surfaces of the construction are observed visually. Movements of smoke indicate leakage of air through the construction.
Method	Assessment of the airtightness by observation of the movements of smoke at the surfaces of the constructions.
Field of application	Joints, connections between precast units, junctions, windows, etc.

Advantages:
Leakage of air right through the construction can be detected. A picture is given of air movements at the point of leakage. The smoke provides information concerning the

direction of flow of the air and its approximate velocity in the room. May also give information concerning leakage paths through the construction.

Limitations:
Time consuming to locate defects. Provides no information concerning the quantities of air leaking through the construction. Dependent on pressure drop across the construction. The smoke may be an irritant.

5. Soap bubble method

Principle	Soapy water is spread over the surface of the construction, and the presence of bubbles indicates a point of leakage.
Method	Assessment of the airtightness of a building by observation of soap bubbles.
Field of application	Joints between precast units, junctions and connections.

Advantages:
Leakage of air right through the construction can be detected. Indicates the position of points of leakage. Clear presentation.

Limitations:
Time consuming to locate points of leakage. Necessitates a drop in pressure across the construction. Unsuitable for use in completed buildings.

D. Investigation of thermal insulation and airtightness by dismantling and visual inspection

Instrument	Various tools and rule.
Principle	The construction is dismantled and the standard of insulation and airtightness is determined visually. Measurement of insulation thicknesses, cracks and gaps.
Method	Assessment of the thermal resistance and the standard of insulation and airtightness by dismantling and visual inspection of certain sections. The appropriate drawings should be examined at the same time.
Field of application	Building elements, joints, junctions, etc.

Advantages:
The method indicates directly the absence or incorrect placing of insulation material. Can be used where damage or defect is suspected.

Limitations:
Difficult to see the placing of material in a second layer, a fold between layers of material or near the surfaces of the construction, etc.

Paths of air leakage may be difficult to detect on visual inspection. Defects may be masked by adjacent material. Destructive method which may be time consuming and expensive. Not suitable as a routine method.

(May be used as a supplement to thermography in order to elucidate conditions.)

Major defects and shortcomings can in certain instances be detected by simple methods, e.g. by feeling by hand or by observing the deposition of dirt on the surface.

3 The parameters involved in thermography

3.1 The principle of the infrared camera

In the infrared technique, the infrared (thermal) radiation emitted by an object is utilised in order to form an image of the object and to determine its temperature. The radiation emitted by a surface at room temperature is within the infrared region (0.7–100 μm). Radiation from a surface is a function not only of the temperature of the surface but also of its emissivity and reflection characteristics. An infrared camera records and reproduces on an oscilloscope the thermal radiation emitted by or reflected from surfaces in the form of a black-and-white image, a thermogram. The technique whereby thermal radiation is reproduced and measured is designated thermography.

The properties of an infrared camera are determined by its sensitivity range, its thermal and optical resolution capacity, the size of the image field, and the rate of scanning. Modern infrared cameras, with a range of sensitivity of 2.0–5.6 μm, are equipped with a scanning system which permits measurement of the individual energy fluxes emitted by a large number of elements over a surface, and the camera is capable in this way of forming a "radiation image" of the surface. This radiation image (thermal image) is presented on the screen of an oscilloscope (FIG. 3a). This thermal image can be photographed with an ordinary camera, in which way a thermogram is obtained (FIG. 3b and 3c).

Certain types of camera can reproduce the temperature distribution both on a grey scale (ranging from black to white) and on a colour scale.

In the black-and-white thermal image (see the detail in FIG. 3b), portions which are darker in the grey scale represent surfaces of a lower temperature than portions of a lighter grey colour.

In a colour thermogram (see FIG. 33), each shade of colour corresponds to a certain temperature interval. A clear picture of the distribution of temperature over the surface is obtained.

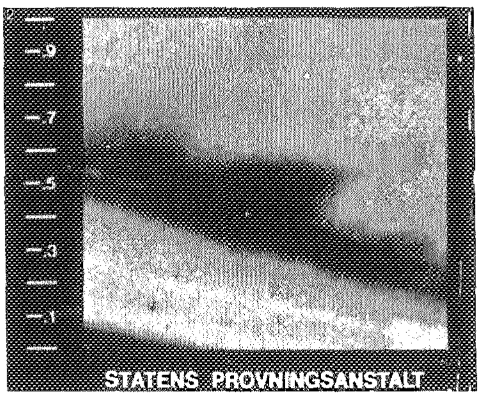
Fig. 3. Thermography by using an IR camera, AGA THV 750, and two different types of thermogram for the same surface.

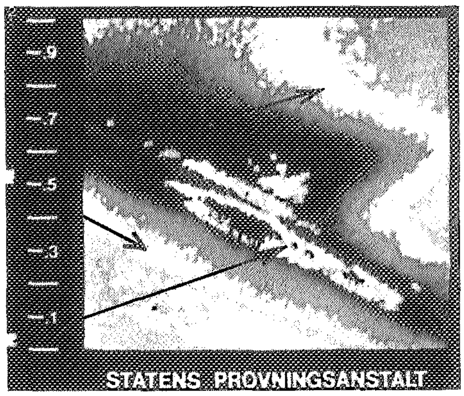
a) 

a) Thermography with an IR camera of sections of the wall and ceiling. The thermal image appears on the oscilloscope screen.

b) Thermogram of the wall-ceiling junction according to a). No isotherms imposed (monochrome image). The measuring range applied is indicated by a number (in this case 2) at top left in the thermogram.

c) Thermogram of the same section as in b) but with two isotherms imposed (isotherm image).

b) 

c) 

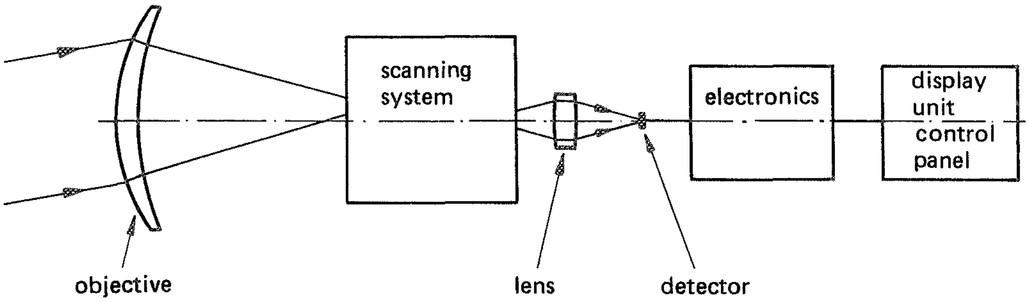


Fig. 4. Block diagram showing path of rays in an IR camera.

Since the camera continuously scans several pictures per second, each containing 7000–10,000 picture elements (depending on the type of camera), a detailed thermal image relatively free of flicker is obtained. A sketch showing the path of rays in an IR camera is given in FIG. 4. The surface is scanned along a number of horizontal lines (which can be seen in some thermograms).

The size of the picture element is determined by the size of the detector and the camera optics, and is usually quoted in terms of an angular resolution. For the types of camera used here, this resolution is given as about 3 millirad for a 20° lens, and about 1 millirad for a 10° lens. The least partial element which can be detected on a surface is thus a function of the distance between the object and the camera. At a large distance, the contours in the thermal image appear more diffuse than at a smaller distance. When the distance between the camera and the object is large, a lens with a smaller picture angle should therefore be used.

Most cameras employ indium antimonide as the detector. This is sensitive over the 0–5.6 μm wavelength range at a temperature of -196 °C (77 K). However, the lower limiting wavelength of the camera is determined by the germanium lenses in the camera to 2 μm. The range of sensitivity of the IR camera is shown in FIG. 5.

In the thermal image (FIG. 3b), the density is a function of the radiated energy and thus the temperature of the different portions of the surface under investigation. The temperature range of the IR camera is about -20 °C to + 2000 °C. In the vicinity of + 30 °C, the infrared camera measures temperature with a resolution of 0.2 °C. At lower temperatures, the sensitivity is somewhat lower. This is also evident from the calibration curve for the camera, FIG. 6b.

A thermal image is different in character from a photographic image which normally reproduces the reflected radiation within the visible range. The thermal image reproduces the radiation emitted and reflected within the range 2.0–5.6 μm over which the infrared camera is sensitive. A photograph reproduces shapes and contours with

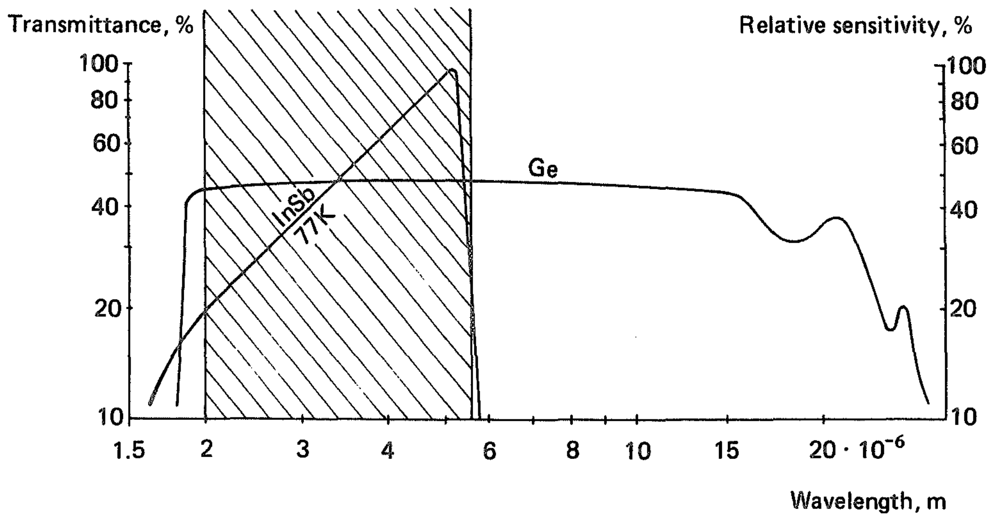


Fig. 5. Spectral transmittance for germanium, Ge, (thickness 2 mm), and relative detectability of indium antimonide, InSb. These materials limit the wavelength region over which the IR camera will function. /13/

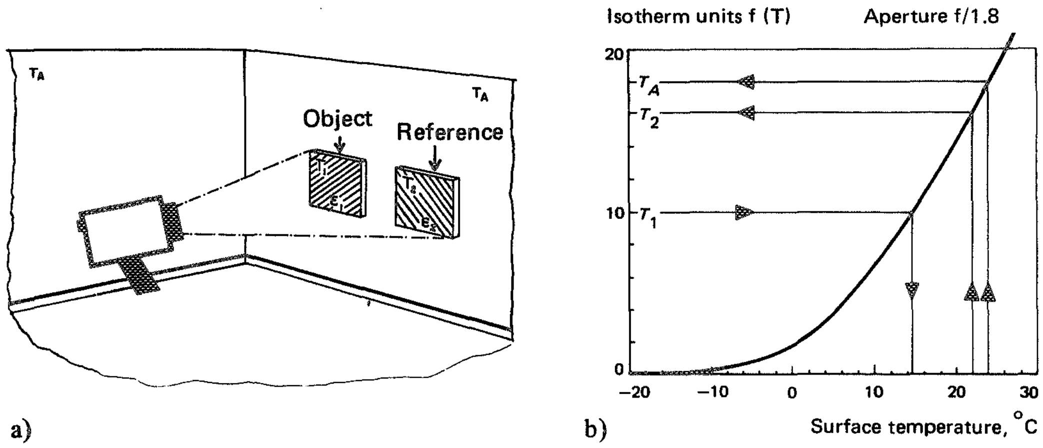


Fig. 6. Determination of the surface temperature of the object of measurement with an IR camera.
a) Surface temperature measurement with an IR camera
b) Calibration curve with application example imposed. /12/

great sharpness, while a thermal image often has a coarser structure and the contours are more diffuse. This is primarily due to the difference in resolution, but also to the fact that the boundaries on the surface are sometimes less definite because of thermal conduction.

In order to facilitate measurement of temperature differences between different portions of the thermal image, the IR camera has been provided with an isotherm function. With the aid of this, portions of the thermal image which have the same temperature can be made to glow – in other words, isotherms are imposed on the image field, and an isotherm image is obtained (FIG. 3c). Isotherms can be set at any temperature, and a variable temperature range can thus be covered in the image. Some types of camera are equipped with two isotherm functions. The isotherm differences read off, in isotherm units, are converted to equivalent differences in degrees centigrade (°C) if the appropriate values are inserted into the calibration function of the camera (Equation 3.1).

For the determination of temperatures likely to be encountered in building structures, normally - 20 °C to + 40 °C, a special calibration curve for the IR camera used should be produced for the appropriate range. See FIG. 126.

It will be evident from the above that the IR camera determines only relative temperature differences in the image field. If the true temperature of the surface is to be determined, it is necessary to know the true temperature of a point of reference on the surface being measured, the emissivity of the reference surface and the entire object, and finally the temperature function and calibration curves of the camera (FIG. 6b).

$$f(T_1) = \frac{\Delta I_{1,2}}{\epsilon_1} + \frac{\epsilon_2}{\epsilon_1} f(T_2) + (1 - \frac{\epsilon_2}{\epsilon_1}) f(T_A) \qquad (3.1)$$

where T_1 thermodynamic temperature at point 1 on the object, K (0 °C = 273 K)

T_2 thermodynamic temperature at point 2 on the object, K

T_A ambient temperature, K

ϵ_1 emissivity at point 1 on the object

ϵ_2 emissivity at point 2 on the object

$\Delta I_{1,2}$ difference in isotherm units between the isotherm markings for points 1 and 2

$f(T_1)$ value of the function for T_1 according to the calibration curve

$f(T_2)$ value of the function for T_2 according to the calibration curve

$f(T_A)$ value of the function for T_A according to the calibration curve

If the quantities on the right-hand side of the equation are known, $f(T_1)$ can be calculated and T_1 determined.

When measurements are made on homogeneous surfaces, ϵ_1 is often = ϵ_2. We then have

$$f(T_1) = \frac{\Delta I_{1,2}}{\epsilon_1} + f(T_2) \qquad (3.2)$$

In FIG. 126, an example is shown of temperature determination with an IR camera according to Equation (3.2). The accuracy of temperature measurement with the IR camera is governed by a number of factors, and is primarily dependent on how well it is possible to determine

- the reflection factor and emissivity of the surfaces (see Subsections 3.2.2 and 3.2.3)
- the true temperature (T_2) at the reference point
- the temperature of the counter-reflecting surfaces (T_A) and the radiation from these surfaces (see Subsection 3.2.3)
- the calibration curve of the IR camera (see FIG. 6b)
- the difference ΔI in isotherm units from the isotherm image (see FIG. 3c)
- the optical and thermal resolution capacity of the IR camera and the influence of the environment in which the measurement is made, as well as the influence of the distance between the object and the camera
- the amount of radiation absorbed by the air between the object and the camera (see FIG. 128).

The influence of the environment on thermography with an IR camera can be divided into the influence of temperature on the measuring apparatus, and the attenuation of thermal radiation in the air.

According to information supplied by the maker of the IR cameras, these can be used at ambient temperatures between -15 °C and + 55 °C. The chief reason for the choice of this temperature interval was to secure the mechanical function (rotation of the prisms, etc) of the IR camera. It is stated that the influence of temperature on the sensitivity and stability of the measuring apparatus is negligible in this interval.

The attenuation of thermal radiation in the atmosphere is primarily due to the absorption which occurs in the molecules of gas, and the absorption and dispersion which occurs in particles. In pure air, the attenuation is chiefly due to absorption by the molecules of water vapour and carbon dioxide. A typical curve of the relationship between transmission of the radiation in air (of a certain CO_2 content and humidity) and the distance between the object and the instrument is shown in FIG. 128. When measurements are made over the distances common in thermography indoors (1–6 m), the influence due to the distance is negligible. When measurements are made over distances greater than 10–20 m, a correction should be made for the attenuation in air. It is then necessary for the reference surface and the object to be at the same distance from the instrument.

Distance also exerts an influence on the camera's recording of temperature radiation by virtue of the fact that optical resolution deteriorates as the distance increases; this has been pointed out above. The optical sharpness of the object in the thermal image can be focussed and adjusted by means of a movable objective.

The size of the image field covered by the camera is determined by the optical system of the camera. The size of the image filed for different camera objectives is shown in FIG. 7.

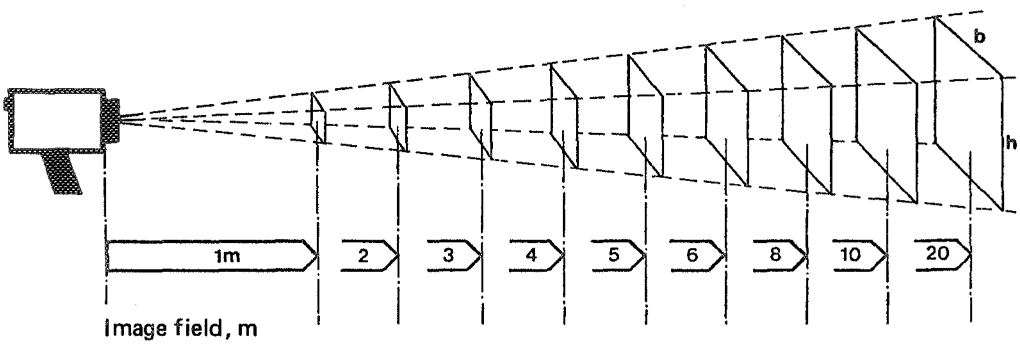


Image field, m

7°-lens	b	0.10	0.22	0.34	0.47	0.59	0.71	0.95	1.2	2.4
	h	0.09	0.20	0.31	0.41	0.53	0.63	0.85	1.1	2.1
20°-lens	b	0.33	0.68	1.0	1.4	1.7	2.1	2.8	3.6	7.0
	h	0.29	0.61	0.92	1.2	1.5	1.9	2.5	3.2	6.2

Fig. 7. The image field of the IR camera for different object-camera distances, for 7° x 7° and 20° x 20° lenses. /11./

The probable error in determining differences in surface temperature with an IR camera in the range approximating to room temperature can, by assessing the errors in the components along the chain of measurements, be estimated at ± 10% of the measured temperature difference, but no better than ± 0.5 °C.

In our investigations, we have mainly used two types of infrared camera made by AB AGA, models THV 680 and THV 750. The function and properties of these two models are approximately the same. THV 750 is a small portable equipment suitable for measurements in the field. THV 680 is larger and more suitable for laboratory use.

Thermograms taken with these two types of camera are broadly composed in the same way. There are some differences regarding scales and the indication of the appropriate measuring range. In thermograms taken with THV 680, the grey scale (graduated into ten sections) is at the bottom of the thermogram, FIG. 13b. This grey scale is not shown in thermograms taken with THV 750, FIG. 3. In these, the graduated scale is placed vertically along the left of the thermogram. The measuring range is indicated in THV 680 by the position of the black mark on the vertical scale at the left or right. In THV 750, the measuring range is indicated by a number at the top of the thermogram, see FIG. 3b.

The image frequency of THV 680 is 16 pictures per second, and that of THV 750, 25 pictures per second.

3.2 Thermal radiation

The fundamental basis of measurement of radiation with an infrared camera is that all objects in our surroundings emit infrared radiation, which is a form of electromagnetic radiation. The terms thermal radiation and temperature radiation are also used parallel with the term infrared radiation. Infrared radiation extends over a wavelength region situated in the interval 0.7–1000 μm, FIG. 8. In the literature, the IR region is sometimes subdivided into a near region (NIR 0.7–3 μm), an intermediate region (MIR 3–6 μm), a far region (FIR 6–15 μm) and an extreme region (XIR 15–1000 μm).

In the region 0.7–2 μm, reflected sunshine or artificial light sources can be used for the detection of objects (active IR). This is used in certain cases for surveillance and detection purposes in the dark by the military.

IR photography using a film sensitive to IR radiation at temperatures over 400 °C cannot be employed to reproduce thermal radiation emitted by surfaces at a temperature of about + 20 °C, which is the temperature range of interest in building technology. IR photography with an IR-sensitive film is normally used in the range 0.7–1.2 μm. In thermography with an IR camera, it is primarily the IR radiation emitted by the object within the wavelength region 2.0–5.6 μm which is utilised, FIG. 8.

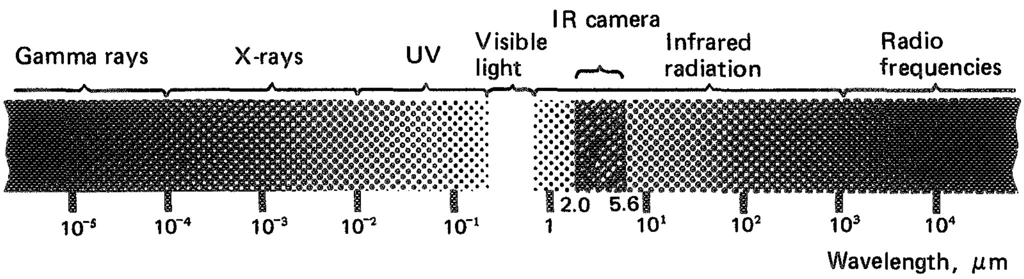


Fig. 8. The electromagnetic spectrum. /11./

3.2.1 Black body radiation

A black body is defined as a body which absorbs all incident radiation regardless of the wavelength.

For all objects other than a black body, a certain proportion of the radiation incident on the surface is absorbed (α), a certain proportion is transmitted (τ), and a certain proportion is reflected (ρ). If the symbols α, τ and ρ indicate the relative proportions, we have the expression

$$\alpha + \tau + \rho = 1 \qquad (3.3)$$

For a black body,

$$\alpha = 1 \text{ and } \tau = \rho = 0$$

An opaque surface absorbs or reflects all incident radiation, i.e.

$$\alpha + \rho = 1 \text{ and } \tau = 0 \qquad (3.4)$$

In buildings, the latter is most often the case. Windows and, occasionally, PE film, constitute an example.

The intensity of thermal radiation emitted by a black body is a function of both the wavelength (λ) and the temperature (T), and is described by Planck's distribution law

$$E_{\lambda,T} = \frac{2\pi \cdot h \cdot c^2}{\lambda^5 \cdot (e^{hc/\lambda kT} - 1)} \ \text{W/m}^3 \qquad (3.5)$$

where

$E_{\lambda,T}$ = spectral black body radiation at the wavelength λ (μm) and temperature T (K)
c = velocity of light, $3 \cdot 10^8$ m/s
h = Planck's constant, $6.63 \cdot 10^{-34}$ Ws
k = Boltzmann's constant, $1.38 \cdot 10^{-23}$ Ws/k
T = thermodynamic temperature, K

In the nomogram in FIG. 9, the spectral intensity of radiation is illustrated in an inclined system of coordinates in which the intensity of radiation corresponds to the y-axis and the wavelength to the x-axis, with the temperature as a parameter. /11./

The range of sensitivity of the IR camera has been indicated in the nomogram.

It will be seen from the nomogram that the intensity of radiation at 300 K (+ 27 °C) is situated chiefly within the wavelength region 3-100 μm. For all wavelengths, the intensity increases with temperature. This increase is larger at shorter wavelengths, and at higher temperatures the radiation maximum is displaced towards shorter wavelengths. The largest proportion of the emitted radiation thus comes within the range of sensitivity of the camera, 2.0–5.6 μm. The wavelength at the maximum spectral intensity of radiation is given by Wien's displacement law

$$\lambda_{max} = \frac{2898}{T} \ (\mu\text{m}) \qquad (3.6)$$

By integrating the spectral intensity of radiation in the interval 0 to ∞, we obtain the total radiation flux (Stefan-Boltzmann formula)

$$E = \sigma \cdot T^4 \ \mathrm{W/m^2} \tag{3.7}$$

where $\sigma = 5.67 \cdot 10^{-8}\ \mathrm{W/(m^2K^4)}$

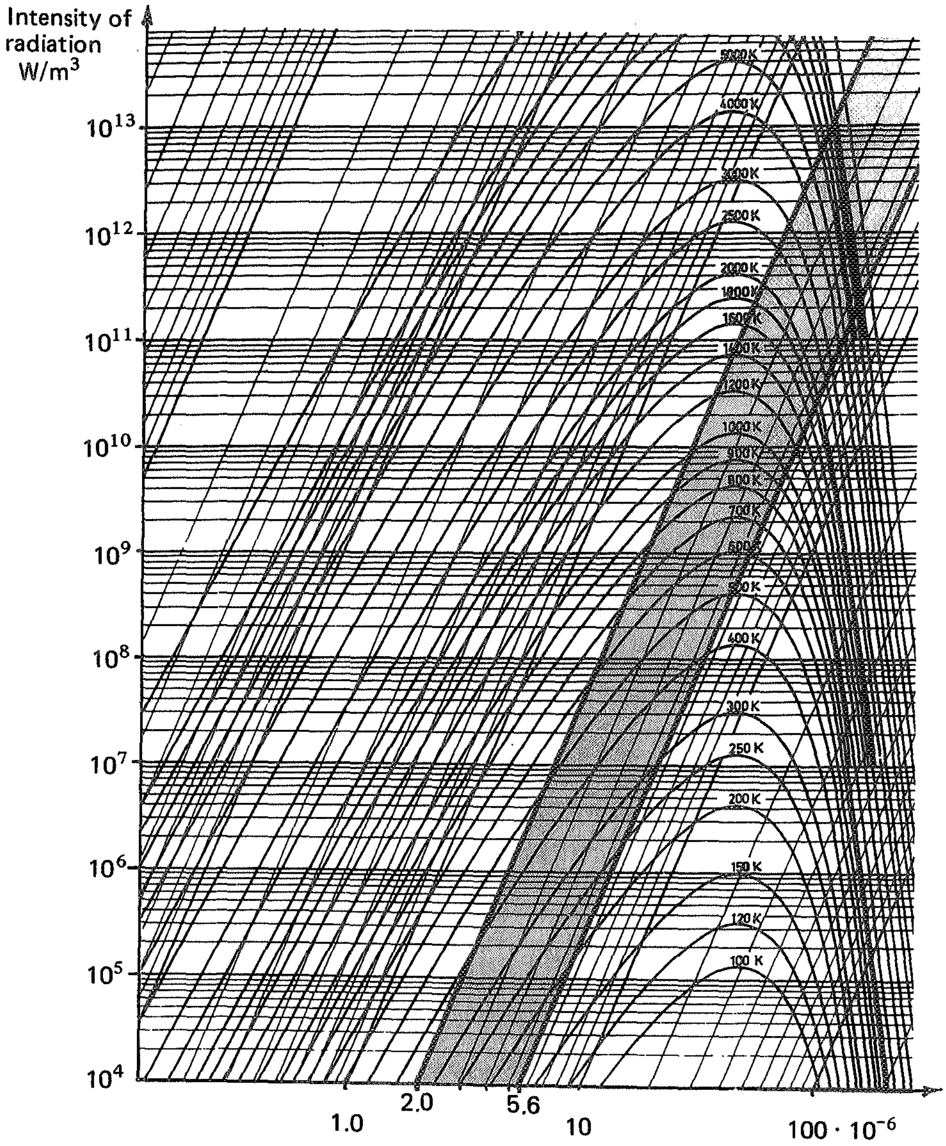


Fig. 9. Intensity of radiation for a black body at different thermodynamic temperatures (100–5000 K) as a function of the wavelength, with the range of sensitivity (2.0–5.6 μm) of the IR camera marked. /11./

surfaces can normally be considered diffuse. Metals constitute an exception. However, see FIG. 11 in relation to large angles of incidence.

For metals, the directivity of ϵ is in accordance with the top of FIG. 11. The value of emissivity here is practically constant (0.04–0.06) between 0° and about 40°. When ϕ is greater, the value of ϵ increases.

If the surface is grey and diffuse, it should be possible to use one value of the emissivity. This should simplify the assessment of radiation emitted by the surface.

Tables set out the values of ϵ for different materials for certain wavelengths, and also mean values for the entire wavelength region. Most surface materials used in buildings, with the exception of shiny metals, have an emissivity of 0.90 ± 0.05. The values of ϵ which are appropriate for use with the IR camera were previously determined, and are set out in the Appendix, TABLE 17. /12./

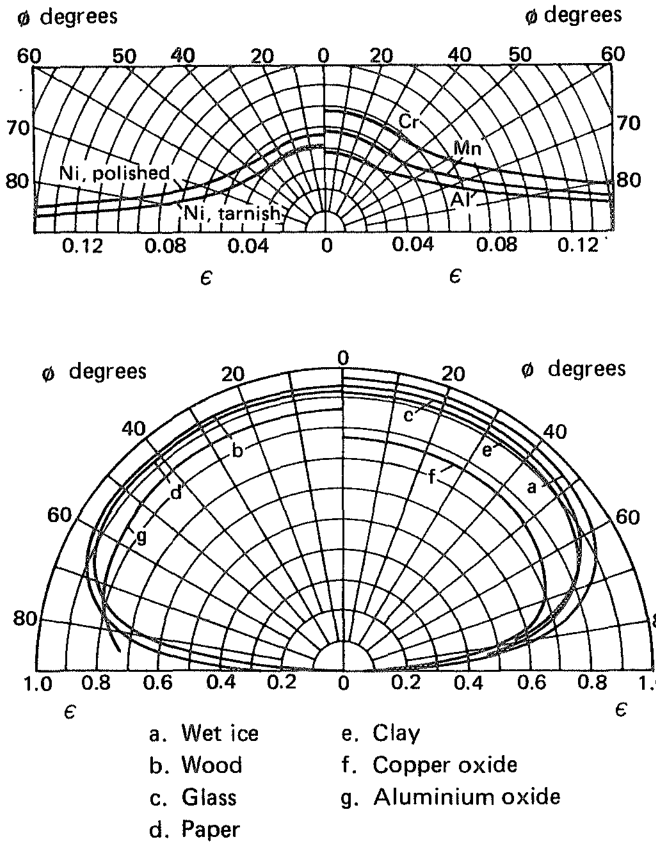


Fig. 11. The emissivity of different materials in different directions (according to Schmidt & Eckert). The temperature of the metallic surfaces was about + 150°C, and that of the non-metallic surfaces was between 0 and + 90°C.

For shiny metals, ϵ generally has a value less than 0.1. When measurements are made on such surfaces, most of the radiation emitted by the surface will therefore be due to radiation from counter-reflecting surfaces which is reflected in this surface.

According to Equation 3.7, the energy flux emitted by an actual surface is

$$E = \epsilon\, \sigma \cdot T^4 \ \ W/m^2 \tag{3.9}$$

3.2.3 Reflectance, ρ

When radiation is measured with the IR camera, this records the thermal radiation, E_{tot}, which is the sum of the radiation emitted, E_e, and reflected, E_r, by this surface.

$$E_{tot} = E_e + E_r \tag{3.10}$$

According to previous expressions, we have

$$\rho = 1 - \tau - \alpha = 1 - \tau - \epsilon$$

For opaque surfaces ($\tau = 0$), we have

$$\rho = 1 - \epsilon$$

For materials with $\epsilon \approx 0.9$, reflection thus constitutes approximately 10% of the radiation incident on this surface. Reflection is generally diffuse in character.

Equation 3.10 gives

$$E_{tot} = \epsilon_1 \cdot \sigma\, T_1{}^4 + (1 - \epsilon_1)\, E_{in} \tag{3.11}$$

where

E_{in} = radiation incident on the surface

$E_{in} \approx \epsilon_0 \cdot \sigma \cdot T_0{}^4$

ϵ_0 and T_0 are the emissivity and thermodynamic temperature respectively of the counter-reflecting surface. The contribution due to reflection in this surface is ignored. The value of ϵ_1 is assumed to be independent of temperature.

This yields

$$E_{tot} = \epsilon_1 \cdot \sigma \cdot T_1{}^4 + (1 - \epsilon_1)\, \epsilon_0 \cdot \sigma \cdot T_0{}^4 \tag{3.12}$$

The difference in radiation emitted by the partial surfaces is due to temperature differences between these surfaces, on condition that ϵ_1, ϵ_0 and T_0 are constant.

According to Equation (3.12), the radiation emitted by a surface is a function of the temperature of both the object and the surroundings. Varying values of the reflection factor (for e.g. shiny and partly oxidized metallic surfaces) may be reproduced in the thermal image in a way that is difficult to interpret.

For shiny metallic surfaces, variations in radiation due to reflections may give rise to apparent differences in temperature in the thermal image. If the surface is coarse, the reflection is diffuse, while if the surface is very even (fine grained), an optical reflection is obtained, FIG. 12. Smooth surfaces may cause remarkable reflections, in spite of the emissivity being high (for instance, in the case of certain plastics materials).

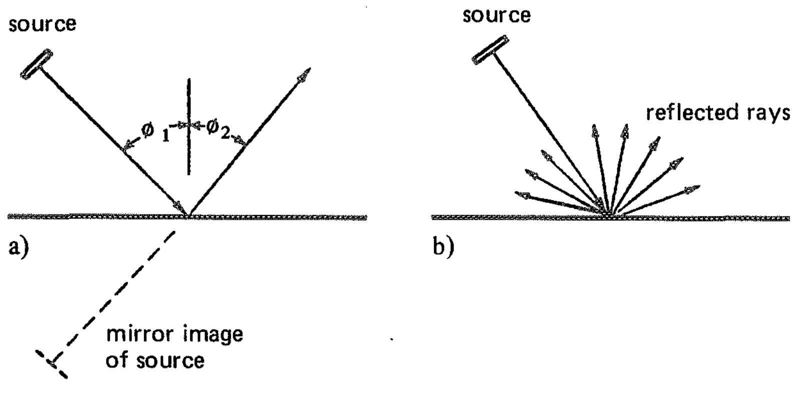


Fig. 12. Different types of reflection on a surface.
a) Optical reflection. b) Diffuse reflection.

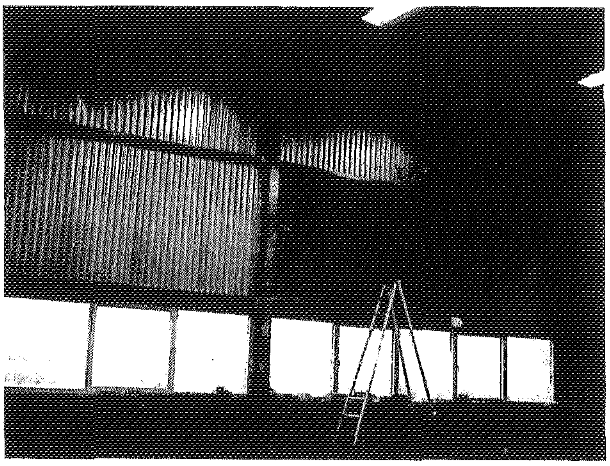
When surfaces of low emissivity are being thermographed, they can be treated so as to increase emissivity. This may be done by painting the surface with a sufficiently thick coat of paint, for instance whiting or oil paint of high emissivity. See FIG. 13a and 13b.

In order to decide whether a variation in radiation from the surface concerned is due to reflection from a counter-reflecting object, it is best to study the surface from different positions. A reflection will then change its position. Differential cooling or heating of the surface which is due to a change in the resistance of the construction maintains the same position on the surface irrespective of the position from where the thermogram is taken.

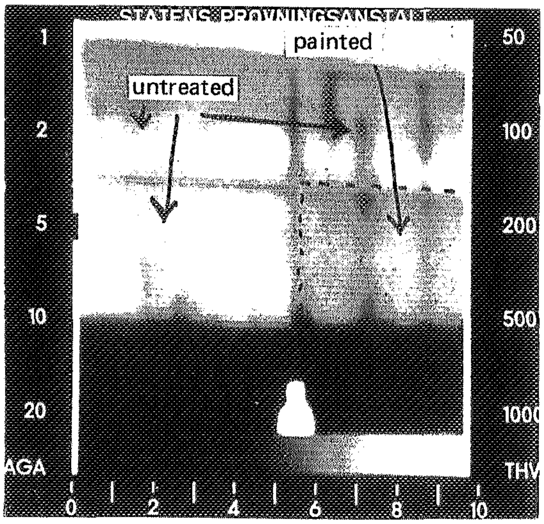
3.2.4 Transmittance, τ

Measurement of the temperature of glass surfaces imposes special problems. Ordinary glass material is transparent in the near infrared region, FIG. 14. Normal window glass is transparent to radiation within the wavelength region 0–5 μm. The glass thus lets through radiation over the greatest part of the range of sensitivity of the IR camera (2–5.6 μm). If, therefore, thermography of a window is perform-

Fig. 13. Examples of the way in which reflections in a surface can affect the appearance of the thermogram.



a) Photograph of external wall taken from the inside. The wall cladding consisted of shiny corrugated steel sheeting and of painted (dull-grey colour) corrugated steel sheeting (section A).



b) Thermogram of same section of surface as in a), taken at a slightly different angle. Interference due to reflection is seen in the thermogram at the top of the wall, corresponding to the unpainted surfaces. A light region, which is the upper part of the body of a person, appears in the bottom of the thermogram.

ed in the usual way, the thermogram will contain heat radiation transmitted through the glass. This problem is best solved by the fitting of a radiation filter on the camera which removes the incident radiation within the wavelength region 0–5 μm. Such filters are supplied as extras with the camera, and give this a different sensitivity and calibration curve.

Measurement on thin plastics film, for instance PE film, involves similar problems. The transmission wavelengths for this plastics film are however different from those for glass, and this means that the radiation filter for plastics film is transparent over a small interval around 3.4 μm, FIG. 15.

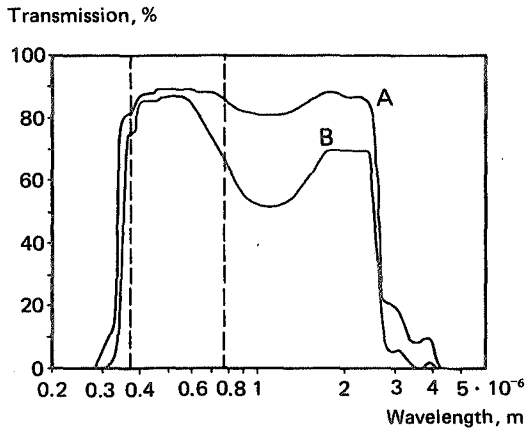


Fig. 14. Transmission for common glass material. /7./

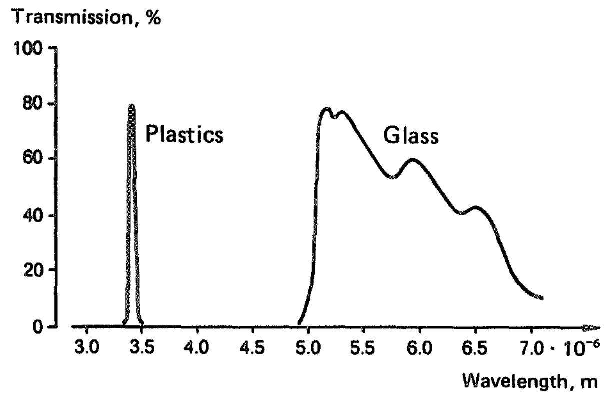


Fig. 15. Transmission for a filter which can be used for measurements on both glass and thin plastics film. /11./

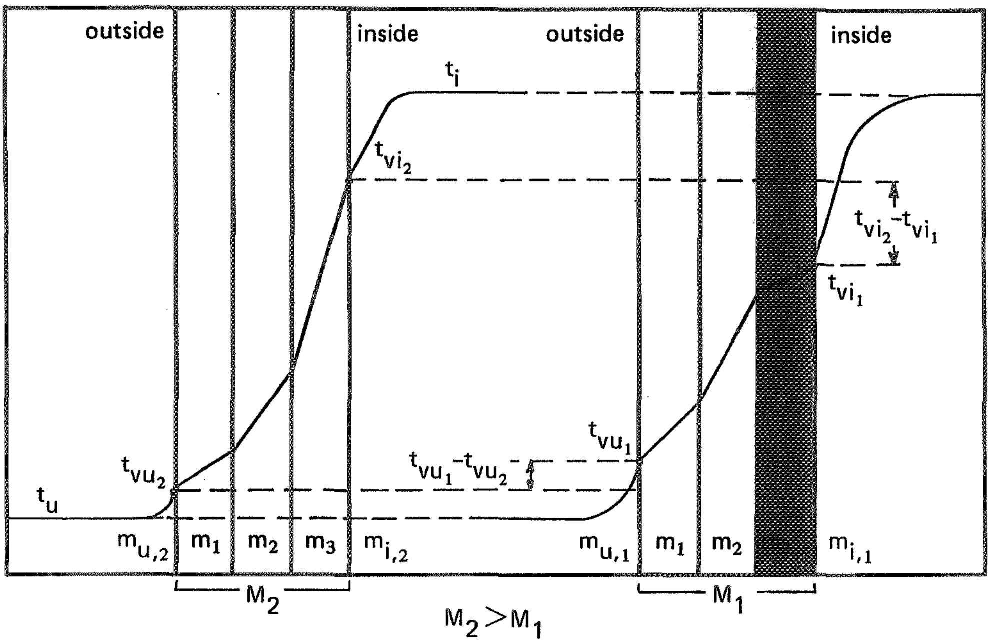


Fig. 16. Changes in temperature in wall of thermal resistances M_1 and M_2 ($M_2 > M_1$)

Variations in thermal resistance of a construction result in variations in temperature over its surface. For a wall comprising two leaves 1 and 2, of thermal resistances M_1 and M_2, the surface temperatures at the warm surface of the construction are determined as follows, see FIG. 16.

$$t_{vi_1} = t_i - \frac{m_{i,1}\,(t_i - t_u)}{m_{i,1} + m_{u,1} + M_1} = t_i - m_{i,1} \cdot k_1\,(t_i - t_u) \quad (3.17)$$

$$t_{vi_2} = t_i - \frac{m_{i,2}\,(t_i - t_u)}{m_{i,2} + m_{u,2} + M_2} = t_i - m_{i,2} \cdot k_2\,(t_i - t_u) \quad (3.18)$$

Assuming that $m_{i,1} = m_{i,2}$, we have

$$t_{vi_2} - t_{vi_1} = m_{i,1}\,(k_1 - k_2)\,(t_i - t_u) \quad (3.19)$$

3.3.2 Surface thermal resistance

When thermography is performed outdoors, i.e. over the cold surface of a construction, interference due to external climatic factors (rain, sun and wind) can arise. The surface thermal resistance at the outside of a wall is usually lower than at the inside. This means that, when the thermal resistance of the wall changes, the temperature difference at the cold surface of the wall will be less than that at the warm surface. The resolution of the results is thus worse when measurements are made outdoors, FIG. 16.

The inner surface coefficient of heat transfer, α_i, is defined according to the expression

$$q = \alpha_i (t_i - t_{vi}) \tag{3.20}$$

where q = density of heat flow rate, W/m^2

Thus, in principle, α can be determined by measuring the difference in temperature, $t_i - t_{vi}$, and the density of heat flow rate, q.

Heat from a wall surface is transmitted to the ambient air mainly by convection and radiation from counter-reflecting surfaces. Transmission of heat by condensation and evaporation is ignored.

Heat is transmitted from the wall surface by convection according to the defined relationship

$$q_k = \alpha_k (t_i - t_{vi}) \tag{3.21}$$

The following relationship can be employed in order that a measure of the value of the convective surface coefficient of heat transfer may be obtained for a wall surface in a normal habitable room

$$\alpha_k = 1.85 (t_i - t_{vi})^{0.32} \quad /5./ \tag{3.22}$$

FIG. 17,a) shows the way in which α_k varies with $(T_i - T_{vi})$. 0 °C (t) is equivalent to 273 K. (T).

If reflection between the surfaces is ignored, and if ϵ_0 and ϵ_n are independent of the temperature, the quantity of heat transmitted by radiation is given by

$$q_s = \Sigma\, \phi_n \epsilon_0 \cdot \epsilon_n C_s \left\{ \left(\frac{T_n}{100}\right)^4 - \left(\frac{T_0}{100}\right)^4 \right\} \tag{3.23}$$

where

C_s = radiation constant for a black body, 5.67 W/m^2K^4

ϕ_n = the angular coefficient of the nth emitting surface

T_n = the thermodynamic temperature of the nth emitting surface, K

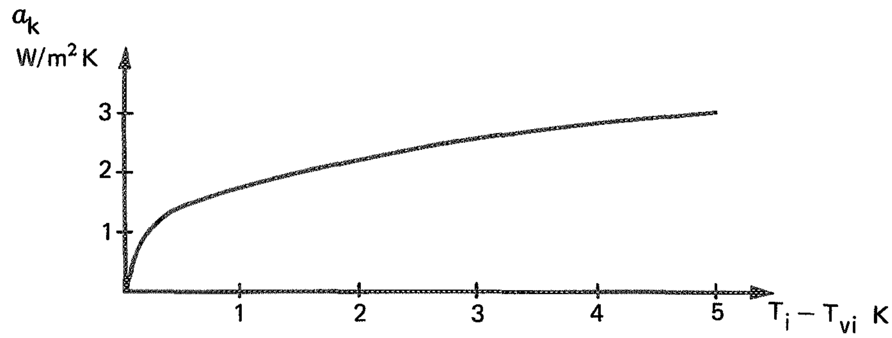
ϵ_n = the emissivity of the nth emitting surface

T_0 = the thermodynamic temperature of the receiving surface, K

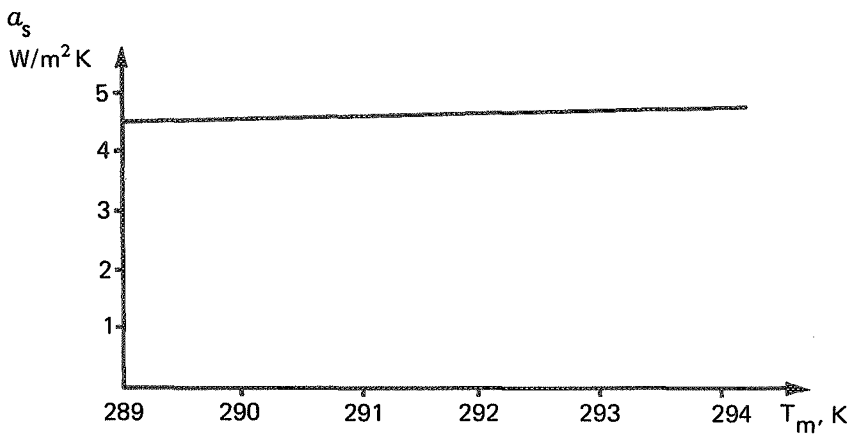
ϵ_0 = the emissivity of the receiving surface

The angular coefficient ϕ_n is defined as that proportion of the radiation leaving the nth surface in all directions which arrives at the receiving surface.

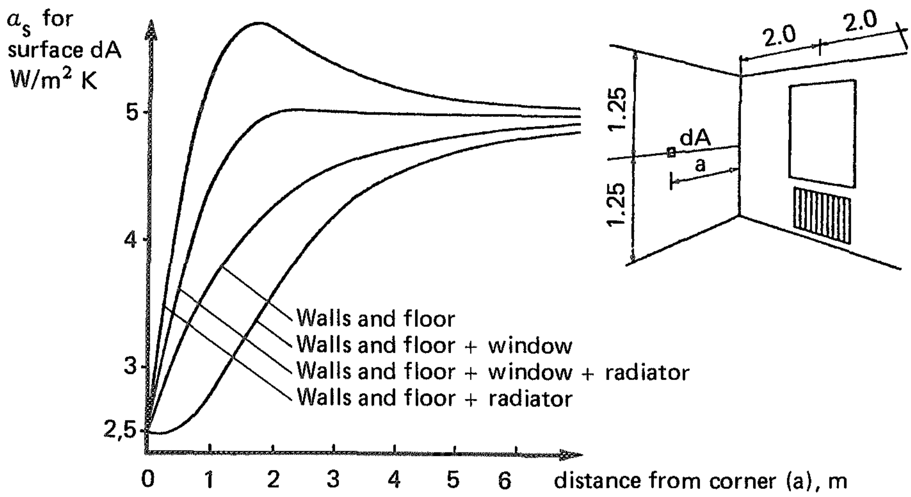
$\Sigma\phi_n$ varies between 0 and 1. When the surrounding surfaces together form a "half room" as seen from the receiving surface, $\Sigma\phi_n = 1$.



a) Variation of α_k as a function of the temperature difference $T_i - T_{vi}$



b) Variation of α_s as a function of the mean temperature T_m



c) Example of the variation in the value of the coefficient of heat transfer α_s at different distances from the corner of the external wall.

Fig. 17. Variation in the value of the coefficient of heat transfer.

In simple cases, for instance for two plane parallel walls (1 and 2) of such dimensions that the distance between them can be regarded as small, counter-reflection can be taken into account. On considering the transmission of radiation at the inner surface of an external wall, it is sometimes assumed that the temperature of the inner walls is the same as the room air temperature ($T_n = T_i$).

If $T_0 = T_{vi}$, $\epsilon_0 = \epsilon_1$ and $\epsilon_n = \epsilon_2$, we have

$$q_s = \epsilon_{12} \cdot C_s \left\{ \left(\frac{T_i}{100}\right)^4 - \left(\frac{T_{vi}}{100}\right)^4 \right\} \tag{3.24}$$

where

ϵ_{12} = resultant emissivity

$$\frac{1}{\epsilon_{12}} = \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1$$

For purposes of comparison with α_k, α_s can be simplified by expansion in series form, the following relationship being applied:

$$(a^4 - b^4) = (a - b)(a^3 + a^2 b + ab^2 + b^3)$$

In buildings, the difference between T_i and T_{vi} is generally quite small compared with their absolute values. In view of this, we have

$$q_s = \epsilon_{12} \cdot C_s \frac{T_i - T_{vi}}{100} \cdot 4 \left(\frac{T_m}{100}\right)^3 \tag{3.25}$$

where the mean temperature

$$T_m = \frac{T_i + T_{vi}}{2} \tag{3.26}$$

$$q = q_k + q_s$$

Equations 3.20, 3.21, 3.25 and 3.26 give

$$\alpha_i = \alpha_k + 0{,}04 \cdot \epsilon_{12} \cdot C_s \left(\frac{T_m}{100}\right)^3 \tag{3.27}$$

Putting $\alpha_s = 0{,}04 \cdot \epsilon_{12} \cdot C_s \left(\frac{T_m}{100}\right)^3$ (3.28)

we have $\alpha_i = \alpha_k + \alpha_s$ (3.29)

The value of α_s can thus be determined if the thermodynamic temperatures T_i and T_{vi} and ϵ_{12} are known.

FIG. 17b shows the way in which α_s varies with T_m, the following assumptions being made.

ϵ_{12} = 0,82
C_s = 5.67 W/m² K⁴
T_i = 294 K (t_i = 21 °C)
T_{vi} = 284–294 K (t_{vi} = 11–21 °C)
T_m = 289–294 K (t_m = 16–21 °C)

The value of α_s is also dependent on geometric conditions, and may vary appreciably, for instance at the corners of external walls. FIG. 17c shows the way in which α_s varies at different distances from the corners of external walls.

The value of α_k is also dependent on the geometry of the surface of the construction.

At the thermodynamic temperatures T_i = 294 K and T_{vi} = 292 K, the following values of α_i are obtained in the middle of the external wall.

$$\alpha_i = \alpha_k + \alpha_s = 4.7 + 2.3 = 7.0 \text{ W/(m}^2 \cdot \text{K)}$$

or $m_i = 0.14 \text{ m}^2 \text{ °C/W}$

If the thermal surface resistances m_i and m_u at the warm and cold wall surfaces respectively were known, and also the temperatures T_i and T_{vi}, a quantitative determination of the thermal resistance M of the wall would be possible, see Equation 3.13.

3.3.3 Experimental investigation of the surface thermal resistance

With the aim of investigating the variation in the value of α over a wall surface under different environmental conditions, a preliminary investigation was carried out at the Swedish National Testing Institute. These investigations were made both in the laboratory and in the field.

Laboratory measurement

A test wall, the construction of which is shown in FIG. 18, was used in the laboratory investigation.

The investigation was performed in a climatic installation comprising a climatic room and a cold room, both equipped with temperature regulation facilities and divided by the above test wall.

Radiation conditions in the measurement room (climatic room) are broadly comparable with those in a habitable room in a dwelling, there being however a modification of the placing of the heat source.

The radiation properties of the measurement room were defined as follows: the walls and ceiling were painted with a light-coloured oil paint, and the floor was covered with a grey cork mat. The heat source in the measurement room was placed at the rear wall behind a metal sheet to prevent direct emission of radiation.

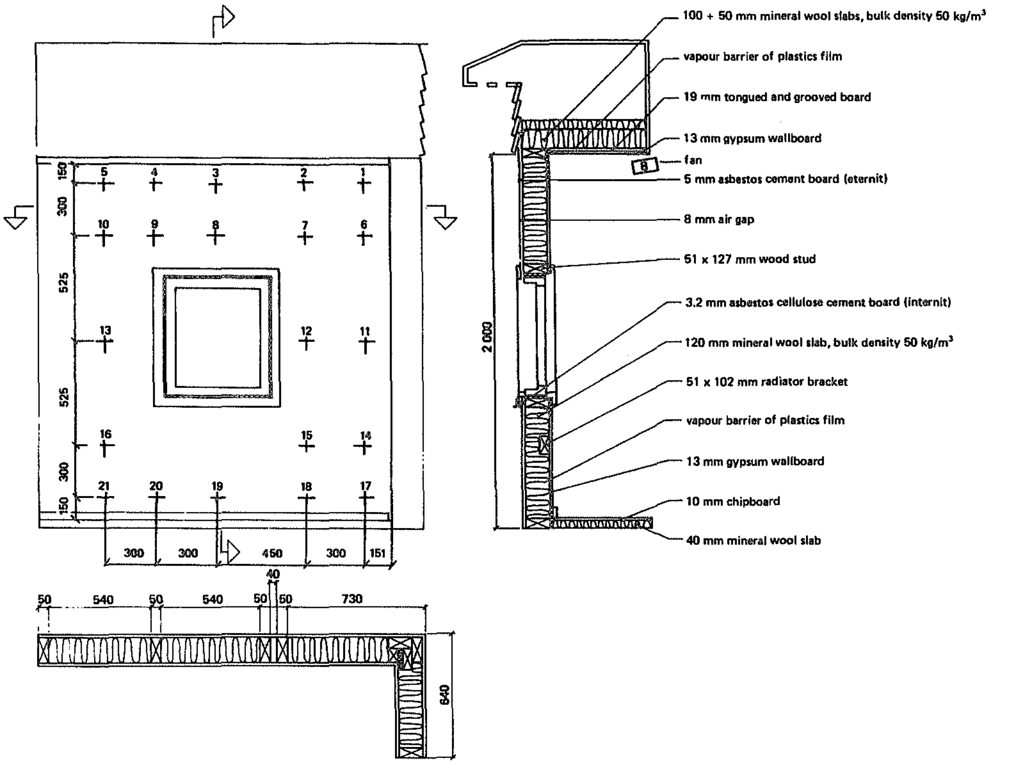


Fig. 18. Construction of external wall (framed wall No 1) used in determining the distribution of the value of α over the surface. The positions of the measuring points are marked 1–21. /12./

The value of α was determined from the measured temperatures and heat flows, Equation 3.20 being used. The heat flows through the wall were measured with the aid of a number of thermo-electrical heat flow meters placed on the warm surface of the wall at points 1–21 according to FIG. 18.

The signals from the heat flow meters were recorded with a compensating recorder. The surface temperatures on the warm side of the heat flow meter (t_{vi}) were measured with a thermocouple at each point. The air temperatures on the warm side (t_i) were measured 10 cm in front of each heat flow meter with a thermocouple protected from radiation. This distance was chosen after preliminary studies of the distance from the wall over which there is a drop in air temperature. The temperature difference $t_i - t_{vi}$ was measured by means of series-coupled thermocouples.

Measurements were made under three conditions:
1. Normal case (no sources of interference).
2. Sources of interference in the form of fans directed to-

wards the test wall in order to give high convective values of α. The fans were placed below the ceiling and directed towards the top of the test wall, FIG. 18. This caused a variation in air velocity near the wall surface between about 0.2 and 1 m/s.

3. Source of interference in the form of a point source (250 W heat lamp) placed about 2 m from the warm wall surface, centrally in the climatic room. The lamp was directed at right angles to the surface.

The air temperature in the cold room was set at - 20 °C and was maintained constant under all three conditions of measurement. During the different conditions, the air temperature on the warm side varied between 21 and 23 °C. Measurements were made under steady conditions, and were repeated three times. The results obtained are set out in TABLE 2. The accuracy of the measured values was estimated at about ± 8%.

Table 2. Coefficient of heat transfer (a) at a wall surface, case 1–3.

Point	1			2			3		
	q W/m²	t_i-t_{vi} °C	a W/(m²·K)	q W/m²	t_i-t_{vi} °C	a W/(m²·K)	q W/m²	t_i-t_{vi} °C	a W/(m²·K)
1	11.3	1.6	7.1	11.9	1.0	11.9	11.8	1.0	12.1
2	10.2	1.4	7.3	11.2	0.8	14.0	9.7	0.8	12.1
3	9.1	1.3	7.0	9.8	0.8	12.3	9.2	0.7	13.1
4	16.9	2.6	6.5	19.2	1.8	10.7	17.7	2.2	8.0
5	8.8	1.3	6.8	9.5	0.9	10.6	9.5	0.9	10.6
6	9.5	1.6	5.9	10.0	0.7	14.3	9.7	0.5	19.4
7	9.0	1.4	6.4	10.0	0.6	16.7	9.7	0.4	24.3
8	10.1	1.4	7.2	10.8	0.8	13.5	10.0	0.3	33.3
9	17.0	2.4	7.1	20.3	1.7	11.9	17.0	1.8	9.4
10	9.2	1.1	8.4	9.1	0.6	15.2	8.7	0.5	17.4
11	12.2	1.9	6.4	13.0	1.5	8.7	12.1	0.5	17.3
12	10.1	1.4	7.2	11.5	0.9	12.8	10.2	0.7	14.6
13	9.1	1.2	7.6	10.4	0.8	13.0	9.3	0.7	13.3
14	10.4	1.3	8.0	11.1	1.5	7.4	11.1	0.5	22.2
15	9.4	1.1	8.5	10.5	1.2	8.8	9.8	0.4	24.5
16	8.6	1.0	8.6	9.4	0.8	11.8	8.2	0.3	27.3
17	13.9	1.9	7.3	15.5	2.0	7.8	14.7	0.9	16.3
18	10.3	1.0	10.3	11.5	1.4	8.2	11.3	0.5	22.6
19	10.2	1.0	10.2	11.4	1.2	9.5	10.2	0.6	17.0
20	18.0	2.1	8.6	19.9	2.4	8.3	19.3	1.4	13.8
21	14.2	1.4	10.1	15.4	1.5	10.3	14.2	0.7	20.3
Mean values			7.8			11.3			17.6

Mean values of surface temperature, t_{vi}, were as follows: case 1, 17.9°C; case 2, 21.8°; case 3, 21.4°C.

It will be seen from the results that α varied between about 6 and 10 W/(m^2 · K) in condition 1, between about 7 and 17 in condition 2, and between about 8 and 33 in condition 3.

During measuring condition 1, the variation in the value of α was relatively small, 6.4–8.4 W/(m^2 · K), along a horizontal line at a certain height above the floor. In the vertical direction the variation was somewhat larger, about 7–10. Extreme values were obtained at the edges of the wall, with the highest values at the bottom of the wall. In the normal case, the value of α appears to vary symmetrically and in a relatively constant manner in the horizontal direction, with the exception of portions of the surface near corners. In the vertical direction there is a certain variation. The higher value at the bottom of the wall has probably to do with the placing of the heat source in the test room and with the air flow conditions along the test wall.

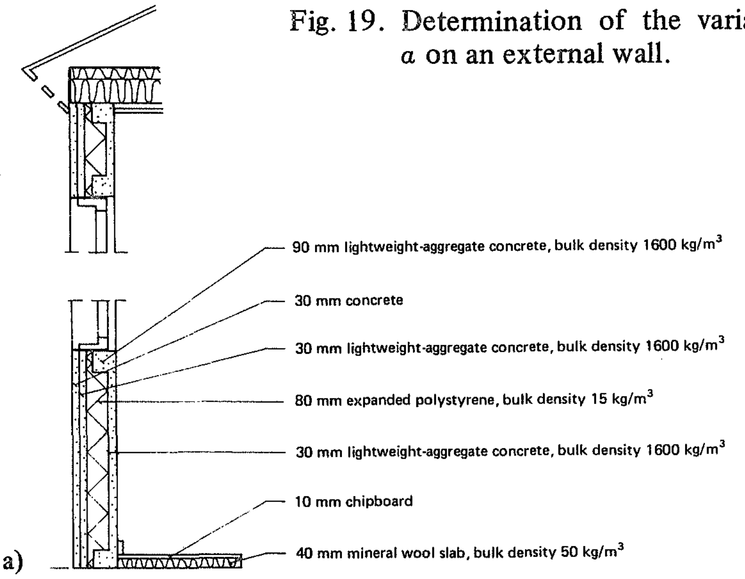
During measuring condition 2, the value of α rose due to the higher air velocity at the wall surface. The imposed disturbance was not symmetrically distributed over the wall surface, and a somewhat uneven effect on the value of α was therefore obtained. The value of α had the greatest increase at the top of the wall where the fans were placed. Such an uneven disturbance of air flow at the inside of the wall has a local effect on the temperature of the surface of the wall. A constant increase in the value of α along the entire surface has the effect of equalising the temperature distribution over the surface of the wall.

During measuring condition 3, the disturbance was in the form of a heat lamp placed centrally at a certain distance from the surface of the wall. The effect of this source of radiation on the value of α is relatively evenly distributed – with the exception of the values at points 4 and 9 – over the entire exposed surface, with a somewhat greater effect over the central portions of the wall. There was a marked rise in the value of α, and the temperature difference between the wall surface and the room air diminished. Such variations in the value of α can have a local effect on the temperature of the surface, so that differences in surface temperature which correspond to the variation in thermal resistance, are reduced.

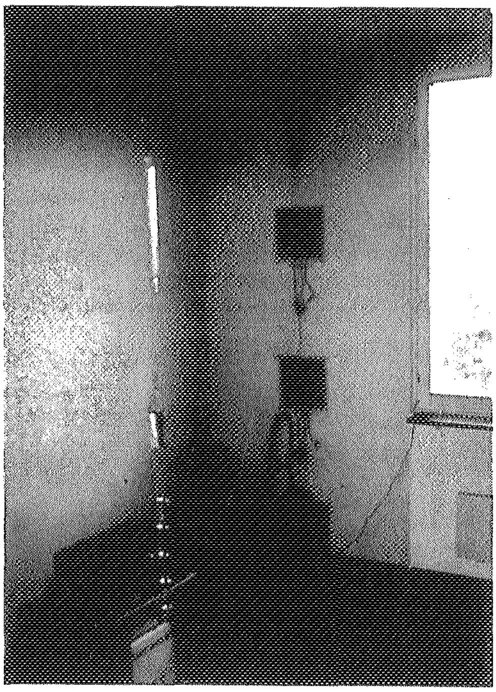
Measurements in the field

Measurement of the variation in the value of α along the surface of an external wall was performed in a dwelling in a block of flats. The construction of the external wall is shown in FIG. 19a. Measurements here were made at four points on the surface of the wall along a vertical line, at heights of 20, 90, 165 and 235 cm above floor level. The height of the ceiling in the dwelling was 250 cm. The external wall had a window and a radiator in it. Photographs

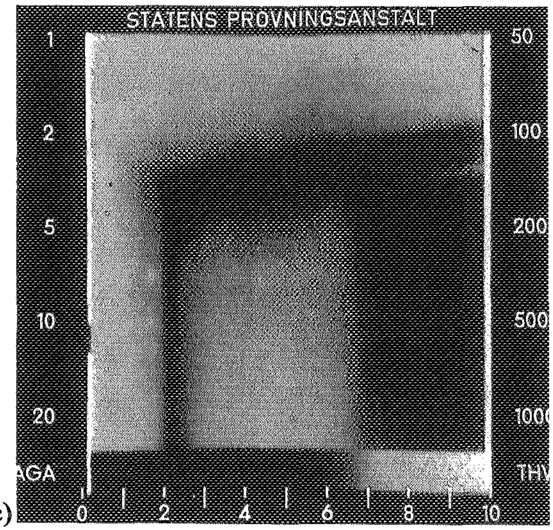
Fig. 19. Determination of the variation in the value of a on an external wall.



a)



b)



c)

a) Construction of external wall on which measurements were made to determine the variation in a along the surface. /12/.

b) Measuring equipment for determination of the value of a.

c) Thermogram of top of external wall, to the left of the window.

of the external wall and the test set-up are shown in FIG. 19b and 19c. Counter-reflecting surfaces consisted of walls, floor and ceiling which abutted onto heated spaces. During the measurements, the dwelling was not furnished or inhabited. Temperatures and heat flows were measured in the same way as in the laboratory. The air temperature was however measured at the geometrical midpoint of the room, and for this reason t_{im} in this case is a mean value of the variation of the room air temperature in the room. The value of α_i was determined according to the previously defined expression (equation 3.20), but with this temperature.

Repeated measurements were made over an extended period (about 1 month). The mean values of α_i at points situated 20, 90, 165 and 235 cm above floor level were 5.4, 6.6, 6.2 and 5.0 W/(m^2 · K) respectively.

The results show that the variation in the value of α is relatively small over the midsection of the wall. The lowest values were obtained near the floor and the ceiling. Compare also with the thermogram relating to the section in question, FIG. 19c.

3.3.4 Sources of interference during thermography

The risk that during thermography temperature variations due to defects in insulation will be mistaken for variations related to the natural variation in the value of α along the warm surface of a construction is considered to be small in normal conditions.

The changes in temperature which have to do with the variation in the value of α are generally gradual and symmetrically distributed over the surface. Such variations are naturally located in the vicinity of the ceiling and floor junctions and the corners of walls.

Changes in temperature due to leakage of air or a defect in insulation are in most cases more obvious, with sharp contours of characteristic shape. The temperature pattern is usually unsymmetrical.

During thermography and the interpretation of thermograms, comparative thermograms can provide valuable information for purposes of assessment.

The most common sources of interference during thermography are the influence of sunshine on the surface to be thermographed (insolation through a window), hot radiators and pipes, light bulbs directed towards and placed near the surface, air currents (e.g. from an air intake) directed towards the surface, and, possibly, the condensation of moisture on the surface.

Thermography must not be carried out on sunlit surfaces. If there is a risk of interference due to sunshine, the windows must be covered up (the blinds drawn).

A hot radiator appears as a markedly light area in the thermogram. The surface of the wall near a heated radiator has a higher temperature which may mask defects in the construction.

In order that the interference due to hot radiators may be avoided to the greatest possible extent, these can be turned off a short time before measurements are made. However, this must not cause the air temperature in the room to drop so as to affect the distribution of surface temperature on the construction. Electric radiators have a relatively small inertia, and therefore cool down comparatively quickly after being turned off (in 20–30 minutes).

Before the surface behind a radiator is thermographed, the radiator must be removed so that the surface of the wall may be exposed to the IR camera. It must be borne in mind in this connection that such surfaces may be influenced by heat stored in the construction for some time after removal of the radiator.

Light bulbs placed near the wall surface must be turned off when measurements are made.

During thermography, there must be no air currents (e.g. from open windows, open vents, fans directed towards the surface) which may exert an influence on the surfaces being thermographed.

Surfaces may be moist, for instance due to condensation, and this will have an appreciable effect on the transmission of heat at the surface and on the surface temperature. When there is moisture on a surface, evaporation nor- mission of heat at the surface and on the surface temperature. When there is moisture on a surface, evaporation nor- mally occurs. This requires heat and the surface can thus be cooled down several degrees. There may be a risk of surface condensation near major thermal bridges and defects in insulation. FIG. 127 gives details of saturation temperatures for different values of the air temperature and relative humidity. Any surface moisture must be carefully noted during thermography.

Major sources of interference of the above type can normally be detected and eliminated prior to commencement of the measurements.

If it is impossible during thermography to screen the surfaces concerned from interference, this must be taken into account during interpretation and assessment of the results. The conditions during measurement must be carefully noted on each occasion.

3.4 Surface temperature and leakage of air

Defects in the airtightness of a building due to small openings in the construction can be detected by measurement of surface temperatures. If the building under investigation is at a pressure below that outdoors, air will enter the room through points of leakage in the construction. Cold outside air which flows through small openings in a wall normally causes a drop in temperature on adjacent parts of the wall. The result is that colder areas of characteristic shape appear on the inner surface of the wall. With the aid of thermography, such colder areas can be detected. Movements of air near the wall surface can be measured with an air velocity meter. If the building under investigation is at a pressure higher than that outdoors, warm room air will leave the building through points of leakage in the wall, causing local heating of the outside surface of the wall near the points of leakage.

The magnitude of air movement is dependent on the nature of these points of leakage and also on the pressure differential across the construction.

3.4.1 Pressure conditions in a building

The most important reasons for a pressure differential across an element of construction in a building are

- wind conditions around the building
- the effect of the ventilation system
- difference in temperature between indoors and outdoors (thermal pressure difference).

The actual pressure conditions in a building are generally due to a combination of these factors.

The resultant pressure gradient through the different building elements can be exemplified by FIG. 20. Owing to the irregular effect of the wind on a building, pressure conditions in practice are relatively varied and complex.

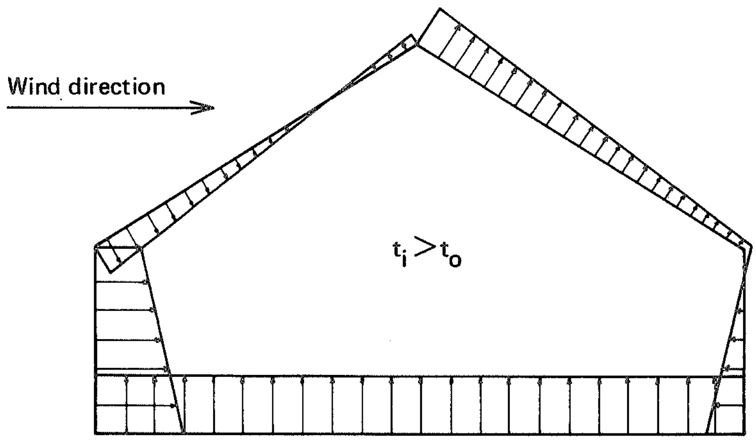


Fig. 20. Distribution of resultant pressure on the surfaces enclosing a building, due to the effect of the wind, ventilation and the difference between indoor and outdoor temperatures.

For an unobstructed air current, Bernoulli's law states

$$\frac{\rho v^2}{2} + p = \text{constant} \tag{3.30}$$

where ρ = density of air, kg/m^3
v = wind velocity, m/s
p = static pressure, Pa
and where

$$\frac{\rho v^2}{2}$$

is the dynamic pressure, and p the static pressure. The sum of these two pressures gives the total pressure.

When wind exerts a load on a surface, the dynamic pressure changes into a static pressure on the surface. The magnitude of static pressure is determined, inter alia, by the shape of the surface and its inclination in relation to the wind direction.

The part of the dynamic pressure which changes into static pressure on the surface (p_{stat}) is determined by a shape factor

$$C = \frac{p_{stat}}{\frac{\rho v^2}{2}} \tag{3.31}$$

If ρ is put equal to 1.23 kg/m^3 (the density of air at a temperature of + 15 °C), the following local pressures are obtained in the wind stream:

$$p_{stat} = C \cdot \frac{\rho v^2}{2} = C \cdot \frac{v^2}{1.63} \ \text{Pa} \tag{3.32}$$

If the entire dynamic pressure is converted into static pressure, C = 1. Examples of the distribution of the shape factor for different wind directions are shown in FIG. 21. /2./

Wind thus gives rise to an internal vacuum on the windward side and an internal excess pressure on the leeward side. The air pressure indoors is a function of wind conditions, points of leakage in the building envelope, and the distribution of these in relation to the direction of the wind. When points of leakage are uniformly distributed over the building, the pressure indoors may vary by ± 0.2 p_{stat}. If there is a larger number of leakage points on the windward side, the indoor pressure will be somewhat higher. In the converse case, when there is a larger number of leakage points on the leeward side, the pressure indoors decreases. /3./

Wind conditions can vary considerably in time and over relatively closely situated areas. During thermography, such variations can have a considerable effect on the results. Examples are shown in FIG. 22. There may be local variations due to the layout of the building development and the shape of the surrounding country.

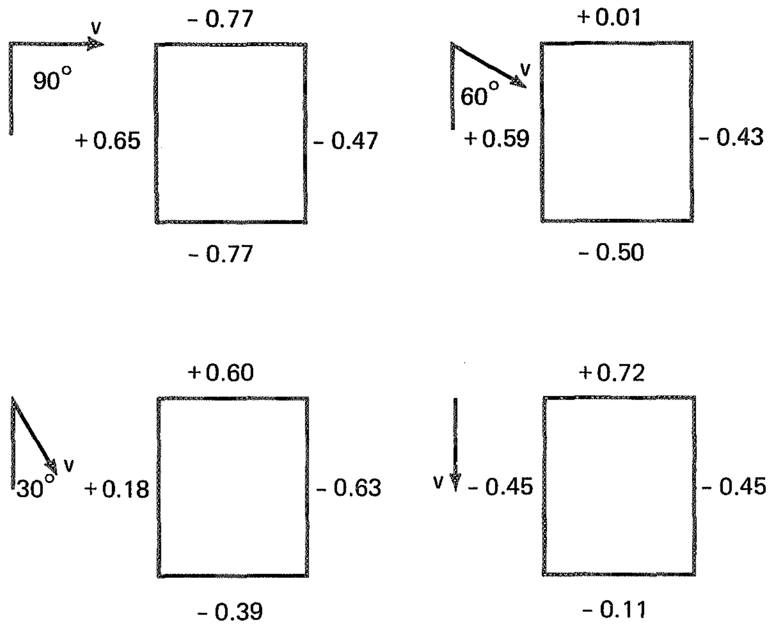


Fig. 21. Distribution of the shape factor (C) over a building for different wind directions and velocities (v). /2/.

Tests have shown that the differential pressure across a facade exposed to a mean wind velocity of about 5 m/s is about 10 Pa.

Mechanical ventilation gives rise to a constant indoor vacuum or excess pressure (depending on the direction of ventilation). Measurements during our investigations have shown that the vacuum caused by mechanical suction (kitchen fan) in a single-family house is generally between 5 and 10 Pa. When ventilation air is extracted mechanically, for instance in blocks of flats, the vacuum is usually a little larger, 10–50 Pa. A mechanical inlet and extract ventilation system is usually adjusted in such a way that there is a small vacuum on the inside (3–5 Pa).

A differential pressure due to temperature differences (chimney effect due to differences in the density of air at different temperatures) causes a vacuum to arise in the lower part of the building and an excess pressure near the top. At a certain height, there is a neutral zone where the pressures indoors and outdoors are the same, FIG. 23. This pressure difference is given by the expression

$$\Delta p = g \cdot \rho_u \cdot h \left(1 - \frac{T_u}{T_i}\right) \text{ Pa} \qquad (3.33)$$

where Δp = difference in air pressure across the construction, Pa

g = acceleration due to gravity, 9.81 m/s²

Fig. 22. The effect of the wind on the temperature distribution on the inside of the wall in a permeable construction. The thermograms have been taken with the same measuring range, 2.

Conditions during measurement:

Cloudiness	cloudy
Outdoor air temp	- 1°C
Indoor air temp	+ 19°C
Wind conditions	1–4 m/s (to facade)
$p_i - p_u$	- 10 Pa to 0 Pa (pulsation due to wind pressure)

a) External wall with steel frame

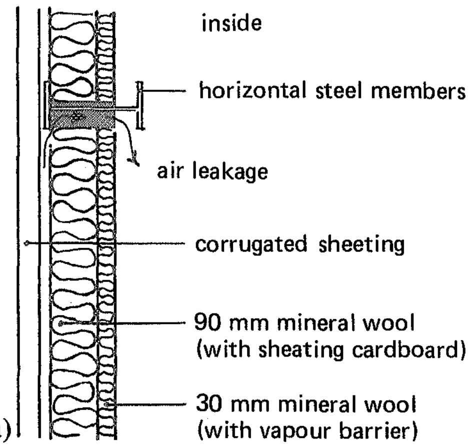
b) 0 minute. The horizontal steel member is colder. Some indications of air leakage appear.

c) After 1 minute. Dark areas appear on the wall surface underneath the steel member.

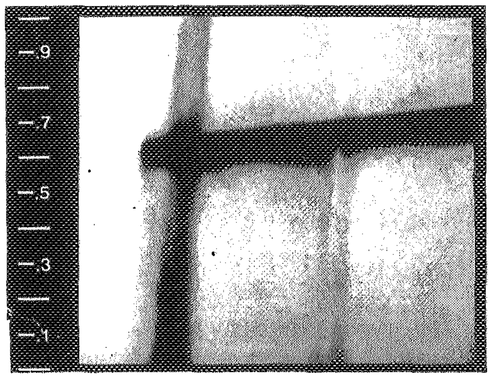
d) After 2 minutes. The dark areas are larger than in c).

e) After 3 minutes. The dark areas underneath the steel member are still apparent.

f) After 4 minutes. The thermogram is similar to that in b).



a)



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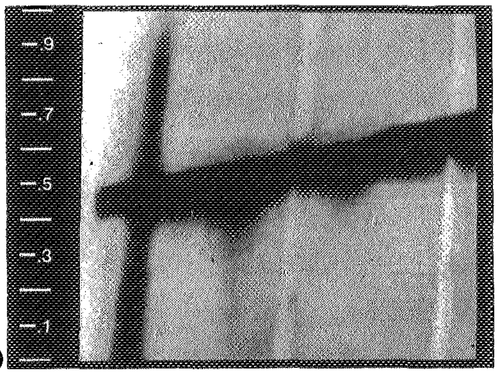

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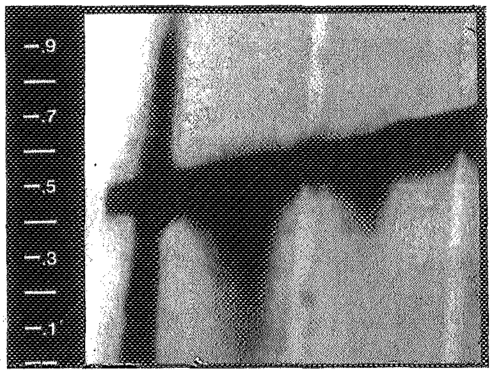

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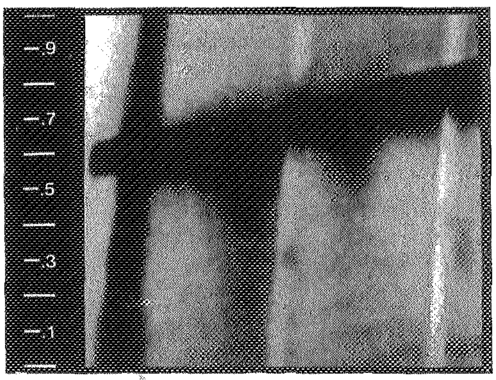

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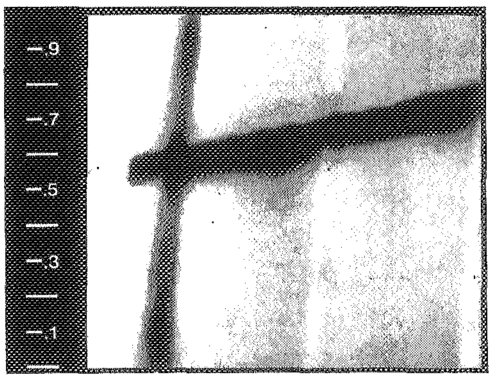


f)

ρ_u = density of air, kg/m^3
T_u = thermodynamic air temperature outdoors, K
T_i = thermodynamic air temperature indoors, K
h = distance to neutral zone, m

If $\rho_u = 1.29$ kg/m^3 (density of air at a temperature of 273 K and an approx. pressure of 100 kPa), we have

$$\Delta p \approx 13 \cdot h \left(1 - \frac{T_u}{T_i}\right) \tag{3.34}$$

For a difference of 25 °C between the indoor and outdoor air temperatures, there is a differential pressure across the construction of about 1 Pa per metre of height.

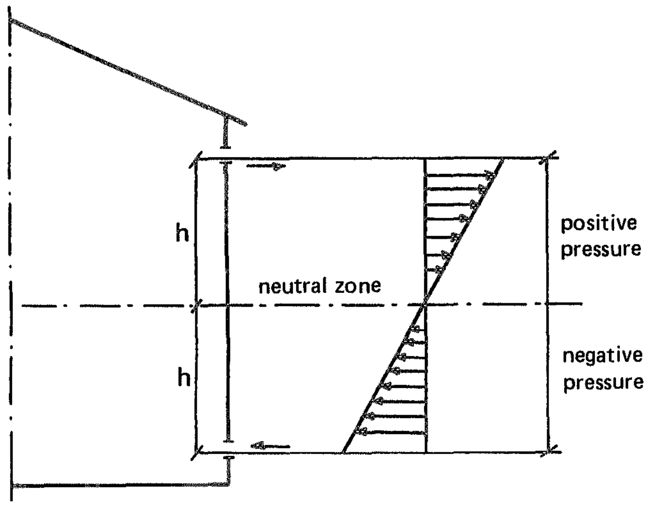


Fig. 23. Distribution of pressure over a wall with two openings. The outdoor temperature is lower than the indoor temperature.

The position of the neutral zone may vary depending on the state of airtightness of the building. If points of leakage are uniformly distributed along the height of the building, this zone is about halfway between the top and bottom of the building. When there is a larger number of leakage points in the bottom half of the building, the neutral zone is displaced downwards, while when there is a larger number of leakage points in the top half, it is shifted upwards. A chimney which discharges above the roof exerts a great influence on the position of the neutral zone, and a vacuum may arise in the entire building. In single-family houses this is the most usual condition.

In a larger building such as a high industrial building, where air leakage occurs through doors and windows in the bottom half of the building, the neutral zone is situated about one third of the height of the building above floor level. Examples of different directions of flow through the same construction at different levels are shown in FIG. 24.

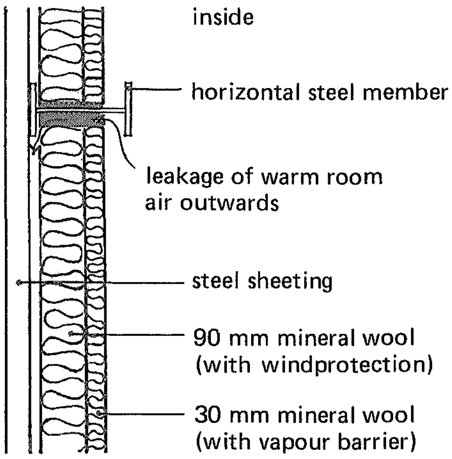
Fig. 24. Insulation and airtightness defects which permit air to leak through the construction. Directions of air flow through the same construction are different at different levels due to positive pressure indoors at the top of the wall and negative pressure indoors at the bottom of the wall.

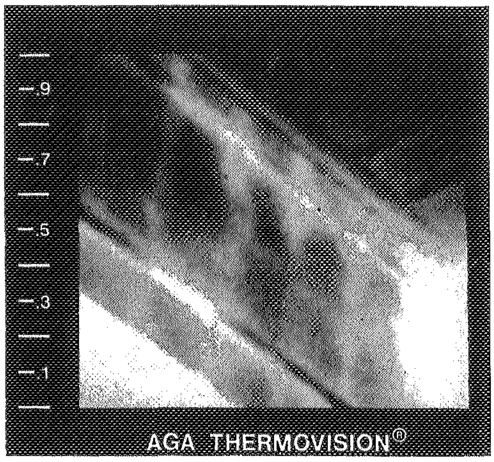
Conditions during measurement:

Cloudiness	cloudy
Outdoor air temp	- 1°C
Indoor air temp	+ 20°C
Wind conditions	3–4 m/s (to facade)

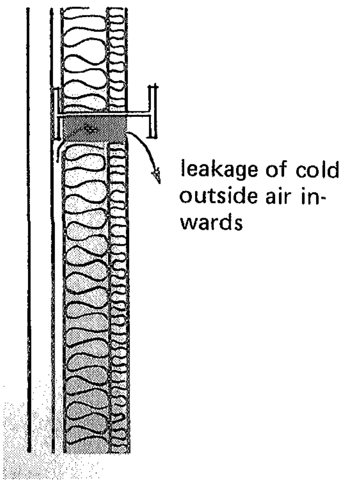
$p_i - p_u = 15$ Pa, top

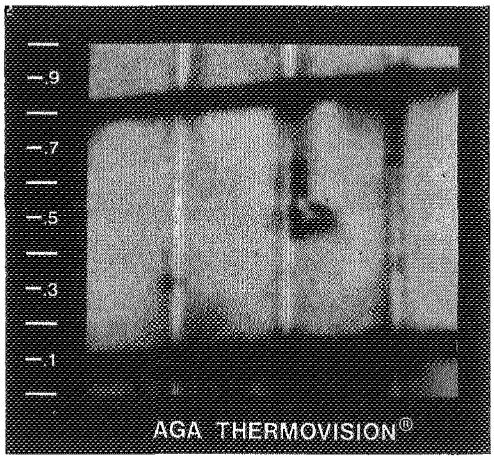
$p_i - p_u = -5$ Pa, bottom





a) Thermogram of inside of wall at the top (about 15 m above floor level). Some areas of the surface are warm due to outward leakage of warm air through the permeable construction.





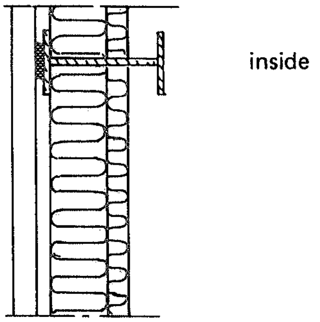
b) Thermogram of the bottom of the wall (about 5 m above floor level). Some areas here are cold due to inward leakage of cold outside air through the permeable construction.

Fig. 25. Thermograms of the same section of wall taken from the inside and the outside.

From the outside:
horizontal member
facade sheeting (painted)
90 mm mineral wool with windprotection
30 mm mineral wool (with vapour barrier)

Conditions during measurement:

Cloudiness	cloudy
Outdoor air temp	- 1°C
Indoor air temp	+ 19°C
Wind conditions	3–4 m/s (about 45° away from facade)
$p_i - p_u$	+ 15 Pa

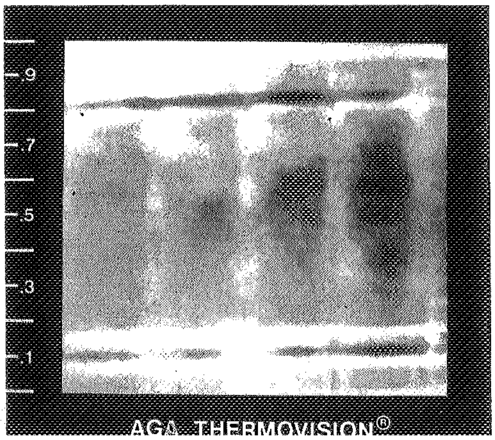


a)

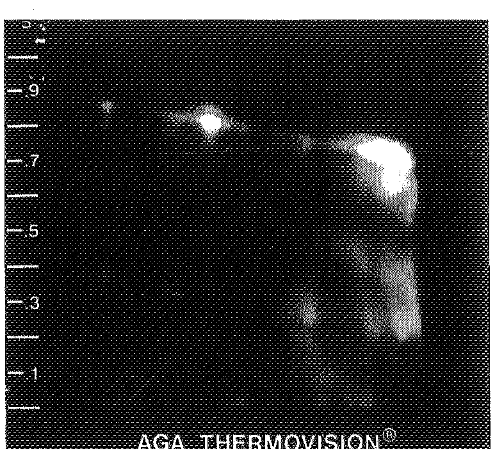
a) Construction of external wall with steel sheeting on the outside.

b) Thermogram of top of wall section (taken from the inside). Certain warmer areas appear near the vertical profiles and also the horizontal wall members. The warmer areas are due to outward leakage of room air. The thermogram of the same wall section, taken from the outside, is shown in c).

c) Thermogram of same section of wall as in b). The warm room air which leaks through the construction warms the surface of the sheeting facade at certain points. Owing to the prevailing wind conditions, these warm areas are slightly displaced to the left in the thermogram.



b)



c)

When thermography is carried out on the inside, it is an advantage if the pressure inside is lower than that outside, and pressure conditions at the different parts of the building are the same. Any points of leakage will then show up clearly and be subject to the same conditions. Cold outside air enters through points of leakage and causes local cooling of the warm surface near these points. On the outside, such leakage has an insignificant effect on the temperature distribution over the wall surface, since the surface temperature is generally almost the same as the temperature of the air which leaks into the building.

When the pressure inside the building is higher than that outside, points of leakage appear in the thermogram, both on the inside and the outside, as warmer areas. Under such conditions leakage is shown up in a more diffuse manner, especially on the warm side where variations in temperature are generally smaller than when air is leaking inwards. The reason for this is that the difference in temperature between the room air and the surface of the wall is generally small. In the latter case, measurement outdoors may be advantageous (see FIG. 25).

When there are only defects in insulation, i.e. if the insulation material has been left out over a certain part of an airtight construction, the surface temperature of the wall is not affected by pressure conditions over the construction. However, leakage of air is the dominant type of defect, and for this reason pressure conditions over the construction are normally of critical significance during thermography.

3.5 Non-stationary temperature conditions

Under actual conditions, temperature conditions in the construction are not normally stationary.

Diurnal variations in air temperature indoors, generally resulting in an elevated daytime temperature and a depressed night temperature, cause both a phase displacement and a change in amplitude in the temperature inside the construction. The magnitude of this effect is governed by the make-up and heat capacity of the construction. The quantity of heat which is stored in a construction is dependent on the thermal characteristics of the building material and on the rate at which a temperature oscillation can be propagated in a material. The latter can be described by the thermal diffusivity, given by

$$a = \frac{\lambda}{\rho c}$$

If the value of a is small, a temperature oscillation is propagated slowly. The heat penetration index $\sqrt{\lambda c \rho}$ is a material constant which indicates how quickly heat can be stored in a material, and the higher the value of this constant, the greater the quantity of heat which can be stored over a certain period.

A construction is generally made up of different materials of different thermal characteristics. Timber studs, mineral wool and lightweight concrete, for instance, are often placed in juxtaposition. A change in temperature outdoors affects the surface temperature inside in different ways, depending on the composition of the construction at the section concerned. An example of a thermogram of such a section is shown in FIG. 28.

Thermography should not be performed when there are large variations in temperature. When there are variations in temperature, the drop in temperature over the construction must be greater if the thermogram is to contain clearly discernible differences. In order to elucidate what conditions should be satisfied, a numerical calculation was made of the variation of surface temperature indoors for variable outdoor temperatures. The calculation was performed by solving the general heat conduction equation in one dimension in a computer using the simple forward difference method.

The following conditions were assumed to hold:

- Unidimensional heat flow.
- Constant indoor air temperature of $t_i = +\ 20\ °C$, with $\alpha_i = 7\ W/(m^2 \cdot K)$.
- Sinusoidal variation of outdoor air temperature over the day, according to

  $$t_{u,e} = t_u + t_i \sin \frac{\pi}{12} (\tau - 8)$$

  with $\alpha_u = 20\ W/(m^2 \cdot K)$. ($\tau$ = time of day).
- The same temperatures during several consecutive days.

Calculations were made for two different constructions, according to FIG. 26 and 27.

The reduction in insulation thickness at section B was selected in such a way that a least drop in resistance of 30–35% of the total thermal resistance of the wall should be detectable during thermography. This figure was indicated by experience gained in practical measurements. For instance, detection of the fact that a slab of insulation 5 cm thick has been omitted in a construction with 5 + 7 cm insulation will be possible in this way.

The calculations were performed for the following outdoor temperatures:

1. $t_u = 10 + 3 \sin \dfrac{\pi}{12} (\tau - 8)$
2. $t_u = 10 + 5 \sin \dfrac{\pi}{12} (\tau - 8)$
3. $t_u = 7 + 3 \sin \dfrac{\pi}{12} (\tau - 8)$

4. $t_u = 7 + 5 \sin \frac{\pi}{12} (\tau - 8)$

5. $t_u = 7 + 10 \sin \frac{\pi}{12} (\tau - 8)$

The surface temperatures at sections A and B at different times were calculated. Examples of the results are given in TAB. 3 and 4.

From the inside:
13 mm plasterboard
polyethylene film
120 mm mineral wool, density = 45 kg/m^3
13 mm bitumen impregnated wood fibre board, density = 300 kg/m^3

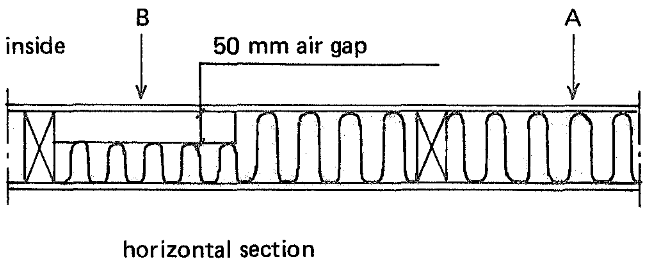


Fig. 26. Construction I of external wall for which the temperature was calculated.

From the inside:
13 mm gypsum wallboard
70 mm mineral wool, density = 45 kg/m^3
150 mm lightweight concrete, density = 500 kg/m^3
plaster

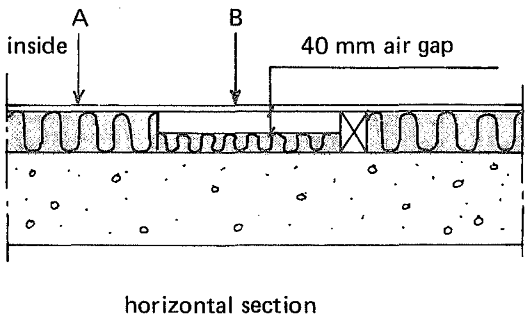


Fig. 27. Construction II of external wall for which the temperature was calculated.

Tables 3 and 4. Calculation of surface temperatures at different times.

Construction type I
Case 1, $t_i = + 20\ °C$

time	t_u, °C	t_{vi} at section, °C A		B
00	7.4	19.50		19.25
01	7.1	19.47		19.22
02	7.0*	19.46		19.20
03	7.1	19.45*		19.19*
04	7.4	19.45*		19.20
05	7.9	19.46		19.22
06	8.5	19.47		19.25
07	9.7	19.50		19.28
08	10.0	19.50		19.33
09	10.3	19.56		19.42
10	11.5	19.59		19.42
11	12.1	19.62		19.47
12	12.6	19.65		19.51
13	12.9	19.67		19.54
14	13.0**	19.69	diff < 0.20	19.55
15	12.9	19.70**		19.56**
16	12.6	19.70**		19.56**
17	12.1	19.69		19.54
18	11.5	19.67		19.51
19	10.3	19.65		19.47
20	10.0	19.62		19.43
21	9.7	19.59		19.38
22	8.5	19.56		19.33
23	7.9	19.52		19.29
24	7.4	19.50		19.25
		19.58 ±0.12		19.38 ±0.19
For stationary condition	10	19.58		19.38

Construction type II
Case 5, $t_i = + 20\ °C$

time	t_u, °C	t_{vi} at section, °C A		B
00	-1.7	19.52		19.33
01	-2.7	19.48		19.26
02	-3.0*	19.43		19.17
03	-2.7	19.37		19.09
04	-1.7	19.32		19.00
05	-0.1	19.27		18.93
06	+2.0	19.22		18.87
07	+4.4	19.19		18.83
08	7.0	19.17		18.81*
09	9.6	19.16*		18.81*
10	12.0	19.17		18.83
11	14.1	19.19		18.87
12	15.7	19.22		18.94
13	16.7	19.27		19.01
14	17.0**	19.32		19.09
15	16.7	19.37		19.18
16	15.7	19.43		19.26
17	14.1	19.48		19.34
18	12.0	19.52		19.40
19	9.6	19.55	diff < 0.20	19.44
20	7.0	19.57		19.46**
21	4.4	19.58**		19.46**
22	2.0	19.57		19.44
23	-0.1	19.55		19.39
24	1.7	19.52		19.33
		19.37 ±0.21		19.13 ±0.33
For stationary condition	7	19.37		19.13

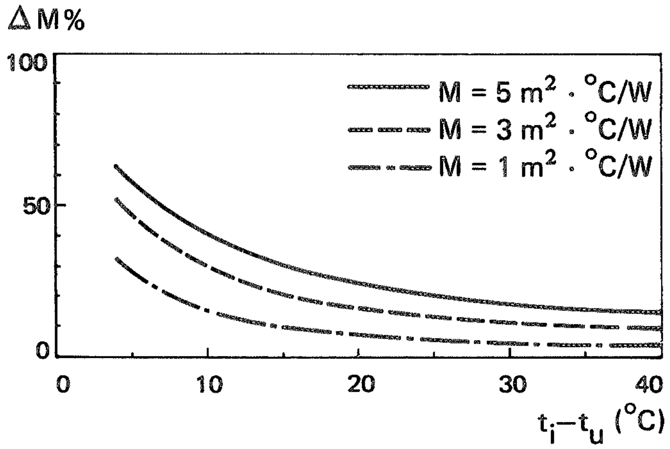
*min **max

For wall type 1, the phase displacement between maximum outdoor temperature and maximum wall temperature indoors is 1–2 hours. The corresponding phase displacement for wall type 2 is 6–7 hours. For both types of wall, the phase displacement of surface temperatures at section A and B is 0.5–1 hour.

If the reduction in insulation thickness at section B is to be capable of detection with the IR camera, $(t_{vi,A} - t_{vi,B}) \geqslant 0.20$ °C.

The periods when $(t_{vi,A} - t_{vi,B}) < 0.20$ °C have been marked in the tables.

The determination of the least temperature difference at which thermography in the field will be meaningful is dependent chiefly on the temperature resolution capacity of the camera and on the temperature state of the wall. The reduction in insulation which can just be detected in stationary conditions, at different air temperature differences (indoor-outdoor) over the construction and at different thermal resistances, is shown below.



Relationship between the reduction in insulation, as a percentage of the thermal resistance of the construction, which can just be detected, and the temperature difference (air-air) over the construction. The thermal resistance of the construction is a parameter. (It is assumed that $m_u = 0.05$ m² °C/W and $m_i = 0.15$ m² °C/W.) (Paljak & Pettersson, 1972).

In practice, the character of defects in insulation is in most cases such that there is a fault in placing the insulation between the timber studs, in combination with leakage of air into or through the construction. This state of affairs generally reinforces the effect of the defect, with the result that there is a greater temperature difference on the surface of the construction. When temperature differences over the construction are small (10–15 °C), differences in temperature over its surface will be relatively small, and external interference can then exert a strong influence on the results. Therefore, when differences in temperature over the construction are small, the requirement that the temperature of the ambient air should be stable is more stringent than when the differences are large.

3.5.1 The influence of sunshine during thermography

In order to find how sunshine and variations in outdoor temperature affect the temperature pattern on the inside of the wall, preliminary measurements were made in the field.

If a wall surface in a room is exposed to direct sunshine, there is an immediate rise in the temperature of the surface, and any variations in temperature tend to be equalized. If the sun shines on the outside of a facade, the temperature on the inside of the wall rises after a certain time, the magnitude of this rise being a function of the construction of the wall and of the intensity of solar radiation. See FIG. 28.

In a test dwelling in a block of flats, a section of an external wall was subjected to thermography under different conditions. Taken from the inside, the construction of the external wall was 13 mm plasterboard, 0.13 mm polyethylene (PE) film, 120 mm mineral wool (between 50 x 120 mm timber studs), 12 mm bitumen impregnated fibre board, and a panel. At a section to the left of the window (seen from the inside, FIG. 29a), the insulation was reduced to about 50% of the original thickness. The section of the wall in question was partially screened from sunshine by a projecting balcony.

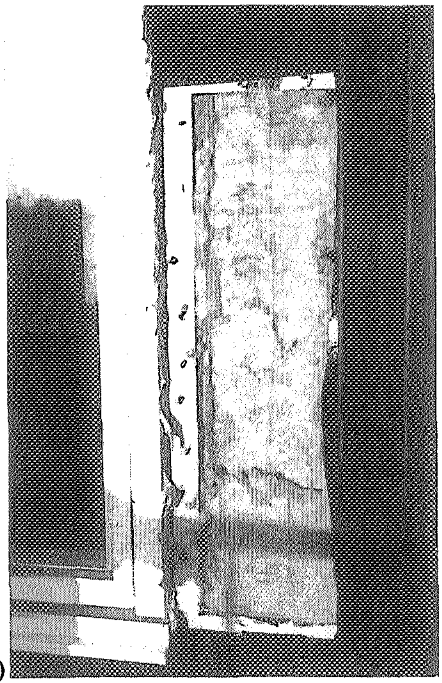
Thermography of this section was carried out from the inside at different times during the day, and under different conditions.

The investigations showed that on typical autumn and winter days, with moderate variations (about ± 3 °C) of the outdoor air temperature over the day, the appearance of the thermal image at such a wall section does not change appreciably. During the measurements, $t_i - t_u$ was greater than 15 °C.

The surface temperature of the colder wall section follows the outdoor variations in a natural manner. The influence of the variations is not so large that there are difficulties in interpretation, FIG. 29.

On a typical spring day with a relatively low night temperature, about 0 °C, and a high day temperature, about + 14 °C, with simultaneous insolation on parts ofthe facade, thermography was found difficult.

Fig. 29. Thermograms taken from the inside at variable outdoor air temperatures.



a)

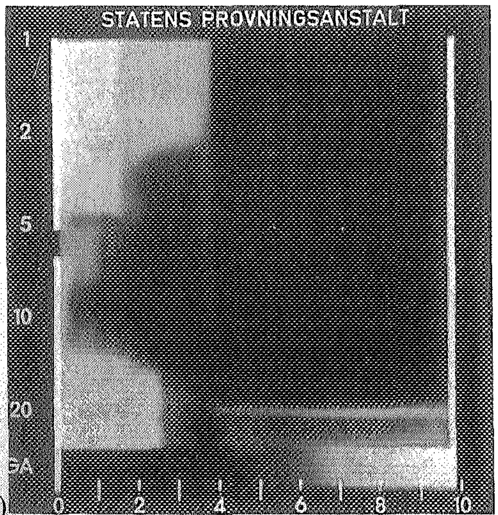
a) Wall exposed on the outside at section where insulation had been reduced by about 50%

b) Thermogram of the wall section shown in a), taken from the inside to the right of the window. The appearance of the colder area was the same over the whole day for the above type of weather. There was some variation in the degree of cooling of the defective section.

c) t_i = + 23°C

t_u = + 5 to + 7°C (variation over the day – not exposed to sun)

Δt = 3.0°C



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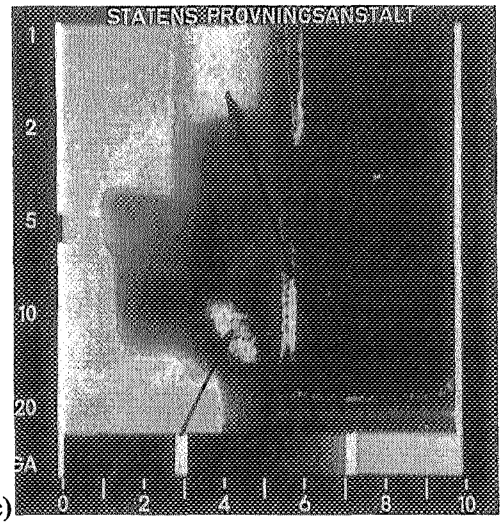


c)

Fig. 30. The effect of the sun on the appearance of the thermogram.

a) Sunshine on facade at 09.00 a.m. Section of surface with reduced insulation has been marked.

b) Sunshine on facade at 03.00 p.m. Section of surface with reduced insulation has been marked.

c) Thermogram at 09.00 a.m.

t_i = + 23 °C

t_u = + 6 °C

t_{vu} = about + 35°C (on surface on which sun is shining)

d) Thermogram at noon.

t_i = + 24 °C

t_u = + 11 °C

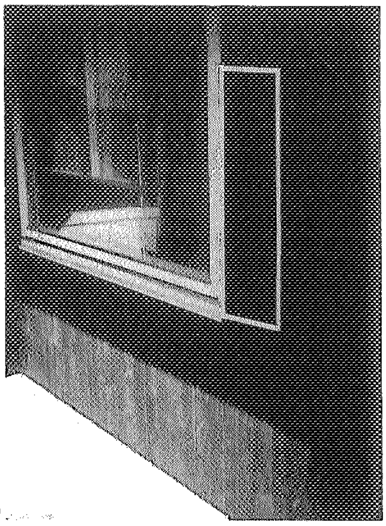
t_{vu} = about + 40°C (on surface on which sun is shining)

e) Thermogram at 03.00 p.m.

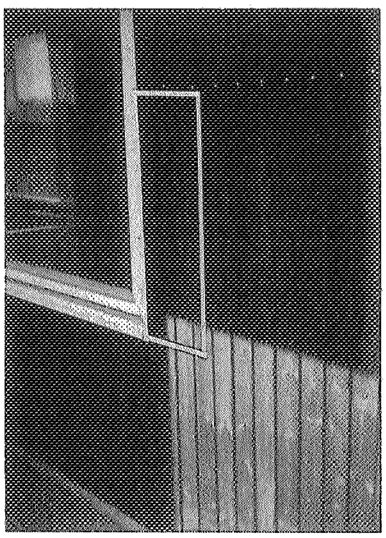
t_i = + 24 °C

t_u = + 14 °C

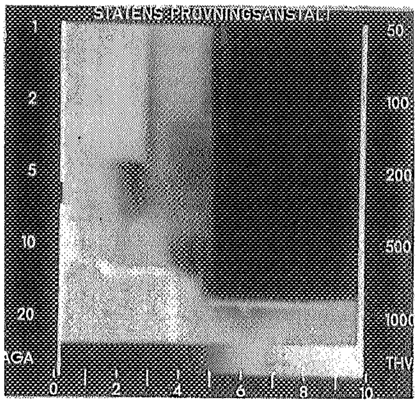
t_{vu} = about + 40°C (on surface on which sun is shining)



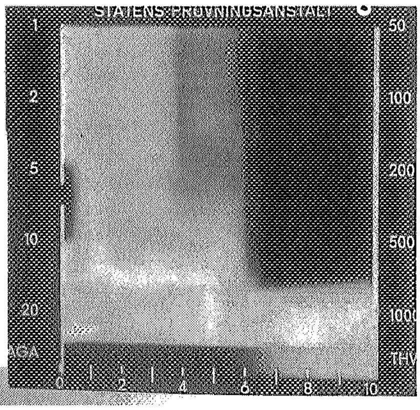
a)



b)



c)



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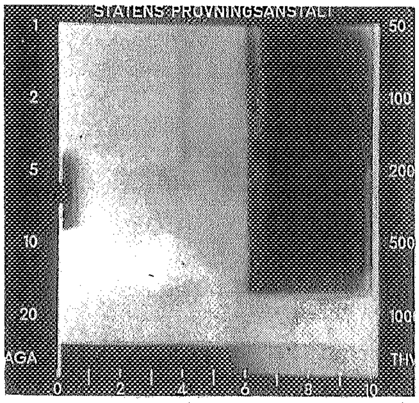


e)

Measurements showed that temperature contrasts at the defective section were equalized relatively quickly, and that the defect was masked over most of the day, the results are partly shown by the thermograms in FIG. 30.

As mentioned before, thermography must not be carried out when solar radiation has affected the building element. Temporary insolation can be accepted, if it is considered that the results will not be affected. For instance, windows should be covered in order to prevent direct sunshine in the room.

When thermography is to be carried out in a building, the maximum and minimum temperature should be determined at the site over a day prior to thermography, for instance with the aid of a maximum-minimum thermometer. Sunshine conditions during the same day should also be known.

4 The use of thermography

4.1 Conditions during measurement, and measuring season

In the light of what has been said above, the following summary may be made concerning the conditions which must prevail when a building is being thermographed.

Thermography is to be carried out in such a way that the least possible interference occurs due to external climatic factors. Measurement should therefore take place indoors, i.e. in a heated building the warm surface of the construction must be studied.

Outdoor thermography is to be applied only for preliminary measurements over large areas of wall. In certain cases, for instance where thermal insulation is very bad or where the pressure indoors is higher than that outdoors, measurements outdoors can provide valuable information. Where the influence of installations placed in the climatic envelope of the building is to be investigated, thermography from the outside of the building may also be warranted.

The following conditions should be satisfied:

1. For at least one 24-hour period before commencement of thermography, and as long as this is in progress, the difference in air temperature across the building element must be at least 10°C. During the same time, the difference in air temperature may not vary by more than ± 30% of the difference at the beginning of thermography. During the time thermography is in progress, the air temperature indoors should not be changed by more than ± 2°C.
2. For at least 12 hours before commencement of thermography and as long as this is in progress, the building element in question shall not be exposed to sunshine of an extent sufficient to cause interference with the results.
3. The pressure drop across the construction shall be $\approx$ 5 Pa.
4. When thermography is carried out only with the aim of locating points of air leakage in the elements enclosing

the building, the stipulations regarding conditions during measurement may be less stringent. A difference of about 5°C between the air temperatures indoors and outdoors should be sufficient in order that such defects may be detected. In order that air movements may be detected, however, some requirements must be imposed with regard to the pressure difference; about 5 Pa should be sufficient.

These stipulations regarding conditions during measurement limit the period during the year when thermography can be carried out in Sweden.

On the basis of statistics from the Swedish Meteorological and Hydrological Institute (SMHI) concerning the mean values of maximum and minimum temperatures for each day during the months Jan–Dec over a 30-year period, 1931–1960, the length of the measuring season can be estimated. See TAB. 5. For the towns of Kiruna (northern Sweden), Stockholm (central Sweden) and Lund (southern Sweden), at an indoor temperature of + 20°C, the periods during which it is possible to carry out thermography in accordance with condition 1 above are as follows:

Kiruna: middle of September–middle of May (about 8 months)
Stockholm: beginning of October–end of April (about 6.5 months)
Lund: middle of October–middle of April (about 6 months)

Table 5. Mean values of maximum-minimum temperatures in three towns in Sweden during the period 1931–1961, according to SMHI.

	Kiruna		Stockholm		Lund	
	max	min	max	min	max	min
jan	- 8.2	- 17.1	- 1.0	- 4.7	+ 1.1	- 2.8
feb	- 8.3	- 17.0	- 1.2	- 5.5	+ 1.4	- 3.2
mar	- 4.3	- 14.4	+ 1.9	- 3.6	+ 4.6	- 1.5
apr	+ 0.5	- 8.5	+ 8.3	+ 0.7	+ 10.6	+ 2.5
maj	+ 6.7	- 1.4	+ 14.6	+ 5.7	+ 16.7	+ 6.7
jun	+ 13.7	+ 4.7	+ 19.2	+ 10.4	+ 20.6	+ 10.6
jul	+ 17.6	+ 8.4	+ 21.8	+ 14.0	+ 22.4	+ 13.1
aug	+ 14.9	+ 6.2	+ 20.2	+ 13.3	+ 21.3	+ 12.7
sep	+ 8.7	+ 1.9	+ 15.3	+ 9.4	+ 17.1	+ 9.8
okt	+ 1.5	- 4.6	+ 9.0	+ 4.8	+ 10.7	+ 5.8
nov	- 3.6	- 10.7	+ 4.5	+ 1.0	+ 6.6	+ 2.5
dec	- 6.4	- 14.6	+ 1.9	- 1.9	+ 3.1	- 0.2

The effect of the sun has not been taken into account. If the indoor temperature is raised, the measuring season can be extended.

When only points of air leakage in a building are to be located, the stipulations regarding conditions during measurement can be less stringent, and this permits the period during which the IR camera can be used to be considerably longer. During such measurements, there is no need for the requirement that the variation in temperature difference must not exceed ± 30% to be satisfied. The requirement concerning differential pressure across the construction must however be satisfied. Location of points of leakage with an infrared camera should be carried out from the inside of the building, and the pressure inside must be lower than that outside the building.

4.2 Interpretation of thermograms

The principal purpose of thermography is to locate defects and shortcomings in the thermal insulation of external walls and floors, and to determine the type and extent of the defect. The task of thermography may also be defined as the determination of whether the element of construction possesses the stipulated insulation and airtightness properties. If the conditions at the time the measurement is made are known, the stipulated thermal insulation properties of the element of construction according to the drawings can be stated in terms of an expected surface temperature distribution over the area being investigated.

In practice, the method involves the following:

With the aid of either laboratory or field measurements, an expected temperature distribution, in the form of typical or comparative thermograms, is prepared in advance for wall constructions of common occurrence, both for constructions free of defect and for constructions incorporating deliberate defects. Examples of typical thermograms are shown in FIG. 31.

If thermograms of parts of a construction taken during field measurements are to be capable of use for purposes of comparison, the design of the construction, the workmanship and the conditions prevailing during measurements must be well known and properly documented.

In order that the causes of deviations from the expected result may be stated, the physical, metrological and structural conditions must be known.

The interpretation of thermograms taken during measurements in the field can be briefly described as follows.

On the basis of the type of wall construction in question and the conditions prevailing during measurements in the field, a comparative thermogram for a construction free of defect is selected. The thermogram of the building element examined is compared with the selected thermogram. Deviations which cannot be explained by the design of the construction or the conditions during measurements, are noted as suspected defects in insulation. The kind and extent of the defect are normally determined with the aid of comparative thermograms incorporating various intentional defects. The principle of interpretation for thermograms is set out in the form of a block diagram on p. 81.

If suitable comparative thermograms are not available, evaluation and assessment must be made on the basis of experience. In such a case, the analysis must be much more exact.

The following should be investigated when thermograms are evaluated:

- Uniformity of density of the thermogram relating to sections of the surface where there are no thermal bridges
- The regularity and incidence of colder sections (dark grey tone), for instance over studs and at corners
- The contours and characteristic shape of the colder section
- The measured difference between the "normal" surface temperature of the construction and the temperature of the selected colder section
- The continuity and uniformity of the isotherm curve over the surface of the construction.

Deviations and irregularities in the appearance of a thermogram often indicate a defect in insulation. Naturally, the appearance of a thermogram relating to a construction with a defect in insulation may vary a lot. Certain types of insulation defect have a characteristic shape in the thermogram. An example of the interpretation of thermograms is shown in FIG. 32.

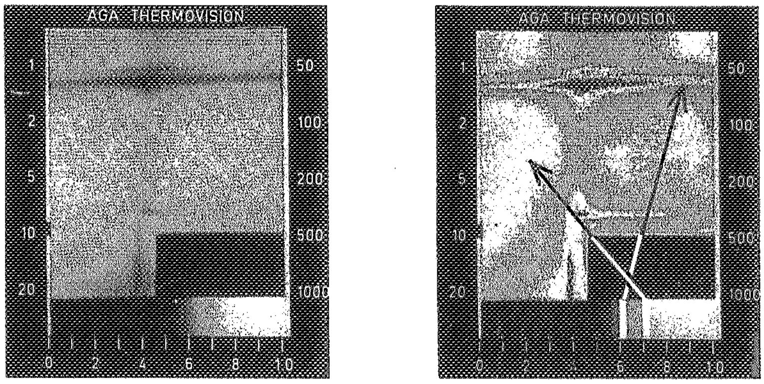
When the same object is being photographed, an endeavour should be made to ensure that thermograms relating to different parts of the object are taken with the same camera setting. This will make comparison of different parts of the surface much easier. When a section of surface is being investigated, a monochrome image and an isotherm image of the same section are normally taken. The isotherms are imposed on the selected parts of the surface of the construction. The reference temperature corresponding to one of the isotherms is determined, for instance with a surface temperature sensor. The differences in temperature between different parts of the surface can then also be determined.

The above principle of interpretation relates primarily to black-and-white thermograms which are the most common. Evaluation of colour thermograms can however be carried out in the same way. In our investigations, black-and-white thermograms have mainly been used, the reasons being as follows:

- Details and temperature variations stand out with great clarity in black-and-white thermograms
- Equipment for the production of black-and-white thermograms is cheaper than that for colour thermograms
- The process of reproduction, and the cost of this, is simpler and cheaper for black-and-white thermograms.

An example of a colour thermogram is shown in FIG. 33b.

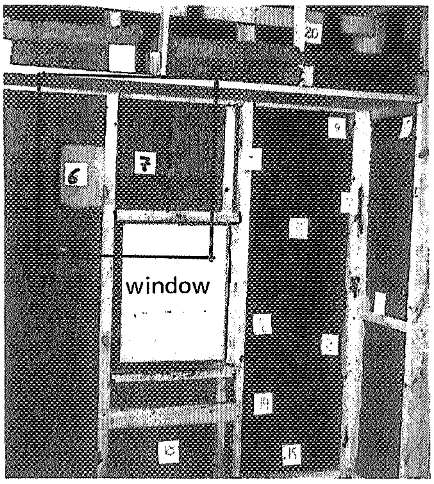
Fig. 31. Use of comparative thermograms.

a) 

a) Typical thermograms of section at wall-ceiling junction for stud wall No. 1, construction free of defect.

$t_i - t_u = +26\ ^\circ C$ $\quad t_{ref} = +20\ ^\circ C$

$p_i - p_u = -50$ Pa $\quad \Delta t = 2.7\ ^\circ C$

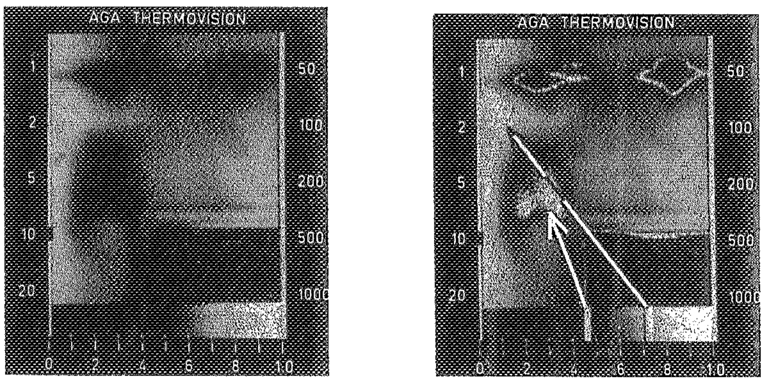
b) 

b) Stud wall No. 1 with gypsum wallboard and plastics film removed. Positions of different defects marked. Make a special note of defects Nos. 6 and 7 where the tickness of insulation has been reduced by 100% and 50% respectively of the original.

c) Typical thermograms of section at wall-ceiling junction for stud wall No. 1 with deliberate defects. Note defects Nos. 6 and 7. Leakage of air inwards occurs through improperly sealed junction at the eaves.

$t_i - t_u = +26\ ^\circ C$ $\quad t_{ref} = +20\ ^\circ C$

$p_i - p_u = -50$ Pa $\quad \Delta t = 4.1\ ^\circ C$

c) 

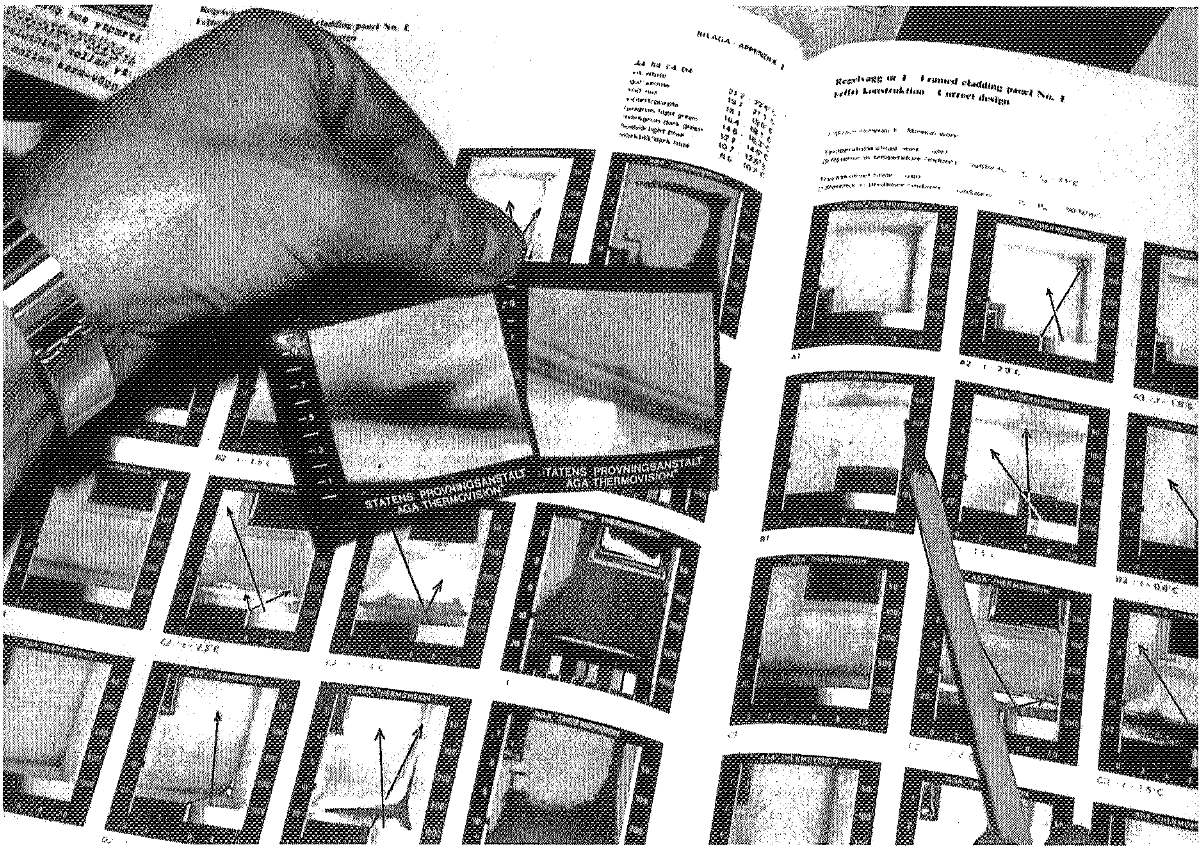
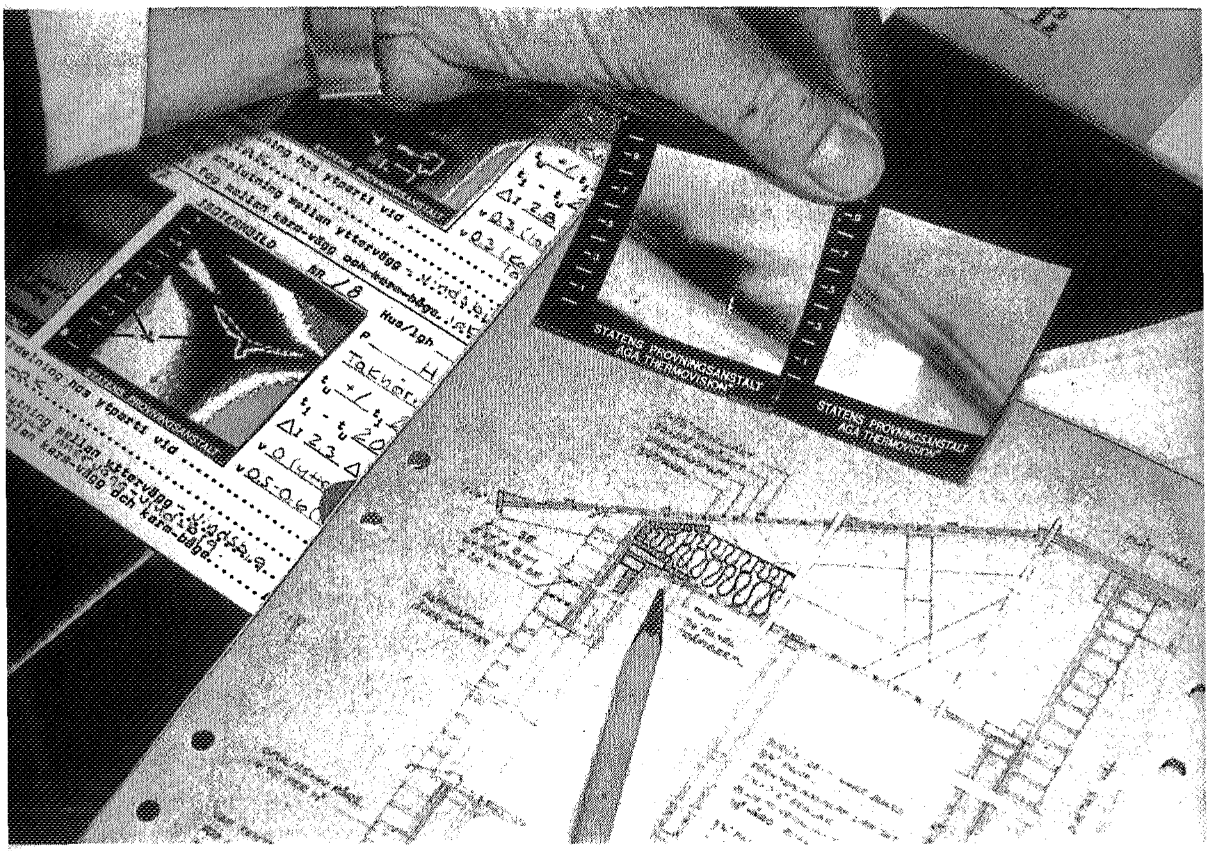


Fig. 32 a) The thermograms are compared with typical thermograms.

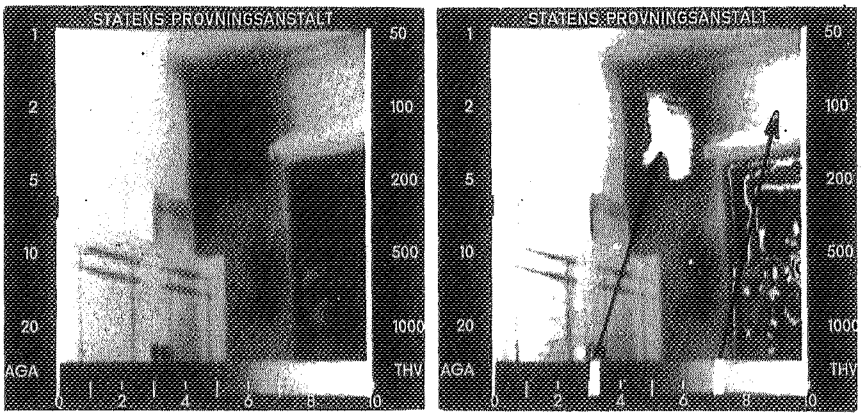


b) The construction in question is studied.

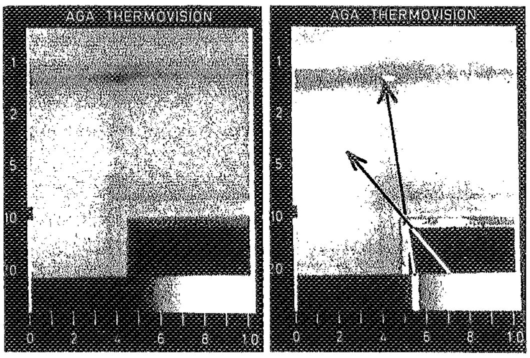
Fig. 32c) Thermograms of section of external wall at wall-ceiling junction. Colder (dark) areas appear in the thermogram to the left of the window (monochrome image at left, and isotherm image at right).

t_i-t_u	$= +21\ ^\circ C$	t_{ref}	$= +21\ ^\circ C$
p_i-p_u	$= -3$ Pa	Δt	$= 2.5\ ^\circ C$ (difference in surface temperature between "normal" wall temperature and temperature of colder section)

c)



d)

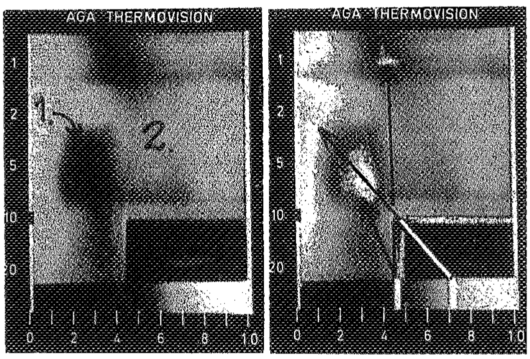


d) Typical thermograms of external wall with the same broad construction (stud wall No. 1) as that in c), conditions during measurement being as follows:

t_i-t_u	$= +26\ ^\circ C$	t_{ref}	$= +20\ ^\circ C$
p_i-p_u	$= 0$ Pa	Δt	$= 3.0\ ^\circ C$

When these are compared with the thermograms in c), differences are found.

e)

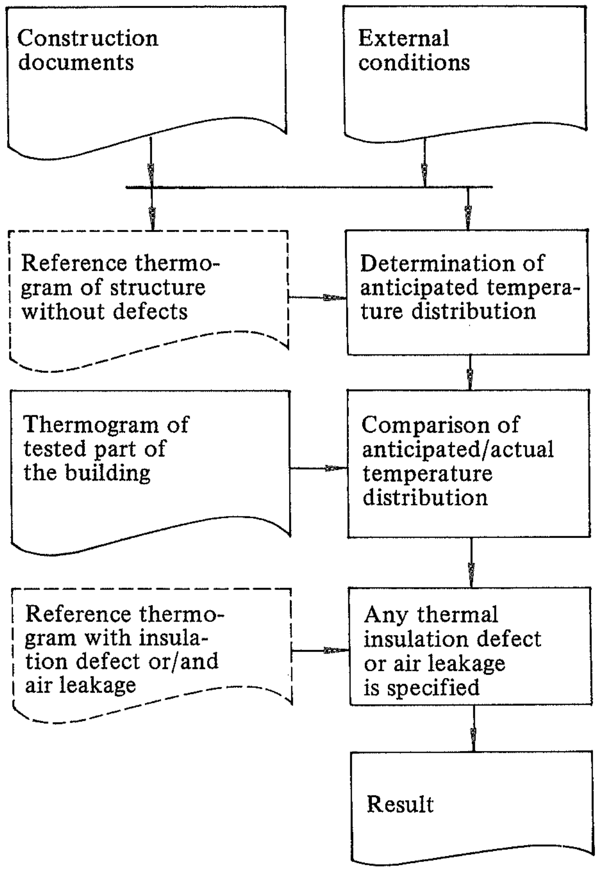


e) Typical thermograms for same external wall as in d), but with deliberate defects. Conditions during measurement the same as in d).

$\Delta t = 4.0\ ^\circ C$

The thermograms in c) and d) are compared. Defect No. 1 corresponds to 100% reduction of insulation in the wall.
Defect No. 2 corresponds to 50% reduction of insulation in the wall.

Conclusion: The construction probably has no insulation at the colder section in c).



Procedure of interpretation of thermograms.

4.3 Camera setting

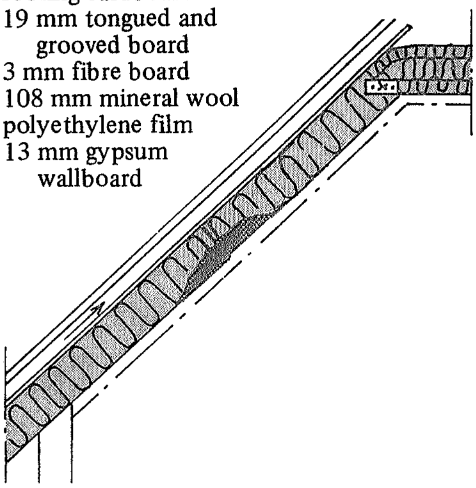
During thermography, it is essential that the setting of the IR camera is such that the correct brightness and contrast are obtained in the thermal image. The instructions of the manufacturer should be observed.

Thermograms taken with different camera settings are shown in FIG. 125 in the appendix. When the appropriate measurement range is being set on the IR camera, it is essential that the temperature variations which it is endeavoured should be illustrated appear as clearly as possible. If a measurement range of excessive sensitivity is selected, there is a great risk that the colder sections will be too dark, and it will thus be difficult to distinguish details in the picture. However, a high sensitivity may be necessary in detailed studies of e.g. isolated sections of an external wall.

The main principle in setting the appropriate measurement range must be to ensure that this range covers the

Fig. 33. Colour thermogram and black-and-white thermograms of the same section of surface.

Inclined ceiling, from the top:
roof covering
roofing cardboard
19 mm tongued and grooved board
3 mm fibre board
108 mm mineral wool
polyethylene film
13 mm gypsum wallboard



a)

Conditions during measurement:

cloudiness	clear (building element concerned not exposed to sun)
outdoor air temp	- 2°C
indoor air temp	+ 21°C
wind conditions	no wind
$p_i - p_u$	- 5 Pa

a) Construction of insulated inclined ceiling with defective insulation.

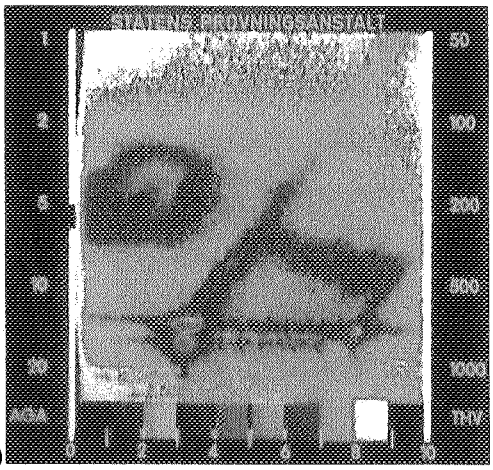
b) Colour thermogram of part of inclined ceiling.

Upper temperature limits for colour shades:

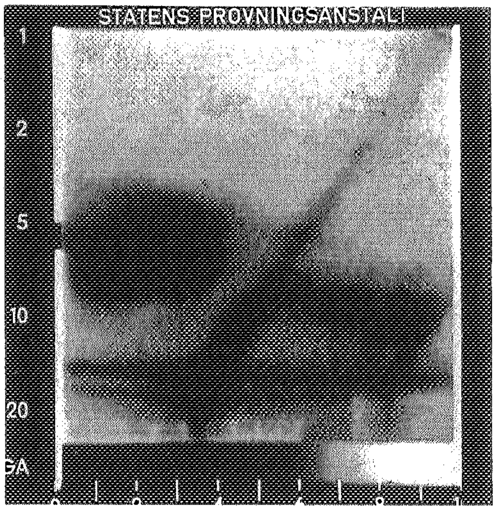
white	+ 21.0°C
yellow	+ 20.4°C
red	+ 19.7°C
violet	+ 19.0°C
light green	+ 18.4°C
dark green	+ 17.7°C
light blue	+ 17.0°C
dark blue	+ 16.3°C

c) Thermogram (monochrome) of same section as in b). The colder (dark) areas are due to defective insulation.

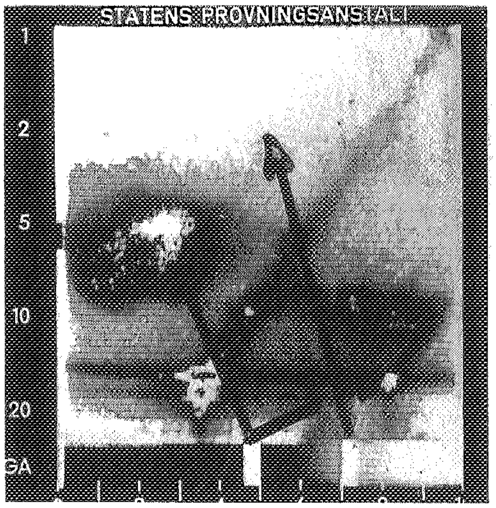
d) Isotherm image.
t_{ref} = + 20°C
Δ I = - 1,2 isotherm units
Δ t = 1.5°C
v = 0 m/s



b)



c)



d)

temperature region in question over the surface being studied.

It is also essential that the aperture setting of the IR camera is correct, and that it is not changed during thermography. This setting is to be f/1.8 for the type of camera which has been used in these investigations.

4.4 The reliability of the measuring method

In about 150 cases, defects located with the infrared camera could be exactly verified either by dismantling and visual inspection of the section of wall concerned, or by means of supplementary measurements using other methods, for instance heat flow measurement. Such methods of verification were mentioned before in Chapter 2.

It is of fundamental interest that no significant defects in insulation should remain undetected, and also that defects located by means of thermography should be true insulation and airtightness defects.

FIG. 34–40 show some examples where the results of thermography have been exactly verified.

Each case of measurement is set out on one page, and includes thermograms of the building element in question, the appearance of the construction, and details of conditions during measurement. The method used for verification of the defect recorded by the IR camera is also described.

Thermograms are displayed in pairs, with the thermogram which shows the temperature distribution according to the grey scale (monochrome image, no imposed isotherms) to the left, and the thermogram of the same section with two isotherms imposed to the right. On the isotherm images, arrows have been drawn between the isotherm markings on the scale and the corresponding section of the surface in the image.

The following symbols are used:

- t_{ref} measured reference temperature on the selected section of the surface, °C
- ΔI difference between the isotherm markings on the isotherm image, isotherm units
- Δt temperature difference corresponding to ΔI, °C
- p_i-p_u pressure across the constructional element, measured with a U-tube manometer, Pa
- v air velocity at the point of leakage (near the surface), measured with a hot-wire anemometer, m/s

Air temperatures are measured with a mercury thermometer. The reference temperature on the surface has been measured with a surface temperature sensor.

The investigations have shown that in all the cases where a defect in insulation or air leakage was located with the

IR camera, such a defect could also be verified by careful examination. During our investigations, the IR camera did not give rise to faulty assessments in those cases where the conditions during measurements were as prescribed.

The following may be said as regards the risk of misinterpretation.

We know with great certainty what the appearance of thermograms is for constructions free of defects. Provided that the conditions during measurements are as laid down, there is little risk that any significant defects will remain undetected. It must be pointed out, however, that the IR camera has difficulty in detecting sections in a construction where the insulation is uniformly substandard. Some guidance can be obtained by a comparison of the temperatures of the outer and inner walls, for instance, and an assessment of the meaning of the temperature reduction on the outer wall. In such cases, however, some form of supplementary measurement may be necessary. Defects such as leakage of air and incorrect placing of insulation combined with convective air movements inside the construction are detected effectively, particularly if the inside of the building is at a pressure below that outdoors.

Owing to its satisfactory capacity to detect defects in insulation, the method of thermography has been used in connection with legal disputes between the buyer and seller of a building. So far, thermography has been applied in about 50 disputes of this nature. Some cases have proceeded to court, and the evidence of thermography has been accorded great importance. Experience has shown that most disputes have been resolved by arbitration. In cases where there have been serious defects, these have been made good, generally without the buyer incurring any expenditure.

If thermography is to be carried out correctly, special knowledge and experience not only in infrared camera techniques but also in building technology and metrology are essential. Correct interpretation and assessment of the results in addition impose special requirements with regard to experience in, and knowledge of, building physics and heating and ventilation techniques.

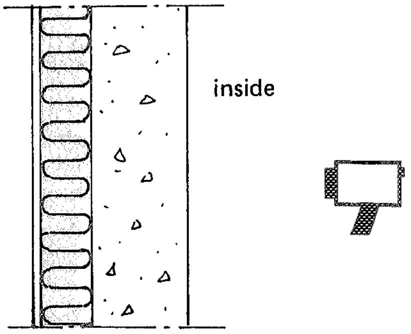
RELIABILITY OF THE METHOD – EXTERNAL WALL.

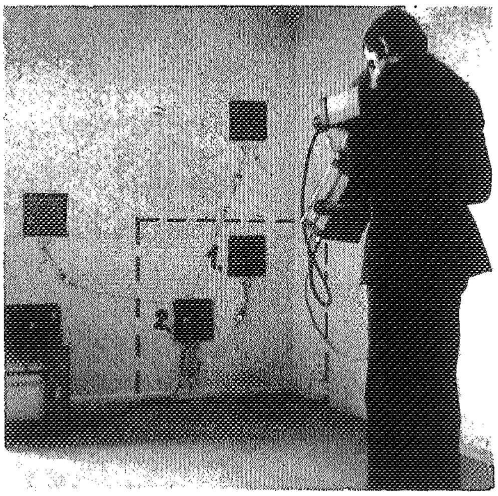
Fig. 34. Investigation of thermal insulation capacity of external wall by measurement of heat flow and by thermography. (The results of heat flow measurement are in good agreement with those given by thermography.)

External wall, from the outside:
facade sheeting
80 mm mineral wool
160 mm concrete
plaster

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	- 1°C
indoor air temp	+23°C
wind conditions	about 3 m/s (away from facade)
$p_i - p_u$	- 3 Pa

a) 

b) 

a) Construction of external wall.

b) Test set-up for simultaneous measurement on external wall with heat flow meter and IR camera. Heat flow meters Nos 1 and 2 etc have been marked, and also section of surface being thermographed.

Measured heat flows:

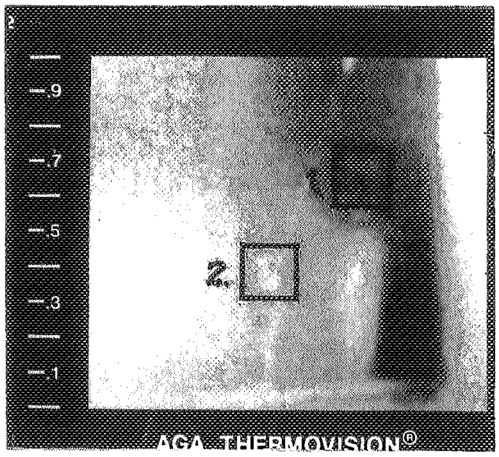
Point 1	14.7 W/m²
Point 2	9.8 W/m²

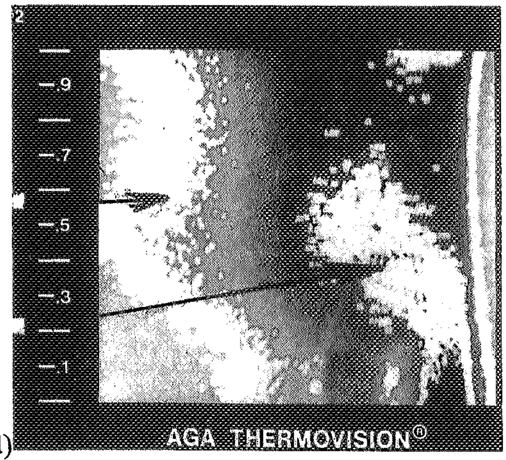
The k-value at these points were found to be

Point 1	0.60 W/m² °C
Point 2	0.40 W/m² °C

c) Thermogram of somewhat colder area marked in b). This is probably due to incorrect placing of the insulation material, combined with convective air movements inside the construction.

d) $t_{ref} = +22°C$
Δ I = -0.7 isotherm units
Δ t = 1.0°C (point 1–2)
v = 0 m/s
According to Equation 3.19, the value of m_i is given as 0.21 m² °C/W

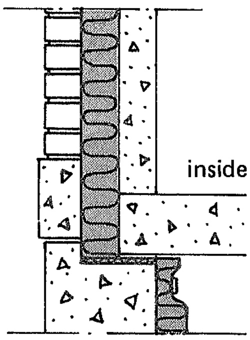
c) 

d) 

RELIABILITY OF THE METHOD – EXTERNAL WALL

Fig. 35. Investigation of the thermal insulation capacity of external wall by measurement of heat flow and by thermography. (The results of heat flow measurements are in good agreement with those given by thermography).

External wall, from the outside:
facing bricks
120 mm mineral wool
120 mm concrete



a)

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	- 1°C
indoor air temp	+20°C
wind conditions	calm
$p_i - p_u$	- 10 Pa

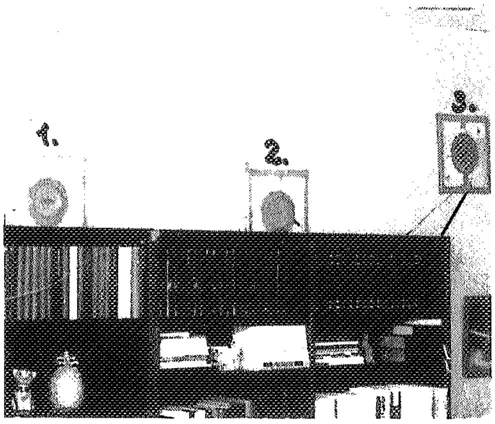
a) Construction of external wall.

b) The positions of the heat flow meters Nos 1, 2 and 3 on the external wall have been marked.
The k-values at these points were found to be
$k_1 = 0.45$ W/m² °C
$k_2 = 0.80$ W/m² °C
$k_3 = 0.30$ W/m² °C

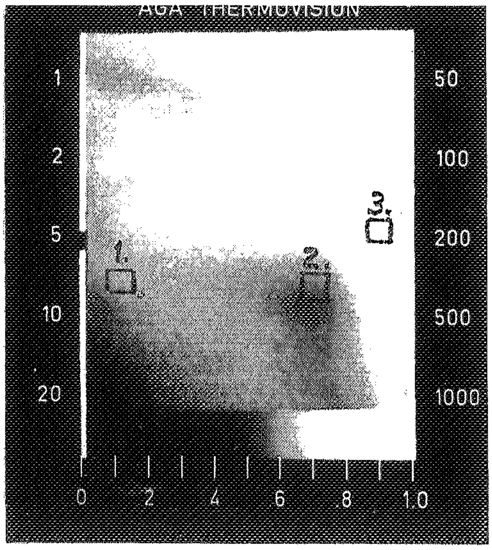
c) Thermogram of somewhat colder section in the middle of the wall. This is probably due to incorrect placing of the insulation material. The slabs of insulation material appear to be badly fitted together and to be not in contact with the concrete.

d) $t_{ref} = +19$°C
$\Delta I = -1.1$ isotherm units (point 1–2)
$\Delta t = 1.5$°C
$v = 0$ m/s

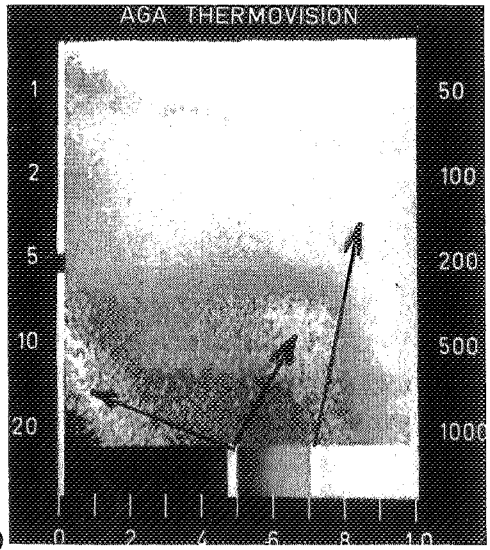
According to Equation 3.19, the value of m_i is given as 0.20 m² °C/W.



b)



c)

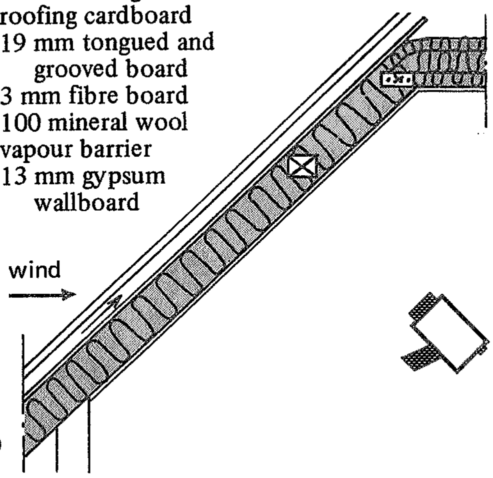


d)

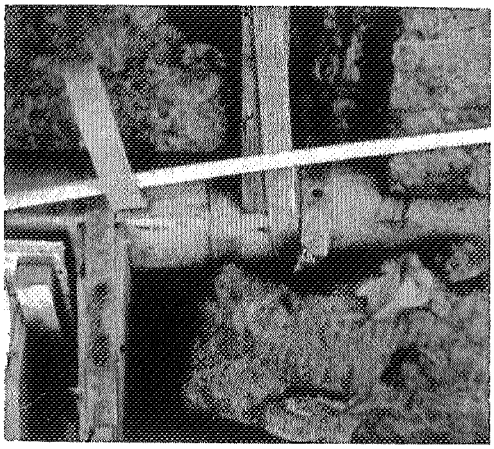
RELIABILITY OF THE METHOD – ROOF

Fig. 36. Investigation of the thermal insulation capacity of section of the roof where a suspected defect – incorrect placing of the insulation material combined with unsatisfactory windprotection – has been verified.

Roof, from the top:
roof covering
roofing cardboard
19 mm tongued and grooved board
3 mm fibre board
100 mineral wool
vapour barrier
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

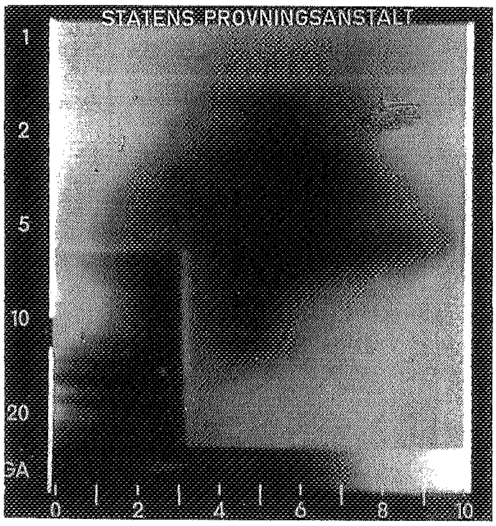
cloudiness	clear
outdoor air temp	0°C
indoor air temp	+20°C
wind conditions	2–3 m/s (perpendicularly to roof)
$p_i - p_u$	- 5 Pa

a) Construction of insulated roof.

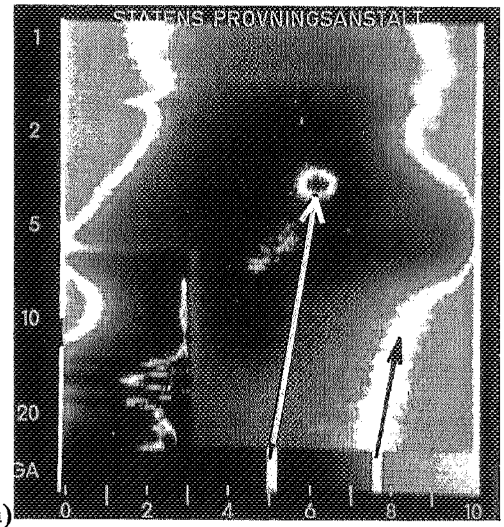
b) Section of roof exposed from the inside. The insulation material is not fitted properly around studs and to the gypsum wallboard. (Complicated construction.)

c) Thermogram of section of the inclined ceiling – colder area to the right of the window section. This due to the defects described in b).

d) $t_{ref} = +19°C$
$\Delta I = -2.6$ isotherm units
$\Delta t = 3.5°C$
$v = 0$ m/s



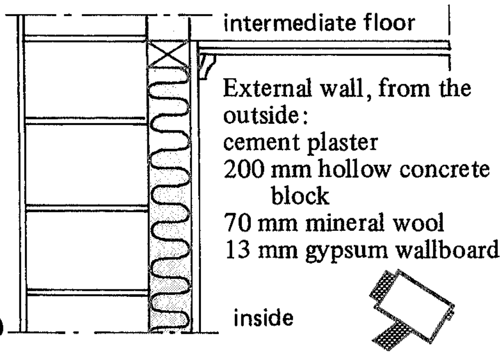
c)



d)

RELIABILITY OF THE METHOD – EXTERNAL WALL

Fig. 37. Investigation of the thermal insulation capacity of section of the external wall of hollow concrete blocks, where a suspected defect – incorrect placing and fitting of insulation material in the construction – has been verified by exposing and visually inspecting the construction.



a)

b)

Conditions during measurement:

cloudiness	clear
outdoor air temp	+5°C
indoor air temp	+21°C
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall.

b) Section of wall exposed from the inside. The insulation material consisted of small pieces which were badly fitted in the space between the studs. Leakage of air into the construction caused deposition of dirt on the insulation material.

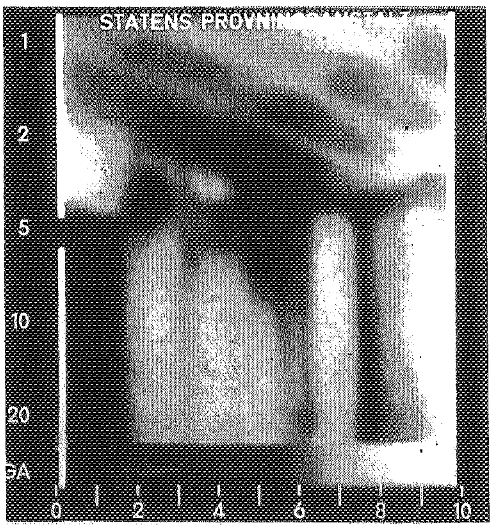
c) Thermogram of somewhat colder wall section. Colder areas are located along the vertical stud in the wall and at the top of the wall.

d) t_{ref} = +20°C

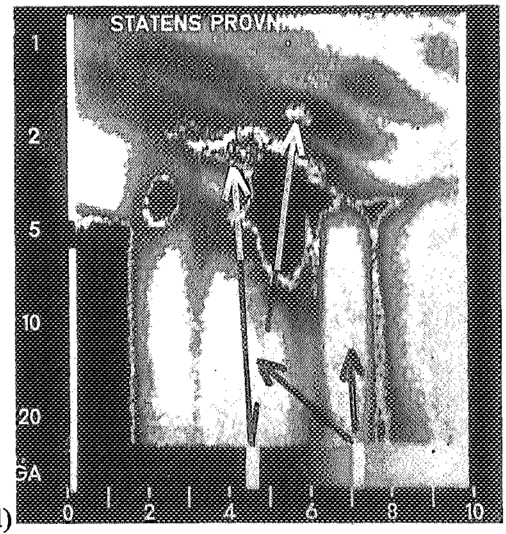
Δ I = - 1.2 isotherm units

Δ t = 1.5°C

v = about 0.5 m/s (at wall-ceiling junction)

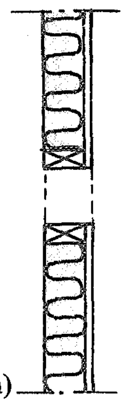


c)

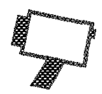


d)

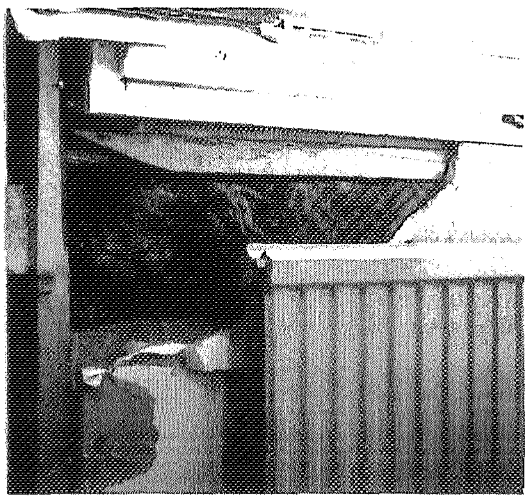
Fig. 38. Investigation of the thermal insulation capacity of section of the external wall where a suspected defect – incorrect placing and partial omission of the insulation material – has been verified by opening up the construction.

a) 

External wall, from the outside:
cardboard
100 mm mineral wool
polyethylene film
13 mm gypsum wallboard
(The wall is adjacent to an uninhabited attic space)



inside

b) 

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	+ 1°C
indoor air temp	+ 23°C
wind conditions	1–2 m/s (to facade)
$p_i - p_u$	- 5 Pa

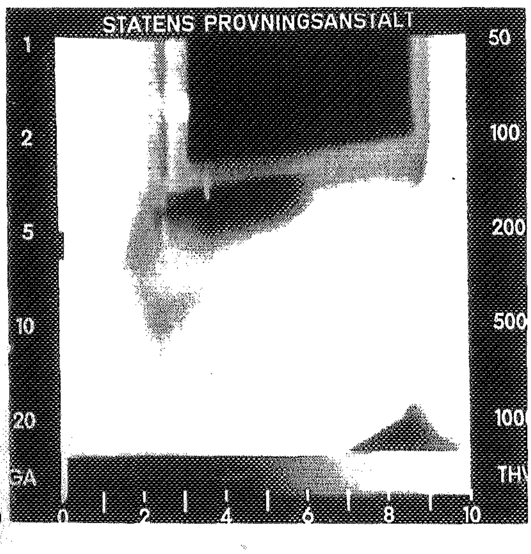
a) Construction of the external wall underneath the windowback section.

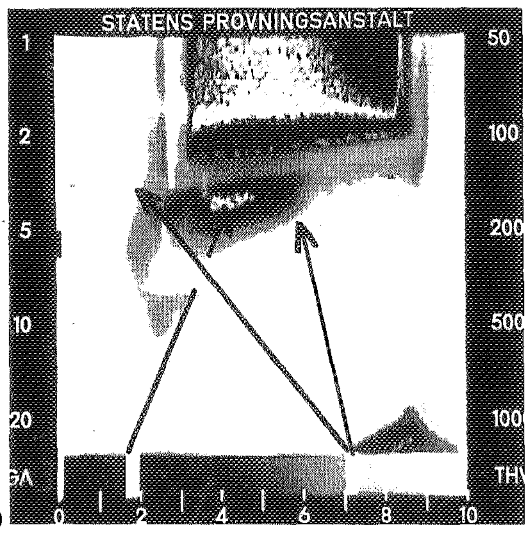
b) Opened up section of wall. Insulation material incorrectly placed and partially omitted.

c) Thermogram of wall section taken from the inside. A colder area appears below the window. This colder area, which is due to the defect in insulation according to b) and to air movements inside the construction, is of relatively limited extent.

d) t_{ref} = + 20°C
Δ I = - 2.7 isotherm units
Δ t = 3.5°C
v = 0.5–0.7 m/s (locally at window frame)

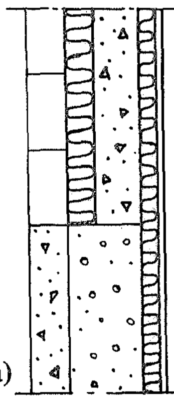
Note. There is some interference due to the warm radiator, which appears as a markedly light area in the thermogram.

c) 

d) 

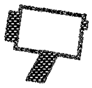
RELIABILITY OF THE METHOD – EXTERNAL WALL

Fig. 39. Investigation of the thermal insulation capacity of section of the external wall, where a suspected defect – cracking in the construction in combination with incorrect placing of the insulation material – has been verified by opening up the construction.



External wall, from the outside:
facing bricks
100 mm mineral wool (quality A)
150 mm concrete
50 mm mineral wool
13 mm gypsum wallboard

inside



115 mm concrete
250 mm lightweight concrete
50 mm mineral wool
13 mm gypsum wallboard

a)

Conditions during measurement:

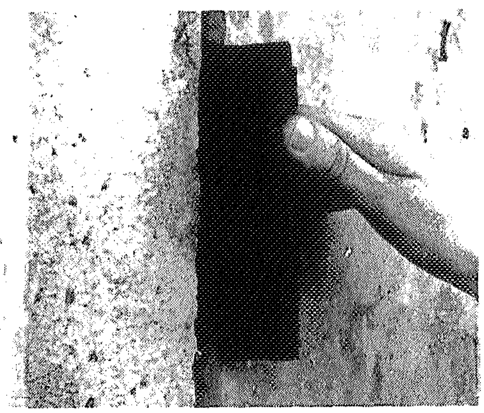
cloudiness	
outdoor air temp	- 4°C
indoor air temp	+ 21°C
wind conditions	3 m/s (away from facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall (horizontal section).

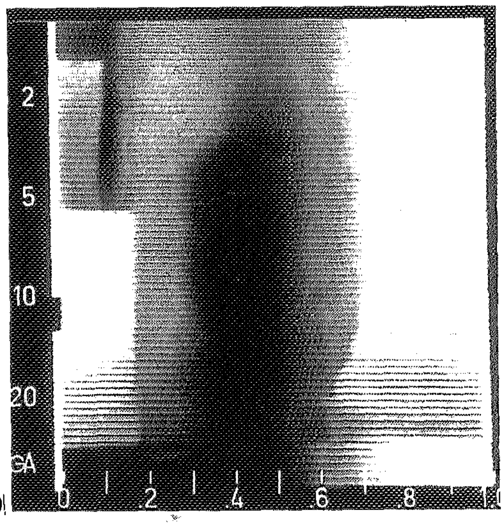
b) Opened up section of wall seen from the warm side. Vertical crack between lightweight concrete block and concrete wall through which cold outside air entered and spread inside the construction, giving rise to colder areas on the surface of the wall.

c) Thermogram of somewhat colder section of wall. The colder area extends in a vertical direction and has relatively diffuse boundaries, corresponding to a relatively large proportion of the external wall from floor to ceiling. This colder area is due to defects according to b).

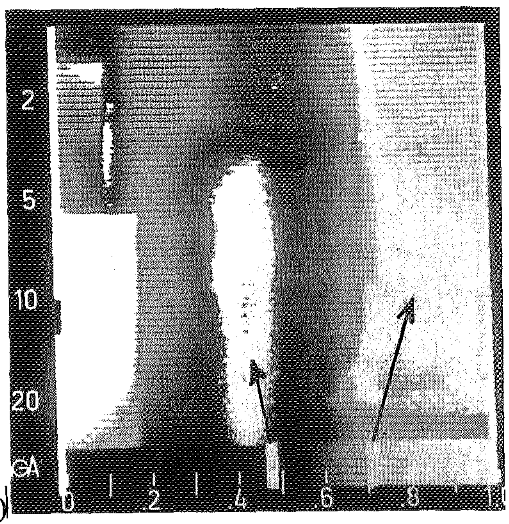
d) $t_{ref} = +20°C$
$\Delta I = -2.4$ isotherm units
$\Delta t = 3.5°C$
$v = 0$ m/s



b)



c)

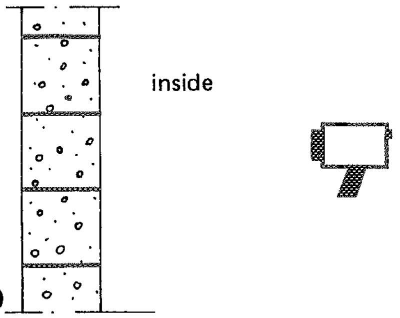


d)

RELIABILITY OF THE METHOD – EXTERNAL WALL

Fig. 40. Investigation of the thermal insulation capacity of external wall of lightweight concrete, where a suspected defect – cracking in the construction – has been verified by visual inspection, smoke test and air flow measurement.

External wall, from the outside:
plaster
250 mm lightweight concrete
plaster



a)

Conditions during measurement:

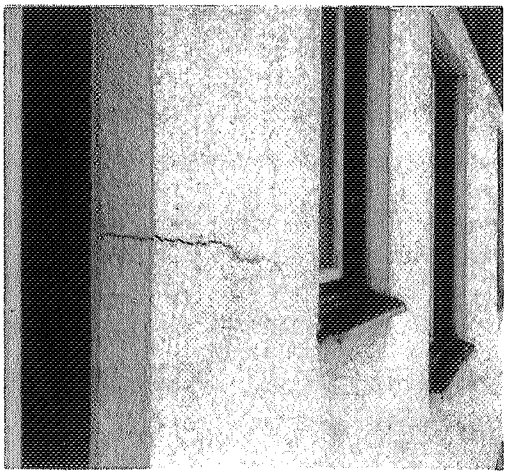
cloudiness	cloudy
outdoor air temp	+3°C
indoor air temp	+23°C
wind conditions	calm
$p_i - p_u$	- 20 Pa

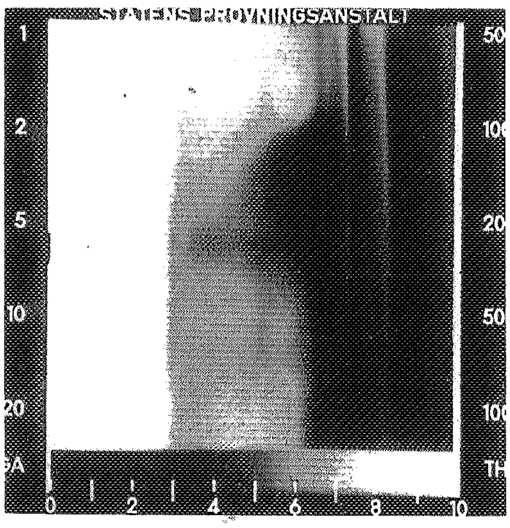
a) Construction of external wall.

b) Cracking in section of external wall. The crack extended right through the wall and caused air to leak directly into the room.

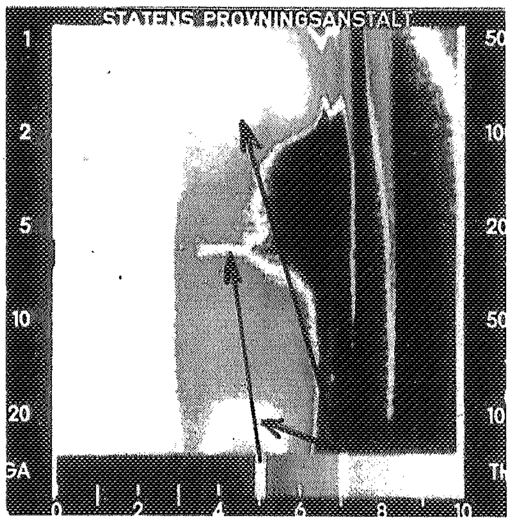
c) Thermogram of somewhat colder section of wall near the window. Air leakage occurred through cracks in the joints between the lightweight concrete blocks and through improperly sealed joint between wall and window frame.

d) t_{ref} = +22°C
Δ I = - 1.1 isotherm units
Δ t = 1.5°C
v = about 0.3 m/s (at wall near crack)


b)



c)



d)

4.5 Measurement of thermal resistance and thermography

The infrared camera offers great opportunities for the performance, under certain conditions, of relatively accurate investigations concerning the variation of surface temperature over the surface of a construction. In this way, a picture of the heat flow and air leakage distribution can be obtained.

In determining the thermal resistance of the construction according to Equation 3.13, the following conditions must be satisfied:

1. The emissivity, reflectivity and transmissivity of the surface must be known and remain constant over the section of the surface concerned.
2. The radiation incident on the surface must be known and be uniformly distributed over the surface.
3. The construction and the ambient air must be in temperature equilibrium and conditions must be stable.
4. The surface thermal resistance at the surfaces of the construction must be known and remain constant over the section of the surface concerned.
5. There must be no internal heat sources in the construction.
6. The relevant temperatures must be measured.

In practice, there is a certain variation in the value of m_i along the surface of a construction, depending on the geometric design of the construction (corners etc) and also on the environment in which the construction is situated. The exact values of m_i and m_u are generally unknown, and the estimated values are generally so uncertain that accurate determination of the thermal resistance of a wall is not meaningful. During measurements in the field, an additional factor of uncertainty arises owing to the fact that, as a rule, there is no temperature equilibrium in the construction concerned.

To sum up, it must be pointed out that thermography is a qualitative method[1] which is used primarily to pinpoint variations in thermal resistance and air leakage. If the thermal resistance and airtightness of a building are to be quantified[2], additional investigations must be carried out.

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1 Qualitative testing is testing performed with the aim of ascertaining whether certain conditions are satisfied (whether the construction can be shown to have certain properties).

2 Quantitative testing is testing performed with the aim of determining magnitudes (the values of the properties concerned). /19./

5 Comparative thermograms obtained during measurements in the field

The typical thermograms in the Swedish Council for Building Research Report *Thermography of buildings* /12/ were produced in the laboratory. This limited the opportunity to produce thermograms of different types of constructions and constructional details, and of types of defects which often occur in practice.

The object of this investigation was to supplement this previously produced material with a number of practical cases. Thermograms have been taken of common defects in insulation and airtightness in different types of constructions in which different types of material have been used.

The purpose of comparative thermograms is to facilitate the interpretation and assessment of thermograms, so that more detailed and unambiguous information may be obtained from the thermal images produced during thermography.

The constructions selected are those which occur most frequently in this country. The walls are of lightweight construction comprising a framework and high-grade insulation, or walls of lightweight concrete or concrete. The floors usually consist of different types of timber constructions with mineral wool insulation, but concrete floors have also been included.

The examples shown have been taken from material comprising a total of some 400 projects, corresponding to about 3000 dwellings in single-family houses and blocks of flats, where each subproject may represent either a small number of objects or several hundred.

The comparative thermograms have been produced under well known conditions in conformity with the requirements described previously. Interpretation and analysis of the thermograms have been performed both by a comparison with typical thermograms and by means of visual inspection or supplementary measurements.

Each practical case is shown in the form of two thermograms (monochrome image and isotherm image).

The presentation includes a drawing of the construction and a short description of the defect concerned. Brief comments regarding the appearance of the thermogram are also given.

The symbols used are the same as in previous chapters. The ambient data have also been measured in the same way.

The examples with the comparative thermograms are divided into groups on the basis of constructional element and type of construction.

On pp. 95–102 examples are shown of defects in insulation and airtightness at the eaves (pitched roofs, flat roofs and pen roofs), FIG. 41–48.

On pp. 103–108 examples are shown of defects in insulation and airtightness in insulated roofs, FIG. 49–54.

On pp. 109–111 examples are shown of defects in insulation and airtightness in attic floors, FIG. 55–57.

On pp. 112–118 examples are shown of defects in insulation and airtightness in intermediate floors, FIG. 58–64.

On pp. 119–123 examples are shown of defects in insulation and airtightness at the junction of the ground floor and the wall, FIG. 65–69.

On pp. 124–138 examples are shown of defects in insulation and airtightness in external walls, FIG. 70–84.

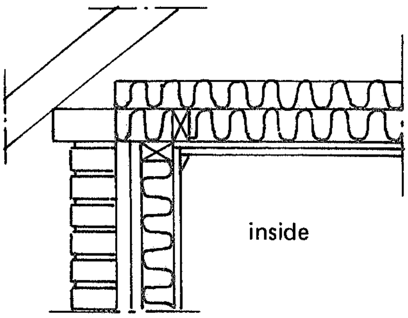
COMPARATIVE THERMOGRAMS – GABLE ROOF (floor junction)

Fig. 41. Insulation and airtightness defect at the eaves due to incorrect fitting of the insulation material and to bad placing of windprotection.

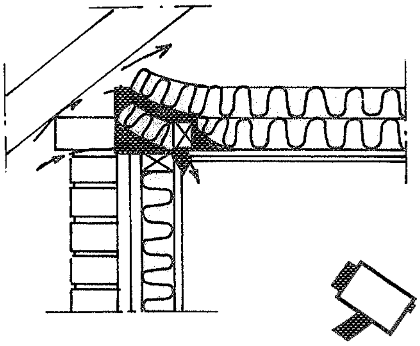
Floor, from above:
75 + 75 mm mineral wool (quality B)
vapour barrier
19 mm secondary spaced boarding
13 mm gypsum wallboard

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	+7°C
indoor air temp	+21°C
wind conditions	about 2 m/s (perpendicularly to facade)
$p_i - p_u$	- 20 Pa



a)



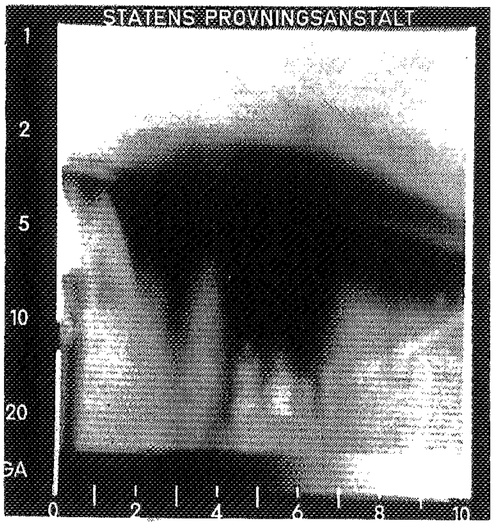
b)

a) Construction at the eaves.

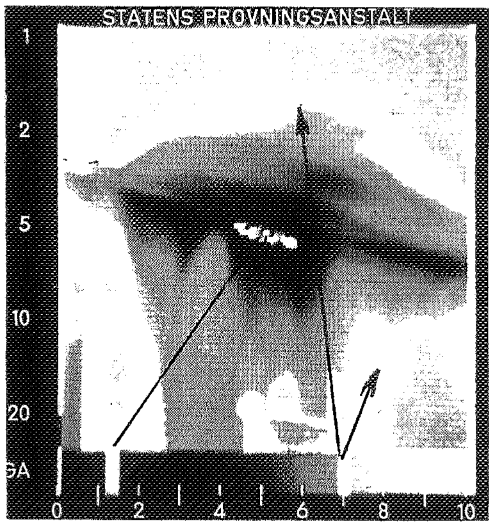
b) Defects found in insulation and airtightness.

c) Thermogram of section at wall-ceiling junction. The colder area here has a typical "serrated" contour, which indicates leakage of air.

d) t_{ref} = +20°C
Δ I = - 11.6 isotherm units
Δ t = 17°C
v = 1.0–1.5 m/s (at wall-ceiling junction)



c)



d)

COMPARATIVE THERMOGRAMS – GABLE ROOF (floor junction)

Fig. 42. Insulation and airtightness defect at the eaves due to incorrect placing of insulation material and to bad placing of windprotection.

Floor, from above:
30 mm mineral wool mat
120 mm mineral wool slab
19 mm secondary spaced boarding
polyethylene film
13 mm gypsum wallboard

Conditions during measurement:

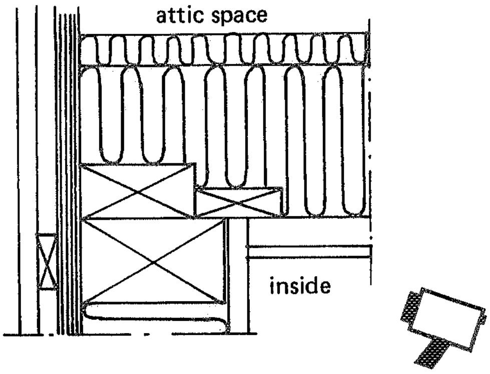
cloudiness	cloudy
outdoor air temp	+2°C
indoor air temp	+21°C
wind conditions	2–3 m/s (perpendicularly to facade)
$p_i - p_u$	- 5 Pa

a) Construction at the eaves.

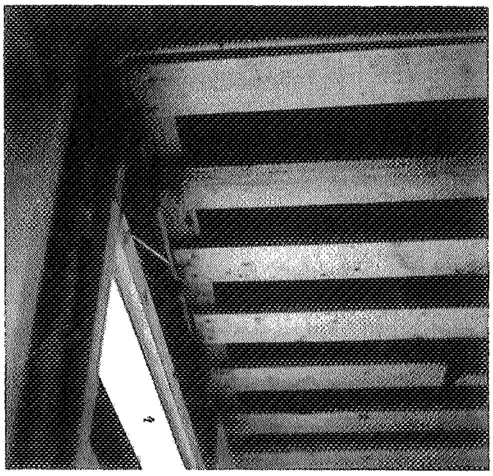
b) Defects found in insulation (PE-film is not mounted here).

c) Thermogram of section at wall- ceiling junction. Colder areas in the ceiling appears as well marked dark strips, which indicates leakage of air into the construction through the ducts formed by the secondary spaced boarding.

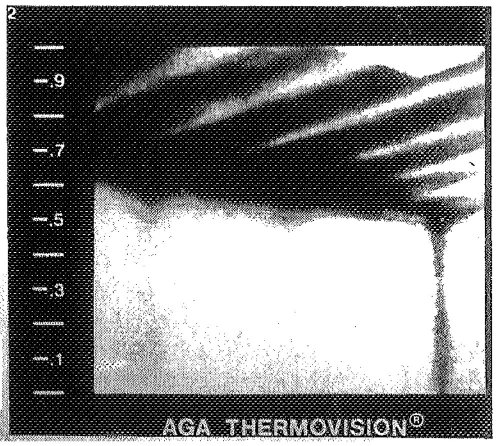
d) t_{ref} = +20°C
Δ I = - 1.1 isotherm units
Δ t = 2.0°C
v = 0 m/s



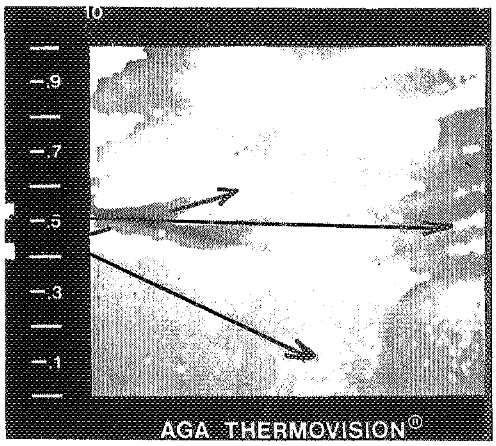
a)



b)



c)

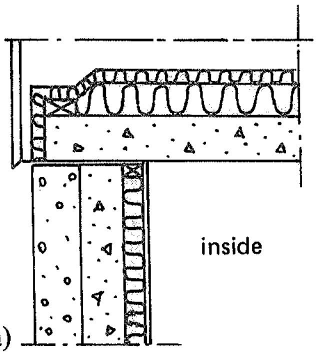


d)

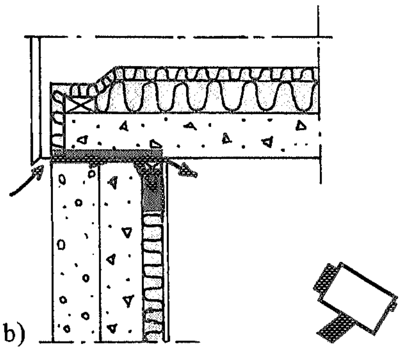
Fig. 43. Defect – cracking – in seal at the eaves junction. Bad sealing of joint between floor and external wall.

Floor, from above:
130 mm mineral wool
160 mm concrete

External wall, from the outside:
plaster
75 mm lightweight concrete
75 mm concrete
20 mm mineral wool
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

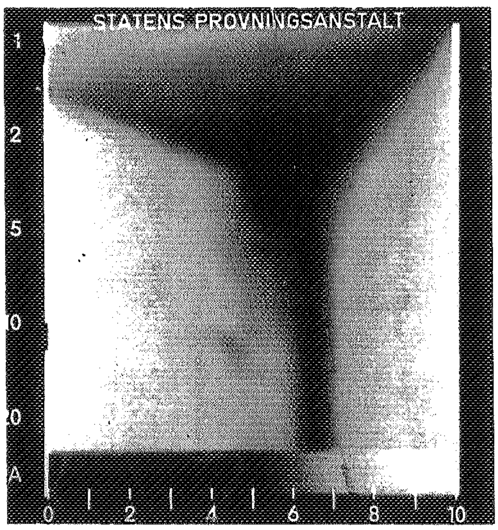
cloudiness	cloudy
outdoor air temp	- 30°C
indoor air temp	+ 23°C
wind conditions	calm
$p_i - p_u$	- 20 Pa

a) Construction at the eaves.

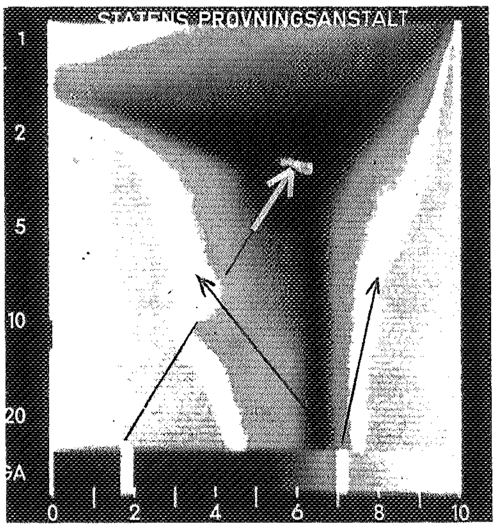
b) Defect found (cracking at the eaves).

c) Thermogram of section at wall-ceiling junction, showing a colder section near the junction. Due to leakage of air through badly sealed joint (crack).

d) $t_{ref} = +22°C$
ΔI = - 5.3 isotherm units
Δt = 7.0°C
v = 1–3 m/s (locally at wall-ceiling junction)



c)

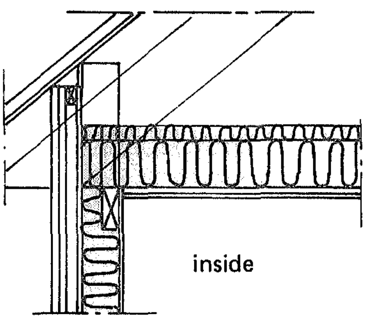


d)

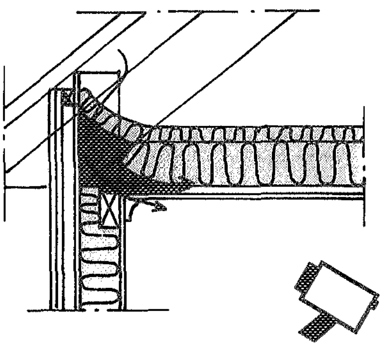
COMPARATIVE THERMOGRAMS – GABLE ROOF (floor junction)

Fig. 44. Insulation and airtightness defect at the eaves due to incorrect placing of insulation material in the construction, and to bad placing of windprotection.

Floor, from above:
50 + 150 mm mineral wool
plastics film
19 mm secondary spaced boarding
13 mm tongued and grooved
fibre plank



a)



b)

Conditions during measurement:

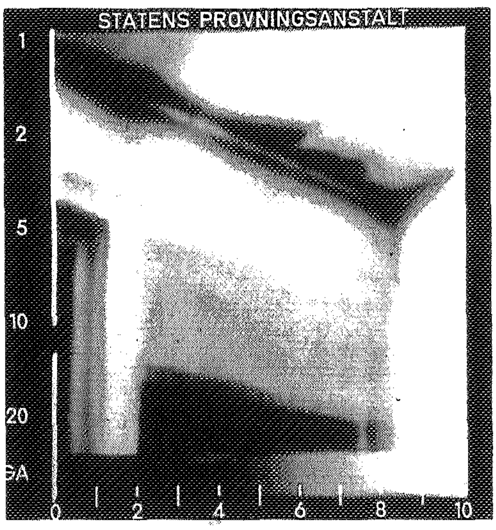
cloudiness	clear
outdoor air temp	- 20°C
indoor air temp	+ 19°C
wind conditions	1–2 m/s (at an angle to facade)
$p_i - p_u$	- 7 Pa

a) Construction at the eaves junction.

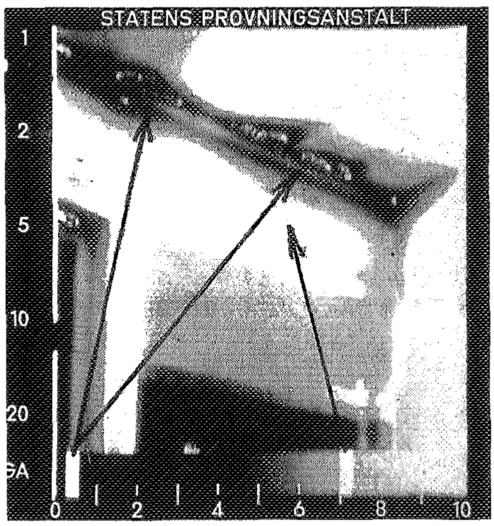
b) Defective insulation at the eaves.

c) Thermogram of section at wall-ceiling junction. The ceiling surface near the moulding is colder. This is due to leakage of air and to incorrect placing of insulation material at the eaves junction.

d) t_{ref} = + 17°C
Δ I = - 6.8 isotherm units
Δ t = 11.0°C
v = 0.5–3.0 m/s



c)

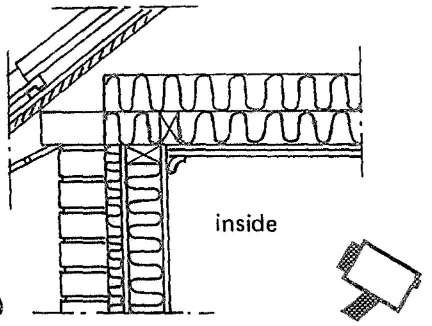


d)

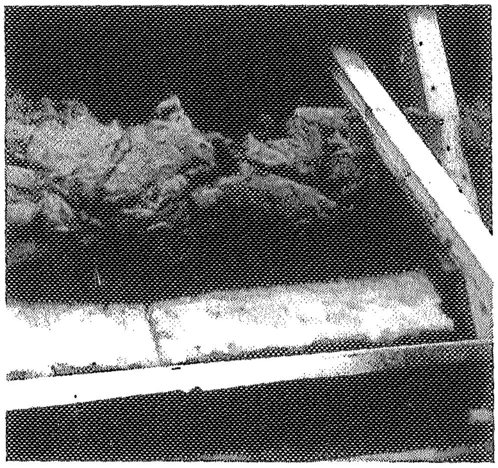
COMPARATIVE THERMOGRAMS — GABLE ROOF (floor junction)

Fig. 45. Insulation and airtightness defect at the eaves junction due to incorrect placing of insulation material in the construction, and to bad placing of windprotection.

Floor, from above:
200 mm mineral wool
19 mm secondary spaced boarding
polyethylene film
13 mm gypsum wallboard



a)



Conditions during measurement:

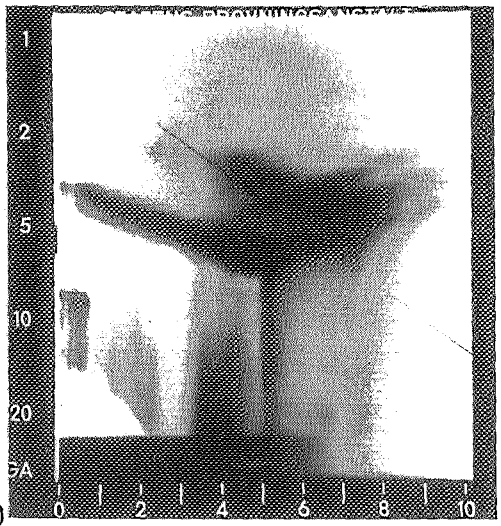
cloudiness	cloudy
outdoor air temp	+2°C
indoor air temp	+20°C
wind conditions	calm
$p_i - p_u$	- 5 Pa

a) Construction at the eaves junction.

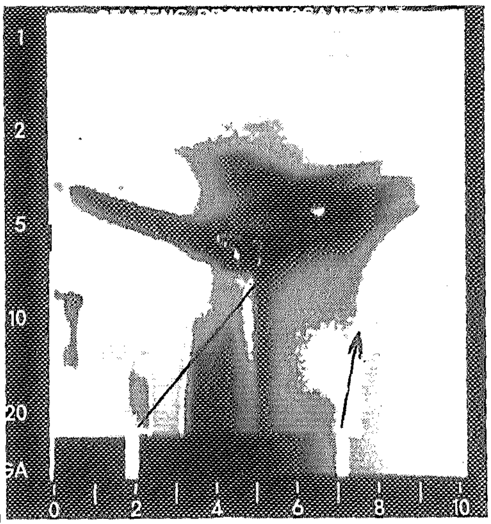
b) Air leakage defect at the eaves. Bad placing of insulation material around the roof truss. There is no continuity in the windprotection at the roof truss itself.

c) Thermogram of section at wall-ceiling junction. The colder area in ceiling near the junction is due to bad insulation around roof truss at the edge of the floor. Colder areas also along the ducts formed by the secondary spaced boarding construction. Some leakage of air into the dwelling.

d) $t_{ref} = +19°C$
ΔI = - 5.2 isotherm units
Δt = 8.0°C
v = 0.7 m/s



c)



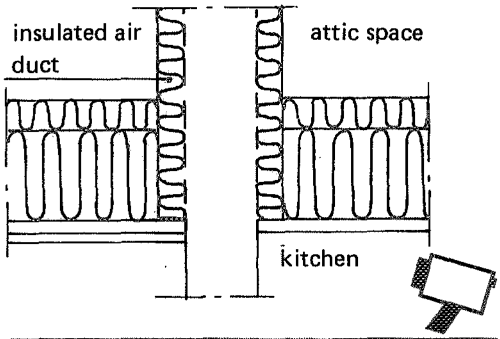
d)

COMPARATIVE THERMOGRAMS – GABLE ROOF (floor junction)

Fig. 46. Insulation and airtightness defect – incorrect fitting of insulation material around air ducts – in attic floor near point where air duct pass through the construction.

Floor, from above:
50 + 150 mm mineral wool
plastic film
19 mm secondary spaced boarding
13 mm tongued and grooved
wood fibre plank
(Where air duct pass through
from drying cupboard)

a)



b)

Conditions during measurement:

cloudiness	clear
outdoor air temp	- 20°C
indoor air temp	+ 19°C
wind conditions	2–3 m/s (about 45° to the facade)
$p_i - p_u$	- 7 Pa

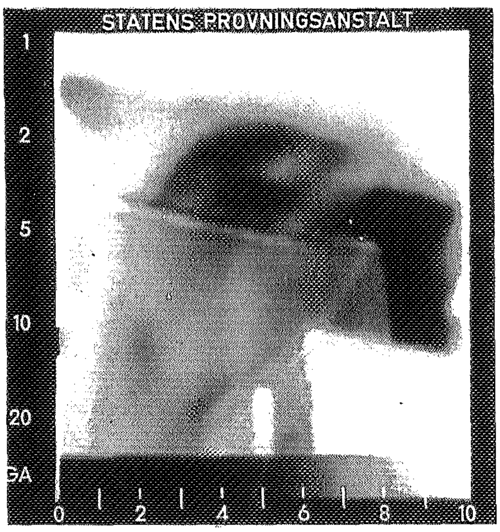
a) Construction of attic floor where air duct pass through the floor.

b) Incorrect placing of insulation at junction between air duct and floor.

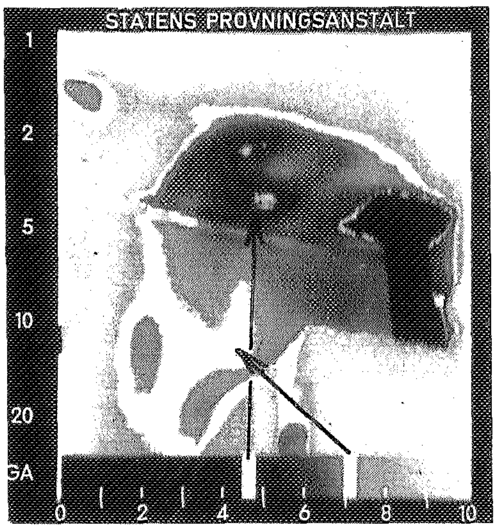
c) Thermogram of section of ceiling where air duct from drying cupboard passes through. Colder area due to irregular performance of insulation material.

d) $t_{ref} = +17°C$
ΔI = - 2.5 isotherm units
Δt = 4.0°C
v = 0 m/s

c)



d)

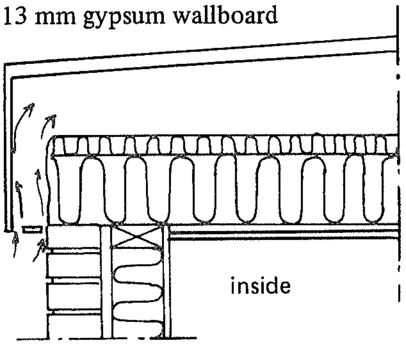


COMPARATIVE THERMOGRAMS – FLAT ROOFS (floor junction)

Fig. 47. Insulation and airtightness defect at the eaves due to bad fitting of insulation material and to bad placing of windprotection.

Roof, from above:
30 + 120 mm mineral wool
19 mm secondary spaced boarding
vapour barrier
13 mm gypsum wallboard

Wall, from the outside:
facing bricks
air gap
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard



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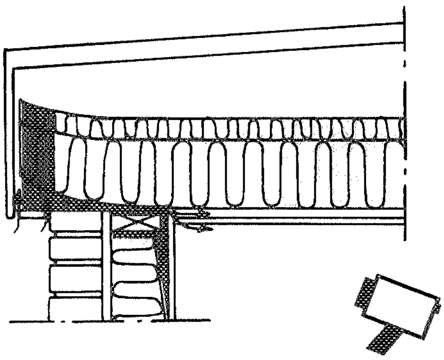


b)

Conditions during measurement:

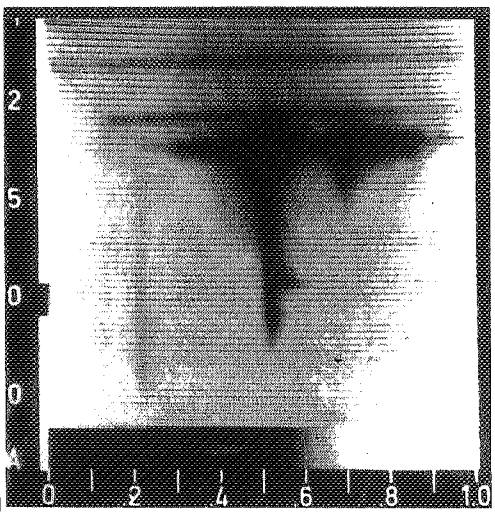
cloudiness	cloudy
outdoor air temp	-4°C
indoor air temp	+21°C
wind conditions	0.5 m/s (at an angle to facade)
$p_i - p_u$	- 5 Pa

a) Construction at the eaves.

b) Defective insulation at the eaves and in the wall.

c) Thermogram of section at wall-ceiling junction showing a colder area of irregular shape. A narrow colder area extends for some distance down the wall. Colder areas are due to leakage of air and to incorrect placing of insulation in the wall and at the eaves.

d) $t_{ref} = +20°C$
ΔI = - 4.5 isotherm units
Δt = 6.5°C
v = 0.5–1.8 m/s (at wall-ceiling junction)



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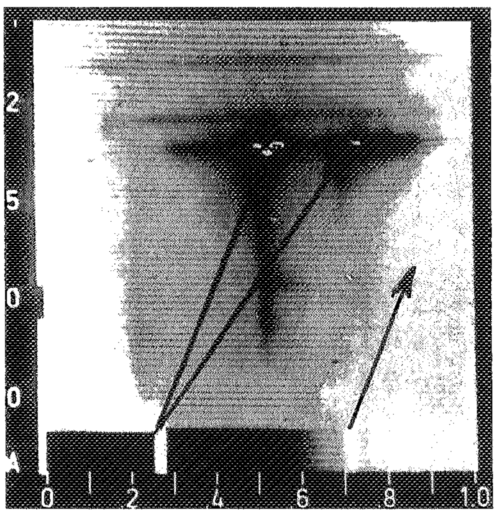
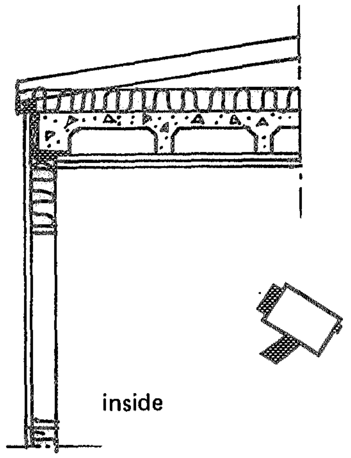


d)

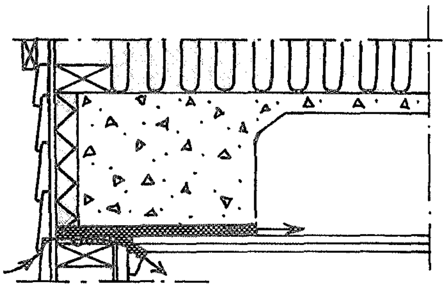
COMPARATIVE THERMOGRAMS – PENTROOF (floor junction)

Fig. 48. Insulation and airtightness defect in flat roof of concrete units owing to thermal bridge effect and to some leakage of air into the construction and the dwelling.

Floor, from above:
150 mm mineral wool
concrete unit
19 mm secondary spaced boarding
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

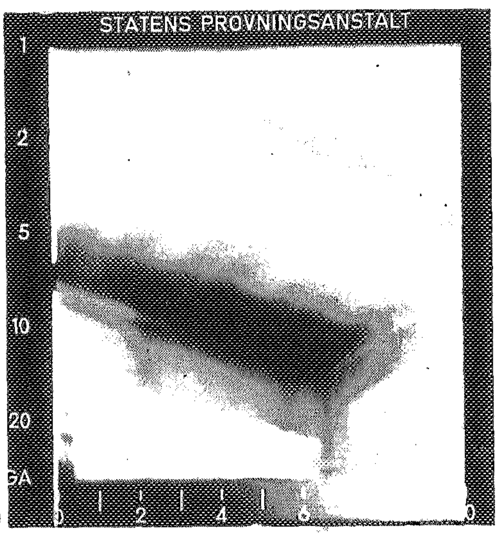
cloudiness	cloudy
outdoor air temp	$+3^{\circ}C$
indoor air temp	$+23^{\circ}C$
wind conditions	calm
$p_i - p_u$	- 5 Pa

a) Construction of floor (concrete unit).

b) Detail of constructional thermal bridge at the eaves junction.

c) Thermogram of section at wall-ceiling junction. Colder area – a strip of 15–20 cm width from the junction – extends along the external wall. There was some leakage of air in the secondary spaced boarding construction, and some air also leaked into the dwelling.

d) $t_{ref} = +22^{\circ}C$
ΔI = - 2.7 isotherm units
$\Delta t = 3.5^{\circ}C$
v = 0.2–0.3 m/s (locally at wall-ceiling junction)



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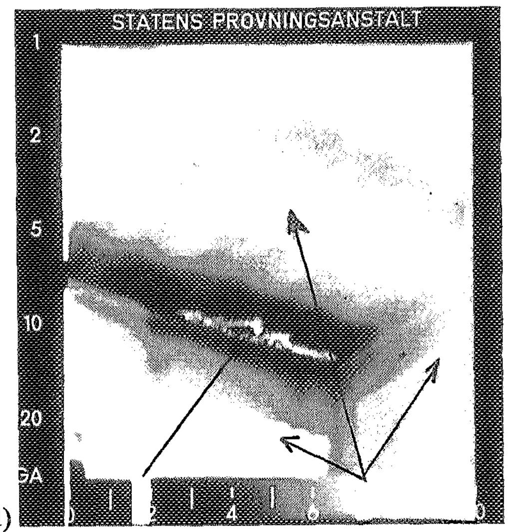


d)

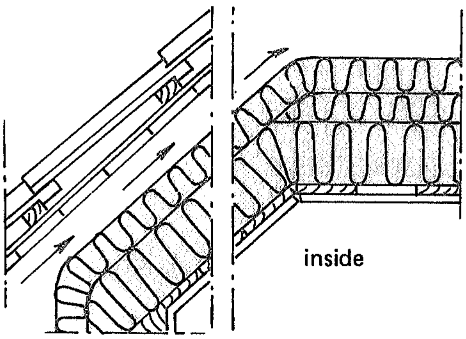
COMPARATIVE THERMOGRAMS – INSULATED ROOF (inclined ceiling)

Fig. 49. Insulation and airtightness defect in inclined ceiling due to bad fitting and incorrect placing of insulation material onto warm side, and to leakage of air into the construction.

Inclined ceiling, from the outside:
roof construction
50 mm air gap
100 + 50 mm mineral wool
19 mm secondary spaced boarding
vapour barrier
13 mm gypsum wallboard

Conditions during measurement:

cloudiness	clear
outdoor air temp	+2°C
indoor air temp	+20°C
wind conditions	2–3 m/s (away from facade)
$p_i - p_u$	- 18 Pa



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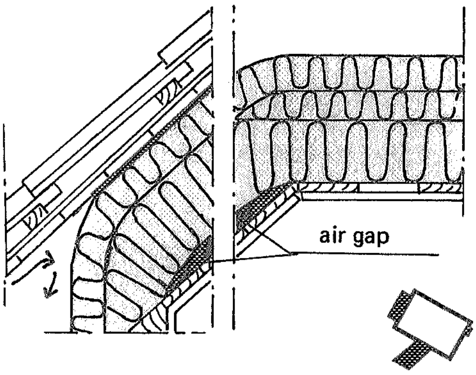


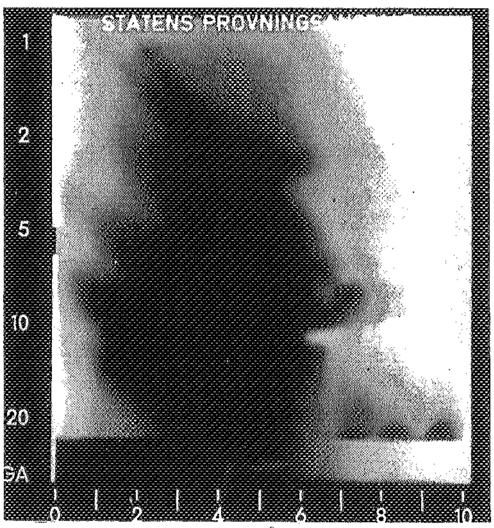
b)

a) Construction of insulated roof.

b) Defective insulation.

c) Thermogram of section of inclined ceiling. Air leaks into the construction, permitting cold air to spread along cavities between the insulation material and the secondary spaced boarding.

d) t_{ref} = + 19°C
Δ I = - 2.6 isotherm units
Δ t = 4.0°C
v = 0 m/s



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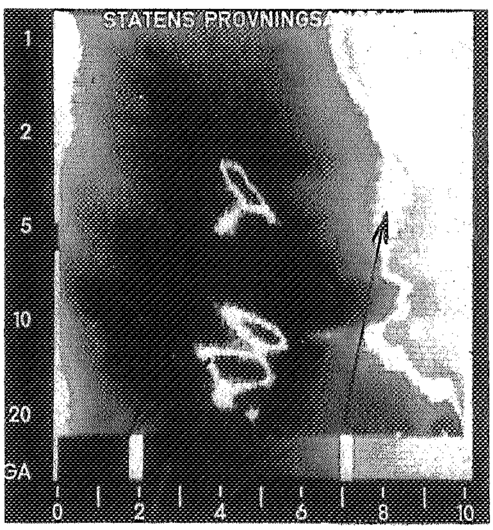
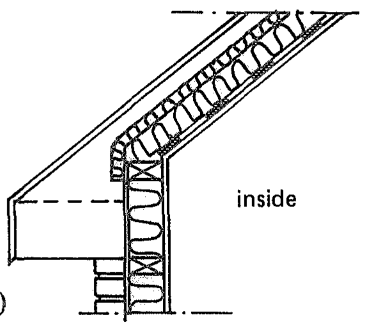


d)

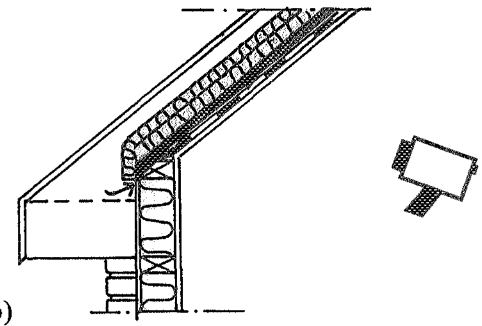
COMPARATIVE THERMOGRAMS – INSULATED ROOF (inclined ceiling)

Fig. 51. Insulation and airtightness defect in inclined ceiling due to leakage of air into construction.

Roof, from above:
roof construction
air gap
30 + 120 mm mineral wool
19 mm secondary spaced boarding
plastic film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

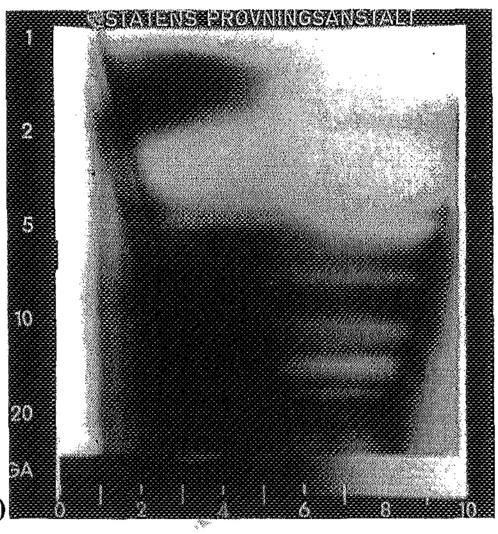
cloudiness	cloudy
outdoor air temp	$-3°C$
indoor air temp	$+21°C$
wind conditions	2–3 m/s (away from facade)
$p_i - p_u$	-5 Pa

a) Construction of insulated roof.

b) Defective insulation.

c) Thermogram of section near roof. The surface has an uneven temperature distribution. To some extent, the colder areas define the ducts in the secondary spaced boarding.

d) $t_{ref} = +20°C$
$\Delta I = -2.7$ isotherm units
$\Delta t = 3.5°C$
$v = 0.7–1.0$ m/s (at wall-ceiling junction)



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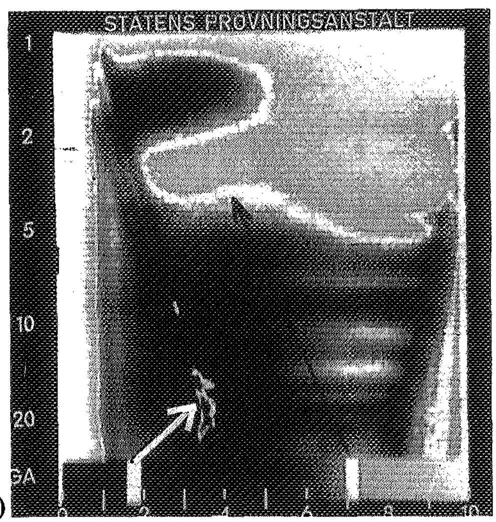
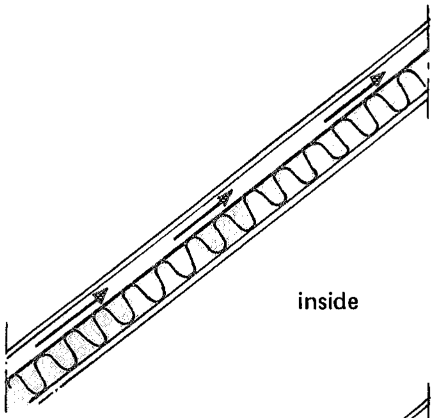


d)

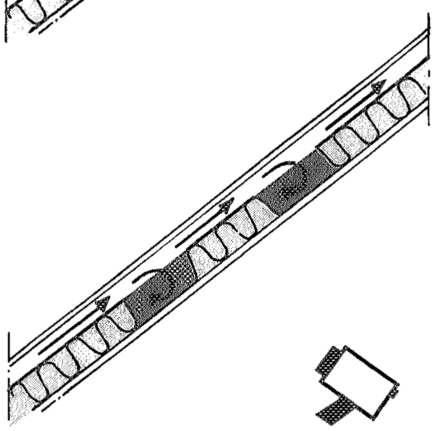
COMPARATIVE THERMOGRAMS – INSULATED ROOF

Fig. 52. Insulation and airtightness defect due to incorrect placing of insulation material, combined with leakage of air into construction.

Roof, from the outside:
roof construction
air gap
sheathing cardboard
100 mm mineral wool (quality B)
polyethylene film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

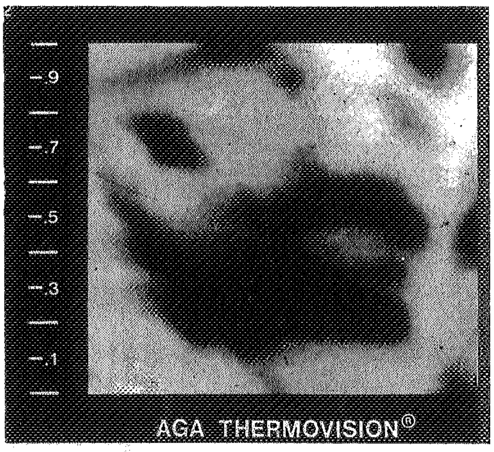
cloudiness	cloudy
outdoor air temp	+3°C
indoor air temp	+19°C
wind conditions	2–3 m/s (at an angle to roof surface)
$p_i - p_u$	- 6 Pa

a) Construction of insulated roof.

b) Defective insulation.

c) Thermogram of section of roof. Colder areas appear as an irregular pattern over the roof surface. These areas are due to incorrect placing of the insulation material, combined with convective air movements inside the construction.

d) t_{ref} = + 18°C
Δ I = - 1.7 isotherm units
Δ t = 3.0°C
v = 0 m/s



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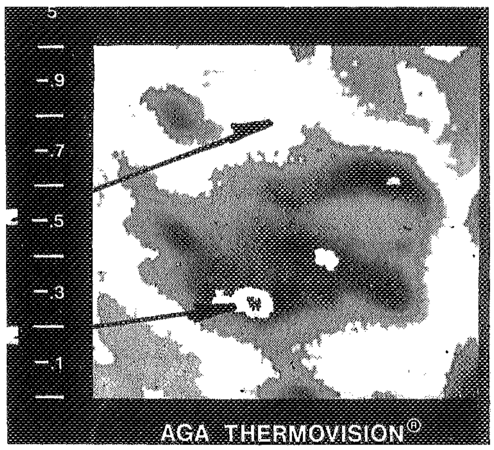


d)

COMPARATIVE THERMOGRAMS – INSULATED ROOF

Fig. 53. Insulation defect due to partial omission of the insulation material.

Roof, from the outside:
roof construction
air gap
sheathing cardboard
120 mm mineral wool
polyethylene film
13 mm gypsum wallboard

Conditions during measurement:

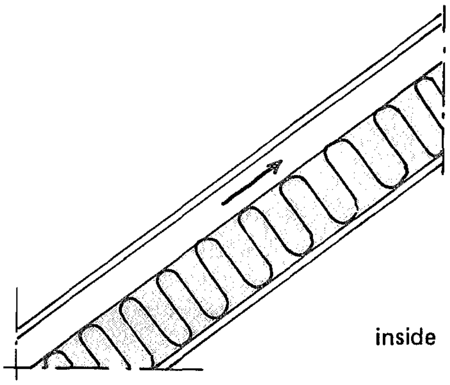
cloudiness	cloudy
outdoor air temp	+3°C
indoor air temp	+19°C
wind conditions	2–3 m/s (at an angle to roof surface)
$p_i - p_u$	- 6 Pa

a) Construction of roof.

b) Defective insulation. Insulation thickness reduced to about 50% of the original thickness.

c) Thermogram of colder section of roof. This area is clearly marked with even contours. Colder area is due to omission of about 50% of insulation material in space between the rafters, according to b).

d) t_{ref} = + 18°C
Δ I = - 1.5 isotherm units
Δ t = 2.5°C
v = 0 m/s



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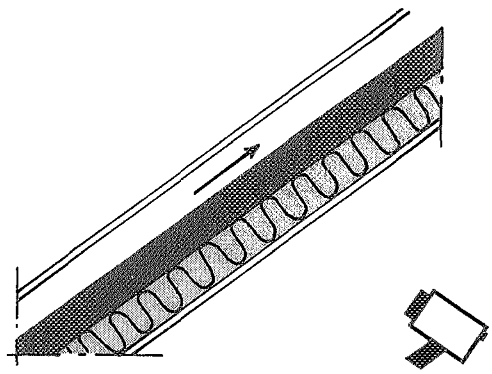

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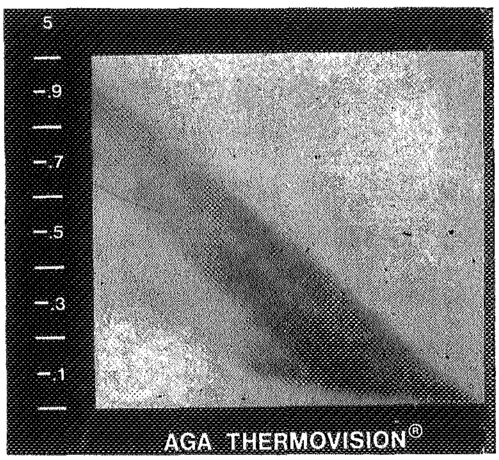

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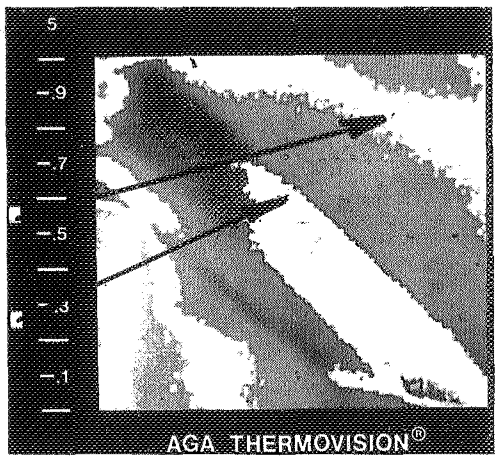
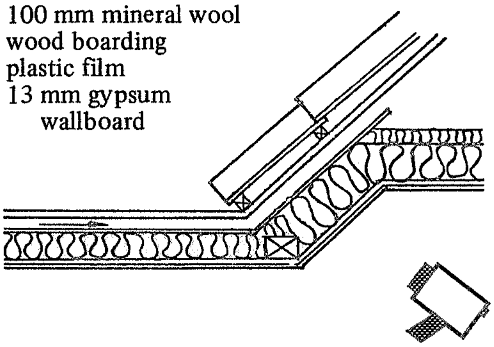


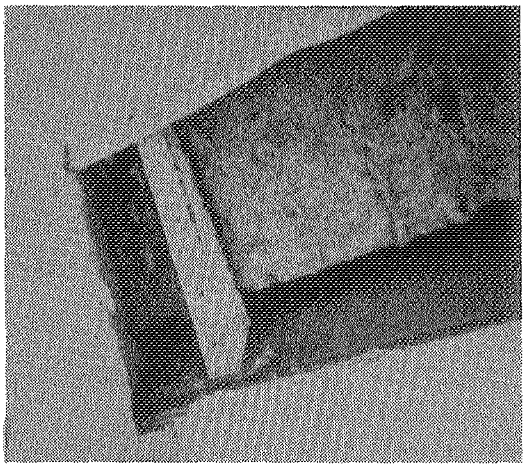
d)

COMPARATIVE THERMOGRAMS – INSULATED ROOF OF TIMBER (junction at window section)

Fig. 54. Insulation and airtightness defect due to bad fitting of insulation material around studs, and to incorrect placing of windprotection.

Inclined ceiling, from the outside:
roof bricks
roofing cardboard
wood boarding
air gap
3 mm fibre board
100 mm mineral wool
wood boarding
plastic film
13 mm gypsum
wallboard

a) 

b) 

Conditions during measurement:

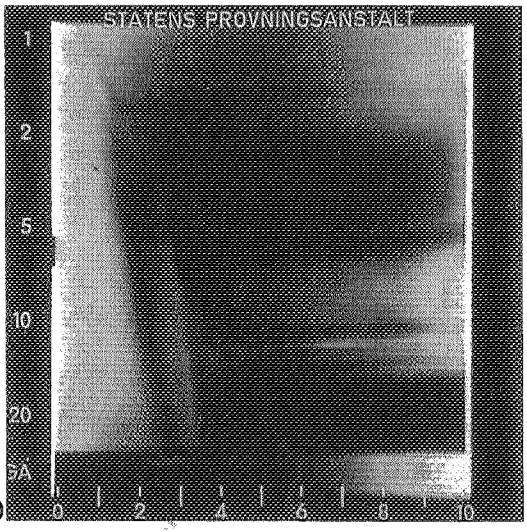
cloudiness	clear
outdoor air temp	0°C
indoor air temp	+20°C
wind conditions	2–3 m/s (parallel to roof)
$p_i - p_u$	- 4 Pa

a) Construction of roof near bay window.

b) Opened up section of wall seen from the inside. The insulation is badly fitted near studs and is not in contact with wall material on the warm side. Air gap of about 5 cm.

c) Thermogram of section of inclined ceiling showing colder areas. These are due to penetration of air into the construction, into the space where the mineral wool is incorrectly placed.

d) $t_{ref} = +19°C$
ΔI = - 2.0 isotherm units
Δt = 3.0°C
v = 0 m/s

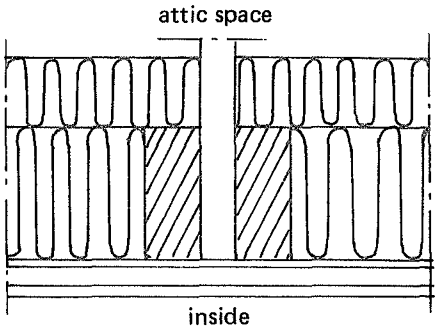
c) 

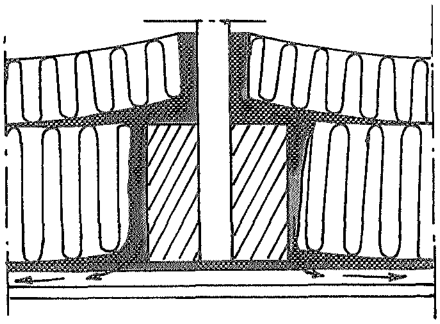
d) 

COMPARATIVE THERMOGRAMS – HORIZONTAL FLAT ROOF

Fig. 55. Insulation and airtightness defect due to incorrect placing of insulation material against parts of the construction, combined with leakage of air into the construction.

Floor, from above:
70 + 150 mm mineral wool
19 mm secondary spaced boarding
plastic film
13 mm gypsum wallboard

a) 

b) 

Conditions during measurement:

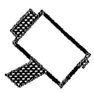
cloudiness	cloudy
outdoor air temp	- 4°C
indoor air temp	+ 21°C
wind conditions	0.5 m/s (perpendicularly to eaves)
$p_i - p_u$	- 5 Pa

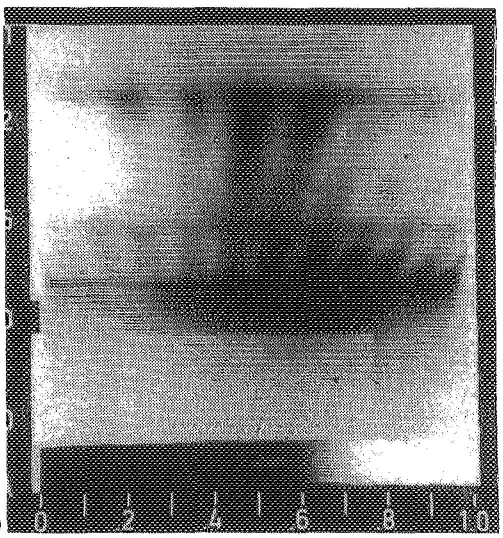
a) Construction of flat roof. In order that insulation performance may be satisfactory, the mineral wool must be carefully fitted around roof trusses.

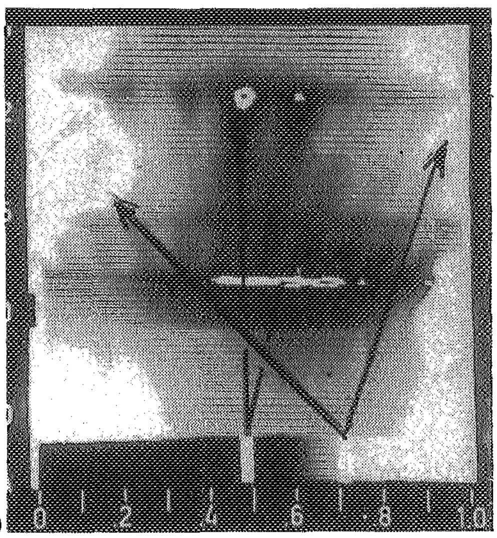
b) Insulation material is incorrectly placed. Outdoor air spreads into the cavities thus formed and along the ducts formed by the secondary spaced boarding construction. The plastic film should be placed between the secondary spaced boarding and the insulation material.

c) Thermogram of section of ceiling and wall-ceiling junction. Colder area in ceiling appears as dark parallel strips, starting at the roof trusses.

d) t_{ref} = + 20°C
Δ I = - 2.2 isotherm units
Δ t = 3.0°C
v = 0.5 m/s



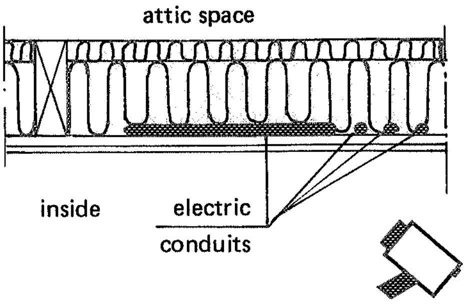
c) 

d) 

COMPARATIVE THERMOGRAMS – HORIZONTAL FLAT ROOF

Fig. 56. Insulation and airtightness defect due to unsatisfactory insulation around electric cables in the construction.

Floor, from above:
30 + 120 mm mineral wool (quality B)
electric cables
19 mm secondary spaced boarding
vapour barrier
13 mm gypsum wallboard



a)

Conditions during measurement:

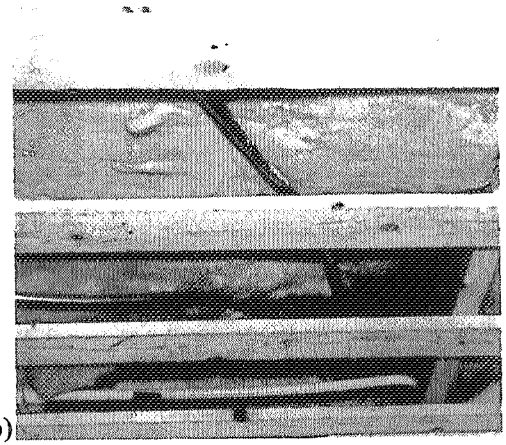
cloudiness	cloudy
outdoor air temp	- 4°C
indoor air temp	+21°C
wind conditions	0.5–1.0 m/s (perpendicularly to facade)
$p_i - p_u$	- 5 Pa

a) Construction of flat roof.

b) Defective insulation adjacent to electric conduits.

c) Thermogram of section of ceiling showing a very much colder area. This is due to incorrectly placed insulation around electric cables. The colder areas spread out from the roof trusses.

d) t_{ref} = +20°C
Δ I = - 5.1 isotherm units
Δ t = 7.5°C
v = 0 m/s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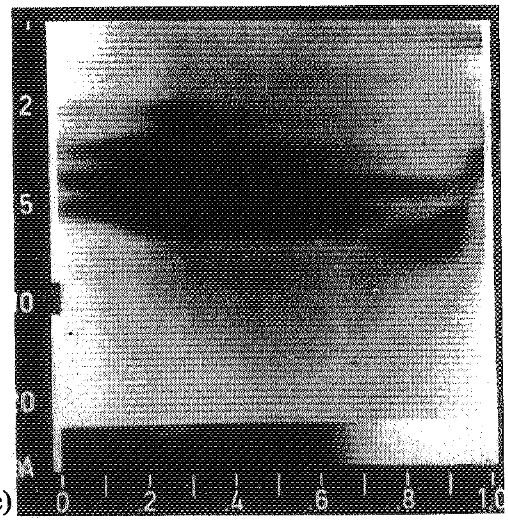
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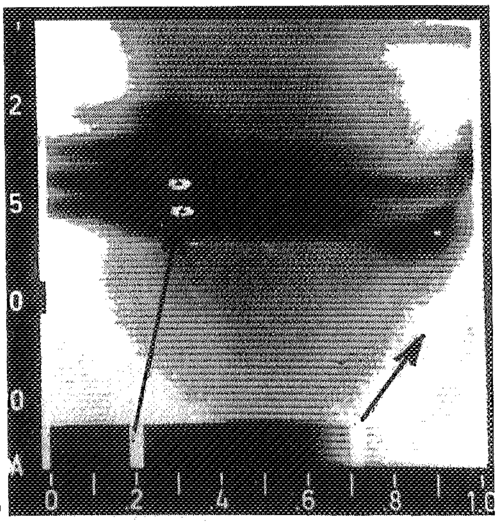

d)

COMPARATIVE THERMOGRAMS – ROOF SLAB OF LIGHTWEIGHT CONCRETE

Fig. 57. Defect in roof slab due to ingress of moisture into construction.

Roof, from the outside:
roof covering
40 mm concrete
150–200 mm expanded clay
300 mm concrete
22 mm battens
25 mm wood boarding

Conditions during measurement:

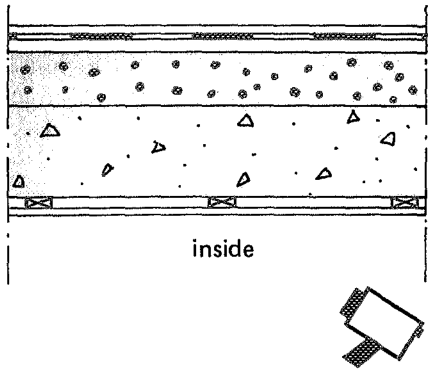
cloudiness	cloudy
outdoor air temp	+4°C
indoor air temp	+16°C
wind conditions	calm
$p_i - p_u$	- 2 Pa

a) Roof construction.

b) Section of roof with wood boarding removed. The surface of the boarding was dry at the time of measurement, but both the concrete and the cardboard were moist due to ingress of moisture into the badly waterproofed construction.

c) Thermogram of section of ceiling showing a colder area. This is due to moisture damage.

d) t_{ref} = +16°C
Δ I = - 0.4 isotherm units
Δ t = 0.5°C
v = 0 m/s



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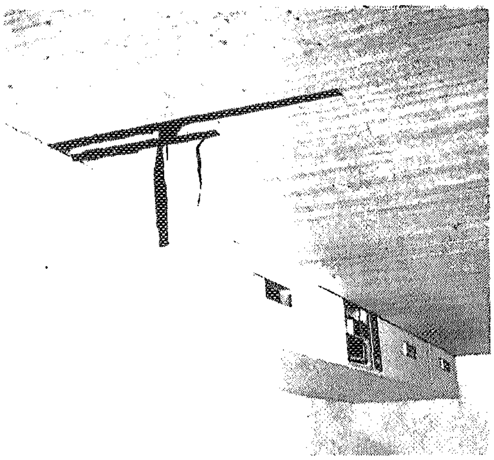

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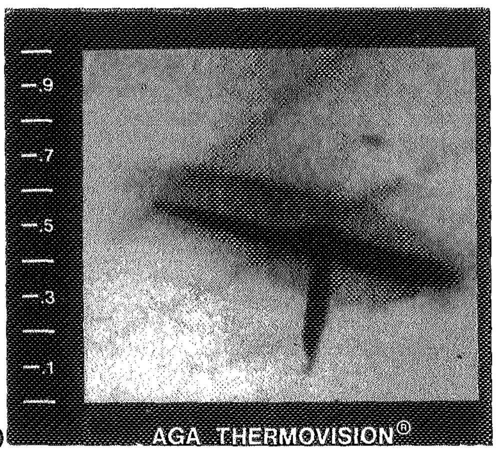

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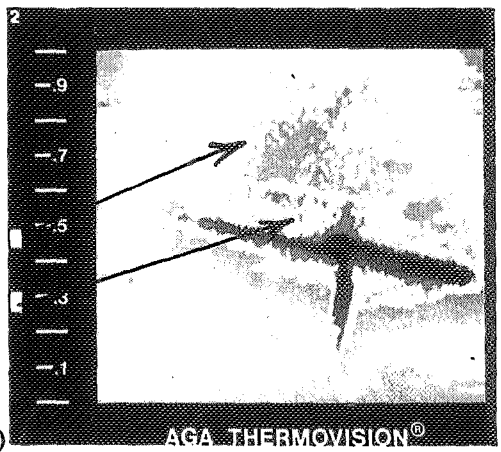


d)

COMPARATIVE THERMOGRAMS – INTERMEDIATE FLOOR OF CONCRETE

Fig. 58. Insulation and airtightness defect at the junction between intermediate floor and brace wall due to incorrect placing of insulation material and to incorrectly placed windprotection.

Floor, from above:
50 mm mineral wool mat with cardboard on top
100 mm mineral wool blanket
100 or 120 mm in situ concrete

Conditions during measurement:

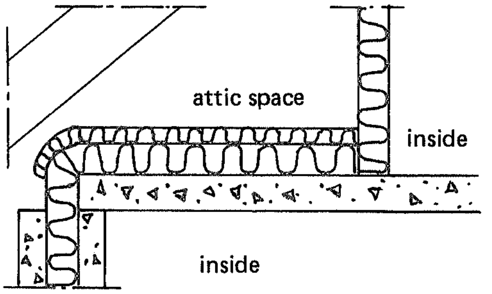
cloudiness	cloudy
outdoor air temp	+3°C
indoor air temp	+18°C
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	-6 Pa

a) Construction of concrete intermediate floor with extra mineral wool insulation.

b) Defective insulation.

c) Thermogram of section of ceiling and wall-ceiling junction. The ceiling is colder due to incorrect placing of the insulation material on the slab, both where the brace wall joins the slab and at the eaves.

d) $t_{ref} = +17°C$
ΔI = - 1.0 isotherm units
Δt = 1.5°C
v = 0 m/s



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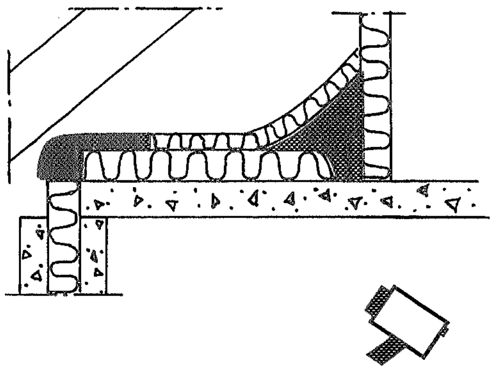
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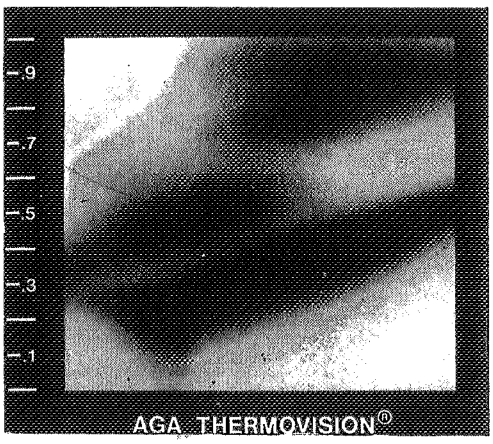

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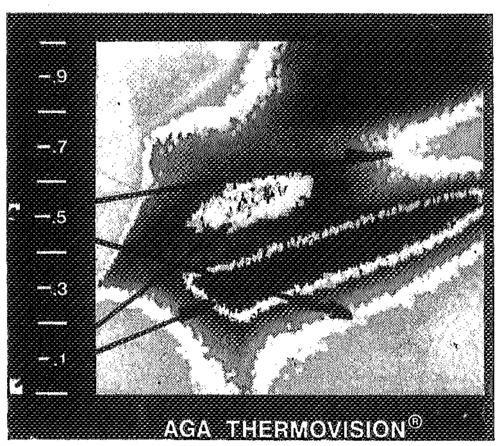


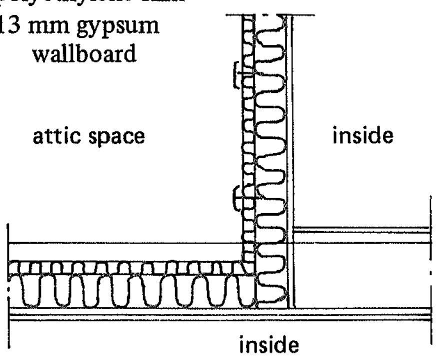
d)

COMPARATIVE THERMOGRAMS – INTERMEDIATE FLOOR OF TIMBER

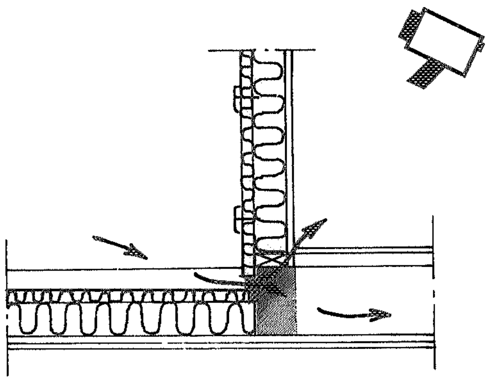
Fig. 59. Insulation and airtightness defect in intermediate floor due to incorrect placing of insulation material at the junction with the brace wall.

Floor, from above:
30 + 120 mm mineral wool
polyethylene film
tongued and grooved board
13 mm gypsum wallboard

Brace wall, from the outside:
cardboard
30 + 100 mm mineral wool
polyethylene film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

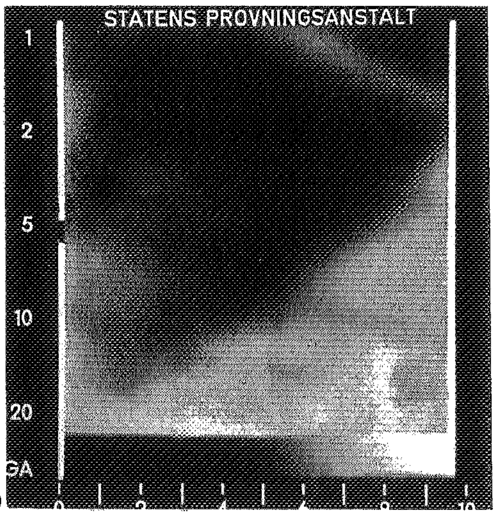
cloudiness	cloudy
outdoor air temp	- 0.5°C
indoor air temp	+22°C
wind conditions	1–2 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of intermediate floor and adjoining brace wall.

b) Insulation and airtightness defect.

c) Thermogram of section of ceiling. The left-hand section of the ceiling is the coldest. This is due to leakage of air into the floor according to b).

d) $t_{ref} = +21°C$
$\Delta I = -1.4$ isotherm units
$\Delta t = 2.0°C$
$v = 0$ m/s



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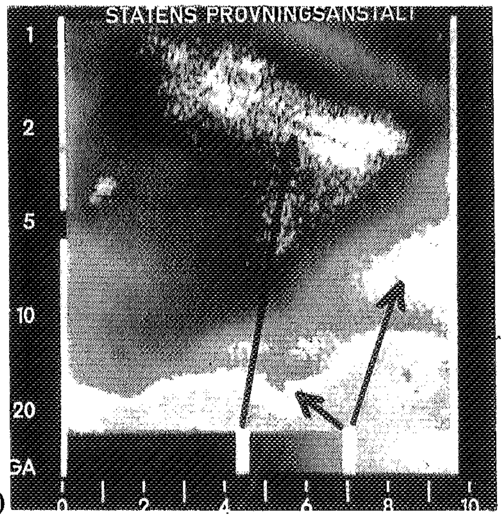
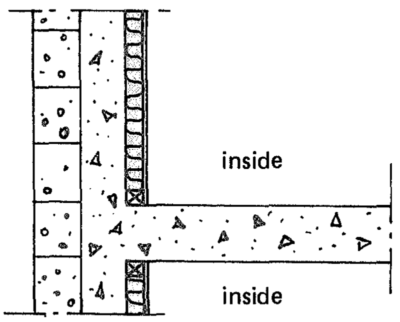


d)

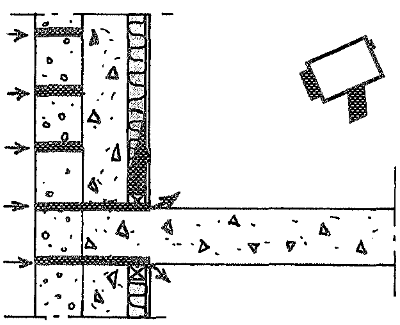
COMPARATIVE THERMOGRAMS – INTERMEDIATE FLOOR OF CONCRETE

Fig. 60. Insulation and airtightness defect – cracking – due to incorrect placing of insulation material in wall, combined with leakage of air through incorrectly sealed joint between floor and external wall.

External wall, from the outside:
150 mm lightweight concrete
150 mm concrete
50 mm mineral wool
50 x 50 mm studs, max 600 mm distance between centres
13 mm gypsum wallboard, covered with aluminium foil



a)



b)

Conditions during measurement:

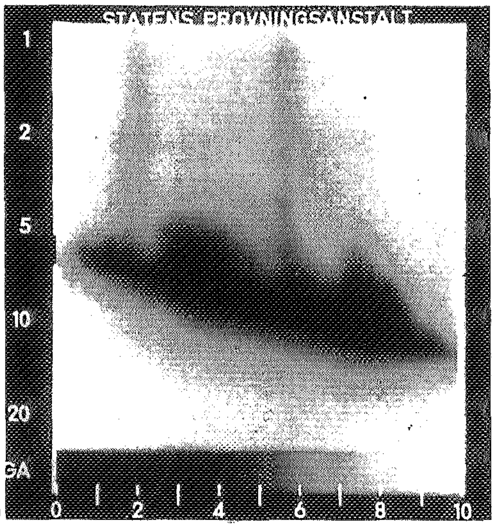
cloudiness	cloudy
outdoor air temp	+1°C
indoor air temp	+23°C
wind conditions	calm
$p_i - p_u$	- 20 Pa

a) Construction of intermediate floor at its junction with external wall.

b) Leakage of air through junction of intermediate floor and gable wall.

c) Thermogram of section at wall-floor junction (upper floor). The colder areas have a relatively uneven contour. Colder areas are due to leakage of air through badly sealed floor junction.

d) $t_{ref} = +22°C$
ΔI = - 3.3 isotherm units
Δt = 5.0°C
v = 1–3 m/s



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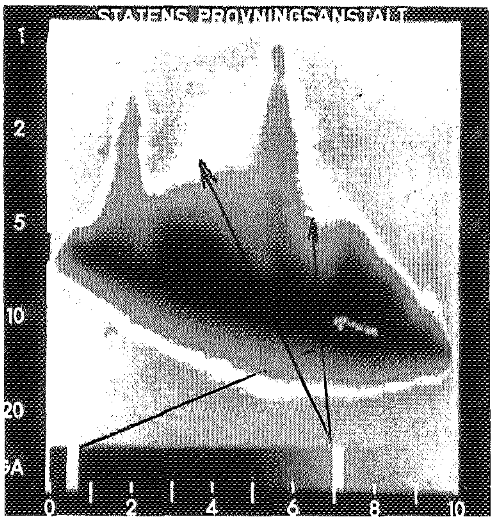
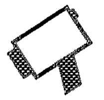


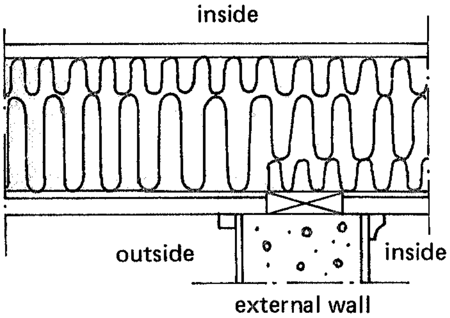
d)

COMPARATIVE THERMOGRAMS – PROJECTING INTERMEDIATE FLOOR OF TIMBER

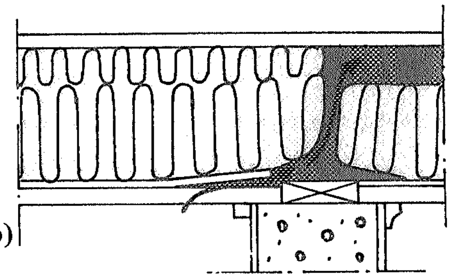
Fig. 61. Insulation and airtightness defect due to incorrect placing of insulation material in floor at its junction with the external wall.

Floor, from above:
22 mm parquet floor
plastic film
220 mm mineral wool
13 mm bitumen impregnated
fibre board
25 mm tongued and
grooved boarding





a)


b)

Conditions during measurement:

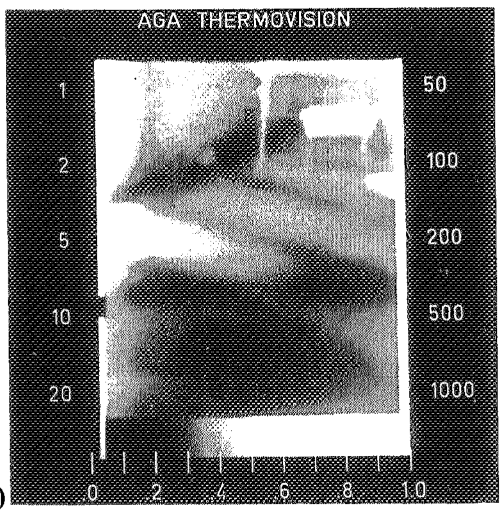
cloudiness	clear
outdoor air temp	- 7°C
indoor air temp	.+ 22°C
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	- 4 Pa

a) Construction of intermediate floor at its junction with the external wall.

b) Defective insulation in intermediate floor.

c) Thermogram of section near floor. Colder areas of uneven contour. These areas are mainly situated in the vicinity of the external wall on the ground floor which is set back in relation to the external wall above. Leakage of air into the floor construction.

d) t_{ref} = +21°C
Δ I = - 2.2 isotherm units
Δ t = 3.5°C
v = 0 m/s



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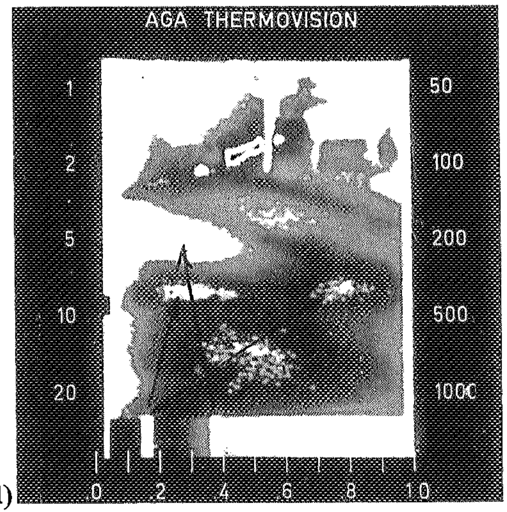


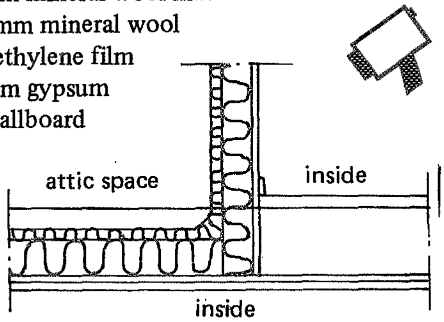
d)

COMPARATIVE THERMOGRAMS – INTERMEDIATE FLOOR OF TIMBER

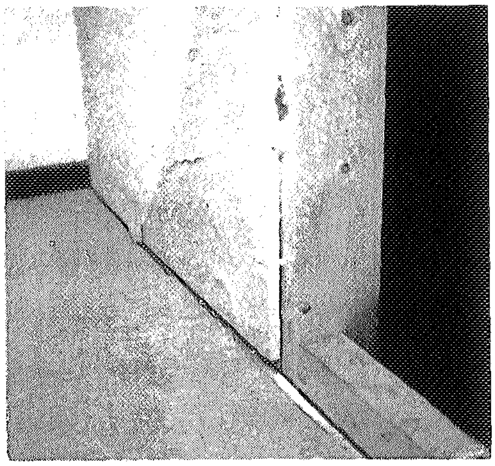
Fig. 62. Insulation and airtightness defect due to unsatisfactory airtight layer at the floor brace wall junction.

Floor, from above:
30 + 120 mm mineral wool
polyethylene film
tongued and grooved board

Wall, from the outside:
30 mm mineral wool mat
100 mm mineral wool
polyethylene film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

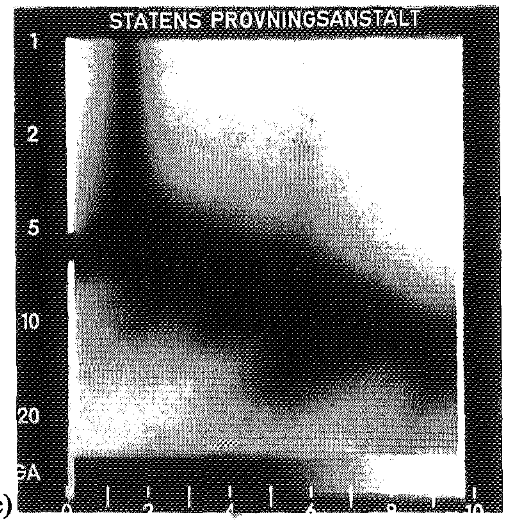
cloudiness	cloudy
outdoor air temp	- 0.5°C
indoor air temp	+23°C
wind conditions	1–2 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of intermediate floor and adjoining brace wall.

b) Section of wall (partly opened-up wall) with skirting-board removed. The inner wall cladding finishes just above the floor.

c) Thermogram of colder section at floor-wall junction. This is due to bad sealing of the junction between brace wall and floor, with strong leakage of air as a consequence.

d) t_{ref} = +22°C
Δ I = - 4.0 isotherm units
Δ t = 5.5°C
v = 0.5–3.0 m/s



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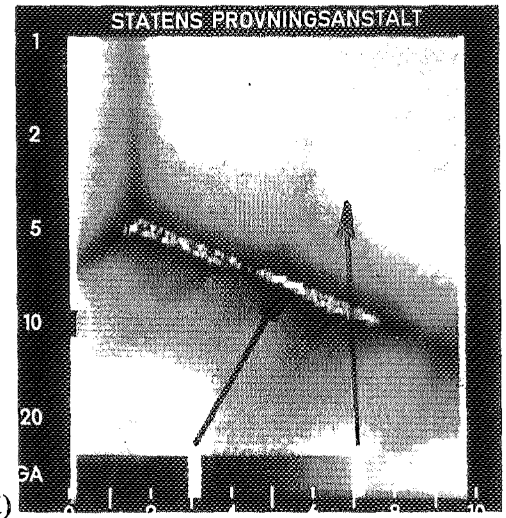
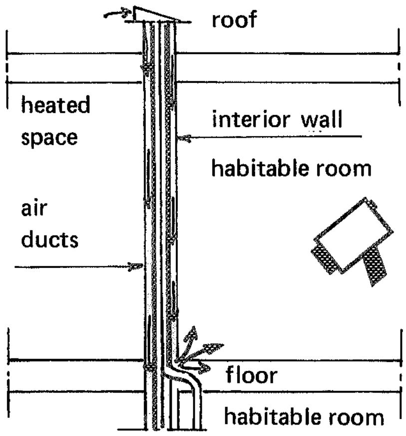


d)

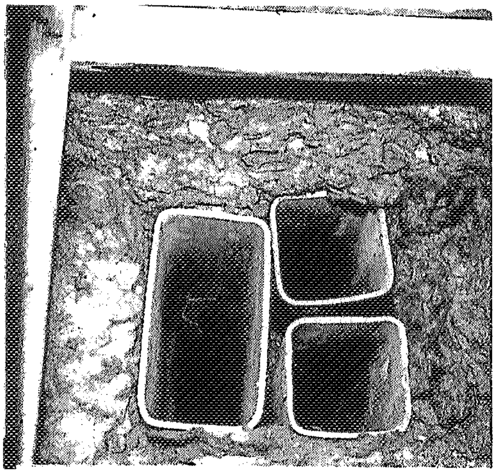
COMPARATIVE THERMOGRAMS – PASSAGE OF AIR DUCT THROUGH FLOOR

Fig. 63. Insulation defect due to incorrect placing of insulation material and bad seal around vertical air ducts.

a)



b)



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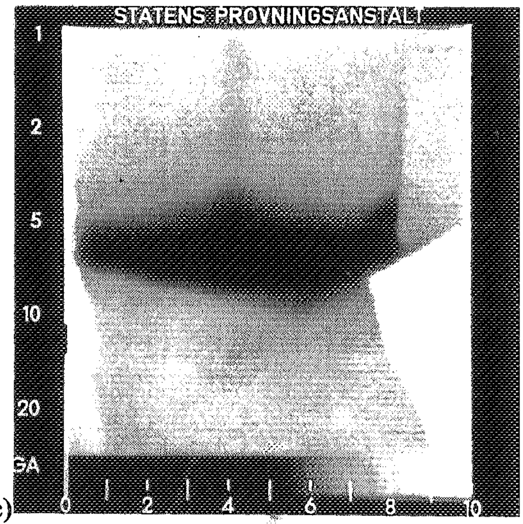

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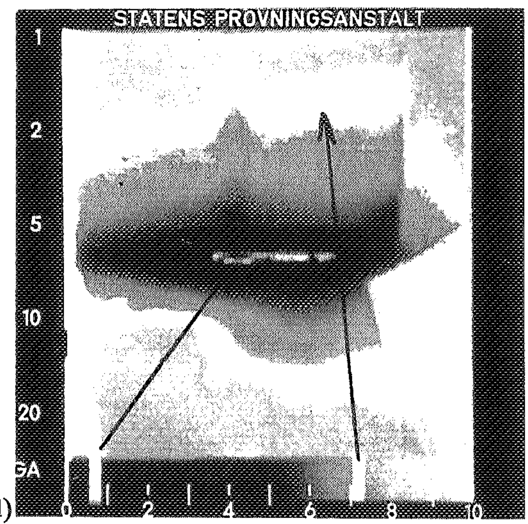


Conditions during measurement:

cloudiness	clear
outdoor air temp	- 7°C
indoor air temp	+ 22°C
wind conditions	2–3 m/s
$p_i - p_u$	- 4 Pa

a) Installation of insulated air ducts according to sketch.

b) Insulation defects around the air ducts, with large air gaps between the ducts.

c) Thermogram of colder section at floor-wall junction where inner wall adjoins intermediate floor. (Heated space behind constructional elements.) Colder area is due to leakage of cold air between the air ducts. The air spreads in the floor, mainly to places where the air duct adjoin in the floor, and leaks into the room.

d) $t_{ref} = +22°C$
ΔI = - 7.4 isotherm units
Δt = 10.5°C
v = 2.0–5.0 m/s (at floor-wall junction)

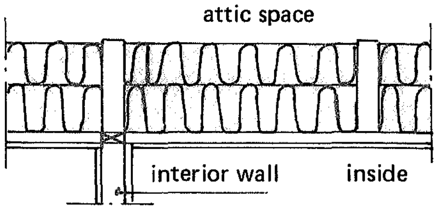
COMPARATIVE THERMOGRAMS – HORIZONTAL INTERMEDIATE FLOOR

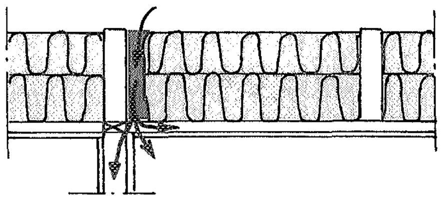
Fig. 64. Insulation and airtightness defect – defective contact between insulation material and constructional elements, and bad fitting of insulation material around these.

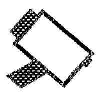
Floor, from above:
150 mm mineral wool
polyethylene film
19 mm secondary spaced boarding
13 mm gypsum wallboard

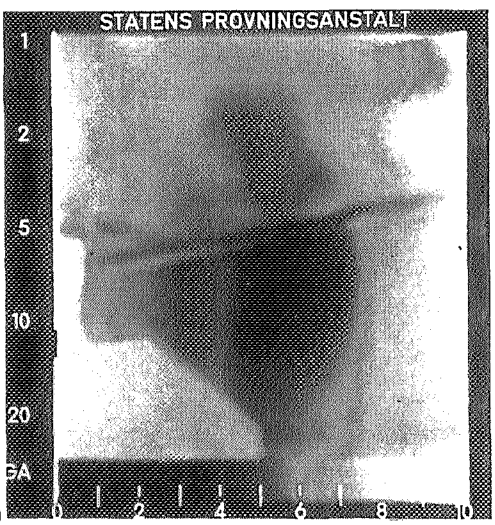
Conditions during measurement:

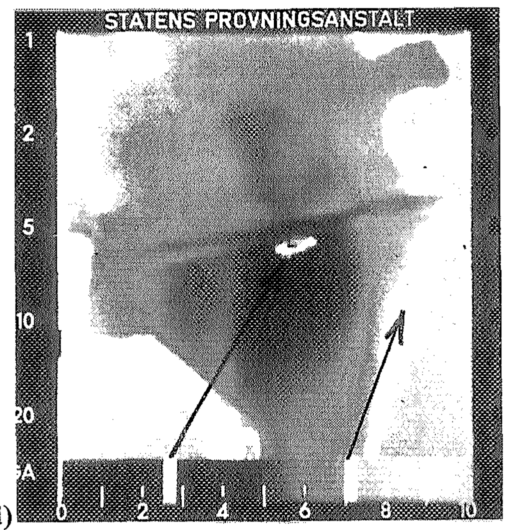
cloudiness	clear
outdoor air temp	+19°C
indoor air temp	+20°C
wind conditions	1–2 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) 

b) 



c) 

d) 

a) Construction of intermediate floor and its junction with interior wall.

b) Defective insulation. The mineral wool is incorrectly placed around roof truss. Leakage of air into construction.

c) Thermogram of section at wall-ceiling junction where inner wall adjoins intermediate floor. Colder areas both in ceiling and on wall. Cold air spreads along both interior wall and floor.

d) $t_{ref} = +19°C$
$\Delta I = -4.5$ isotherm units
$\Delta t = 6.5°C$
$v = 0.2–0.3$ m/s (leakage of air into the room)

COMPARATIVE THERMOGRAMS – CONCRETE GROUND FLOOR SLAB ABOVE CRAWLING SPACE (junction with external timber wall)

Fig. 65. Insulation and airtightness defect due to bad seal at sole plate.

External wall, from the outside:
boarding
air gap
bitumen impregnated fibre board
100 mm mineral wool
polyethylene film
13 mm gypsum wallboard

Conditions during measurement:

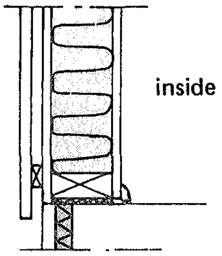
cloudiness	cloudy
outdoor air temp	+1°C
indoor air temp	+23°C
wind conditions	1–2 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction at junction between external wall and ground floor.

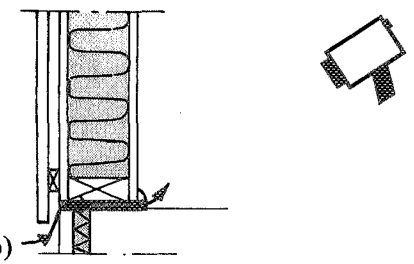
b) Defective seal at sole plate.

c) Thermogram of section at floor-wall junction underneath window with electric heating panels. Uneven colder areas at skirting board. These are due to defective seal at the sole plate according to b).

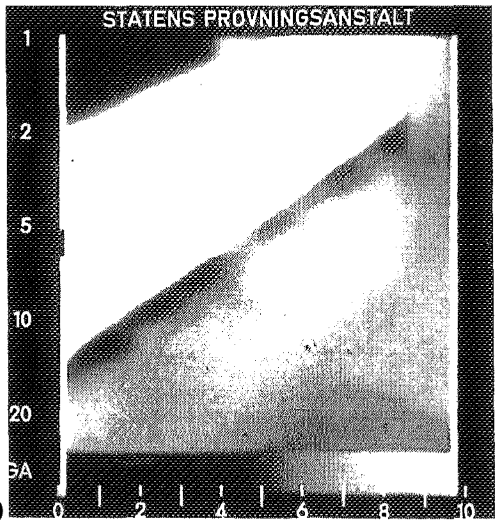
d) $t_{ref} = +22°C$
$\Delta I = 1.9$ isotherm units
$\Delta t = 3.5°C$
$v = 0.5–1.5$ m/s (at floor-wall junction)



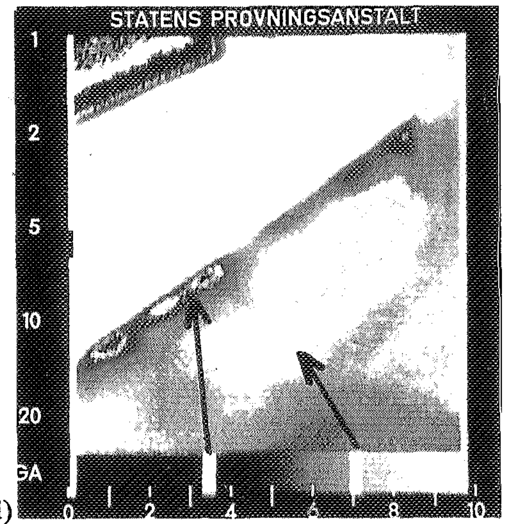
a)



b)



c)



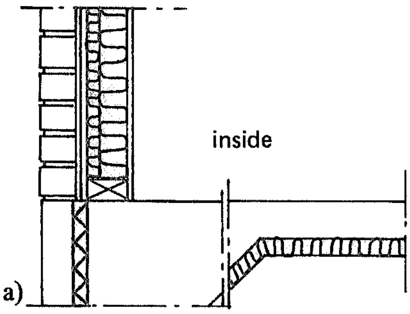
d)

COMPARATIVE THERMOGRAMS – CONCRETE GROUND FLOOR SLAB LAID ON THE GROUND (junction with external wall)

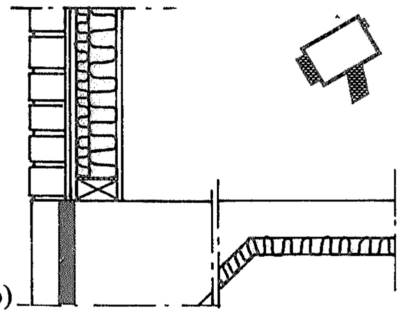
Fig. 66. Insulation and airtightness defect due to insufficient insulation of edge beam.

Wall, from the outside:
facing bricks
19 mm bitumen impregnated board
30 mm mineral wool slab
90 mm mineral wool slab
vapour barrier cardboard
13 mm chipboard

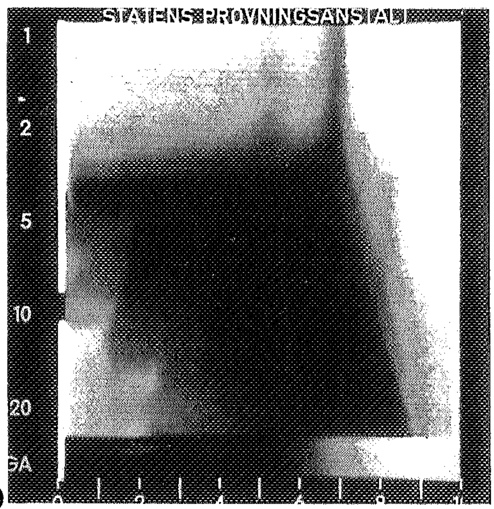
Floor, from above:
120 mm concrete
50 mm mineral wool



a)



b)



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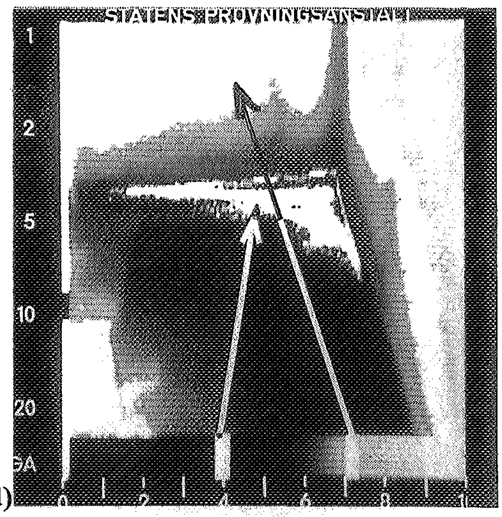


d)

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	+1°C
indoor air temp	+20°C
wind conditions	3–5 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of bottom floor and external wall.

b) Defective construction of bottom floor slab (no edge insulation).

c) Thermogram of colder floor area near external wall. Colder area situated about 0.5 m from external wall, due to omission of edge beam insulation.

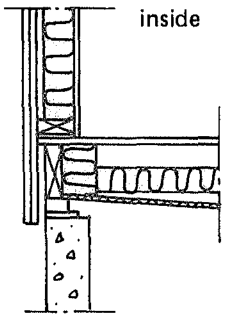
d) t_{ref} = +19°C
Δ I = - 3.1 isotherm units
Δ t = 4.5°C
v = 0 m/s

COMPARATIVE THERMOGRAMS – BOTTOM FLOOR OF TIMBER OVER CRAWLING SPACE (junction with external wall)

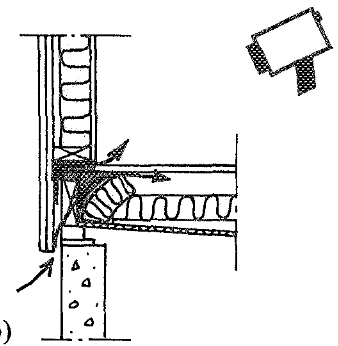
Fig. 67. Insulation and airtightness defect due to incorrect placing of insulation material at edge of floor construction.

External wall, from the outside:
boarding
air gap
bitumen impregnated fibre board
95 mm mineral wool
13 mm gypsum wallboard

Floor, from above:
floor covering
70 mm air gap
70 mm mineral wool
tongued and grooved board



a)



b)

Conditions during measurement:
cloudiness

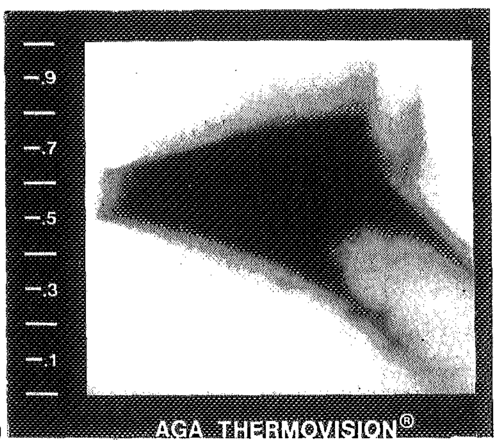
outdoor air temp	0°C
indoor air temp	+21°C
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	- 7 Pa

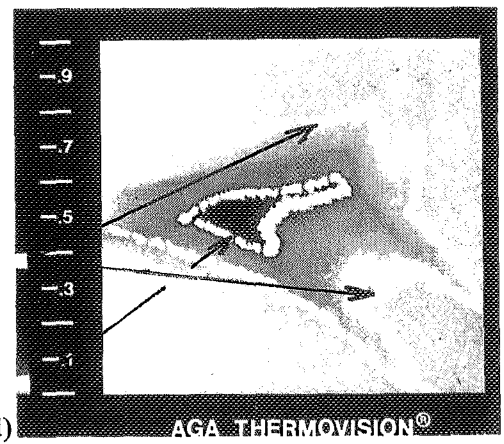
a) Construction of bottom floor.

b) Defective insulation in bottom floor where insulation material does not completely fill the space at the edge of the floor.

c) Thermogram of colder section at floor-wall junction (corner of external wall). Colder area due to leakage of air into floor construction and into the dwelling.

d) $t_{ref} = +20°C$
$\Delta I = -1.8$ isotherm units
$\Delta t = 3.0°C$
$v = 1.0–1.5$ m/s

c) 

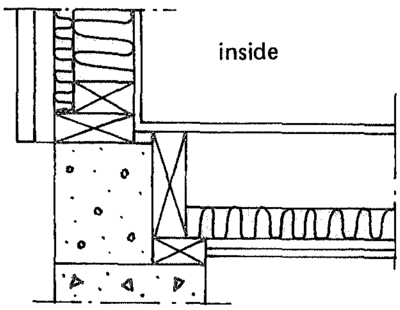
d) 

COMPARATIVE THERMOGRAMS – BOTTOM FLOOR OF TIMBER ABOVE CRAWLING SPACE (junction with external wall)

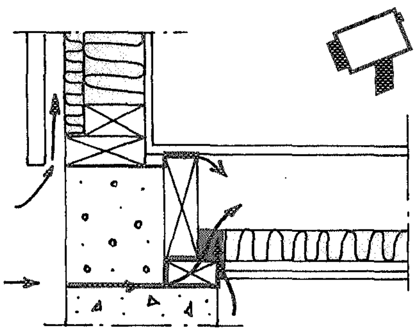
Fig. 68. Insulation and airtightness defect due to incorrect placing of insulation material, with leakage of air into construction as a result.

External wall, from the outside:
wall construction
30 mm mineral wool
95 mm mineral wool

Floor, from above:
20 mm floor covering
125 mm air gap
50 mm mineral wool
blind floor



a)



b)

Conditions during measurement:

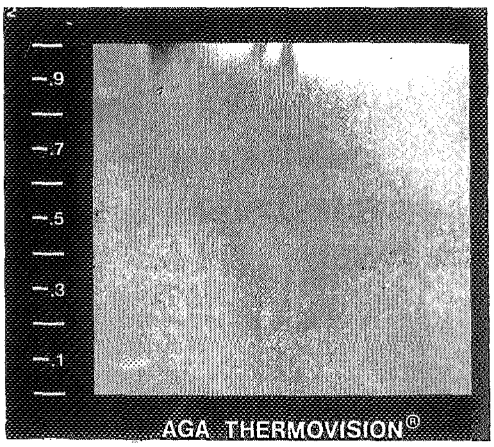
cloudiness	cloudy
outdoor air temp	+2°C
indoor air temp	+20°C
wind conditions	2–5 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of bottom floor of timber.

b) Defective insulation and sealing in bottom floor.

c) Thermogram of section of floor. Colder zone on floor, due to leakage of air into floor construction.

d) $t_{ref} = +19°C$
Δ I = - 0.4 isotherm units
Δ t = 0.5°C
v = 0 m/s



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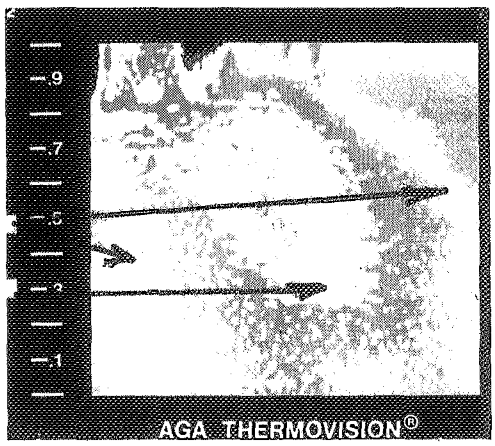
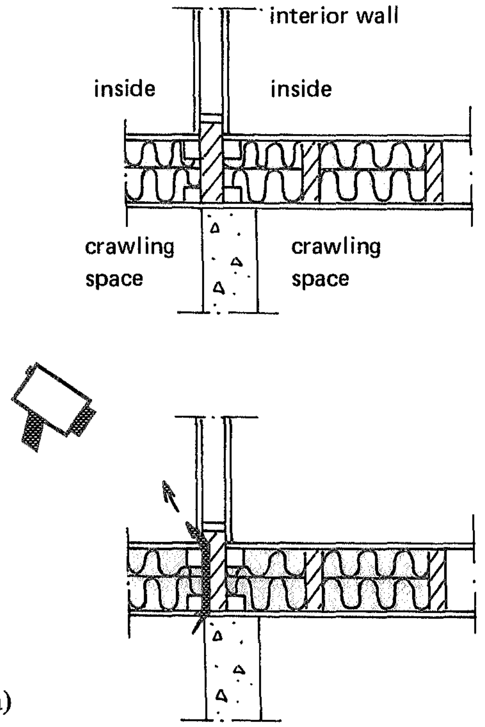


d)

COMPARATIVE THERMOGRAMS – BOTTOM FLOOR OF TIMBER ABOVE CRAWLING SPACE (junction with loadbearing inner walls)

Fig. 69. Insulation and airtightness defect due to insufficient sealing of junction between floor and inner wall.

Floor, from above:
19 mm fibre board
floor joists 50 x 200 mm
70 + 80 mm mineral wool
cardboard
10 mm fibre board



a)

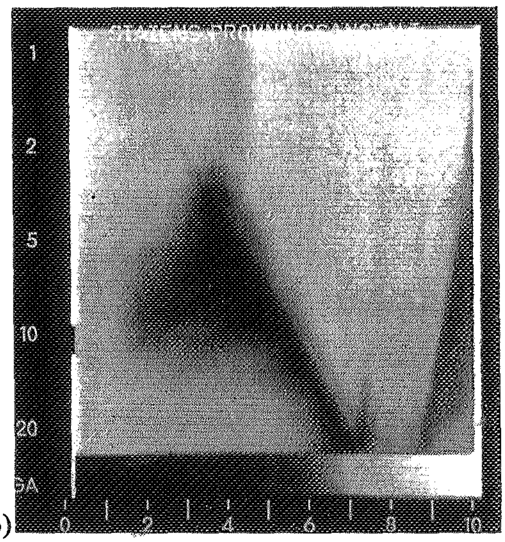
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	+5°C
indoor air temp	+22°C
wind conditions	1–5 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of bottom floor (prefabricated floor units) and junction with inner wall. The air leakage path has been indicated.

b) Thermogram of colder area where inner wall adjoins bottom floor. This is due to leakage of air through incorrectly sealed joints between floor units.

c) $t_{ref} = +22°C$
ΔI = - 5.2 isotherm units
Δt = 7.0°C
v = 0.5–1.5 m/s (at floor-wall junction)



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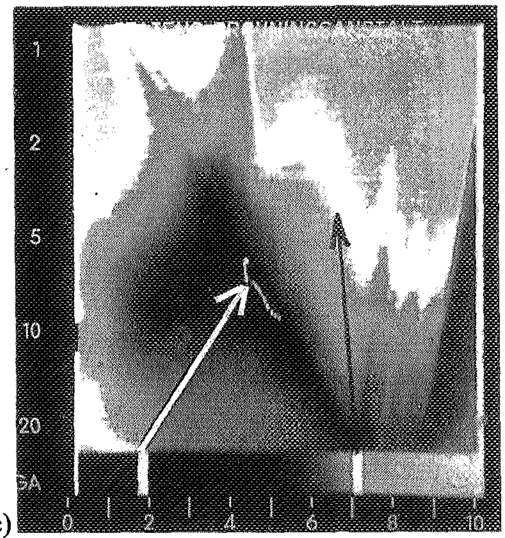
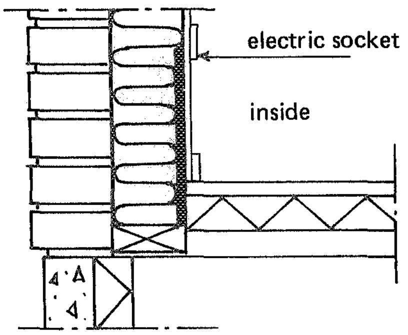


c)

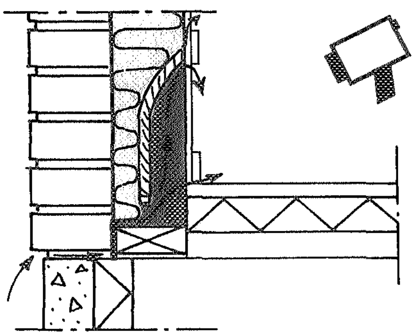
COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF TIMBER WITH CLADDING OF FACING BRICKS

Fig. 70. Insulation and airtightness defect due to incorrect placing of insulation material around electric cables. Polyethylene film torn.

External wall, from the outside:
facing bricks
sheathing cardboard
120 mm mineral wool
polyethylene film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

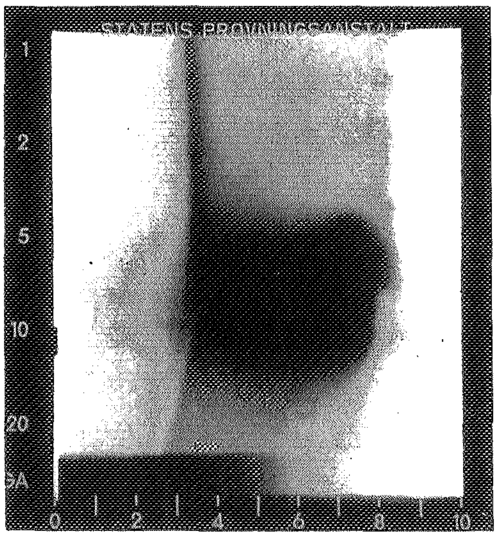
cloudiness	cloudy
outdoor air temp	- 20°C
indoor air temp	+ 19°C
wind conditions	1–2 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall and floor near electric socket.

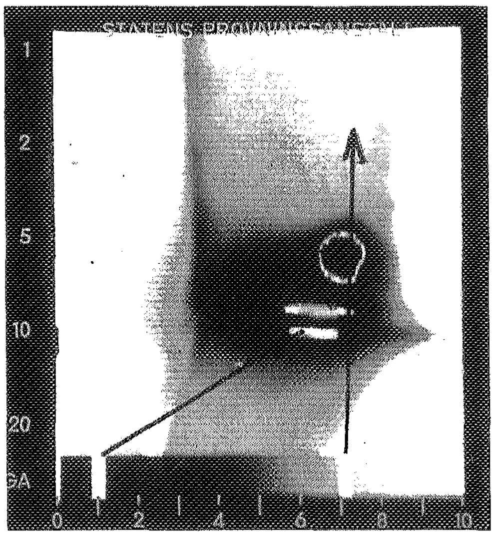
b) Defective insulation around electric cables in the wall.

c) Thermogram of section at floor-wall junction. The area around the socket is very much colder due to defective insulation around electric cables in the wall, and to leakage of air.

d) t_{ref} = + 17°C
Δ I = - 6.1 isotherm units
Δ t = 10.0°C
v = 2–3 m/s (near electric socket and at floor-wall junction)



c)

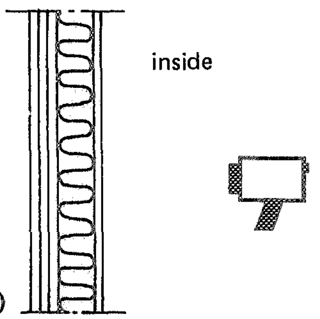


d)

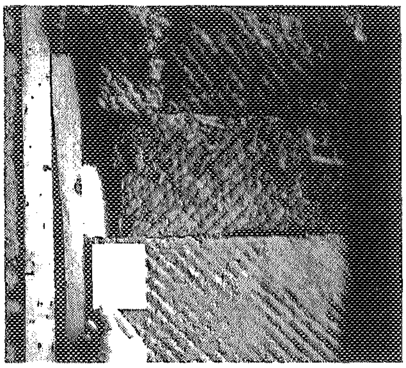
COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF TIMBER WITH INTERNAL CLADDING OF WOOD BOARDING

Fig. 71. Insulation and airtightness defect due to parts of insulation material in wall being incorrectly placed.

External wall, from the outside:
boarding
bitumen impregnated fibre board
38 x 75 mm studs
120 mm mineral wool (quality B)
13 mm gypsum wallboard coated with aluminium foil



a)



b)

Conditions during measurement:

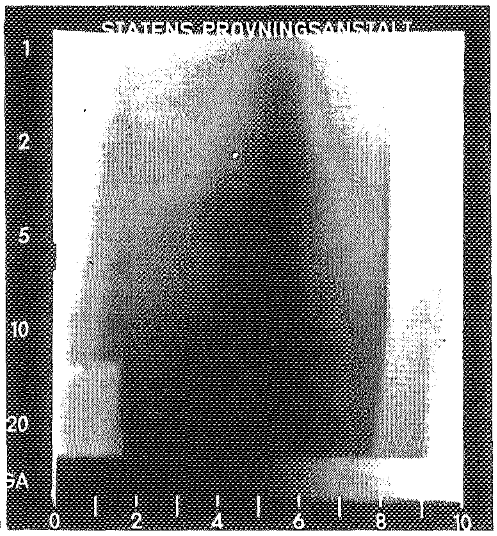
cloudiness	clear
outdoor air temp	- 21°C
indoor air temp	+ 20°C
wind conditions	0.5–1.0 m/s (to facade)
$p_i - p_u$	- 10 Pa

a) Construction of external wall.

b) Opened up wall section where insulation material is incorrectly placed. There is no insulation at some points. (Wall opened up from outside).

c) Thermogram of section in the middle of the wall to the left of window. The area between the vertical studs is colder due to defective performance of the insulation.

d) t_{ref} = + 18°C
Δ I = - 1.2 isotherm units
Δ t = 1.5°C
v = 0 m/s



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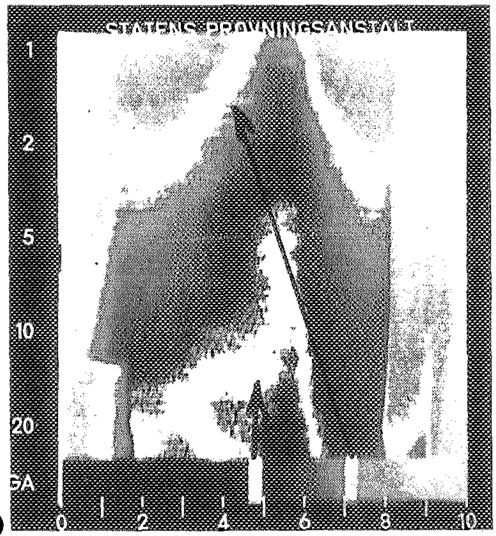
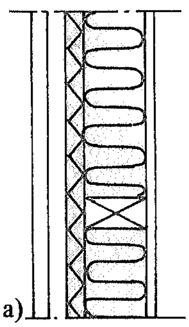


d)

COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF TIMBER WITH EXTERNAL CLADDING OF WOOD BOARDING

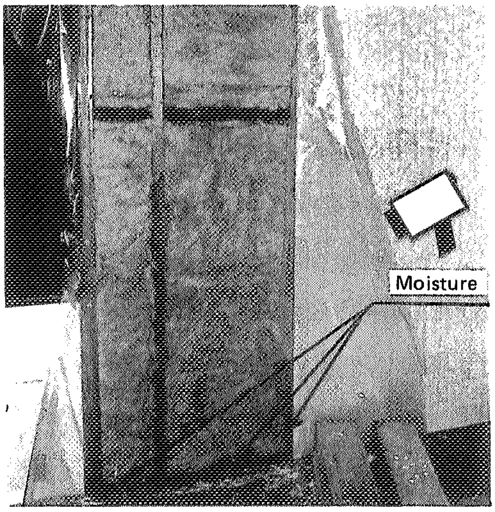
Fig. 72. Defect in insulation due to condensation of moisture in construction. The outer layer of insulation consists of expanded polystyrene.



External wall, from the outside:
boarding
air gap
30 mm expanded polystyrene
100 mm mineral wool
(quality B)
polyethylene film
13 mm gypsum wallboard

inside

a)



b)

Conditions during measurement:

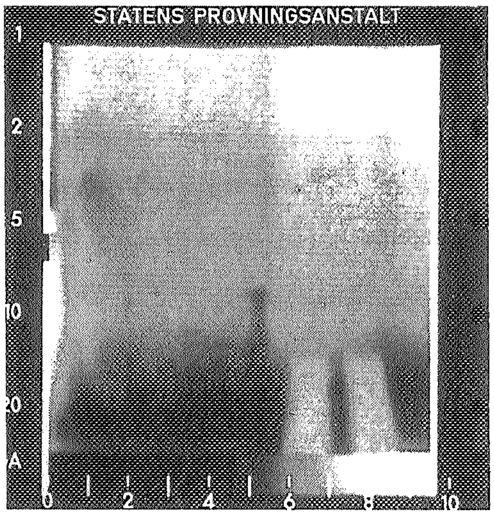
cloudiness	cloudy (rain)
outdoor air temp	$+8^\circ C$
indoor air temp	$+19^\circ C$
wind conditions	approx 2 m/s (perpendicularly to facade)
$p_i - p_u$	-4 Pa

a) Construction of external wall.

b) Opened up wall section corresponding to section of surface in thermograms c) and d). Correct placing of insulation material. The sole plate and parts of the vertical studs are wet (free water).

c) Thermogram of external wall at floor-wall junction. The wall surface has a somewhat irregular temperature distribution. Owing to moisture in the construction, the area near the skirting board exhibits differential cooling. The section corresponds to junction between external wall and intermediate floor.

d) $t_{ref} = +18^\circ C$
$\Delta I = -1.8$ isotherm units
$\Delta t = 2.5^\circ C$
$v = 0$ m/s



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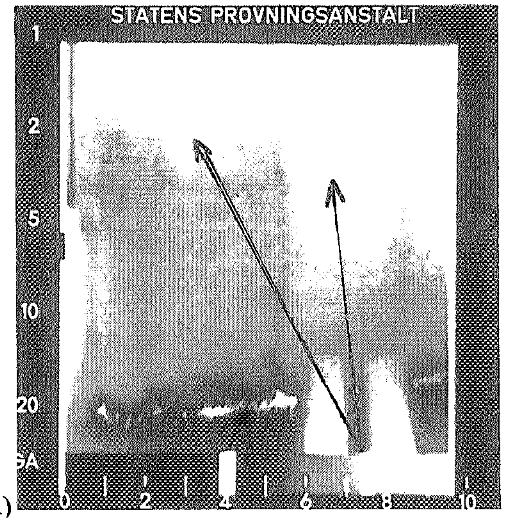


d)

COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF TIMBER WITH EXTERNAL CLADDING OF WOOD BOARDING

Fig. 73. Insulation and airtightness defect due to incorrect placing of insulation material against the warm side (air gaps).

External wall, from the outside:
boarding
air gap
30 mm expanded plastics
100 mm mineral wool (quality B)
Polyethylene film
13 mm gypsum wallboard

Conditions during measurement:

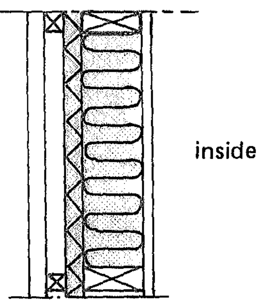
cloudiness	cloudy (rain)
outdoor air temp	+8°C
indoor air temp	+19°C
wind conditions	approx 3 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall.

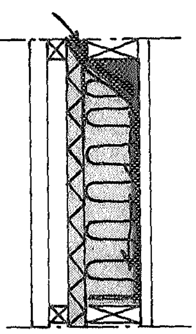
b) Defective insulation and airtightness.

c) Thermogram of wall section below window. Uneven cooling down of wall surface is due to incorrect placing of insulation material in wall, and to incorrect installation of wind-protection.

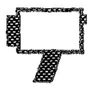
d) $t_{ref} = +18°C$
$\Delta I = -0.9$ isotherm units
$\Delta t = 1.5°C$
$v = 0$ m/s

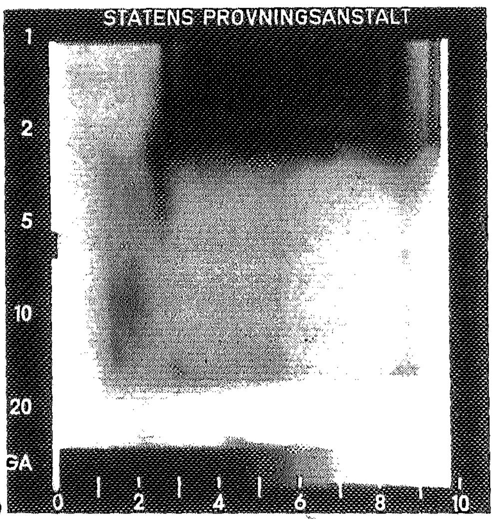


a)



b)





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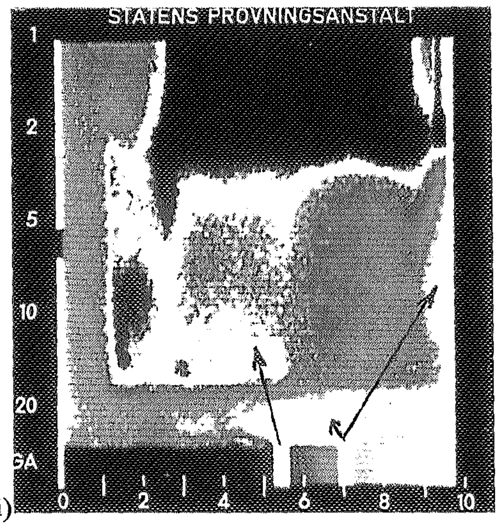
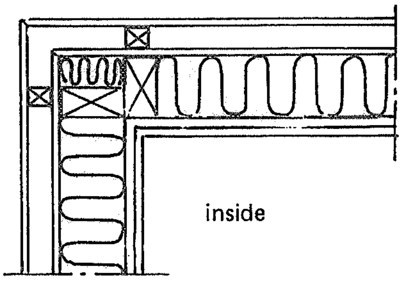


d)

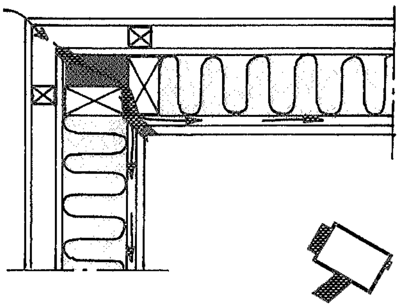
COMPARATIVE THERMOGRAMS – CORNER OF TIMBER EXTERNAL WALL.

Fig. 74. Insulation and airtightness defect due to omission of insulation material at the corner and to incorrect placing of wind protection.

External wall, from the outside:
wall tiles
31 x 50 mm batten
3.2 mm – horizontal sheets of internit
100 mm mineral wool (quality A)
22 mm secondary spaced boarding
vapour barrier cardboard
13 mm chipboard



a)



b)

Conditions during measurement:

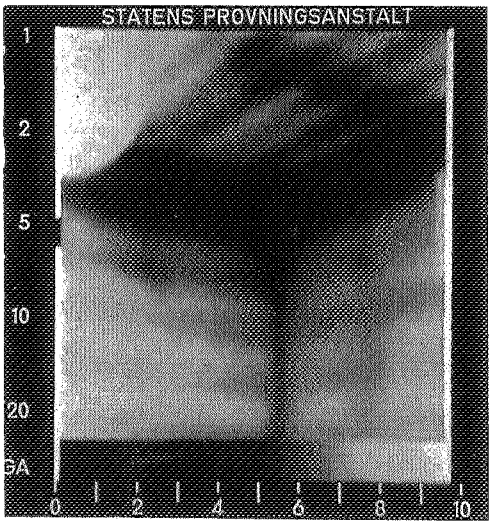
cloudiness	cloudy
outdoor air temp	0°C
indoor air temp	+21°C
wind conditions	5–6 m/s (at an angle to facade)
$p_i - p_u$	- 2 Pa

a) Construction of external wall.

b) Defective insulation at corner of wall.

c) Thermogram of section at corner. The wall and ceiling surfaces are colder, due to leakage of air along ducts formed by the secondary spaced boarding construction.

d) $t_{ref} = +20°C$
Δ I = - 1.9 isotherm units
Δ t = 2.5°C
v = 0.4 m/s (locally at corner of wall)



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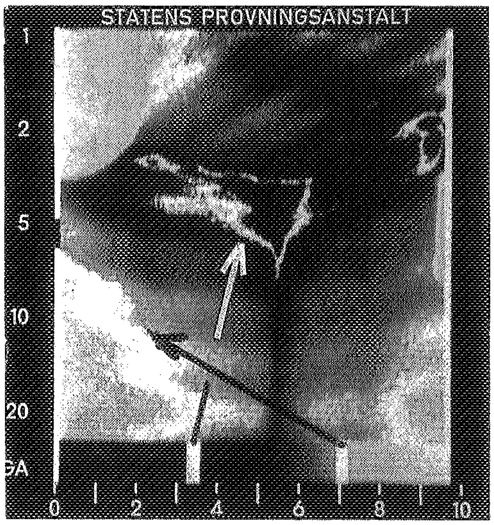


d)

COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF TIMBER WITH EXTERNAL CLADDING OF WOOD BOARDING

Fig. 75. Insulation and airtightness defect due to incorrect placing of insulation material in space between studs over entire storey height.

External wall, from the outside:
boarding
windprotection
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard

Conditions during measurement:

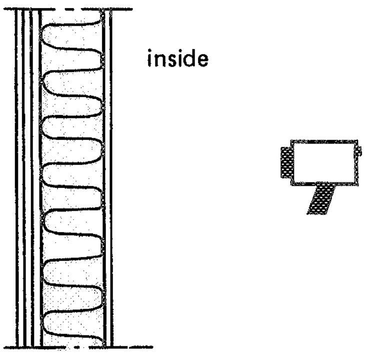
cloudiness	cloudy
outdoor air temp	+1°C
indoor air temp	+23°C
wind conditions	calm
$p_i - p_u$	- 10 Pa

a) Construction of external wall.

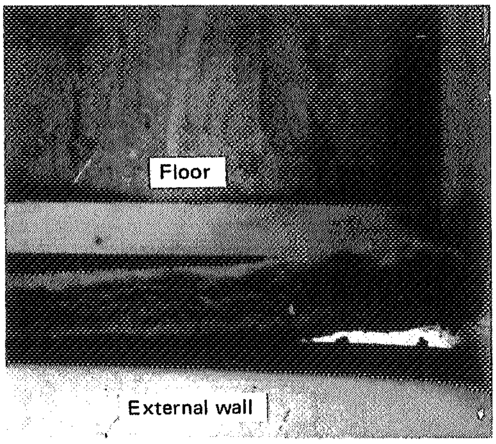
b) Opened up wall section where insulation material is incorrectly placed. In the space between the studs, material is incorrectly placed over the entire storey height.

c) Thermogram of colder wall section. This colder section extends vertically from floor to ceiling.

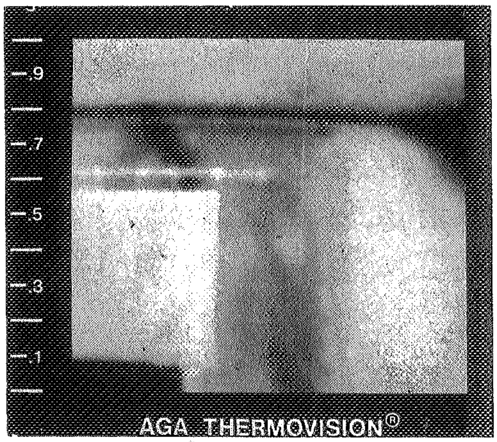
d) $t_{ref} = +22°C$
$\Delta I = -1.4$ isotherm units
$\Delta t = 2.0°C$
$v = 0$ m/s



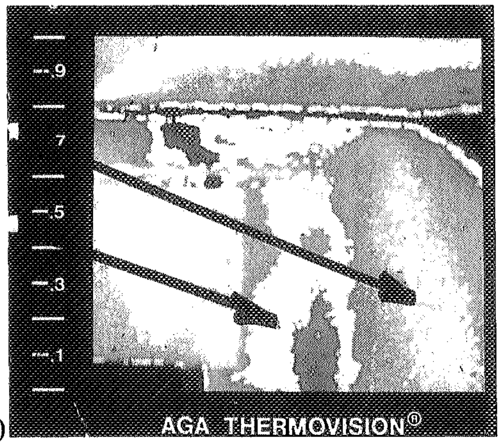
a)



b)



c)



d)

COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF TIMBER AT JUNCTION WITH TIMBER ATTIC FLOOR

Fig. 76. Insulation and airtightness defect due to incorrect placing of insulation material at the junction at the eaves.

External wall, from the outside:
boarding
sheathing cardboard
70 + 50 mm mineral wool (quality B)
vapour barrier
10 mm fibre board

Conditions during measurement:

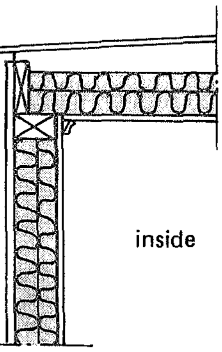
cloudiness	cloudy
outdoor air temp	$+5^\circ C$
indoor air temp	$+22^\circ C$
wind conditions	about 2 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall and floor.

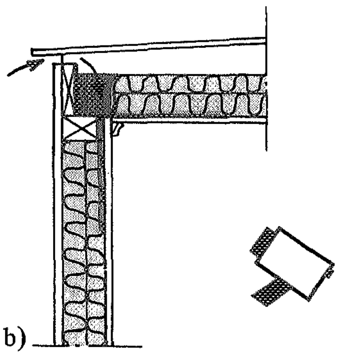
b) Defective insulation and airtightness.

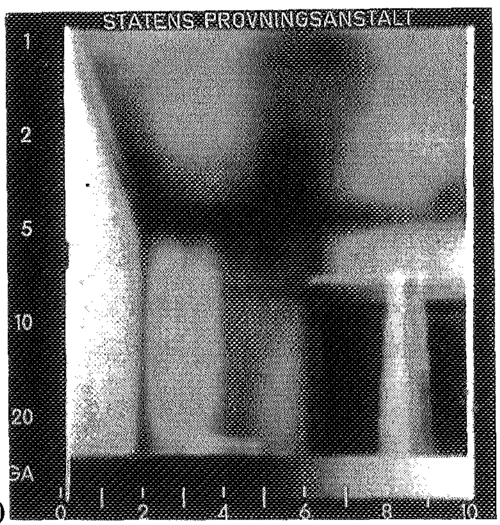
c) Thermogram of colder section at wall-ceiling junction. The uneven temperature distribution over the wall and ceiling is due to convective air movements in the construction.

d) $t_{ref} = +21^\circ C$
$\Delta I = -1.6$ isotherm units
$\Delta t = 2.0^\circ C$
$v = 0$ m/s



a)


b)



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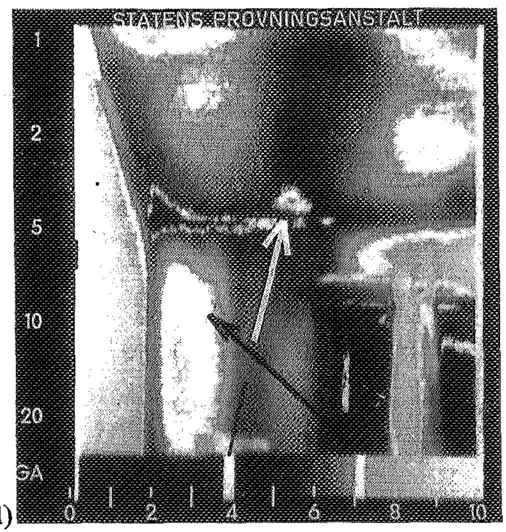
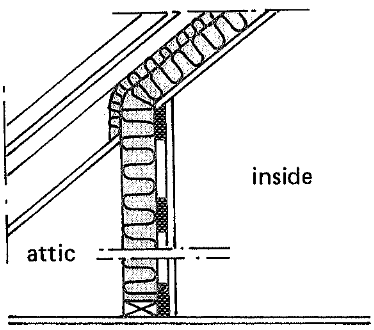


d)

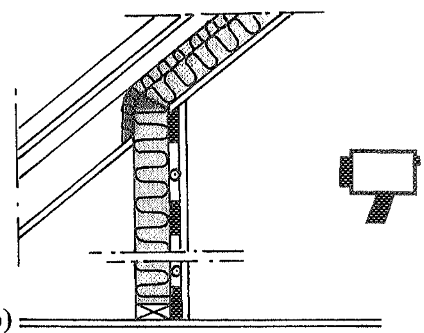
COMPARATIVE THERMOGRAMS – BRACE WALL OF TIMBER AT JUNCTION WITH INSULATED INCLINED CEILING

Fig. 77. Insulation and airtightness defect due to incorrect placing of insulation material and insufficient wind protection.

Brace wall, from the outside:
100 mm mineral wool
posts 45 x 95 mm, 600 mm distance between centres
plastic film
tongued and grooved board (secondary spaced boarding)
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

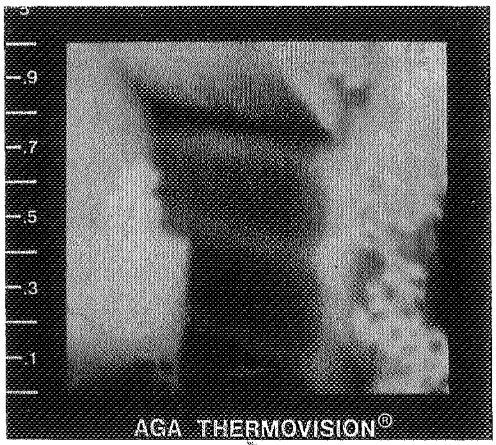
cloudiness	cloudy
outdoor air temp	$+2°C$
indoor air temp	$+20°C$
wind conditions	2–5 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of wall at bay window.

b) Defective insulation and airtightness. Air leaks into construction at studs and in corners, and then spreads along ducts between the panelling planks.

c) Thermogram of section near bay window. The vertical portion of the external wall is cooled down unevenly due to spreading of outside air along ducts formed by the secondary spaced boarding construction.

d) $t_{ref} = +19°C$
$\Delta I = -1.5$ isotherm units
$\Delta t = 2.0°C$
$v = 0$ m/s



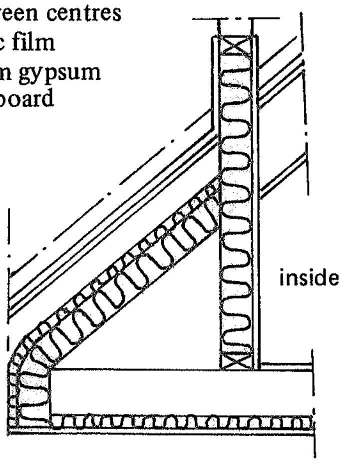
c)

d)

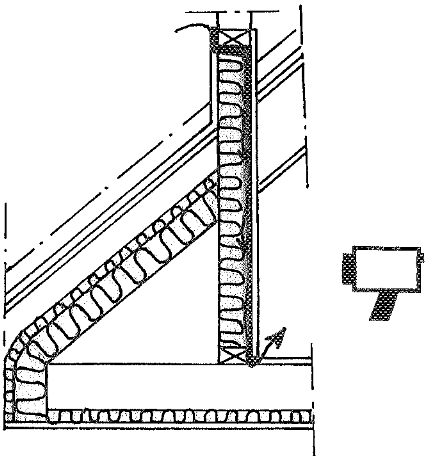
COMPARATIVE THERMOGRAMS – SECTION OF EXTERNAL WALL OF TIMBER AT JUNCTION WITH WINDOW

Fig. 78. Insulation and airtightness defect due to bad fitting of insulation material and insufficient contact between this and the warm side of the construction, combined with convective air movements in the construction.

Brace wall, from the outside:
100 mm mineral wool (quality A)
studs 45 x 95 mm, 600 mm distance between centres
plastic film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

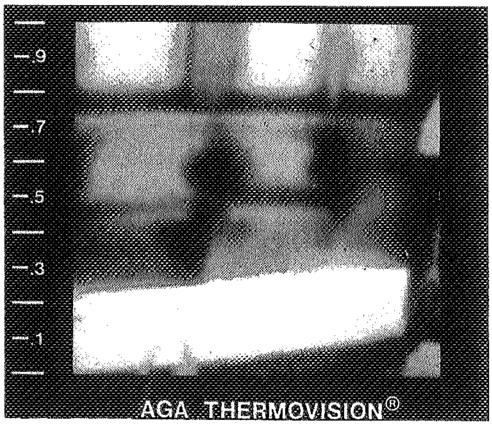
cloudiness	cloudy
outdoor air temp	+2°C
indoor air temp	+20°C
wind conditions	2–5 m/s (onto facade)
$p_i - p_u$	- 6 Pa

a) Construction of brace wall at external wall.

b) Incorrect placing and insufficient contact of mineral wool with the warm surface (particularly at the studs).

c) Thermogram of surface section below window. Certain areas near studs in wall are colder due to unsatisfactory performance of the insulation. The markedly lighter surface at the bottom of the picture is due to a hot electric panel.

d) t_{ref} = +19°C
Δ I = - 2.3 isotherm units
Δ t = 4.0°C
v = 0 m/s



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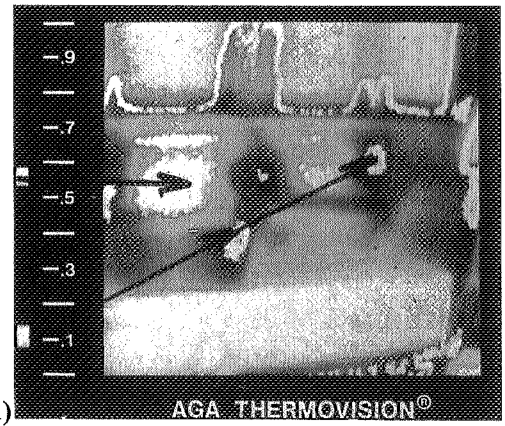
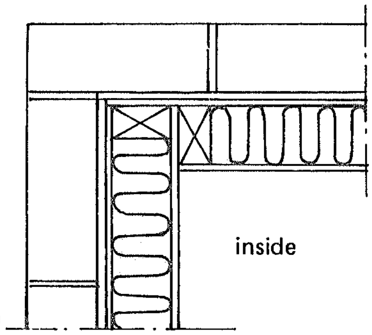


d)

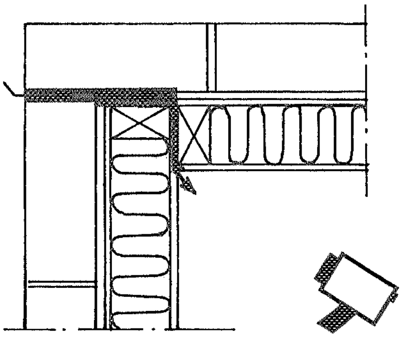
COMPARATIVE THERMOGRAMS – CORNER OF TIMBER EXTERNAL WALL WITH EXTERNAL CLADDING OF FACING BRICKS

Fig. 79. Insulation and airtightness defect due to unsatisfactory seal in corner of wall and some cracking.

External wall, from the outside:
facing bricks
air gap
fibre boards
100 mm mineral wool
plastic film
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

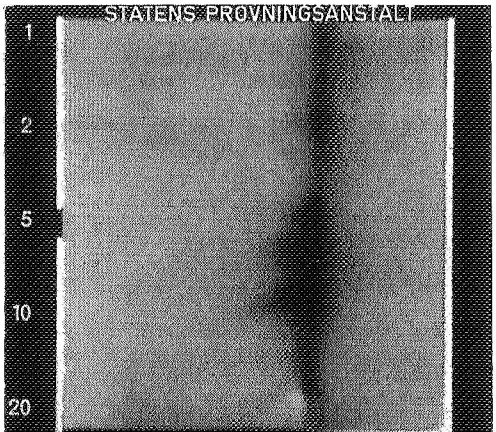
cloudiness	cloudy
outdoor air temp	0°C
indoor air temp	+21°C
wind conditions	5–6 m/s (to facade)
$p_i - p_u$	- 3 Pa

a) Horizontal section of external wall construction, corner (prefabricated wall units).

b) Defective seal due to lack of contact between units at corner.

c) Thermogram of colder section in corner of wall, due to leakage of air through open vertical joint. Variable air leakage due to uneven air resistance of surface layer (partly torn wallpaper).

d) $t_{ref} = +20°C$
ΔI = - 1.3 isotherm units
$\Delta t = 1.5°C$
v = 0.5–2.5 m/s (at vertical joint in corner of wall)



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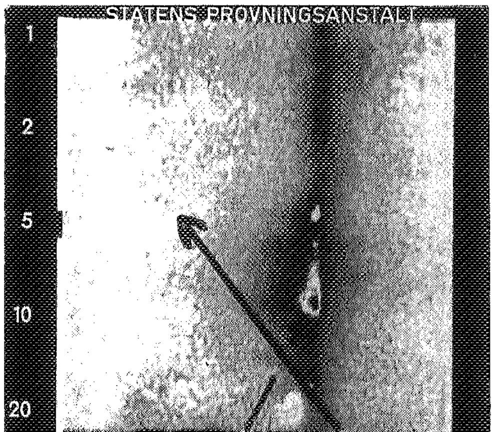
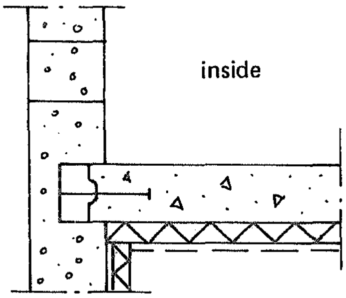


d)

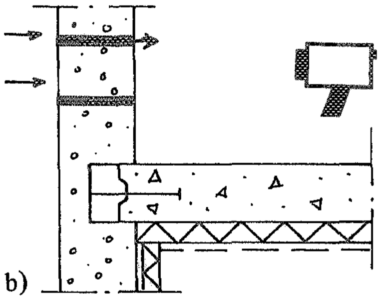
COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF LIGHTWEIGHT CONCRETE

Fig. 80. Defective insulation and airtightness performance due to cracks in the joints between lightweight concrete blocks and in corner of wall (junction of external wall – interior wall).

External wall, from the outside:
thin paster
250 mm lightweight concrete
thin plaster



a)



b)

Conditions during measurement:

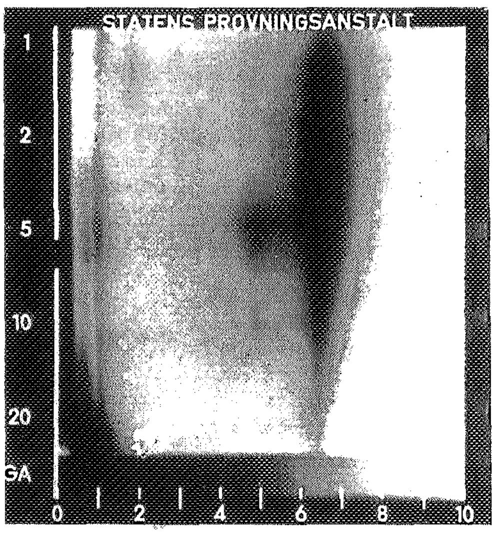
cloudiness	cloudy
outdoor air temp	+ 1°C
indoor air temp	+ 23°C
wind conditions	calm
$p_i - p_u$	- 20 Pa

a) Construction of external wall with junction with intermediate floor.

b) Insulation and airtightness defect. Cracking, chiefly in joints between the blocks.

c) Thermogram of surface section in corner of wall to the right of the window. The joints between the blocks stand out as dark strips. Certain joints and the surface sections around corner are colder, due to leakage of air through cracks.

d) t_{ref} = + 22°C
Δ I = - 1.2 isotherm units
Δ t = 1.5°C
v = 0.3 m/s (near crack in wall)
v = 0.5 m/s (in corner of wall)



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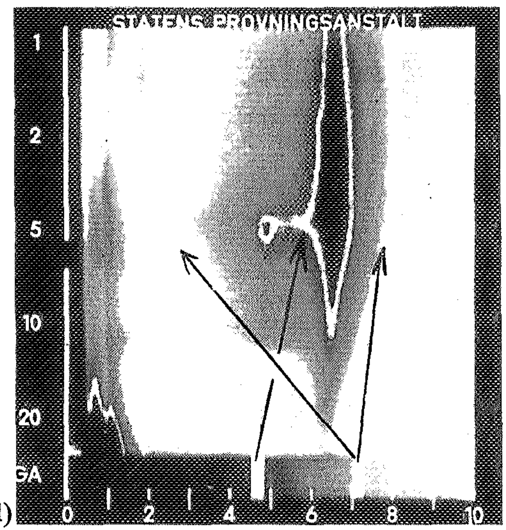
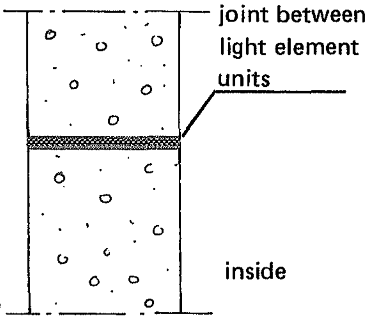


d)

COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF LIGHT ELEMENT

Fig. 81. Airtightness defect due to through crack in joint between light element.

External wall, from the outside:
plaster
250 mm lightweight concrete
plaster



a)

Conditions during measurement:

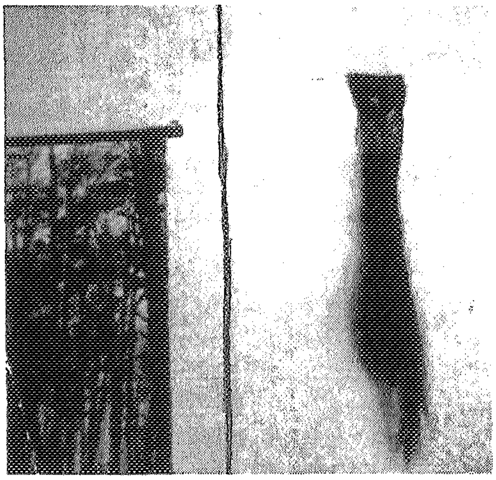
cloudiness	cloudy
outdoor air temp	- 1°C
indoor air temp	+ 17°C
wind conditions	calm
$p_i - p_u$	- 3 Pa

a) Construction (horizontal section) of external wall.

b) Through crack, approx 2 mm, in joint between light element.

c) Thermogram of surface section at wall-ceiling junction. A colder vertical strip appears along joint between light element due to leakage of outdoor air through the crack according to b).

d) $t_{ref} = +16°C$
ΔI = - 0.8 isotherm units
Δt = 1.5°C
v = 0.3–0.5 m/s (near crack in joint)



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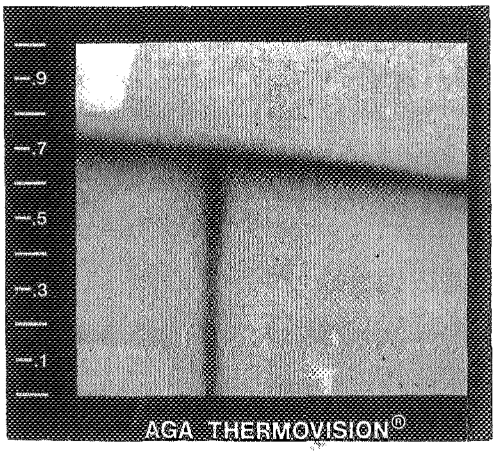
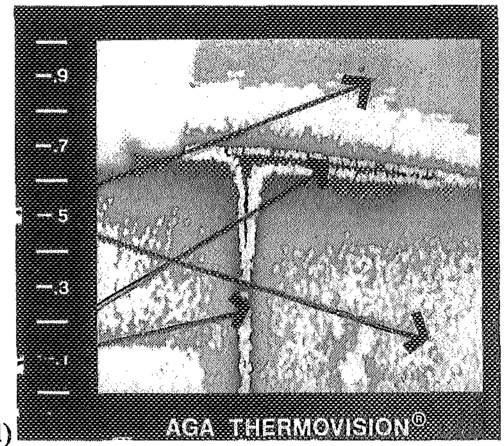


c)



d)

COMPARATIVE THERMOGRAMS – JUNCTION BETWEEN EXTERNAL WALL OF CONCRETE AND LIGHTWEIGHT CONCRETE

Fig. 82. Airtightness defect at the corner of the external wall due to crack in joint between walls of concrete and lightweight concrete.

External wall, from the outside:
150 mm lightweight concrete
150 mm concrete
50 mm mineral wool
13 mm gypsum wallboard

Conditions during measurement:

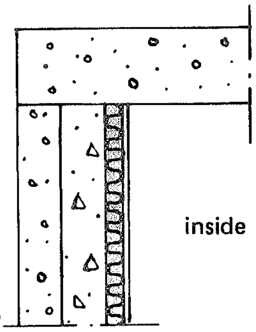
cloudiness	cloudy
outdoor air temp	+1°C
indoor air temp	+24°C
wind conditions	calm
$p_i - p_u$	- 20 Pa

a) Construction of external wall at junction between front wall and gable wall. (Horizontal section).

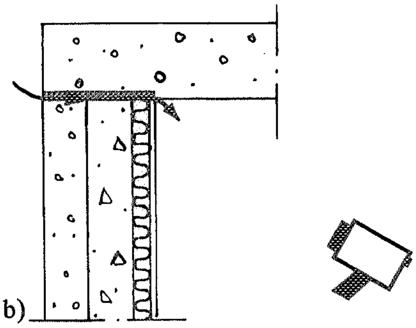
b) Leakage of air through crack in joint.

c) Thermogram of section at corner of wall. The wall surface is colder due to leakage of air through the cracked joint between the front and gable walls.

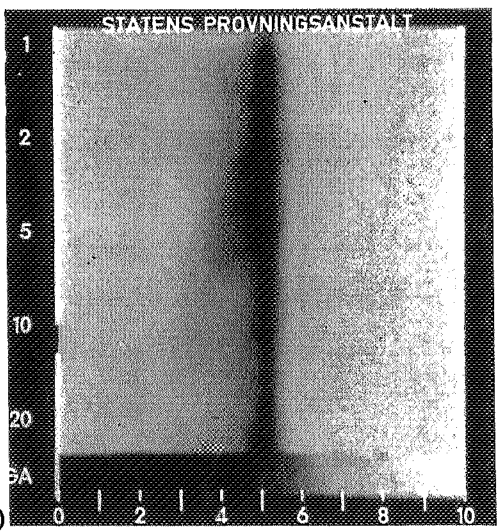
d) t_{ref} = +23°C
Δ I = - 2.6 isotherm units
Δ t = 3.5°C
v = 1–3 m/s



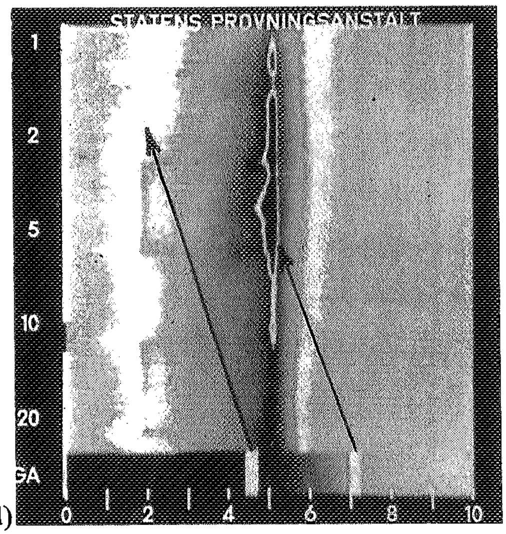
a)



b)



c)

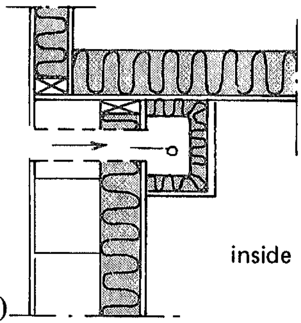


d)

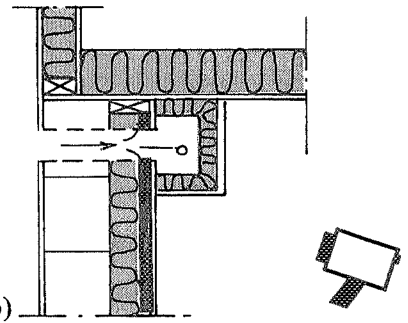
COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF HOLLOW CONCRETE BLOCKS WITH INSULATION ON THE INSIDE

Fig. 83. Defective insulation and airtightness performance in external wall near air duct due to incorrect placing of insulation material in the wall (mainly around studs).

External wall, from the outside:
200 mm hollow concrete blocks
70 mm mineral wool
13 mm gypsum wallboard



a)



b)

Conditions during measurement:

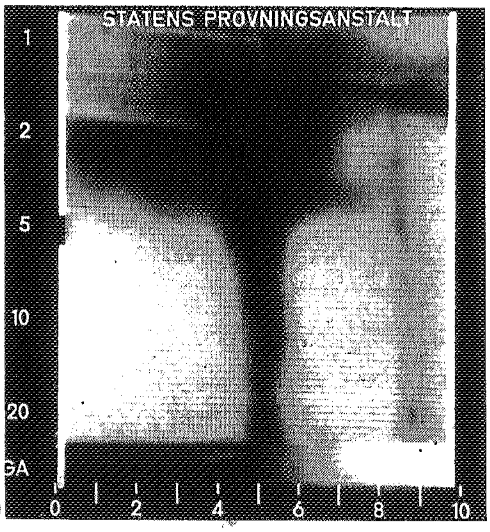
cloudiness	clear
outdoor air temp	$+5^{\circ}C$
indoor air temp	$+21^{\circ}C$
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall at air duct. (Horizontal section).

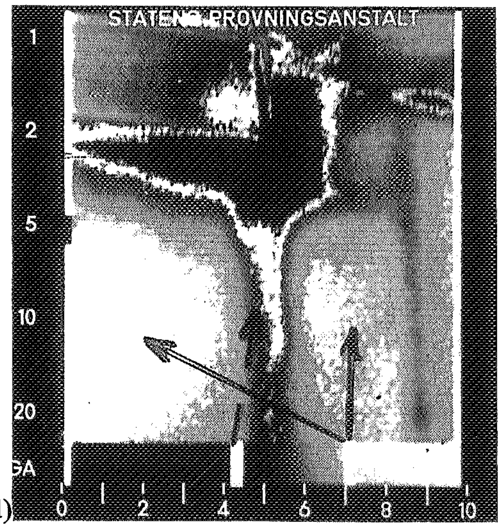
b) Incorrect placing of insulation material in wall around air duct.

c) Thermogram of colder area on wall near wall-ceiling junction where the duct is connected. Outdoor air spreads into cavities formed by incorrect placing of insulation material. The colder area also extends in the vertical direction, which indicates convective air currents inside construction.

d) $t_{ref} = +19^{\circ}C$
$\Delta I = -1.4$ isotherm units
$\Delta t = 2.0^{\circ}C$
$v = 0$ m/s



c)



d)

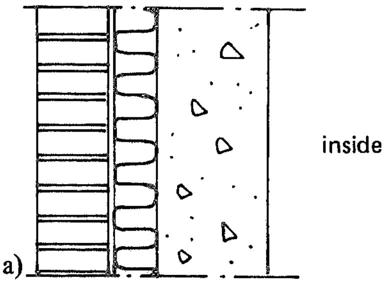
COMPARATIVE THERMOGRAMS – EXTERNAL WALL OF CONCRETE WITH MINERAL WOOL INSULATION AND EXTERNAL CLADDING OF FACING BRICKS

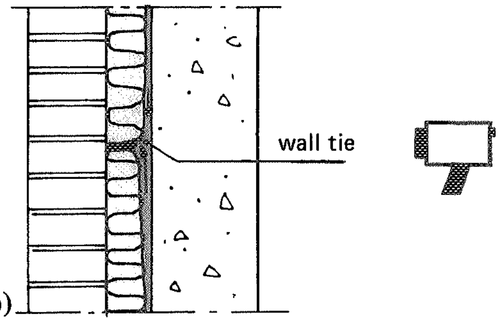
Fig. 84. Defective insulation performance due to insufficient contact between insulation material (quality B) and the concrete.

External wall, from the outside:
120 mm facing bricks (19 perforations)
air gap
70 mm mineral wool (quality B, attached with wall ties)
180 mm concrete

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$+1°C$
indoor air temp	$+20°C$
wind conditions	calm
$p_i - p_u$	-3 Pa

a)


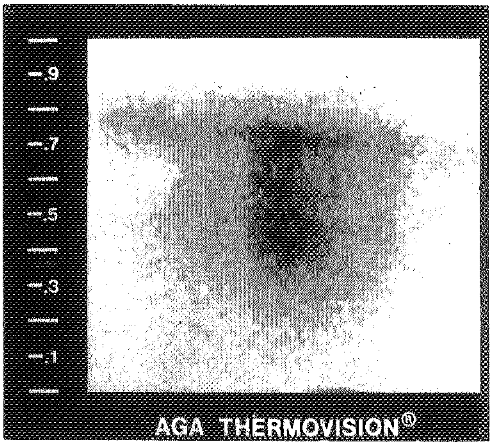
b)


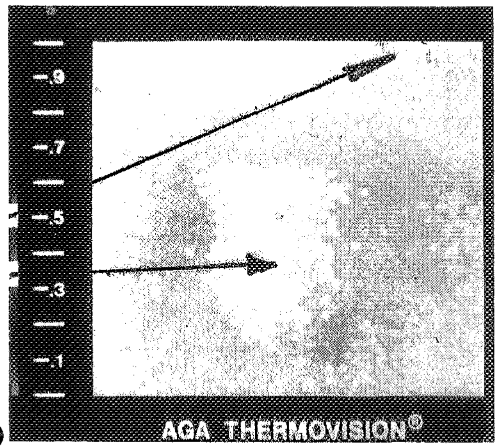
a) Construction of external wall.

b) Defective insulation. Incorrect placing of mineral wool against concrete.

c) Thermogram of section in the middle of the wall. Colder area corresponding to corner of a mineral wool slab. This is due to incorrect placing and lack of contact with outside face of concrete.

d) $t_{ref} = +19°C$
$\Delta I = -0.9$ isotherm units
$\Delta t = 1.5°C$
$v = 0$ m/s

c)


d)


6 Special constructions and constructional details

The investigations have shown that, under practical conditions, it is difficult to produce certain types of constructions and constructional details in a such way that their insulation and airtightness performance is satisfactory.

Examples of this are given in the following sections. These describe the investigations performed in the same way as before.

The figures give details of measuring conditions and readings, and also brief comments concerning the investigation.

6.1 Comparative thermograms of external walls in industrial buildings

FIG. 85–94 show some examples of defects in insulation and airtightness in different external wall constructions intended for industrial buildings.

6.2 Windproofing of external walls

Alternative designs of windproofing consisting of high-density mineral wool insulation have been tested in some projects. Some of the results are shown in FIG. 95–96.

6.3 Joint sealing systems

Different types of joint sealing systems have been tested in different investigations, and the results are set out in FIG. 97–105. Joint sealing systems at the plate and around doors and windows have been given special attention.

6.3.1 Joint sealing systems at the sole plate

The following sealing system designs at the sole plate have been examined with the infrared camera:

a) Sealing with a strip of mineral wool, Gullfiber sole plate insulation No. 5137, FIG. 98.
b) Sealing with Gullfiber joint sealing system No. 1610 "Fogfiber", FIG. 99.
c) Sealing with foamed polyurethane of single-pack type (Fogskum 100), FIG. 100.
d) Sealing with an EPDM rubber strip, Rockwool "S-list" No. 8445, FIG. 101.

Systems a), b) and c) were installed and tested in three-storey blocks of flats of the same construction, situated in the same area of Skellefteå.

Thermography was carried out at the following times:

- At the final inspection.
- About 12 months after the final inspection.

As regards System d), tests were made on two different projects, and only at the final inspection. The reason for this is that the material has been available on the market only for a short time.

Comments.

a) See FIG. 98. Sole plate insulation strips of mineral wool, placed unfolded underneath the sole plate, often given rise to relatively extensive recurring leakage of air at the skirting, especially if the edge of the floor is uneven. Air movements measured at these points exhibited a considerable variation, due, inter alia, to the pressure difference across the construction. At the check measurement 12 months after the final inspection, an increase in the magnitude of air leakage was noted. The results from all the investigated buildings were the same.

b) See FIG. 99. The Gullfiber "Fogfiber" system generally produced satisfactory results. Air leakage of limited extent occurred locally. During measurements 12 months after the final inspection, the results were largely the same.

c) See FIG. 100. The results of investigations on joints filled with foamed polyurethane were generally satisfactory. The values of both insulation and airtightness were satisfactory. At some isolated points, voids occurred in the material, and this gave rise to some movement of air. The results of measurements made 12 months after the final inspection were again satisfactory.

d) See FIG. 101. During the investigations, joint sealing with EPDM rubber strips gave satisfactory results. The results appeared to be comparable with those in b). During checks 12 months after the first measurement, no appreciable change in performance was found.

6.3.2 Joint sealing systems around doors and windows

The following joint sealing systems around doors and windows were tested with the IR camera.

a) Gullfiber sealing strip Type 5097 (5 cm wide), single and unfolded. See FIG. 87 and 102–103.
b) Gullfiber System 1610, Fogfiber. See FIG. 104.
c) Spraying of single-pack polyurethane foam (Fogskum 100). See FIG. 105.

In all the above, the size of joint was the same, 15 ± 5 mm.

Joint sealing systems a)–c) were installed and tested in some parts of 3 three-storey blocks of flats of the same construction, situated in the same area of Skellefteå, and also in 2 three-storey blocks of flats of the same construction, situated in the same area of Lysekil.

Investigation of the different systems, with the exception of c), was carried out at the following times:

– At the final inspection
– About two months after final inspection
– About twelve months after final inspection.

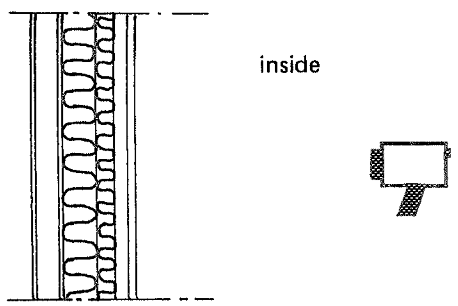
Comments.

a) The performance of joints sealed with single unfolded strips of mineral wool was generally unsatisfactory. There was relatively extensive leakage of air of variable magnitude along large parts of the junction between the wall and the window frame. Depending, inter alia, on the pressure difference across the construction, movements of air near the points of leakage varied. During check measurements two and twelve months after the final inspection, there was a marked deterioration in performance compared to that at the final inspection. See FIG. 102.
b) On measuring the performance of joints sealed with the Gullfiber joint sealing system "Fogfiber", mainly satisfactory results were obtained at the final inspection. However, near spacers and corners, where the sealing strip was not contiguous, some leakage could be noted. The results were unchanged when check measurements were made two and twelve months after the final inspection.
c) Joint sealing using the single-pack polyurethane foam appeared to give satisfactory results even near spacer blocks and in corners. The adhesion of the material used to adjacent materials (with the exception of PE-film) was good. The results of all measurements were the same.

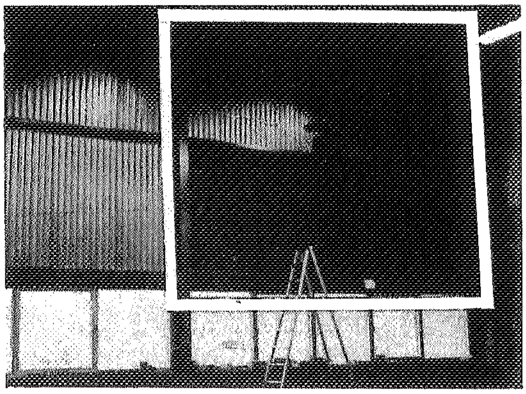
COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS WITH STEEL SHEETING (cladding of metal sheeting on inside and outside)

Fig. 85. Insulation and airtightness defect due to incorrect placing of insulation material, combined with defective windprotection.

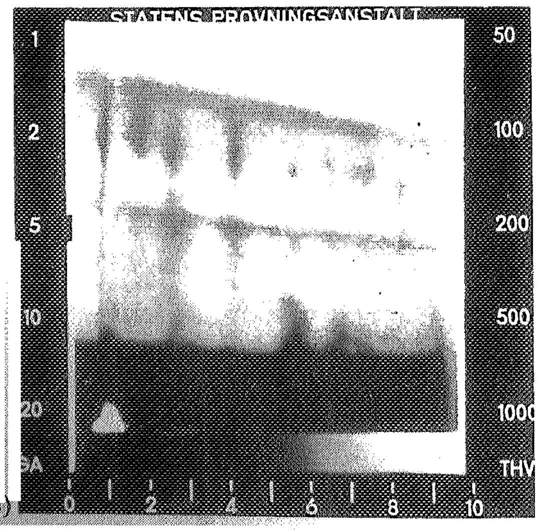
External walls, from the outside:
corrugated facade sheeting
wind protection (cardboard)
70 mm mineral wool
30 mm mineral wool
polyethylene film (taped onto the sheet)
corrugated sheeting (partially perforated)



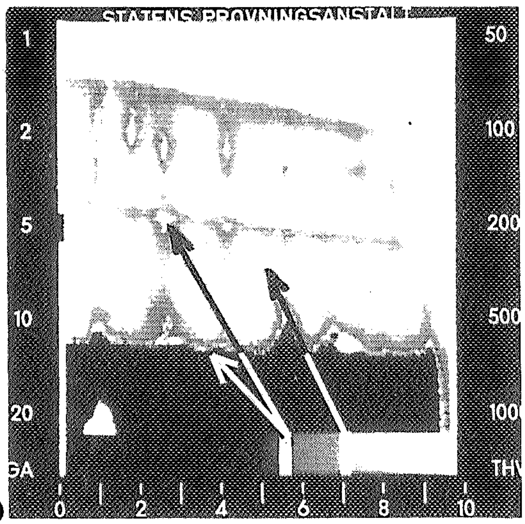
a)



b)



c)



d)

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$+3^\circ C$
indoor air temp	$+18^\circ C$
wind conditions	calm
$p_i - p_u$	- 28 Pa

(Note. Negative pressure indoors.)

a) Construction of external wall with corrugated sheeting on the inside and outside.

b) Sheeting on the inside. Parts of the surface were painted with a flat grey paint (one coat).

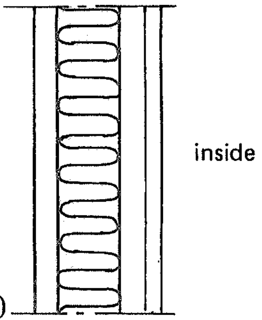
c) Thermogram of section of external wall. Certain colder areas can be seen. These are due to convective air movements inside the construction. Some joints between the mineral wool slabs show up as dark vertical strips.

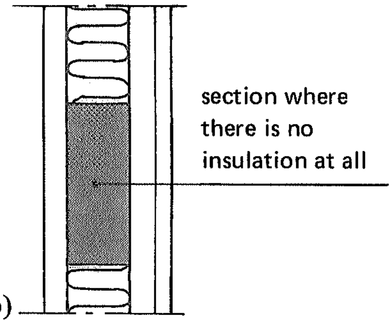
d) $t_{ref} = +16^\circ C$
ΔI = - 0.8 isotherm units
$\Delta t = 1.5^\circ C$
v = 2–4 m/s (through joint between window and wall)

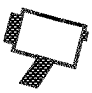
COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS WITH STEEL SHEETING (cladding of metal sheeting on inside and outside)

Fig. 86. Insulation and airtightness defect due to partial or complete omission of insulation material at certain points in the construction.

External wall, from the outside:
trapezoidal steel sheeting
sheathing cardboard
95 mm mineral wool (quality A)
polyethylene film
air gap
trapezoidal steel sheeting

a) 

b) 



Conditions during measurement:

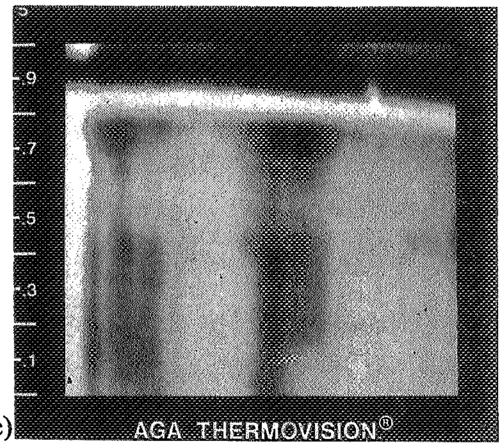
cloudiness	cloudy
outdoor air temp	+1°C
indoor air temp	+12°C
wind conditions	3–4 m/s (to facade)
$p_i - p_u$	- 15 Pa

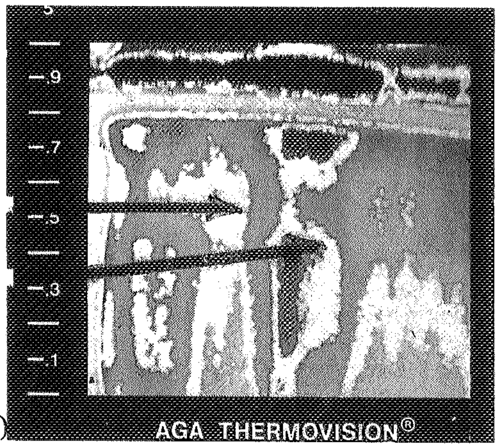
a) Construction of external wall with sheeting on inside and outside.

b) Insulation is completely omitted in some parts of the wall.

c) Thermogram of colder area in the middle of the wall. The defect is due to complete omission of insulation material in some parts of the wall.

d) $t_{ref} = +11°C$
$\Delta I = -1.0$ isotherm units
$\Delta t = 2.0°C$
$v = 0$ m/s

c) 

d) 

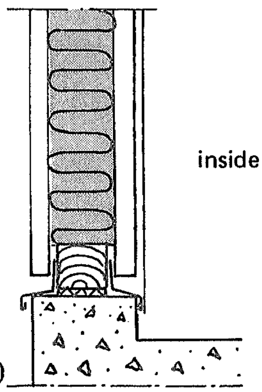
COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS WITH STEEL SHEETING (cladding of metal sheeting on inside and outside)

Fig. 87. Insulation and airtightness defect due to insufficient seal at junction between external wall and concrete base.

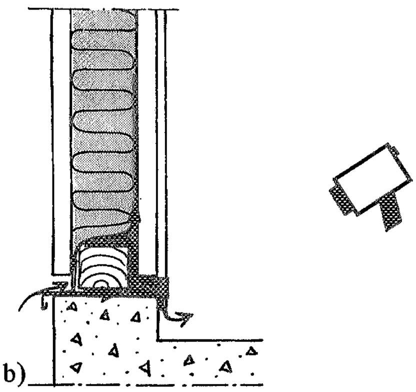
External wall, from the outside:
trapezoidal steel sheeting
sheathing cardboard
95 mm mineral wool
polyethylene film
trapezoidal steel sheeting

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$+1^\circ C$
indoor air temp	$+12^\circ C$
wind conditions	3–4 m/s (to facade)
$p_i - p_u$	- 15 Pa



a)



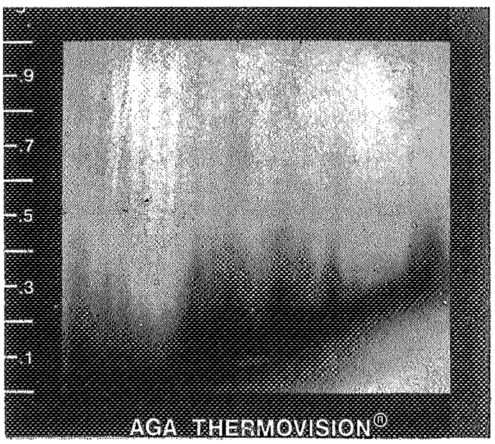
b)

a) Construction of external wall with sheeting on inside and outside.

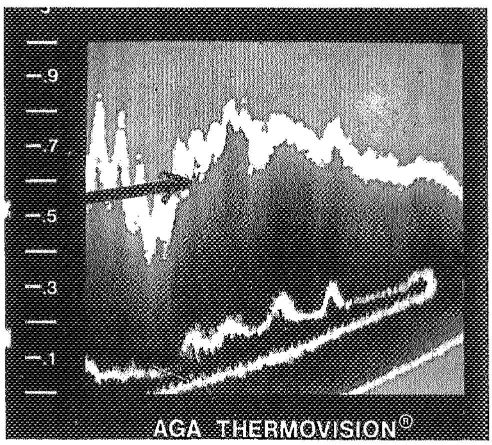
b) Insufficient seal at sole plate, and incorrect placing of insulation material in the wall.

c) Thermogram of section at floor-wall junction where the cladding on the inside adjoins the concrete base. Colder area due to leakage of air through badly sealed joint between sole plate and base. The air also spreads upwards in the wall between the sheeting and the insulation material.

d) $t_{ref} = +11^\circ C$
$\Delta I = -1.9$ isotherm units
$\Delta t = 4.0^\circ C$
$v = 0.5–2.0$ m/s (at junction between sheeting and concrete base)



c)

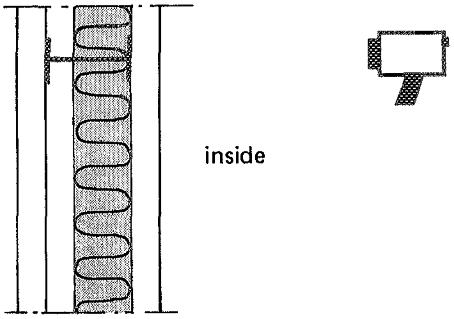


d)

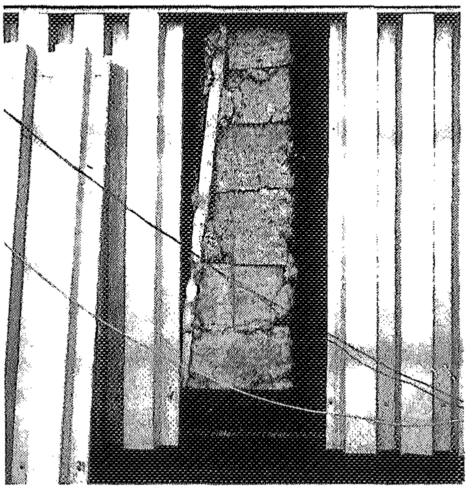
COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS WITH STEEL SHEETING (cladding of metal sheeting on inside and outside)

Fig. 88. Insulation and airtightness defect due to local omission of windprotection and to incorrect placing of insulation material in wall.

External wall, from the outside:
trapezoidal steel sheeting
windproof cardboard
100 mm mineral wool
vapour barrier
trapezoidal steel sheeting



a)



b)

Conditions during measurement:

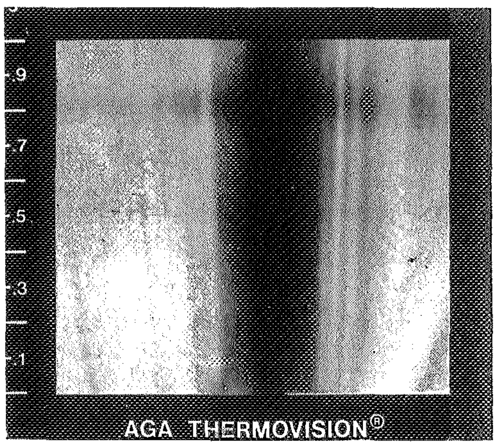
cloudiness	clear
outdoor air temp	$+2^{\circ}C$
indoor air temp	$+17^{\circ}C$
wind conditions	about 3 m/s (parallel to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall with sheeting on inside and outside.

b) Section of wall opened up from the outside. In places there is no wind protection at all. The insulation consists of pieces of mineral wool which fit badly.

c) Thermogram of colder wall section, of about 30 cm width and a vertical extent of about 1.5 m.

d) $t_{ref} = +16^{\circ}C$
ΔI = - 3.4 isotherm units
$\Delta t = 7.0^{\circ}C$
v = 0 m/s



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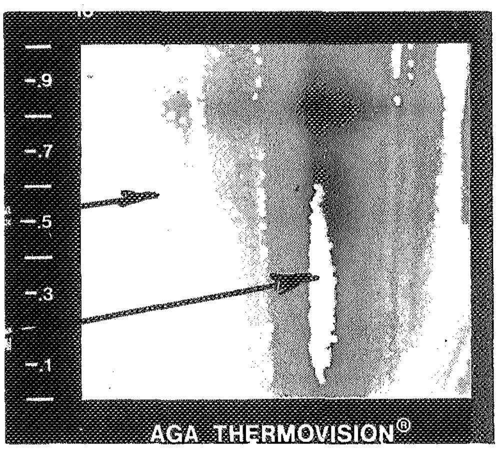


d)

COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALL WITH BRICK CLADDING ON THE INSIDE AND OUTSIDE

Fig. 89. Insulation and airtightness defect due to incorrect placing of insulation material (quality B) in space between brick walls.

External wall, from the outside:
facing bricks
100 mm mineral wool
masonry bricks

Conditions during measurement:

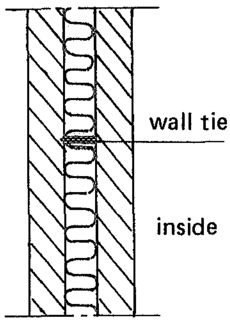
cloudiness	cloudy
outdoor air temp	- 3°C
indoor air temp	+ 18°C
wind conditions	1 m/s (at an angle to facade)
$p_i - p_u$	- 7 Pa

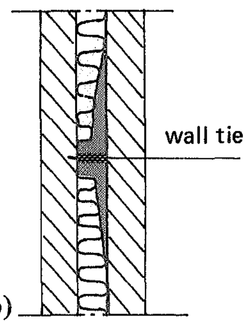
a) Construction of external wall.

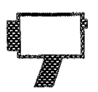
b) Defective insulation and windproofing, mainly near the wall ties.

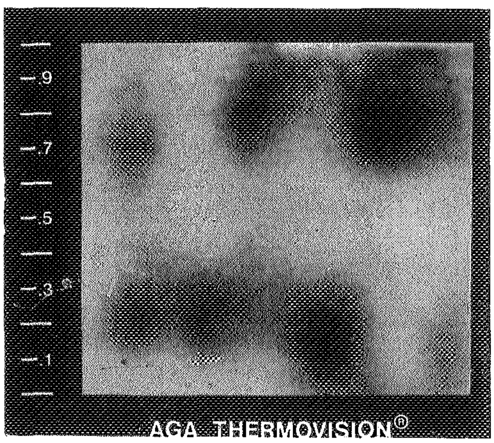
c) Thermogram of section of external wall. Colder areas due to defective insulation combined with convective air movements. The joints (corners) between insulation slabs show up as dark spots.

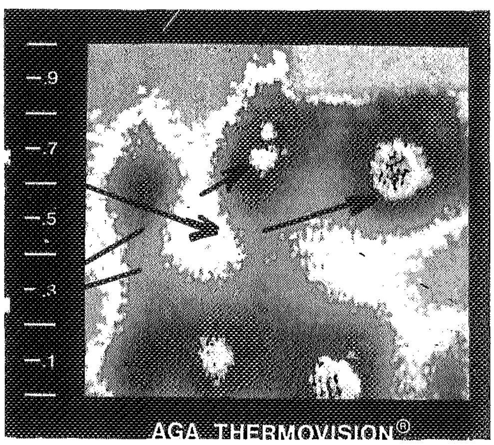
d) $t_{ref} = +17°C$
$\Delta I = -0.8$ isotherm units
$\Delta t = 1.5°C$
$v = 0$ m/s

a) 

b) 



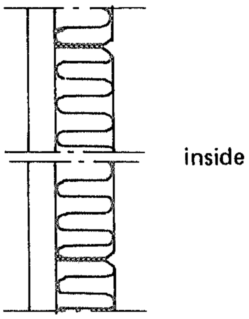
c) 

d) 

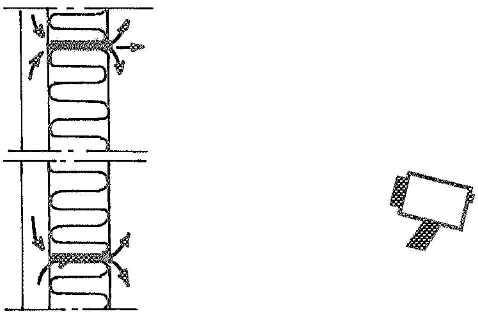
COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS OF SHEET METAL CASSETTES WITH MINERAL WOOL INSULATION

Fig. 90. Insulation and airtightness defect due to leakage of air into construction through the joints between the cassettes.

External wall, from the outside:
facade sheeting
100 mm mineral wool with cardboard on the outside
sheet metal cassettes 0.6 x 6.0 m



a)



b)

Conditions during measurement:

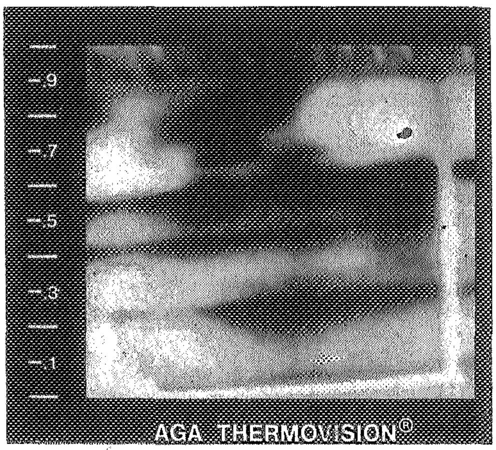
cloudiness	cloudy
outdoor air temp	+2°C
indoor air temp	+21^2
wind conditions	2 m/s (away from facade)
$p_i - p_u$	- 10 Pa

a) Construction of external wall with a cladding of metal sheeting inside and outside. Sheeting cassettes with rubber strips joint seals. The sheeting on the inside was varnished.

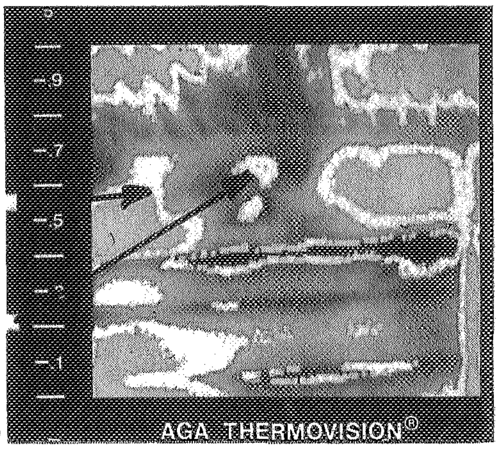
b) Air leakage paths through the construction.

c) Thermogram of somewhat colder section at the top pf the wall. Caused by outdoor air leaking into and through the construction.

d) $t_{ref} = +17°C$
ΔI = - 1.6 isotherm units
Δt = 3.0°C
v = 1.0–2.0 m/s (through horizontal joints between cassettes)



c)

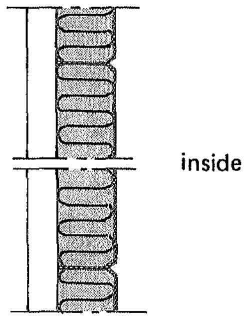


d)

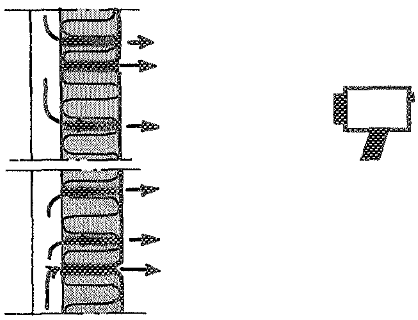
COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS OF SHEET METAL CASSETTES WITH MINERAL WOOL INSULATION

Fig. 91. Insulation and airtightness defect due to leakage of air through the construction at the joints between the cassettes.

External wall, from the outside:
facade sheeting
100 mm mineral wool with cardboard on the outside
sheet metal cassettes 0.6 x 6.0 m (perforated)



a)



b)

Conditions during measurement:

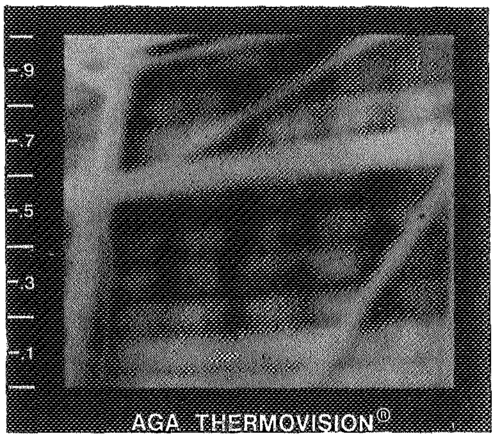
cloudiness	cloudy
outdoor air temp	+2°C
indoor air temp	+21°C
wind conditions	about 2 m/s (at an angle to facade)
$p_i - p_u$	- 10 Pa

a) Construction of external wall with sheet metal cladding on inside and outside.

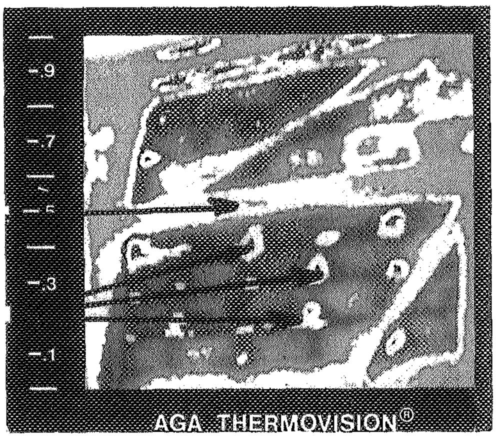
b) Leakage of air through the construction at gaps formed by badly fitting slabs of mineral wool.

c) Thermogram taken from the inside of somewhat colder section. These colder areas form a certain pattern, due to leakage of air through badly sealed points in the construction, mainly gaps between slabs of mineral wool, which causes sections of the surface to be colder.

d) t_{ref} = +20°C
Δ I = - 1.5 isotherm units
Δ t = 2.5°C
v = 0.3–1.0 m/s (at surface of wall. Variation over surface is due to perforations in the sheeting)



c)

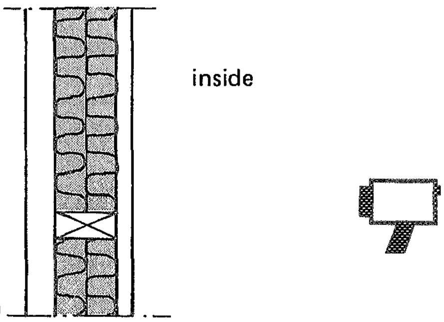


d)

COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS OF SHEET METAL CASSETTES WITH MINERAL WOOL INSULATION

Fig. 92. Insulation and airtightness defect due to incorrect placing of mineral wool insulation.

External wall, from the outside:
corrugated sheeting
sheathing cardboard
50 + 50 mm mineral wool
polyethylene film
corrugated sheeting



a)

Conditions during measurement:

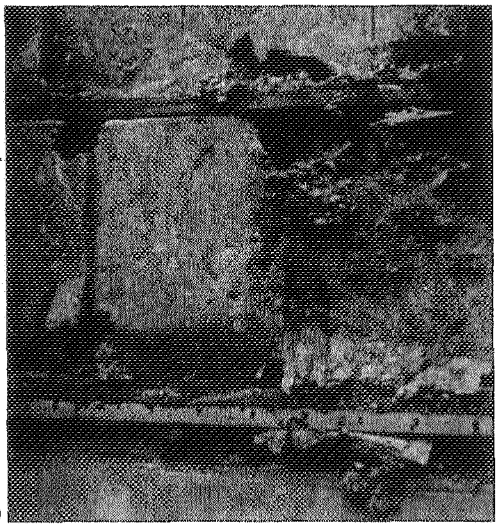
cloudiness	cloudy
outdoor air temp	+ 3°C
indoor air temp	+ 12°C
wind conditions	0.5 m/s (at an angle to facade)
$p_i - p_u$	- 5 Pa

a) Construction of external wall with sheet metal cladding on inside and outside.

b) Photo of opened up wall section (from the outside).

c) Thermogram of section near vertical steel member, showing uneven temperature distribution. Presence of colder areas is due to incorrect placing of mineral wool. The holes in the bays between studs are due to rats having removed the insulation material.

d) t_{ref} = + 11°C
Δ I = - 1.1 isotherm units
Δ t = 2.5°C
v = 0.5–1.0 m/s (at vertical column)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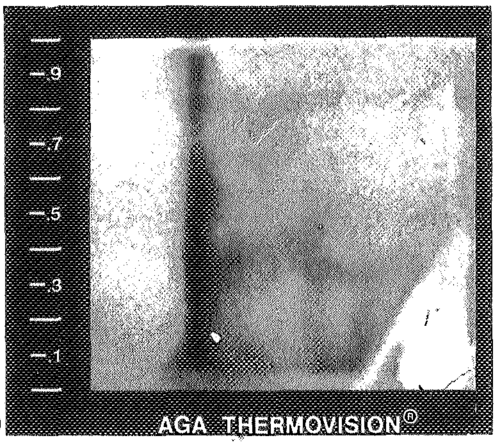

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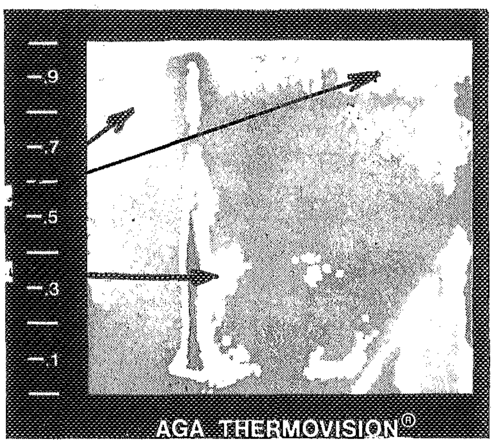


d)

COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS WITH STEEL SHEETING (cladding of sheet metal on the outside)

Fig. 93. Insulation and airtightness defect due to insufficient contact between mineral wool insulation and steel joists.

External wall, from the outside:
corrugated sheeting
90 mm mineral wool with windproof cardboard
vapour barrier
30 mm mineral wool (staple fibre)

Conditions during measurement:

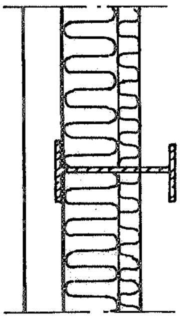
cloudiness	cloudy
outdoor air temp	- 1°C
indoor air temp	+ 17°C
wind conditions	3–4 m/s (at an angle to facade)
$p_i - p_u$	- 10 Pa

a) Construction of external wall.

b) Incorrect placing of insulation material, with leakage of air as a result.

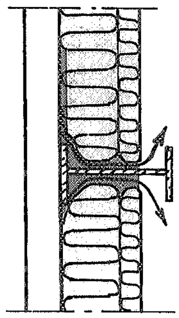
c) Thermogram of colder areas on external wall, due to leakage of air through badly sealed points in the construction, mainly in the vicinity of the horizontal steel joists.

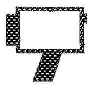
d) $t_{ref} = +17°C$
ΔI = - 1.4 isotherm units
Δt = 2.5°C
v = 0.5–2.0 m/s (at the horizontal steel joists).



inside

a)





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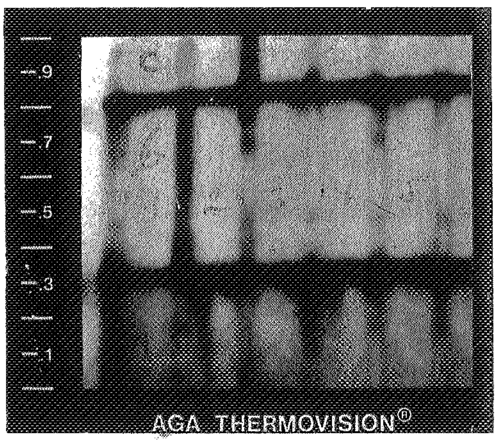

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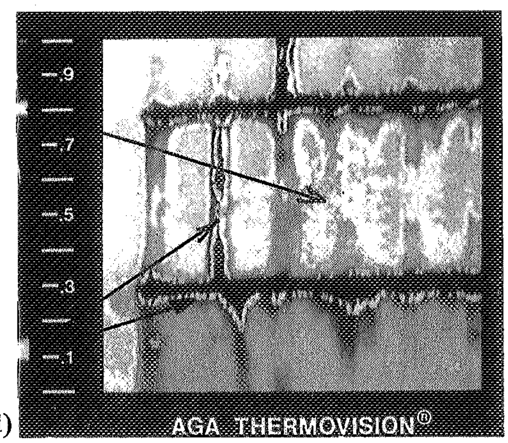
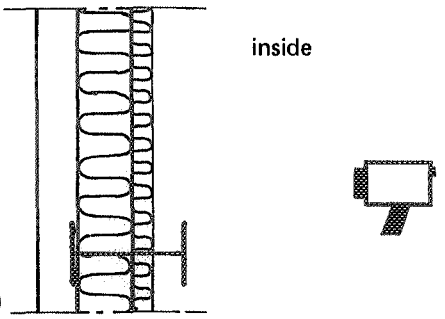


d)

COMPARATIVE THERMOGRAMS – INDUSTRIAL BUILDINGS – EXTERNAL WALLS WITH STEEL SHEETING (cladding of sheet metal on the outside)

Fig. 94. Insulation and airtightness defect due to unsatisfactory performance of airtight layer.

External wall, from the outside:
corrugated sheeting
90 mm mineral wool with windproof cardboard
vapour barrier
30 mm mineral wool



a)

b)

Conditions during measurement:

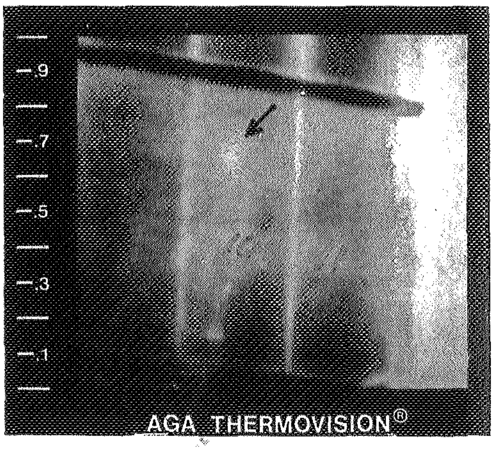
cloudiness	cloudy
outdoor air temp	- 1°C
indoor air temp	+ 18°C
wind conditions	3–4 m/s (away from facade)
$p_i - p_u$	+ 10 Pa

a) Construction of external wall.

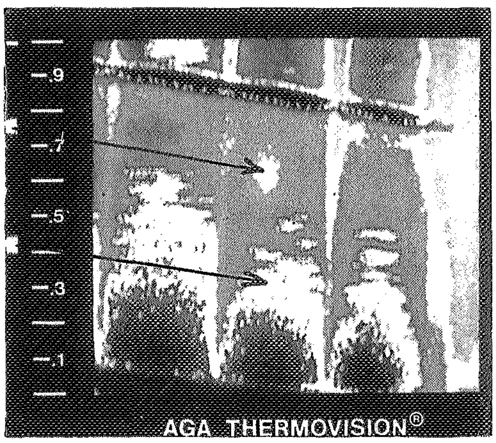
b) External wall seen from the inside. A darker (dirty) section appears in the middle of the wall. This is due to outward leakage of dirty indoor air through local permeable points in the section.

c) Thermogram of section. A warm area shows up in the middle of the insulated wall section. This is due to outward leakage of warm air.

d) t_{ref} = + 17°C (the lower isotherm value)
ΔI = + 0.7 isotherm units
Δt = 1.0°C
v = 0.2–0.3 m/s (outward leakage of room air)



c)

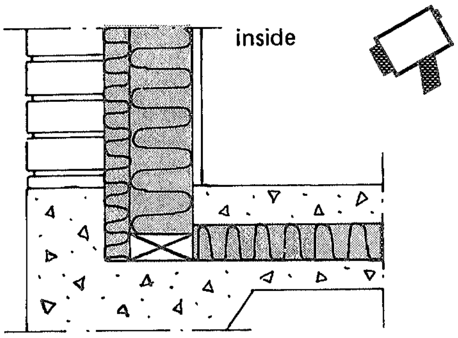


d)

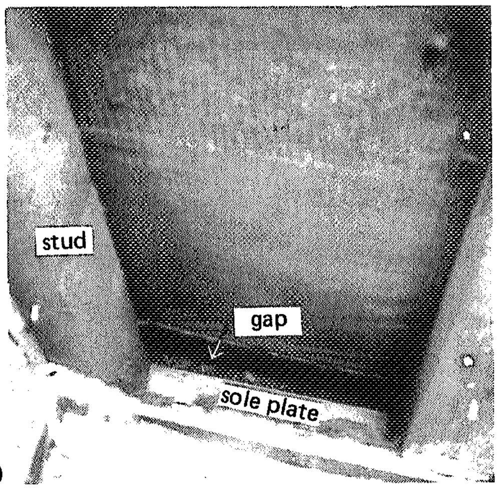
WINDPROTECTION IN EXTERNAL WALL – MINERAL WOOL INSULATION OF HIGH DENSITY WITHOUT A COATING OF CARDBOARD

Fig. 95. Insulation and airtightness defect in external wall due to lack of contact between outer mineral wool insulation, wall studs and sole plate.

External wall, from the inside:
13 mm cardboard
polyethylene film
95 mm mineral wool (quality A)
30 mm mineral wool (high density)
facing bricks



a)



b)

Conditions during measurement:

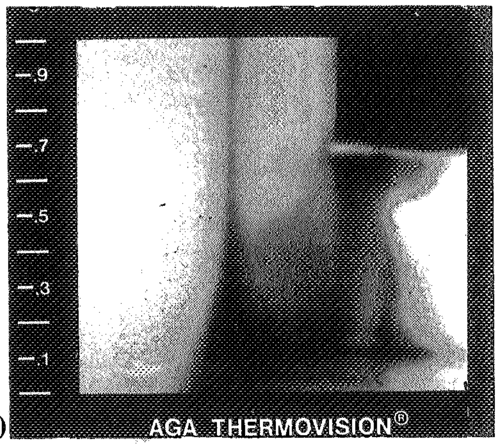
cloudiness	cloudy
outdoor air temp	$+4^{\circ}C$
indoor air temp	$+16^{\circ}C$
wind conditions	5–6 m/s (at an angle to facade)
$p_i - p_u$	- 15 Pa

a) Construction of external wall.

b) Contact between inside face of outer mineral wool slab and the studs. At the sole plate, the slab is not in contact with the sole plate. There is a gap of about 3 cm here.

c) Thermogram of section of wall at corner and to the left of, and below, the window. The warm radiator can be seen at the right of the thermogram (light area). Temperature distribution over wall surface is uneven. This indicates irregular performance of wall insulation. Convective air movements, due to this, occur in the wall section.

d) $t_{ref} = +15^{\circ}C$
ΔI = - 1.5 isotherm units
$\Delta t = 3.0^{\circ}C$
v = 1–2 m/s (at skirting-board and in corner of floor).



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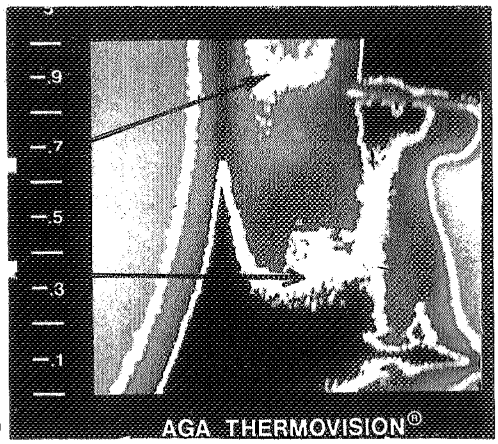


d)

WINDPROTECTION IN EXTERNAL WALL – MINERAL WOOL INSULATION OF HIGH DENSITY WITHOUT A COATING OF CARDBOARD

Fig. 96. Satisfactory insulation and airtightness performance in external wall, with perfect contact between outer mineral wool insulation, wall studs and sole plate.

External wall, from the inside:
13 mm gypsum wallboard
polyethylene film
95 mm mineral wool (quality A)
30 mm mineral wool (density 100 kg/m^3)
facing bricks

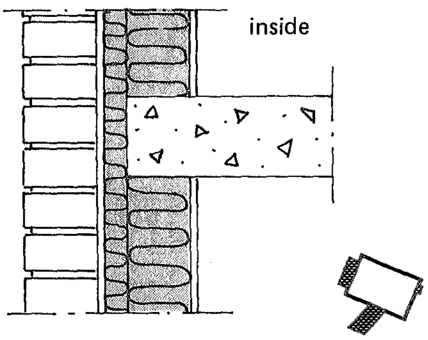
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	- 1°C
indoor air temp	+ 21°C
wind conditions	3–4 m/s (at an angle to facade)
$p_i - p_u$	- 20 Pa

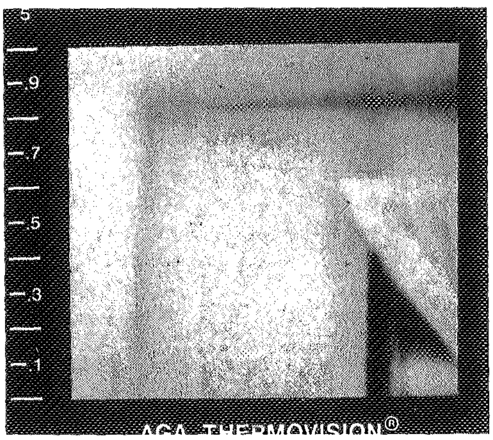
a) Construction of external wall.

b) Thermogram of section at wall-ceiling junction and corner to the left of the window. Uniform temperature distribution over wall surface indicates satisfactory performance of insulation and seal around window.

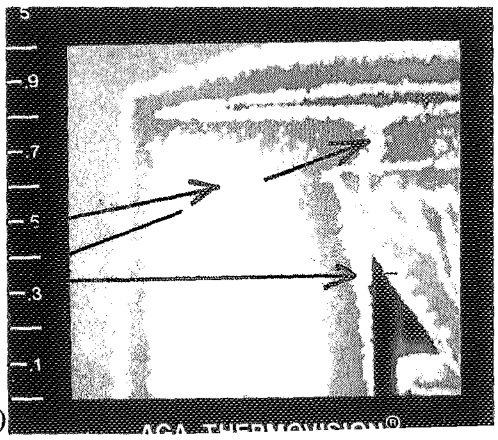
c) $t_{ref} = +20°C$
ΔI = - 0.6 isotherm units
Δt = 1.0°C
v = 0 m/s



a)

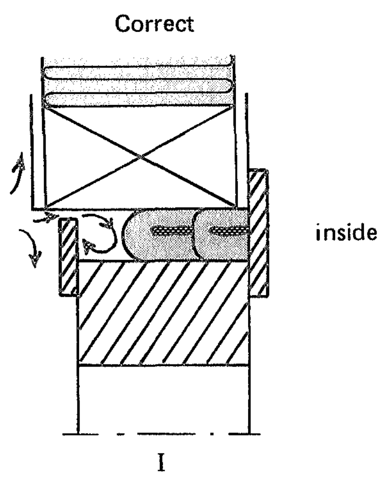


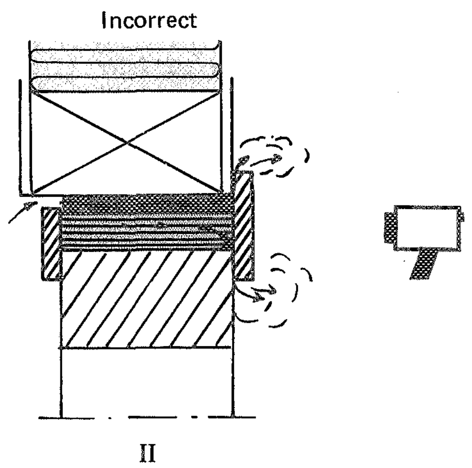
b)



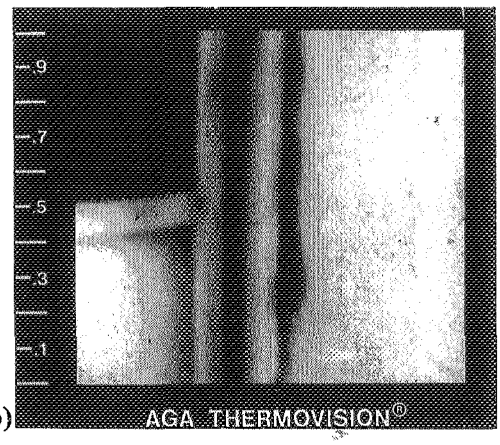
c)

Fig. 97. Correct and incorrect sealing of joint with mineral wool strips





a)



b)

a) Sealing of joint between door frame and wall should be done according to I. Joints are often sealed according to II, i.e. with only one sealing strip which is installed unfolded. Outdoor air enters through the insufficiently sealed joint. The section of wall near the door frame will then be colder.

b) Thermogram of surface section of wall at its junction with the door frame. The difference between normal temperature and that of the colder area is about 4°C in this case. Air velocity near the point of entry at the wall surface is about 1 m/s.

JOINT SEALING SYSTEMS – SEALING STRIPS OF MINERAL WOOL

Fig. 98. Defective performance of seal in joint at sole plate, with extensive leakage of air as a result.

External wall, from the outside:
facing bricks
13 mm bitumen impregnated fibre board
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard

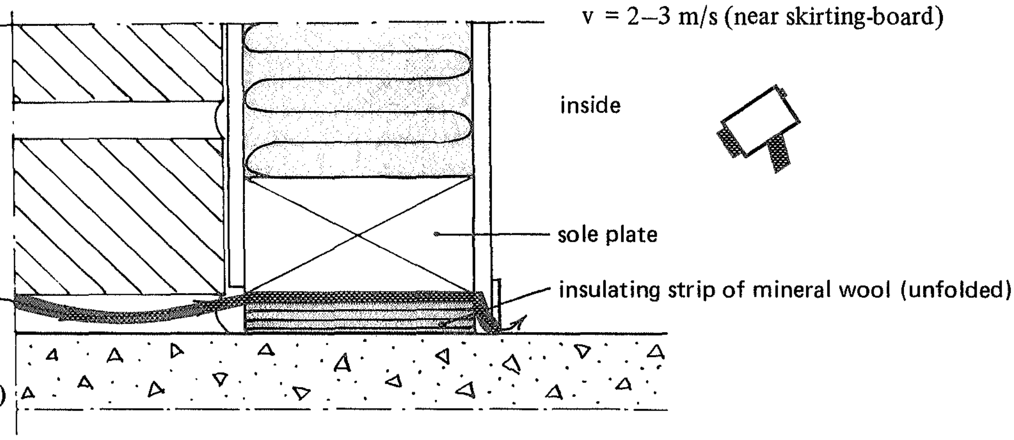
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	- 4°C
indoor air temp	+ 23°C
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	- 35 Pa

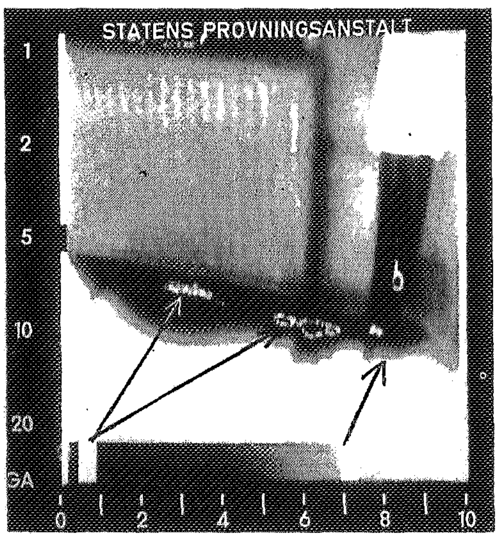
a) Seal in joint at sole plate consisting of mineral wool strip.

b) Thermogram of colder surface section at floor-wall junction. Colder area is due to leakage of air through improperly sealed joint between sole plate and concrete.

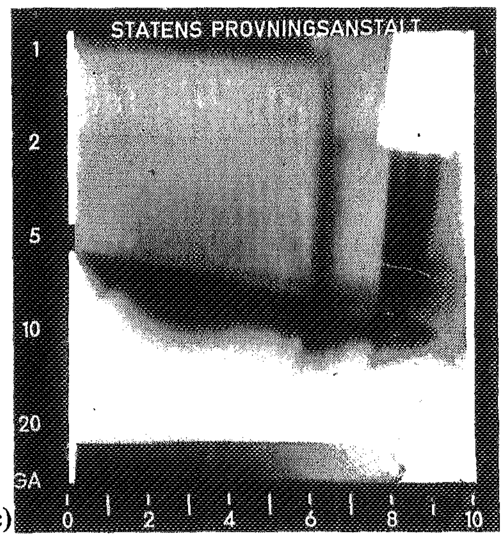
c) $t_{ref} = +22°C$
ΔI = - 3.2 isotherm units
Δt = 4.0°C
v = 2–3 m/s (near skirting-board)



a)



b)



c)

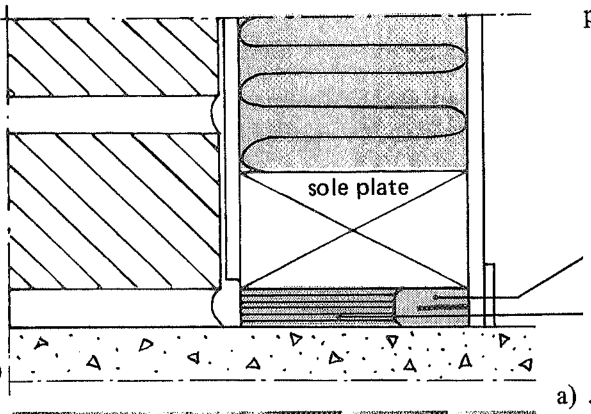
JOINT SEALING SYSTEMS – SOLE PLATE INSULATION WITH THE "FOG-FIBER" SYSTEM

Fig. 99. Acceptable performance of joint at sole plate with small local leakage of air through joints in sealing material.

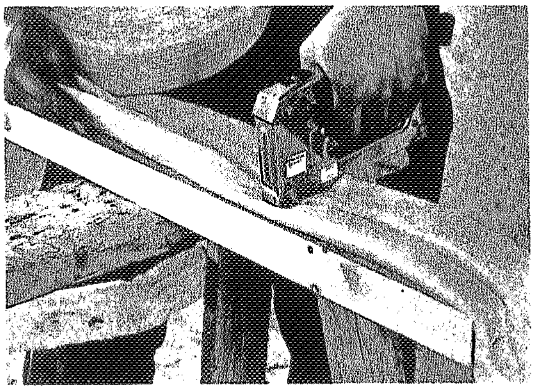
External wall, from the outside:
facing bricks
bitumen impregnated fibre board
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard

Conditions during measurement:

cloudiness	cloudy
outdoor air temp	- 12°C
indoor air temp	+ 19°C
wind conditions	about 1 m/s (parallel to facade)
$p_i - p_u$	- 6 Pa



a)



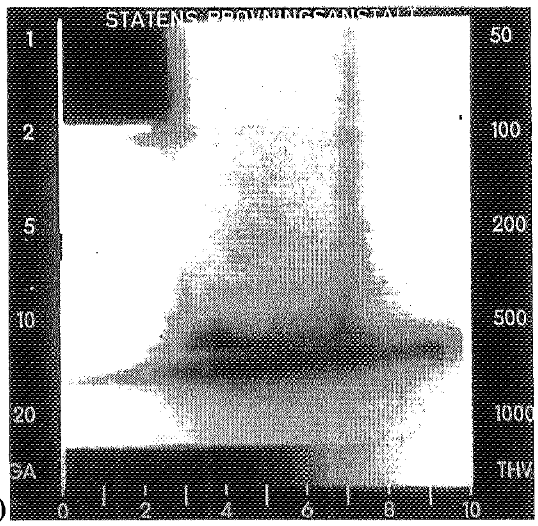
b)

a) Joint seal at sole plate consisting of the "Fogfiber" system.

b) Photo showing installation of "Fogfiber".

c) Thermogram of section at floor-wall junction. Some colder areas of limited extent could be observed when this system was used. Leakage of air is of limited extent and of local character.

d) t_{ref} = + 18°C
Δ I = - 1.4 isotherm units
Δ t = 2.0°C
v = 0.2–0.3 m/s (locally)



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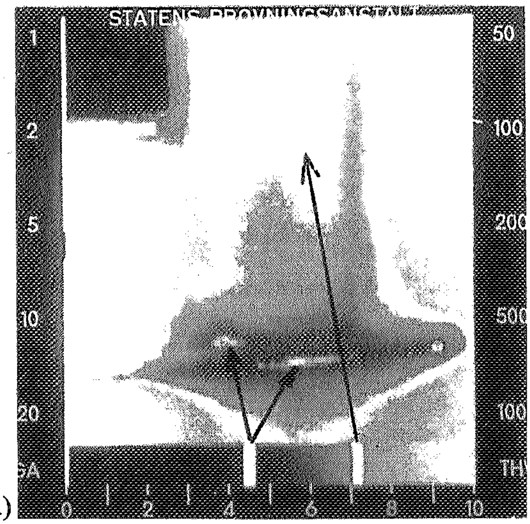


d)

JOINT SEALING SYSTEMS – SOLE PLATE INSULATION WITH FOAMED POLYURETHANE

Fig. 100. Satisfactory performance of joint at sole plate.

External wall, from the outside:
facing bricks
13 mm bitumen impregnated fibre board
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard

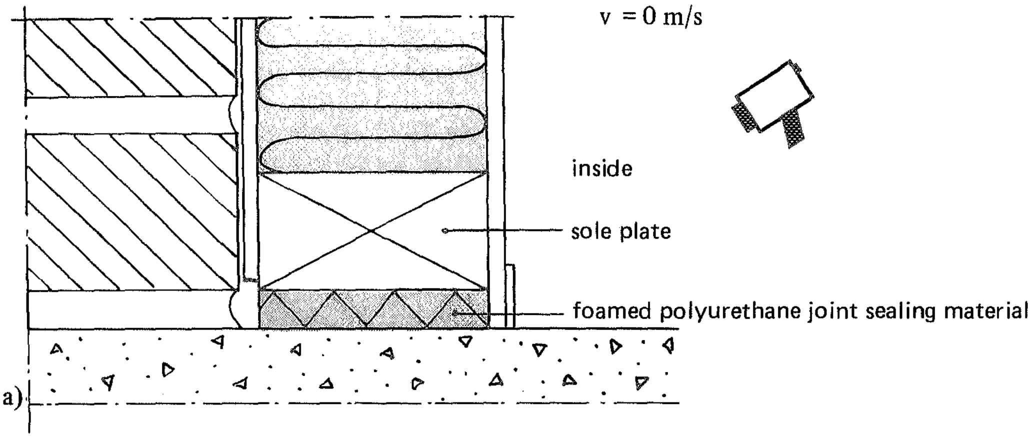
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$-12°C$
indoor air temp	$+19°C$
wind conditions	about 1 m/s (parallel to facade)
$p_i - p_u$	-6 Pa

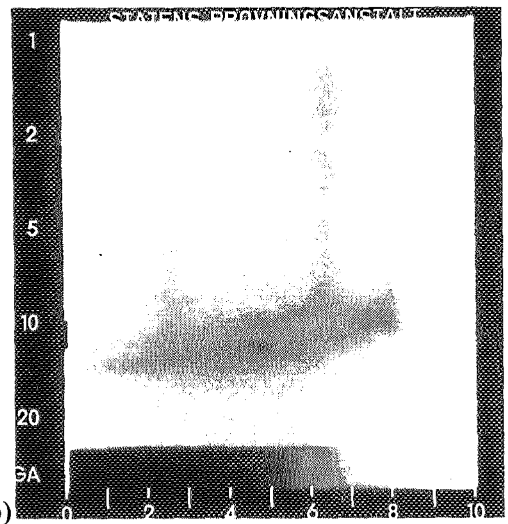
a) Joint seal at sole plate of foamed polyurethane.

b) Thermogram of section at floor-wall junction. With the exception of a minor defect, the airtightness of the joint when sealed with this system was satisfactory.

c) $t_{ref} = +18°C$
$\Delta I = -1.6$ isotherm units
$\Delta t = 2.5°C$
$v = 0$ m/s



a)



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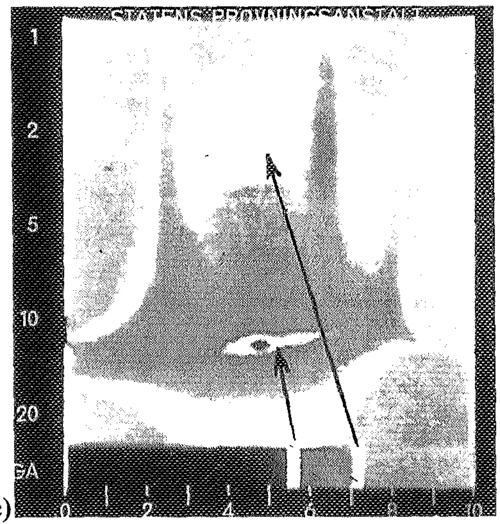
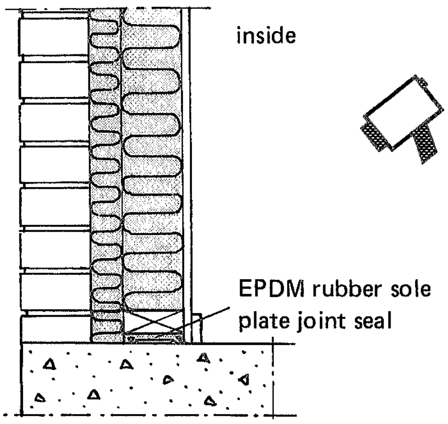


c)

JOINT SEALING SYSTEMS – SOLE PLATE INSULATION WITH EPDM RUBBER (Rockwool S-list)

Fig. 101. Satisfactory performance of joint at sole plate.

External wall, from the outside:
facing bricks
50 mm mineral wool
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard



a)

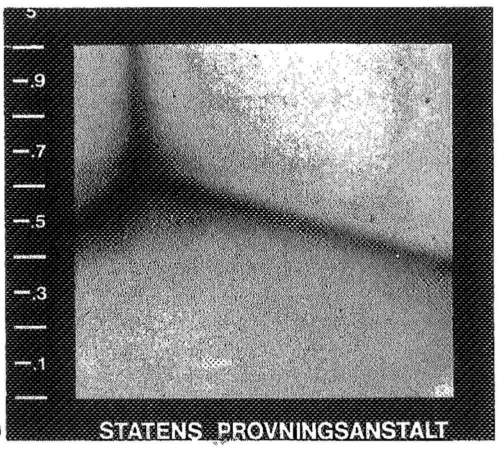
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$+5°C$
indoor air temp	$+24°C$
wind conditions	2–3 m/s (to facade)
$p_i - p_u$	- 17 Pa

a) Joint seal at sole plate consisting of Rockwool S-list.

b) Thermogram of section at floor-wall junction. When this system is used, airtightness is satisfactory.

c) $t_{ref} = +23°C$
$\Delta I = -2.1$ isotherm units
$\Delta t = 3.0°C$
$v = 0$ m/s

b) 

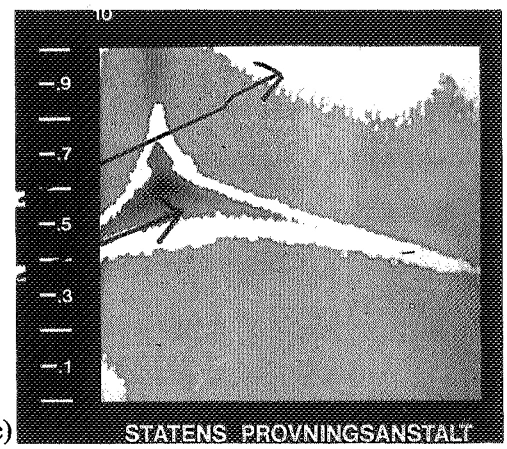
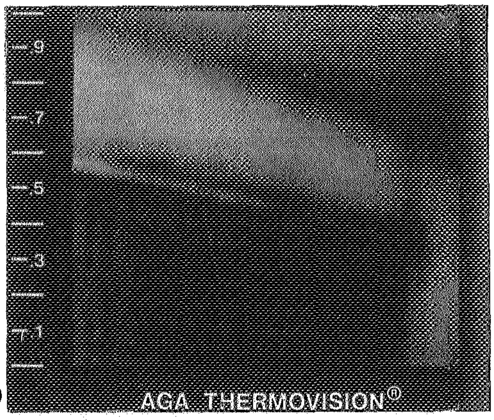
c) 

Fig. 102. Defective performance of joint between window and wall (measurements two months apart), deterioration in performance two months after final inspection.

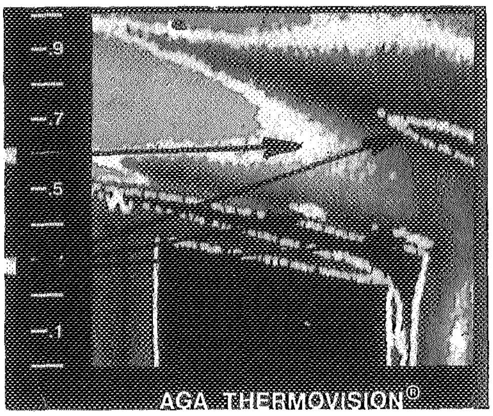
Measurement No. 1.

Conditions during measurement: (a and b)

cloudiness	cloudy
outdoor air temp	+4°C
indoor air temp	+20°C
wind conditions	6–8 m/s (to facade)
$p_i - p_u$	- 25 Pa



a)



b)

Measurement No. 2.

Conditions during measurement: (c and d)

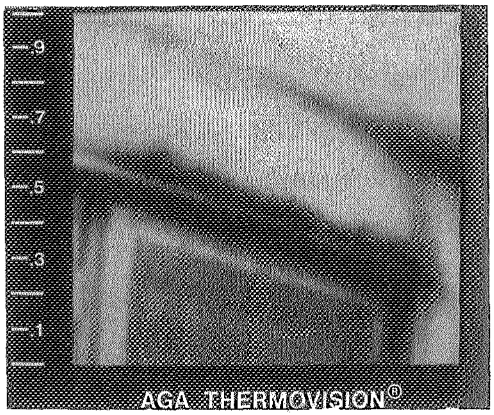
cloudiness	cloudy-clear
outdoor air temp	+3°C
indoor air temp	+20°C
wind conditions	2–3 m/s (away from facade)
$p_i - p_u$	- 20 Pa

a) Thermogram of section above window. Colder area at upper frame, due to leakage of air through incorrectly sealed joint between window frame and wall.

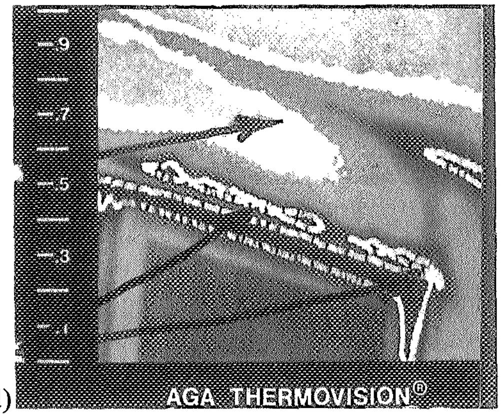
b) t_{ref} = + 19°C
Δ I = - 1.6 isotherm units
Δ t = 2.5°C
v = 0.3–0.8 m/s (at window frame-wall joint).

c) Thermogram of same section as in a) about two months later. The colder areas are more heavily marked due to increase in air leakage compared with previous measurement. Increase is caused by movements in the timber construction.

d) t_{ref} = + 19°C
Δ I = - 2.5 isotherm units
Δ t = 4.5°C
v = 0.5–1.5 m/s (at window frame-wall joint).



c)



d)

JOINT SEALING SYSTEMS – WINDOWS AND DOORS – SEAL CONSISTING OF UNFOLDED STRIP OF MINERAL WOOL

Fig. 103. Defective performance of seal in joint between window and wall due to only one unfolded strip being laid in the joint, with considerable leakage of air as a result.

External wall, from the outside:
facing bricks
13 mm bitumen impregnated fibre board
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard

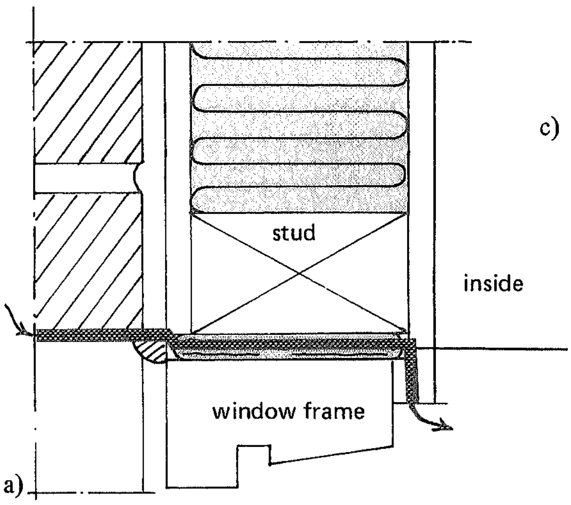
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$-4°C$
indoor air temp	$+23°C$
wind conditions	2–3 m/s (parallel to facade)
$p_i - p_u$	-35 Pa

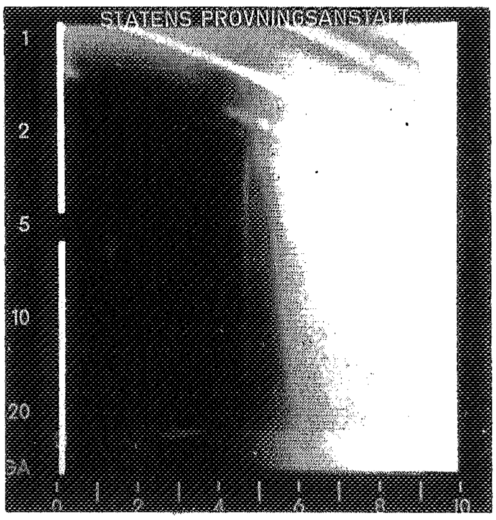
a) Sealing system between wall and window frame. (Mineral wool sealing strip).

b) Thermogram of section at window-wall junction. Areas near both the upper horizontal joint and the vertical joint at the window frame are colder. This is due to leakage of air through improperly sealed joint between window frame and wall.

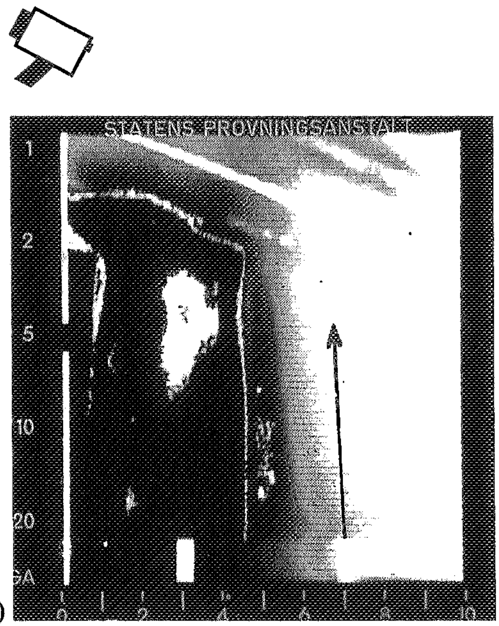
c) $t_{ref} = +22°C$
$\Delta I = -2.0$ isotherm units
$\Delta t = 2.5°C$
$v = 0.3–1.0$ m/s (at window frame-wall junction).



a)



b)



c)

Fig. 104. Satisfactory performance of joint between window and wall (exception: locally at wedge).

External wall, from the outside:
facing bricks
13 mm bitumen impregnated fibre board
95 mm mineral wool
vapour barrier
13 gypsum wallboard

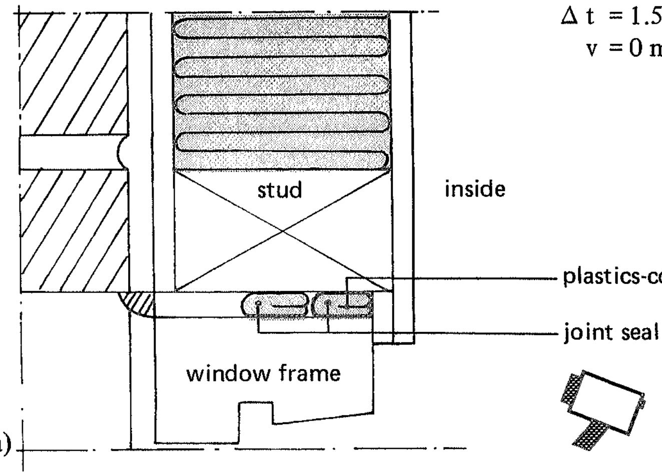
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	$-12^\circ C$
indoor air temp	$+19^\circ C$
wind conditions	about 1 m/s (parallel to facade)
$p_i - p_u$	-35 Pa

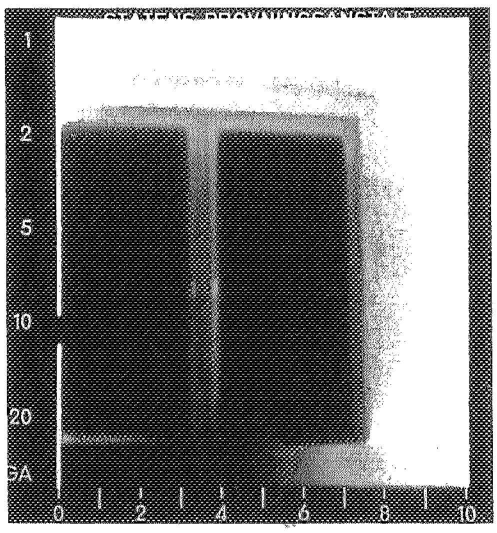
a) Joint seal of "Fogfiber" system.

b) Thermogram of section at window showing satisfactory performance of seal in joint between window frame and wall.

c) $t_{ref} = +18^\circ C$
$\Delta I = -1.0$ isotherm units
$\Delta t = 1.5^\circ C$
$v = 0$ m/s



a)



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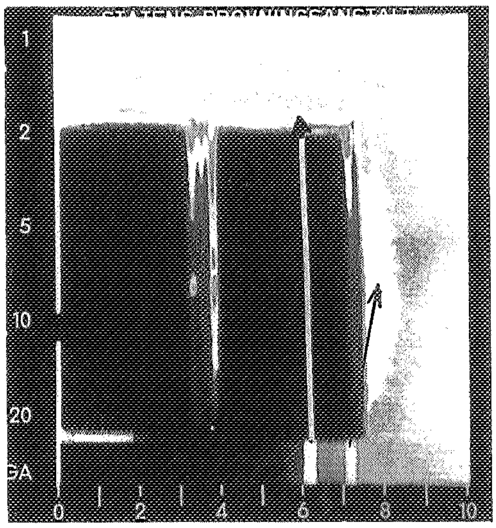


c)

JOINT SEALING SYSTEMS – WINDOWS AND DOORS – SEAL OF FOAMED POLYURETHANE

Fig. 105. Satisfactory performance of joint between window and wall.

External wall, from the outside:
facing bricks
13 mm bitumen impregnated fibre board
95 mm mineral wool
vapour barrier
13 mm gypsum wallboard

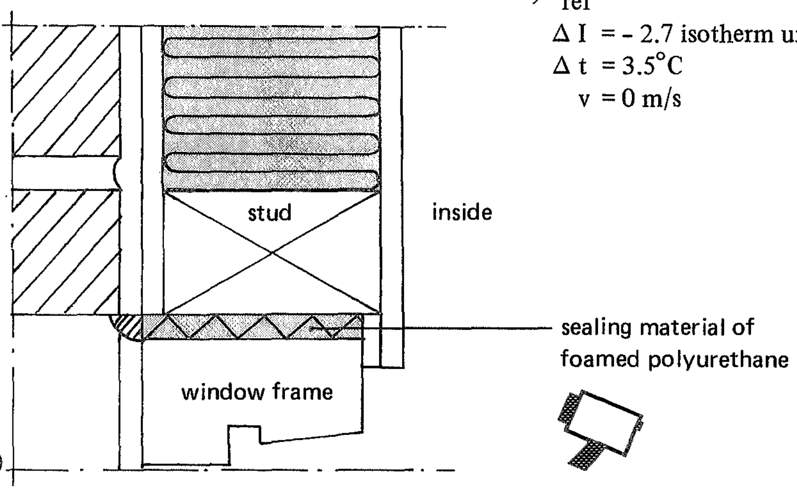
Conditions during measurement:

cloudiness	cloudy
outdoor air temp	- 4°C
indoor air temp	+ 23°C
wind conditions	2–3 m/s (parallel to facade)
$p_i - p_u$	- 35 Pa

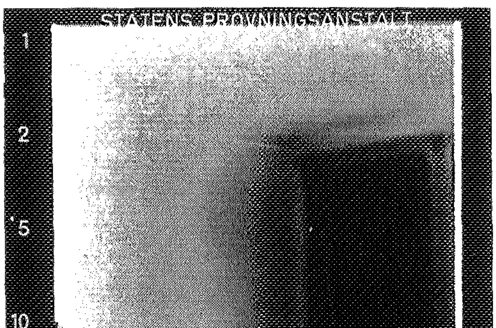
a) Joint seal of foamed polyurethane between window frame and wall.

b) Thermogram of section at junction between window and wall. Satisfactory performance of seal in joint between window frame and wall.

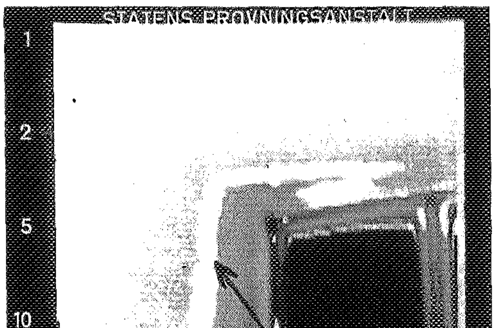
c) t_{ref} = + 22°C
Δ I = - 2.7 isotherm units
Δ t = 3.5°C
v = 0 m/s



a)



b)



c)

7 Examples of improvements

In conjunction with the investigations, thermography was also used to check the effectiveness of certain improvements carried out at places where defects in insulation and airtightness were first discovered with the aid of the infrared camera. Such examples are shown in FIG. 106–122.

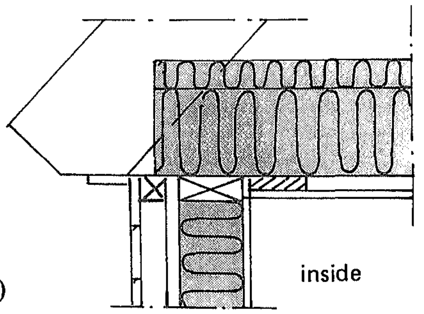
Each example is generally shown on two pages (with the exception of FIG. 122), details being given of the construction in question and the defect in insulation and airtightness. The improvement carried out is also shown.

Thermograms of the section of surface concerned are shown both before and after the improvement. The figures give details of measuring conditions and readings in the same way as in previous chapters. Brief comments on the investigation concerned are given alongside the figures

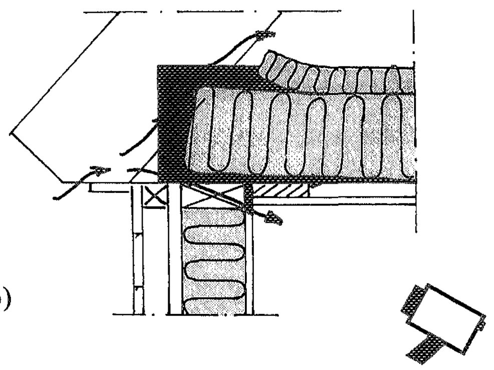
IMPROVEMENTS – FLAT ROOF – ADDITIONAL INSULATION OF WOOD SHAVINGS AT THE EAVES

Fig. 106. Insulation and airtightness defect at the eaves. Placing of wood shavings, well compacted around constructional elements to prevent leakage of air into construction. Mounting of chipboard sheet to obtain an air gap between roof and mineral wool.

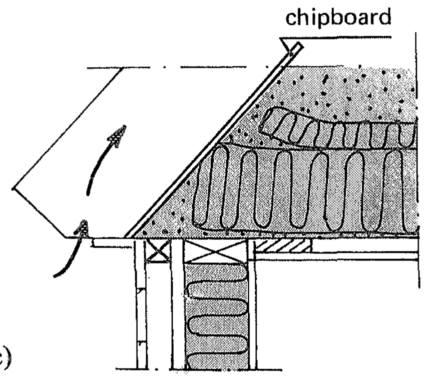
From above:
50 + 150 mm mineral wool
19 mm secondary spaced boarding
polyethylene film
13 mm gypsum wallboard



a)



b)



c)

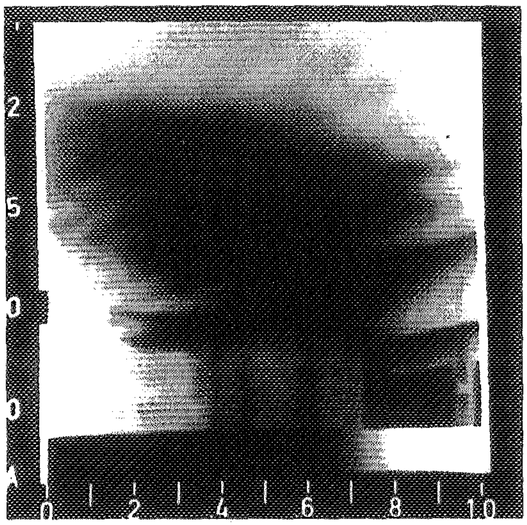
a) Construction of flat floor.

b) Defect found. Incorrect cutting and fitting of mineral wool on flat floor, to some extent due to electric installation.

c) The following measures were taken:
A fill of wood shavings about 20 cm thick was placed on existing mineral wool insulation and thoroughly compacted around roof trusses and at the eaves. NOTE. Chipboard was mounted at the eaves in order to get the material into the intended place, and to secure ventilation of the roof construction.

Results:
Thermographic investigation of the building element after the improvement showed that both the thermal insulation and airtightness of the construction were satisfactory. There was no more leakage of air at the eaves. Checks were made about 1 year after initial thermography, see Fig. 107.

Fig. 107. Thermograms taken before and after improvement according to Fig. 106.



Conditions during measurement:

	Before improvement	After
cloudiness	cloudy	clear
outdoor air temp	- 2°C	- 17°C
indoor air temp	+21°C	+20°C
wind conditions	calm	calm
$p_i - p_u$	- 5 Pa	- 5 Pa

a) Thermogram of colder area on ceiling (before improvement), due to insulation and airtightness defect according to Fig. 106, b). Leakage of air through incorrectly sealed joint at the edge of the floor construction.

b) $t_{ref} = +20°C$

Δ I = - 1.9 isotherm units

Δ t = 2.5°C

v = 0.3–0.4 m/s (at wall-ceiling junction).

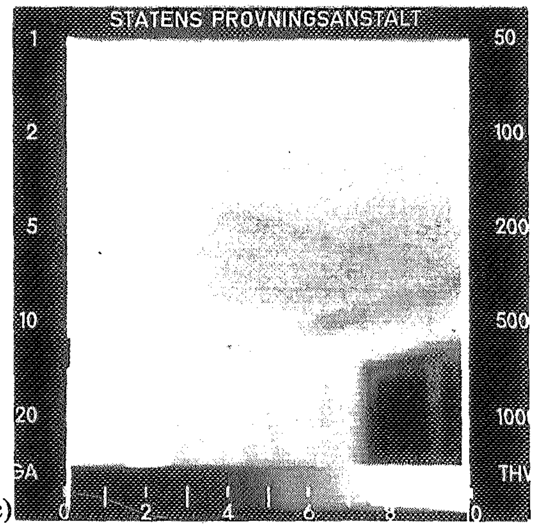
c) Thermogram taken after improvement on same surface section of ceiling as in a). It shows that thermal insulation and airtightness performance is satisfactory.

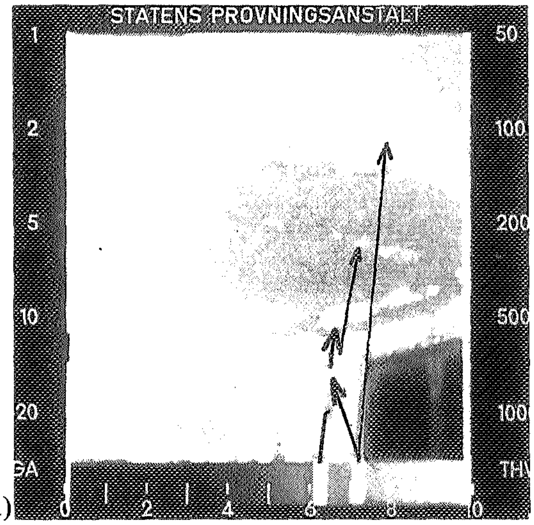
d) $t_{ref} = +17°C$

Δ I = - 0.9 isotherm units

Δ t = 1.5°C

v = 0 m/s

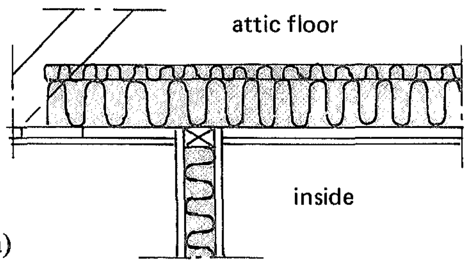




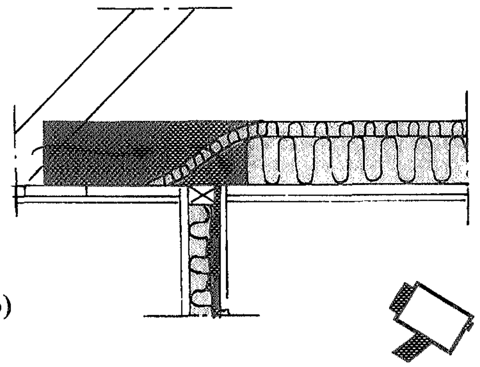
IMPROVEMENTS – FLAT ROOF – ADDITIONAL INSULATION OF FLAT ROOF WITH WOOD SHAVINGS

Fig. 108. Additional insulation to prevent leakage of air into construction at the eaves and at junctions between floor and constructional timber.

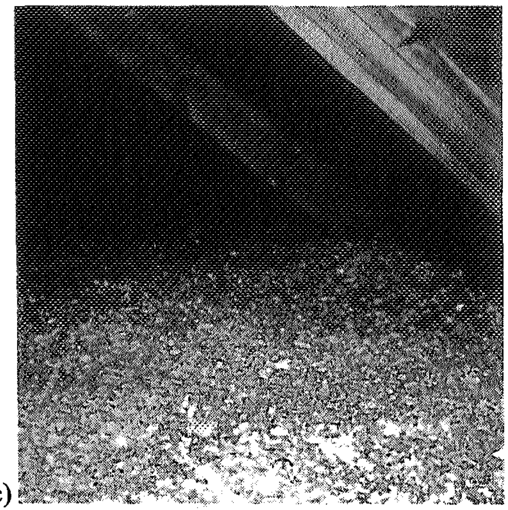
Floor, from above:
50 + 150 mm mineral wool
19 mm secondary spaced boarding
polyethylene film
13 mm gypsum wallboard



a)



b)



c)

a) Construction of flat roof at inset balcony.

b) Defects noted in insulation and airtightness on the flat roof.

c) Insulation of flat roof after placing the additional insulation.

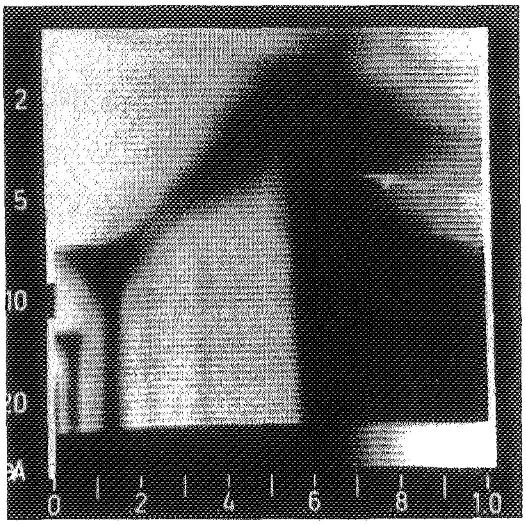
The following measures were taken:
Filling with sawdust about 20 cm thick on original insulation of about 20 cm, see Fig. 109.

Results:
Thermographic investigation of the building element after the improvement showed that thermal insulation and airtightness performance of construction had greatly improved. There were no more convective air movements in the wall construction, see Fig. 109.

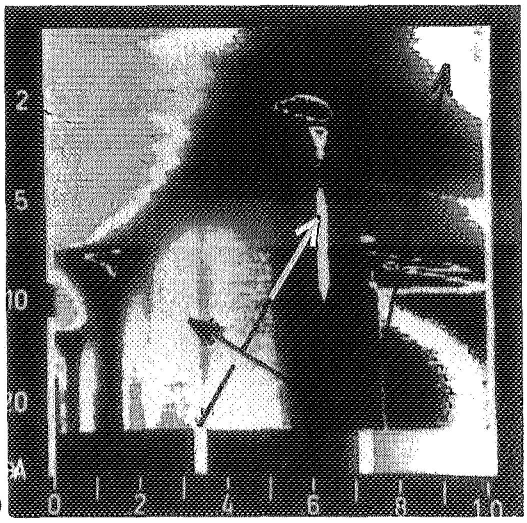
Fig. 109. Thermograms taken before and after improvement according to Fig. 108.

Conditions during measurement:

	Before improvement	After
cloudiness	cloudy	clear
outdoor air temp	- 2°C	- 17°C
indoor air temp	+ 21°C	+ 20°C
wind conditions	calm	calm
$p_i - p_u$	- 5 Pa	- 5 Pa

a) 

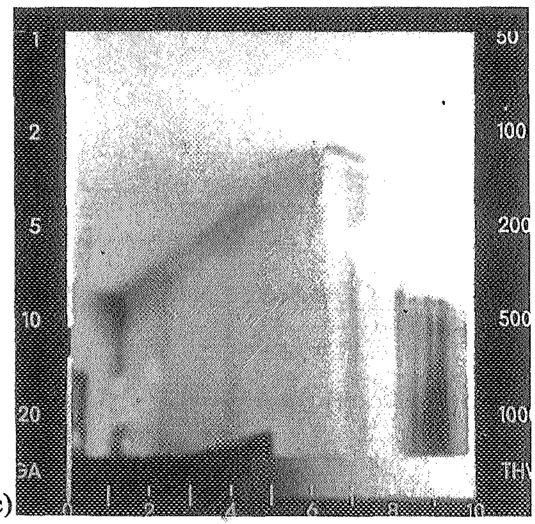
a) Thermogram of colder area at wall-ceiling junction and on wall to the left of french doors (before improvement). For cause of defect see Fig. 108 b).

b) 

b) t_{ref} = + 20°C
Δ I = - 3.8 isotherm units
Δ t = 5.5°C
v = 0 m/s (air leaking into construction).

c) Thermogram of same surface section as in b), taken after improvement.

d) t_{ref} = + 18°C
Δ I = - 2.8 isotherm units
Δ t = 4.0°C
v = 0 m/s

c) 

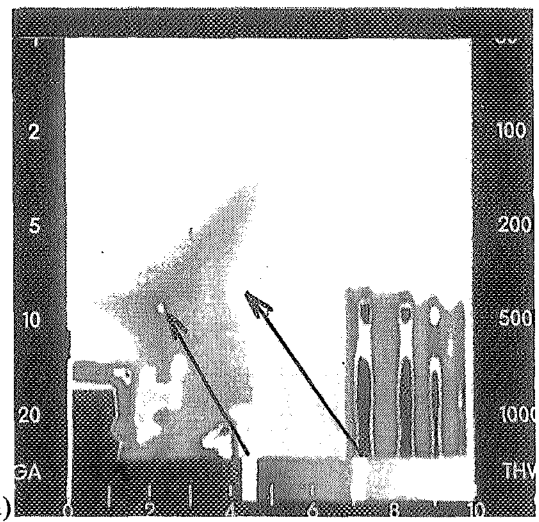
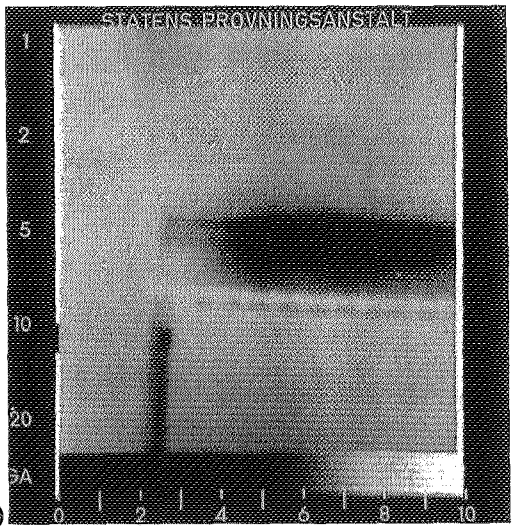
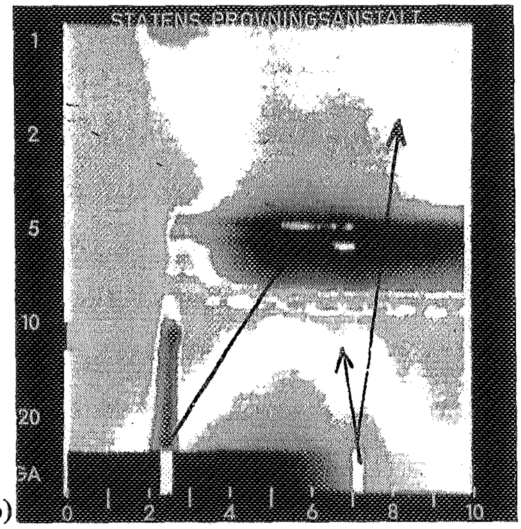
d) 

Fig. 111. Thermograms taken before and after improvement according to Fig. 110.

a) 

b) 

Conditions during measurement:

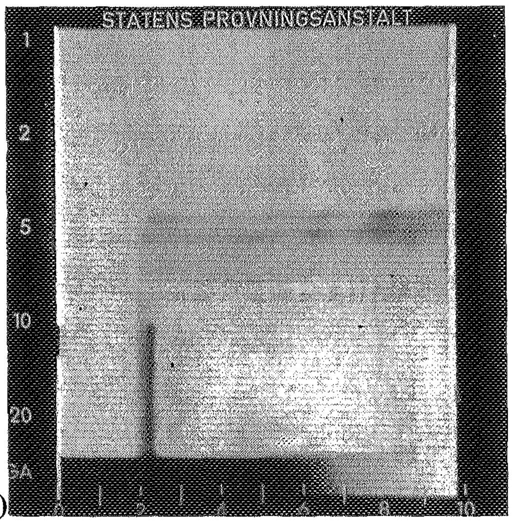
	Before improvement	After
cloudiness	cloudy	clear (thermographed facade not exposed to the sunshine)
outdoor air temp	- 1°C	+4°C
indoor air temp	+21°C	+21°C
wind conditions	1.0–1.5 m/s (parallel to facade)	2 m/s (parallel to facade)
$p_i - p_u$	- 5 Pa	- 5 Pa

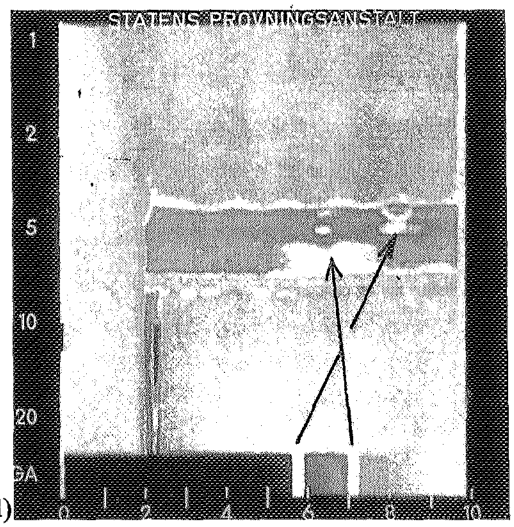
a) Thermogram of colder area at wall-ceiling junction (before improvement), due to insulation and airtightness defect according to Fig. 110, b).

b) $t_{ref} = +20°C$
$\Delta I = -4.8$ isotherm units
$\Delta t = 7.0°C$
$v = 0.3–0.6$ m/s (at ceiling moulding).

c) Thermogram after improvement of same surface section as in a). Thermogram shows satisfactory insulation and airtightness performance in the building element.

d) $t_{ref} = +20°C$
$\Delta I = -1.3$ isotherm units
$\Delta t = 2.0°C$
$v = 0$ m/s

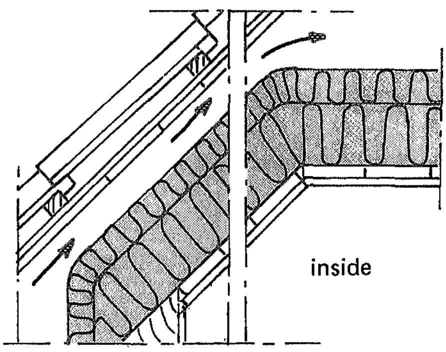
c) 

d) 

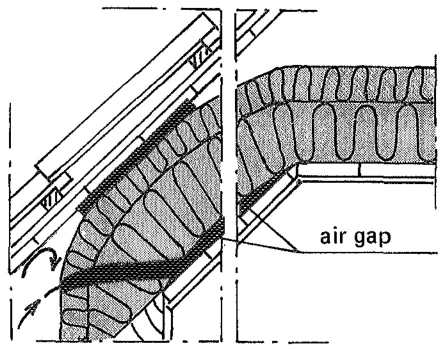
IMPROVEMENTS – INSULATED ROOF (INCLINED CEILING) – ADDITIONAL INSULATION WITH MINERAL WOOL SLABS

Fig. 112. Additional insulation of inclined ceiling with mineral wool slabs, and installation of fibre board on battens to obtain an air gap between insulation and boarding. Acceptable insulation and airtightness performance after the improvement.

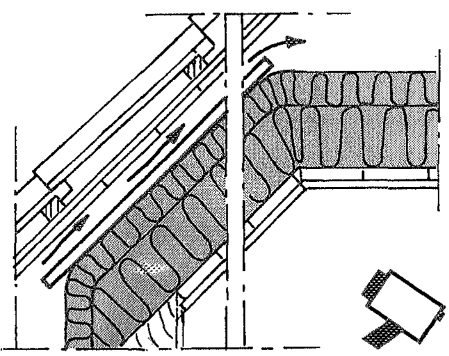
Inclined ceiling, from above:
roof covering
roof boarding
50 mm air gap
95 + 50 mm mineral wool
19 mm secondary spaced boarding
polyethylene film
13 mm gypsum wallboard



a)



b)



c)

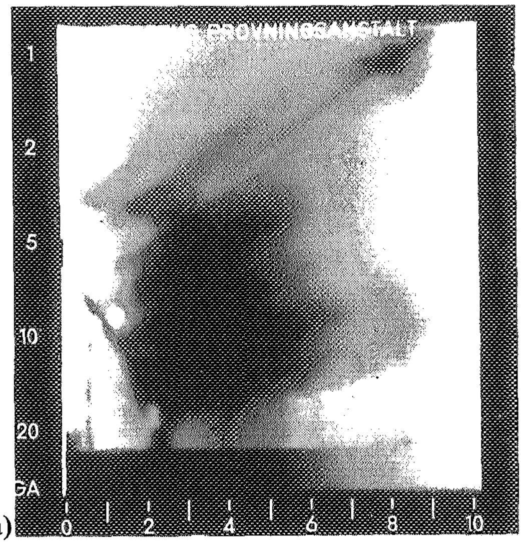
a) Construction of insulated inclined ceiling in habitable attic storey (one and a half-storey building).

b) Defect noted in insulation.

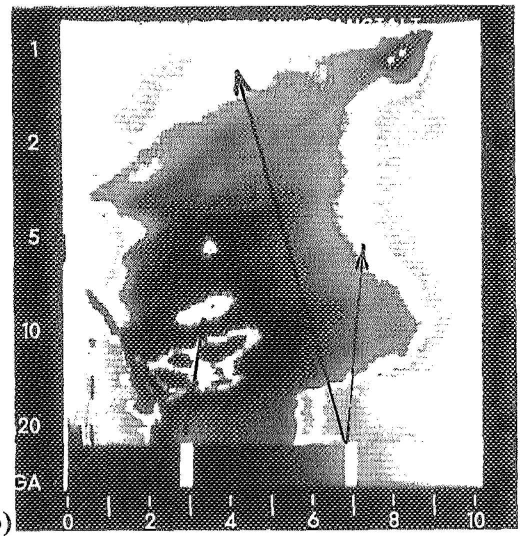
c) Sketch of improvement made.
The following improvement was made:
A fibre board on battens (3 battens per bay) inserted between roof panel and mineral wool insulation so that insulation on warm face was compressed, an air gap of limited extent being obtained for ventilation of the roof. The insulation material was adjusted as regards fitting around and contact with roof trusses.

Results:
Thermography of surface section about 1 month after the improvement showed much better performance of thermal insulation in building element than before, see Fig. 113.

Fig. 113. Thermograms taken before and after improvement according to Fig.112.



a)



b)

Conditions during measurement:

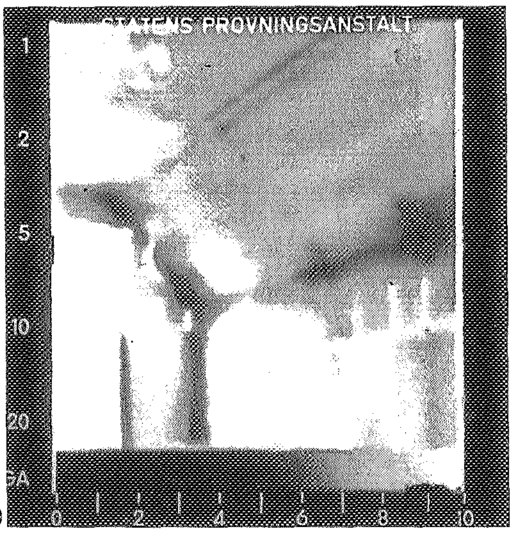
	Before improvement	After
cloudiness	cloudy	clear (thermographed element not appreciably affected by sunshine)
outdoor air temp	- 1°C	+ 4°C
indoor air temp	+ 21°C	+ 21°C
wind conditions	1.0–1.5 m/s (parallel to facade)	about 2 m/s (parallel to facade)
$p_i - p_u$	- 5 Pa	- 5 Pa

a) Thermogram of colder area at inclined ceiling (before improvement), due to the defect described in Fig. 112, b).

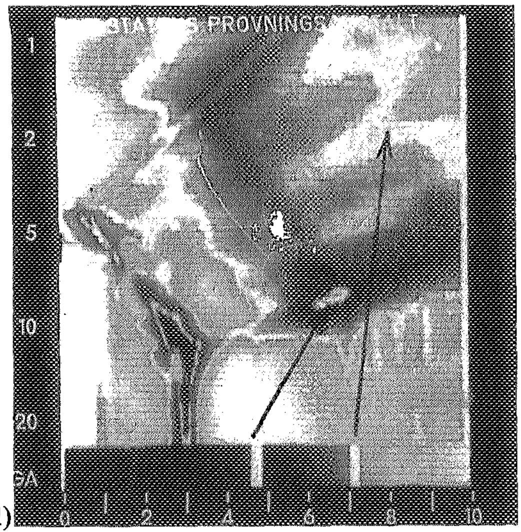
b) $t_{ref} = +20°C$
Δ I = - 2.0 isotherm units
Δ t = 3.0°C
v = 0 m/s

c) Thermogram after improvement of same surface section as in a), showing appreciable improvement in insulation performance of building element. NOTE. Sunshine through window affects parts of wall and ceiling (no effect on measurement on ceiling).

d) $t_{ref} = +20°C$
Δ I = - 1.2 isotherm units
Δ t = 1.5°C
v = 0 m/s



c)

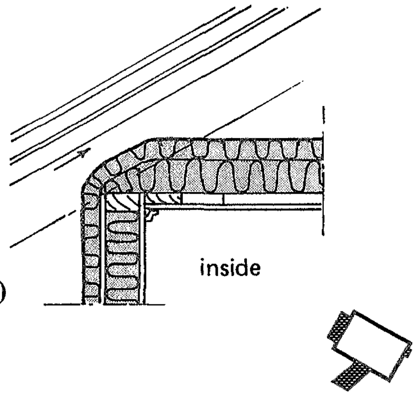


d)

IMPROVEMENTS – FLAT ROOF – ADDITIONAL INSULATION OF MINERAL WOOL AND WOOD SHAVINGS

Fig. 114. Additional insulation at eaves of gable roof by opening up construction from the outside and installing mat of mineral wool with windproof cardboard. Sealing around roof trusses with wood shavings. Acceptable insulation and airtightness performance after the improvement.

Floor, from above:
50 + 100 mm mineral wool
19 mm secondary spaced boarding
polyethylene film
13 mm gypsum wallboard



a)

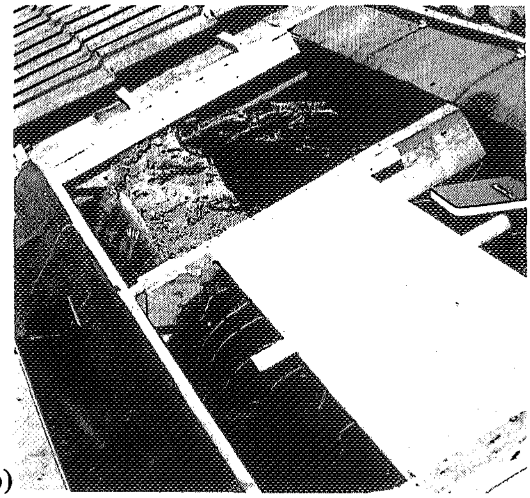
a) Construction of flat roof.

b) Defect found in insulation and airtightness (left-hand bay). Improvements to wind protection and insulation (from the ouside) shown at right of photo.

c) Photo of improvement made.

The following improvement was made:
The mat of mineral wool was lifted up and wood shavings were rammed into spaces around roof trusses at the eaves. The mat was carefully put back and was secured to joists by battens. Wind protection was improved by a fibre board placed on the outside.

Results:
Thermography investigation of building element about 5 months after the improvement showed satisfactory insulation and airtightness performance, see Fig. 115.

b) 

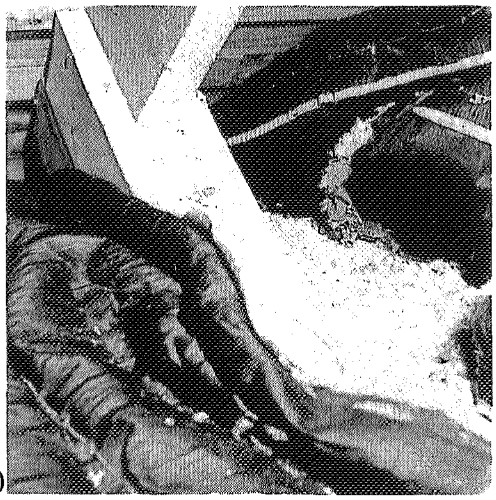
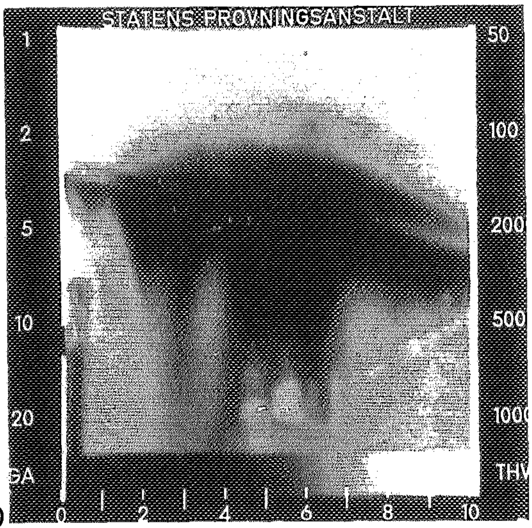
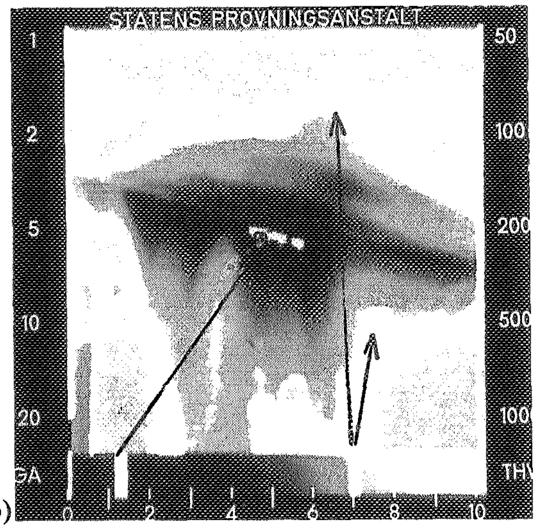
c) 

Fig. 115. Thermograms taken before and after improvement according to Fig. 114.



a)



b)

Conditions during measurement:

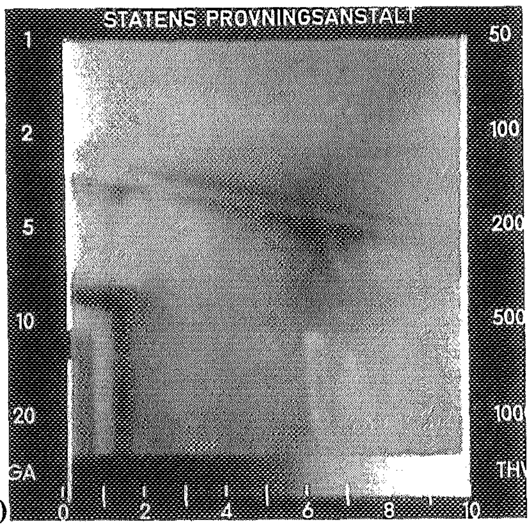
	Before improvement	After
cloudiness	cloudy	cloudy
outdoor air temp	+7°C	+8°C
indoor air temp	+21°C	+21°C
wind conditions	2 m/s	5–6 m/s (at an angle to facade)
$p_i - p_u$	- 20 Pa	- 20 Pa

a) Thermogram of colder area at wall-ceiling junction (before improvement). Extensive air leakage due to insulation and airtightness defect, see Fig. 114, b).

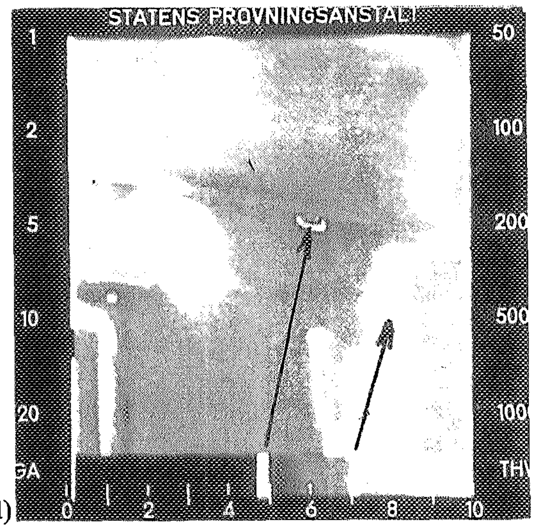
b) $t_{ref} = +20°C$
Δ I = - 11.6 isotherm units
Δ t = 18°C
v = 1–2 m/s (about 60% of length of joint in the room).

c) Thermogram after improvement of same surface section as in a). Slight air leakage can be seen at wall-ceiling junction. Insulation and airtightness performance much better.

d) $t_{ref} = +20°C$
Δ I = - 2.2 isotherm units
Δ t = 3.0°C
v = 0.5–1.0 m/s (locally and of limited extent).



c)



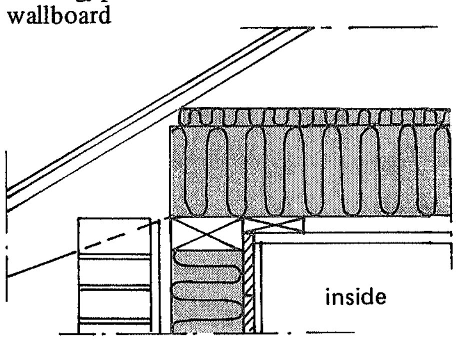
d)

IMPROVEMENTS – FLAT ROOF – ADDITIONAL INSULATION OF MINERAL WOOL MAT

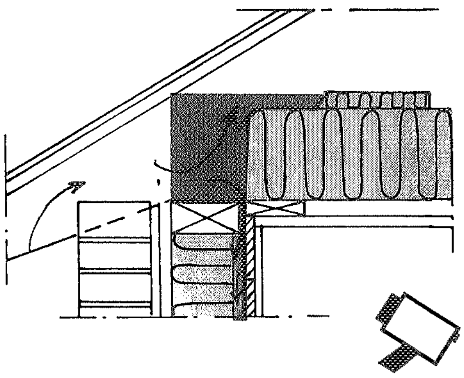
Fig. 116. Additional insulation at the eaves of gable roof by opening up the construction from the outside. Existing mineral wool insulation corrected, and additional mineral wool mat, with windproof cardboard, installed and secured by battens. Acceptable insulation and airtightness performance after the improvement.

Floor, from above:
30 mm mineral wool mat
150 mm mineral wool blanket
19 mm secondary spaced boarding
13 mm fibre board

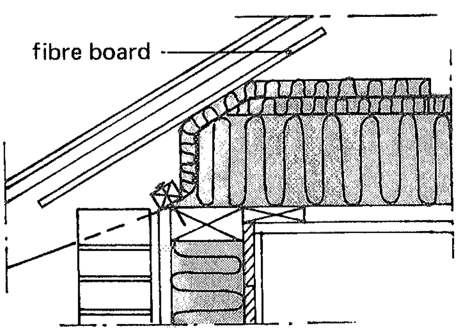
Wall, from the outside:
120 mm brick
air gap
13 mm bitumen impregnated fibre board
120 mm mineral wool slab
impervious cardboard
17 mm panel
13 mm gypsum wallboard



a)



b)



c)

a) Construction at eaves.

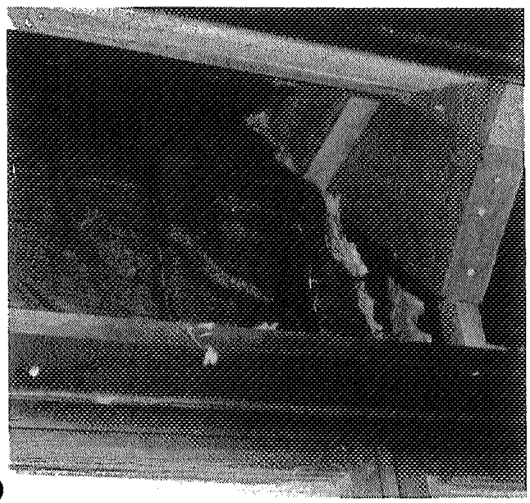
b) Defect noted. Omission of wind protection at the eaves, and bad fitting of mineral wool insulation around roof trusses and top plates.

c) Sketch of improvement.

The following improvement was made: Correction of existing insulation around roof trusses and top plates. Mounting of mineral wool mat at eaves as wind protection. Mat secured by battens to roof trusses and top plates. A fibre board on battens mounted against roof panelling to secure satisfactory ventilation of roof.

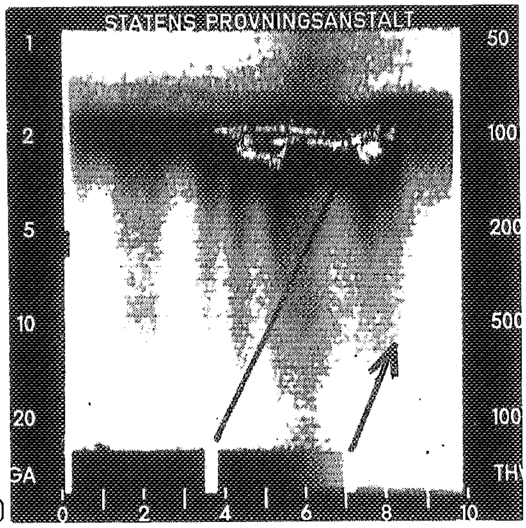
d) Photo of improvement at the eaves.

Results:
Thermographic investigation after the improvements showed satisfactory seal at the eaves and uniform temperature distribution over the surface. Check made about 2 years after initial thermography, about 1 1/2 year after the improvement, see Fig. 117.



d)

Fig. 117. Thermograms taken before and after improvement according to Fig. 116.

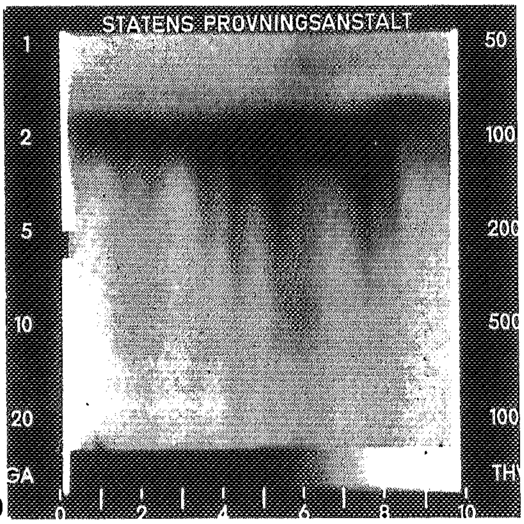


a)

Conditions during measurement:

	Before improvement	After
cloudiness	clear (thermographed element not affected by sunshine)	cloudy
outdoor air temp	+5°C	+1°C
indoor air temp	+22°C	+21°C
wind conditions	2–3 m/s (to thermographed element)	1–2 m/s (at an angle to thermographed element)
$p_i - p_u$	- 3 Pa	- 5 Pa

a) Thermogram of colder area at wall-ceiling junction (before improvement). The serrated shape of the colder surface shows that it is due to leakage of air. Leakage of air into room could not be measured or observed. Cooling is due to ingress of outdoor air into construction and spread of this inside wall between mineral wool and gypsum wallboard.



b)

b) $t_{ref} = +22°C$

ΔI = - 1.7 isotherm units

Δt = 2.5°C

v = 0 m/s (no leakage into room).

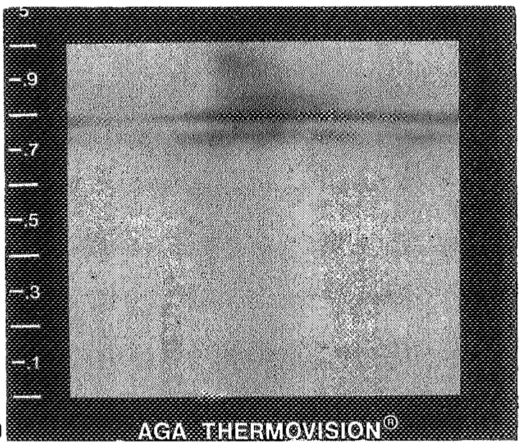
c) Thermogram after improvement of same surface section as in a), showing considerable improvement in insulation and airtightness performance.

d) $t_{ref} = +20°C$

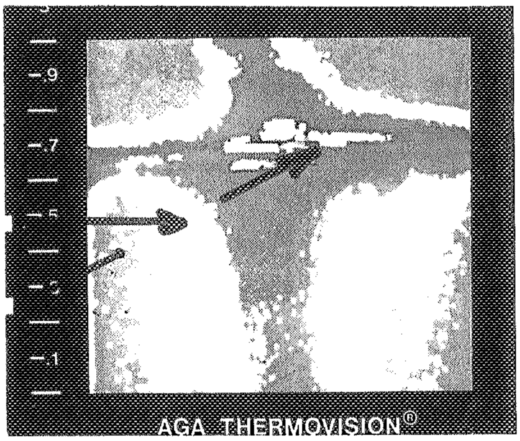
ΔI = - 1.1 isotherm units

Δt = 2.0°C

v = 0 m/s



c)

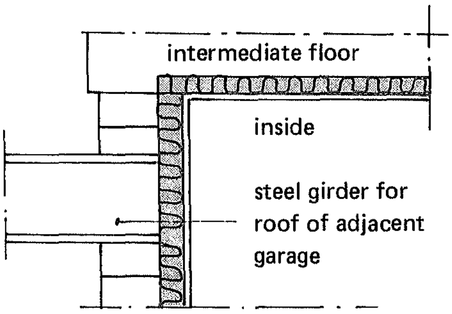


d)

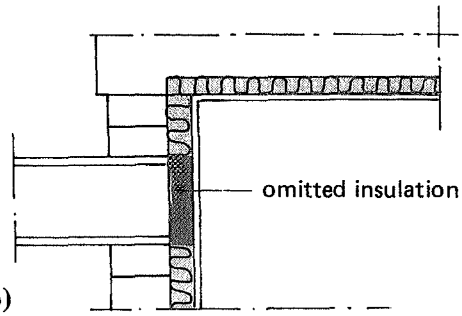
IMPROVEMENTS – EXTERNAL WALL OF HOLLOW CONCRETE BLOCKS – JUNCTION WITH GIRDER

Fig. 118. Additional insulation with mineral wool of external wall at section where there is a thermal bridge due to insufficient insulation. Satisfactory insulation and airtightness performance after improvement.

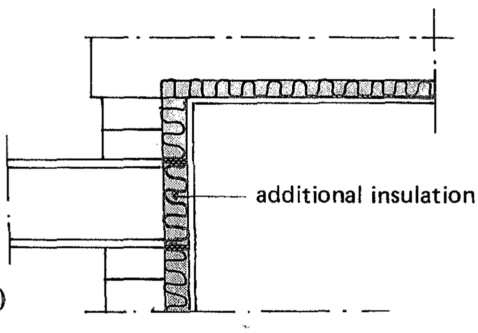
External wall, from the outside :
cement plaster
200 mm hollow concrete blocks
70 mm mineral wool
13 mm gypsum wallboard



a)



b)



c)

a) Construction of wall at junction with load-bearing girder.

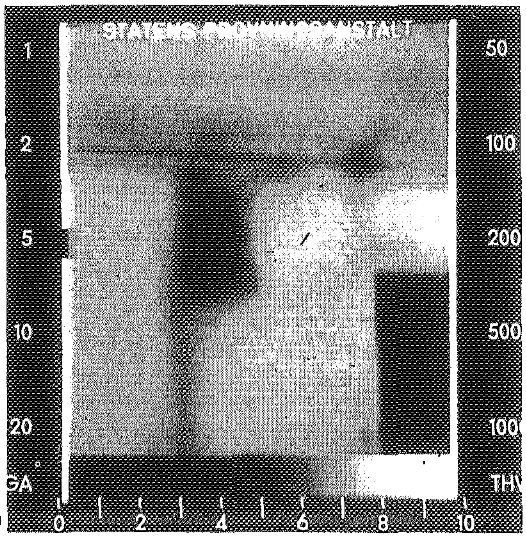
b) Defect noted. Colder wall area due to unsatisfactory insulation at girder. No insulation between steel girder and internal wall cladding.

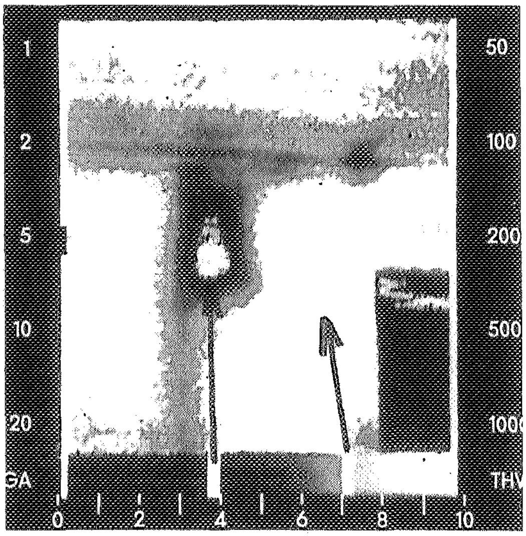
c) Sketch of improvement.

The following improvement was made:
Wall opened up from inside and 7 cm additional insulation placed.

Results:
Thermography of wall section after the improvement shows satisfactory insulation performance. Check made about 2 years after initial thermography, about $^1/_2$ year after the improvement, see Fig. 119.

Fig. 119. Thermograms showing wall surface section before and after improvement according to Fig. 118.

a)


b)


Conditions during measurement:

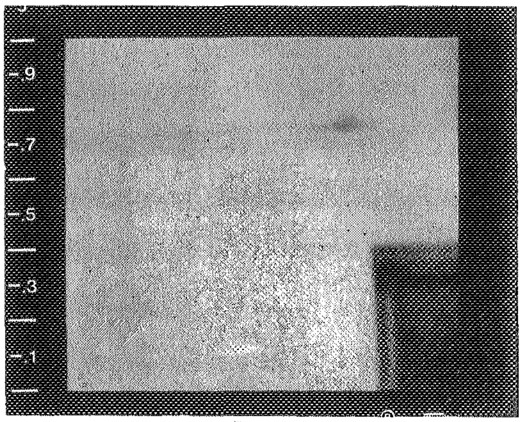
	Before improvement	After
cloudiness	clear	cloudy
outdoor air temp	+ 5°C	+ 1°C
indoor air temp	+ 21°C	+ 20°C
wind conditions	2–3 m/s (to facade)	1–2 m/s (at an angle to facade)
$p_i - p_u$	- 3 Pa	- 5 Pa

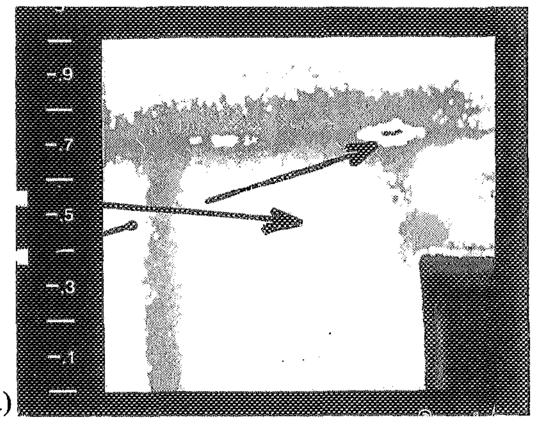
a) Thermogram of somewhat colder wall surface section at wall-ceiling junction (before improvement), due to presence of steel girder. No insulation on the warm side, see Fig. 118, b).

b) t_{ref} = + 20°C
Δ I = - 1.6 isotherm units
Δ t = 2.0°C
v = 0 m/s

c) Thermogram after insulation of end of girder of same wall surface section as in a). The thermogram shows satisfactory the wall insulation performance.

d) t_{ref} = + 19°C
Δ I = - 0.9 isotherm units
Δ t = 1.5°C
v = 0 m/s

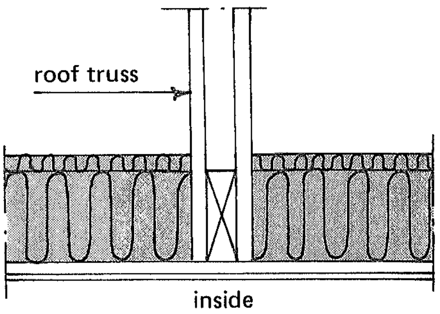
c)


d)


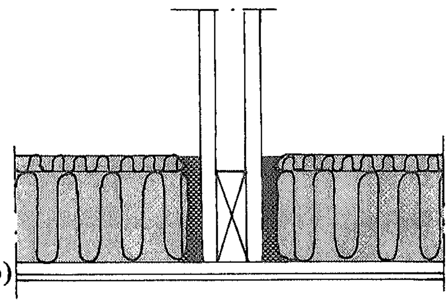
IMPROVEMENTS – FLAT ROOF

Fig. 120. Additional of floor insulation by mineral wool insulation. The cardboard coated mineral wool mat has been corrected and secured in the correct position by battens. Acceptable insulation and airtightness performance after the improvement.

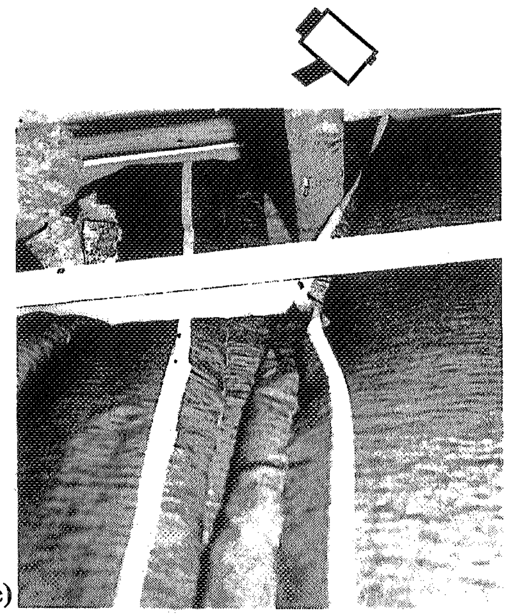
Floor, from above:
30 mm mineral wool mat
150 mm mineral wool blanket
19 mm secondary spaced boarding
polyethylene film
13 mm fibre board



a)



b)



c)

a) Construction of flat roof.

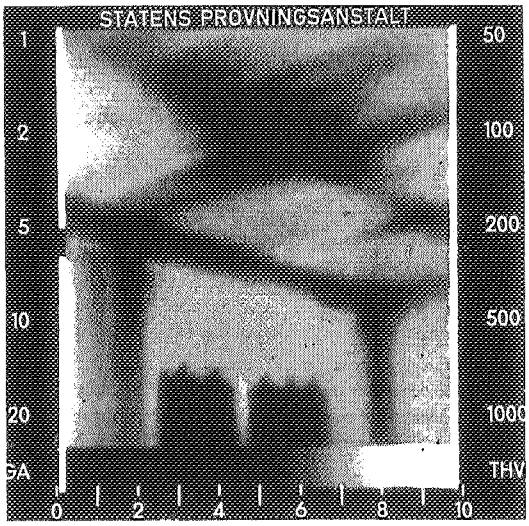
b) Insulation and airtightness defect on flat roof around roof truss.

c) Insulation on floor after improvement.

The following improvement was made:
The lower mineral wool slab was augmented so as to fit around roof truss. The position of the cardboard-coated mineral wool mat on the floor was corrected and the mat was nailed to the eaves by means of battens.

Results:
Thermographic investigation of building element after the improvement gave satisfactory results, but a minor defect in the ceiling at the electric socket for the lamp still appears, see Fig. 121.

Fig. 121. Thermograms showing surface section of flat roof before and after improvement according to Fig. 120.

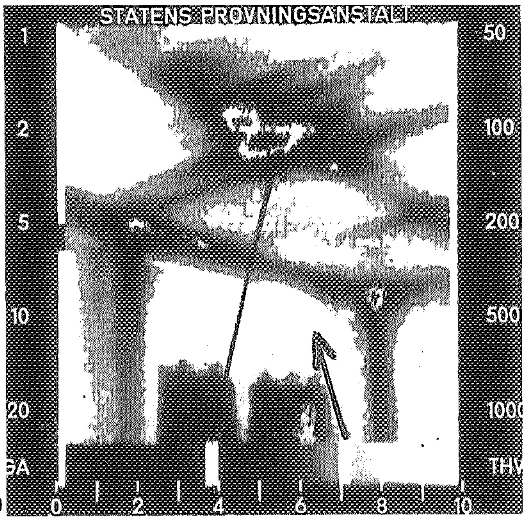


a)

Conditions during measurement:

	Before improvement	After
cloudiness	clear (thermographed element not affected by sunshine)	cloudy
outdoor air temp	+5°C	+1°C
indoor air temp	+22°C	+21°C
wind conditions	2–3 m/s (parallel to facade)	1–2 m/s (at an angle to facade)
$p_i - p_u$	- 3 Pa	- 5 Pa

a) Thermogram of colder surface section on ceiling and at wall-ceiling junction (before improvement). The shape of the colder surface shows that convective air currents occur inside the construction.

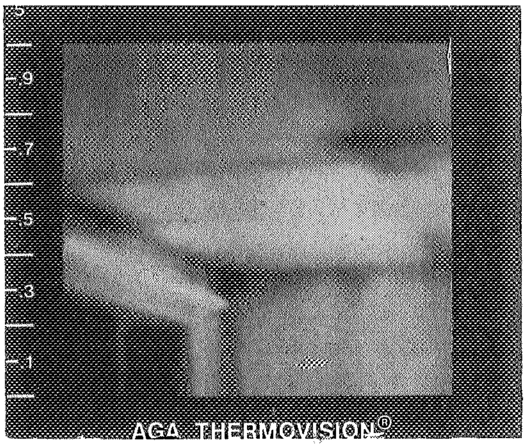


b)

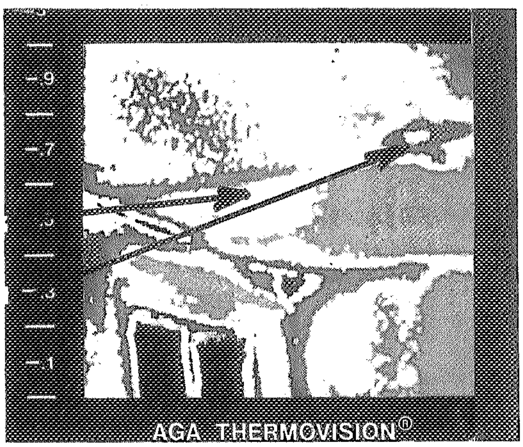
b) $t_{ref} = +21°C$
ΔI = - 1.6 isotherm units
Δt = 2.0°C
v = 0 m/s

c) Thermogram after the improvement of the same surface section as in a). Some colder areas of limited extent still occur on ceiling surface and at wall-ceiling junction. However, the picture shows an evident improvement compared with previous. The performance of the thermal insulation in the building element is acceptable.

d) $t_{ref} = +20°C$
ΔI = - 1.0 isotherm units
Δt = 1.5°C
v = 0 m/s



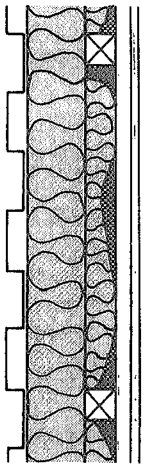
c)



d)

IMPROVEMENTS – EXTERNAL WALL WITH CLADDING OF METAL SHEETING ON THE OUTSIDE AND INSULATED WITH MINERAL WOOL

Fig. 122. Additional insulation of part of the wall by injection of urea resin foam. Part with additional insulation has satisfactory insulation and airtightness performance, while part not injected remains defective.

a) 

External wall, from the outside:
corrugated sheeting
100 mm mineral wool
50 mm mineral wool
secondary spaced boarding
13 mm gypsum wallboard with plastic film

inside

Conditions during measurement:

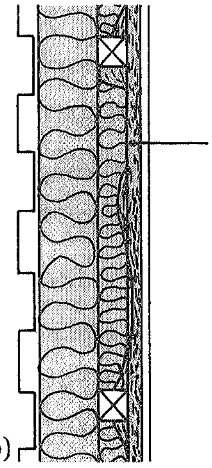
cloudiness	cloudy
outdoor air temp	0°C
indoor air temp	+23°C
wind conditions	calm
$p_i - p_u$	- 8 Pa

a) Horizontal section of external wall. Mineral slabs badly fitted and incorrectly placed in the wall.

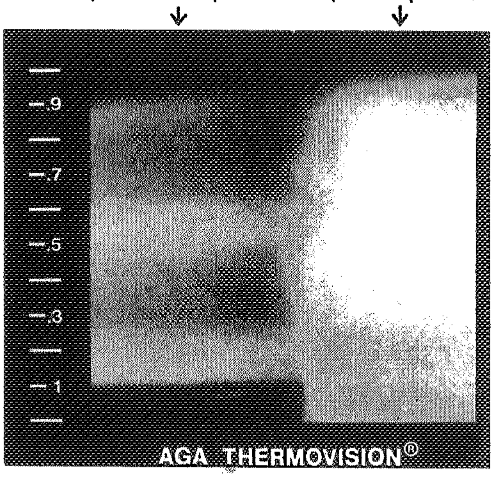
b) External wall given additional foam insulation.

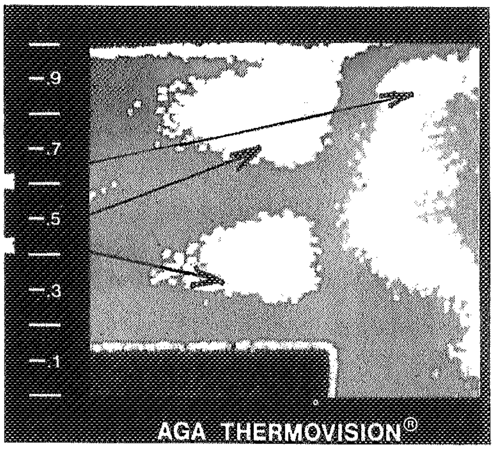
c) Thermogram of wall section surface section to right with additional insulation according to b). Surface section to left not improved.

d) $t_{ref} = +22°C$
$\Delta I = -0.9$ isotherm units
$\Delta t = 1.5°C$
$v = 0$ m/s

b) 

part not improved part improved

c) 

d) 

8 Defects in insulation and airtightness

8.1 Conditions

This report on building defects is based on field investigations with the infrared camera over the period 1972–1976. The investigations were carried out to check the insulation and airtightness performance of buildings.

Of the total number of investigated projects, about 400, some 150 were subjected to closer inspection regarding systematic defects in insulation and airtightness. The projects were studied with the IR camera for the following reasons:

1. Complaints regarding unsatisfactory indoor climate (unpleasant draughts and radiation from cold surfaces) by the inhibitants, and allegations of abnormally high energy consumption.
2. The investigation was prescribed by a clause in the construction documents, or was made as a result of the request by the building owner or contractor that tests and checks should be performed during the construction or at the time final inspection took place.

The projects selected are distributed over the whole of Sweden, with the emphasis on central Sweden. In choosing the projects, the design of the construction, choice of material and construction method were taken into account. Measurements were mainly made on buildings 1–5 years old.

The projects were selected from the available material without any regard to satistically correct sampling principles. The material cannot be considered to give a correct picture of defect frequency in buildings in general. On the other hand, the material presented can give an idea of the types of defect which occur, and the constructional elements and types of construction which are most often subject to defect.

In cases where the building projects concerned were divided into different construction stages, only the buildings and dwellings which are comprised in the stage investigated have been included in this report. The material comprises about 3000 investigated dwellings in single-family houses and blocks of flats. The proportion of dwellings in single-family houses is smoewhat greater, about 65%. Generally speaking, the investigated dwellings constituted 15–20% of the number of dwellings in the whole of the construction stage. The report does not include cases where only one dwelling was studied.

When assessing whether the insulation and airtightness defect in a certain building element is acceptable, the following simplified principles were applied:

- It was considered that performance is defective if cooling of the surface is considered to be equivalent to a reduction in specified insulation thickness of about 40%, and the size of the colder area is more than about 20% of the building element concerned in a certain room
- the measured velocity of the air entering at the point of leakage is in excess of 0.3–0.4 m/s at a normal pressure drop of about 5 Pa across the construction, and air leakage occurs over more than 30% of the total length of joint or junction
- the measured velocity of air near the point of leakage is in excess of 1–2 m/s at a normal pressure drop of 5 Pa. If convective air movements occur inside the construction, then the assessment is made in view of the requirement concerning economic management of energy and also a satisfactory indoor climate, as well as the risk of condensation and damage.

A nomogram showing the risk of condensation at different temperatures and relative humidities is given in FIG. 127.

The effect of structural thermal bridges and substandard design of insulation in walls and floors has not been presented separately.

8.2 Presentation of constructional defects

The material is set out in tabular form. Each table gives information on the following:

- Type of construction
- The number of projects which the material comprises
- The total number of single-family houses or dwellings in blocks of flats included in the project
- The number of investigated single-family houses or dwellings in blocks of flats with the type of construction in question
- The proportions of single-family houses or dwellings in blocks of flats in which the building element concerned had acceptable or defective insulation and airtightness.

In presenting the defects found in the insulation and airtightness performance of buildings, each of the following building elements have been dealt with separately:

- ground floor with its junctions
- intermediate floor with its junctions
- loft ceiling beams with its junctions
- insulated roof (inclined ceiling in attic storey)
- external walls.

Brief comments on the types of defect, etc found in the different building elements are given in the following sections.

Bottom floor, type bb 1. Concrete slab laid on the ground carrying a floor on joists, with mineral wool insulation between the concrete slab.

Defective insulation and airtightness performance occurs to a relatively large extent, chiefly in the regions next to the external wall. The defects here are generally due to incorrect placing and fitting of the insulation material at the edge of the floor. There is often leakage of air through defective seal at the sole plate. Cold outside air can spread into the floor construction and leak into the room. Effective and thorough sealing at the sole plate, and proper placing of the insulation material in the bays between the floor joists, especially in the outer edge zone, is essential if the performance is to be satisfactory. In this way, the effect of any thermal bridges which may occur will be comparatively small.

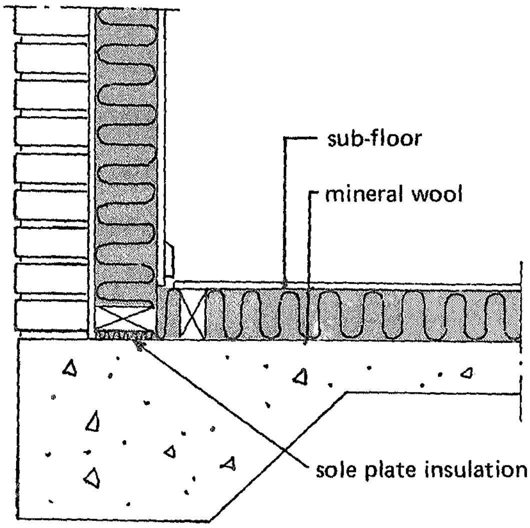


Table 6. Total number of buildings/dwellings in the investigated projects. Single-family houses: 1365. Blocks of flats: 20/291.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	10	240	38	26	62	74
Blocks of flats	5	14/81	29/38	0/0	71/62	100/100

Bottom floor, type bb 2. Concrete slab laid on the ground, with mineral wool insulation placed underneath the concrete slab.

The defects found here are due to incorrect sealing of the sole plate, with direct leakage of air into the room as a consequence, and also to non-uniform performance of the insulation in the edge beam. Owing to these two causes, sections of the floor next to the external wall are often very much colder. Leakage of air at these points generally gives rise to large local temperature variations, with distinct boundaries in the thermogram. The non-uniform performance of the insulation in the edge beam causes smaller temperature variations, the boundaries of the colder surfaces being generally diffuse. However, in this type of construction the floor temperatures are lower than in construction type bb 1.

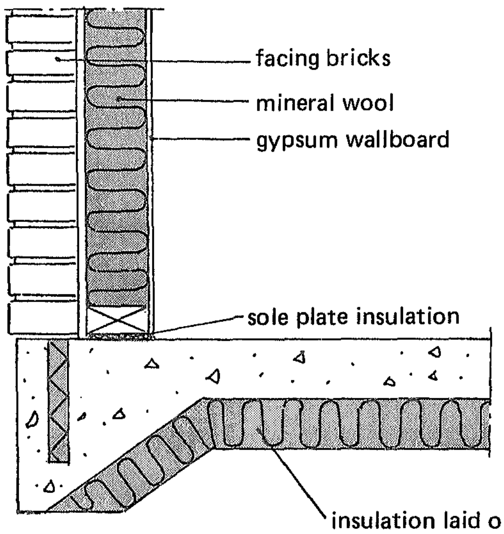


Table 7. Total number of buildings/dwellings in the investigated projects. Single-family houses: 205. Blocks of flats: 7/165.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	6	60	100	58	0	42
Blocks of flats	4	4/33	100/100	75/64	0/0	25/36

Bottom floor, type bb 3. Floor laid on the ground with expanded clay insulation (edge beam with expanded clay aggregate and surface-stabilized expanded clay).

The defects noted in this type of construction are due mainly to leakage of air owing to faulty performance of the sole plate insulation. The colder areas are generally limited to the edge zone of the floor, adjacent to the edge of the floor slab. The insulation performance of the floor slab is not affected in other respects.

From the point of view of airtightness, this construction is dependent on accurate surface finish at the edges of the floor slab, and on the effectiveness of the joint sealing system. This construction, in the same way as construction type bb 2, gives rise to floor temperatures somewhat lower than those in the case of construction type bb 1.

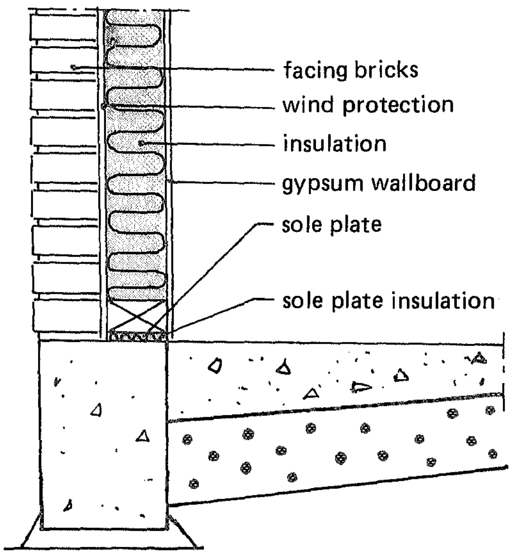


Table 8. Total number of buildings/dwellings in the investigated projects. Single-family houses: 1758. Blocks of flats: 56/997.

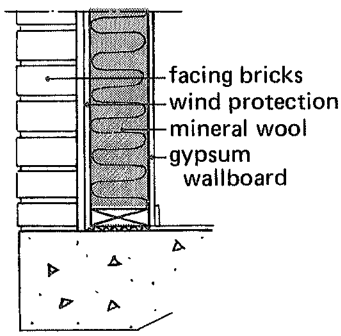
BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	36	293	100	48	0	52
Blocks of flats	19	33/198	100/100	36/24	0/0	64/76

Studwall with mineral wool insulation and external cladding of facing bricks or boardings yv 1.

Defects found in these external walls are mainly due to leakage of air through incorrectly sealed junctions between different building elements. This can have a deleterious effect on the heat insulation performance in sections of the wall near points of leakage, due to spreading of cold outdoor air into the construction, with convective air movements and reduced thermal resistance as a consequence. The defects here are therefore generally located at sections near joints and junctions (chiefly the joint with the floor construction). The results indicate that the insulation performance of the wall is consistently better when a high-grade mineral wool is used (quality A). Defects in insulation in the middle of unbroken wall sections appear to be of limited extent.

In constructions which have an air gap (to equalize pressures) between the thermal insulation material and the cladding, it was found that there was a lesser risk of air leakage through the construction than if this air gap had been omitted. When there is a wind on the facade, local defects in the airtight layer on the wall have a greater effect if the pressure equalization air gap is absent than if it has been provided. The investigations have demonstrated the importance of the airtight layer on the wall being intact.

It was also found that vertical air gaps due to improper placing of insulation material near studs, electric cables, etc may exert a significant effect on the thermal insulation performance, owing to air movements in these gaps.



In prefabricated buildings the thermal insulation of the external walls, and particularly their airtightness, is markedly better than in buildings constructed in situ.

Table 9. Total number of buildings/dwellings in the investigated projects. Single-family houses: 3110. Blocks of flats: 86/1558.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	74	659	87	49	13	51
Blocks of flats	27	46/280	61/59	39/38	39/41	61/62

Intermediate floor of lightweight concrete, mb 1.

Defects in this type of construction are generally due to incorrectly sealed junctions at the edge of the floor, often with leakage of air into the room as a consequence. The colder surfaces are limited to the edges of the floor. In other respects, the performance of the floor construction is satisfactory. When the performance of the sole plate seal is fully satisfactory, the effect of the thermal bridge here is relatively small.

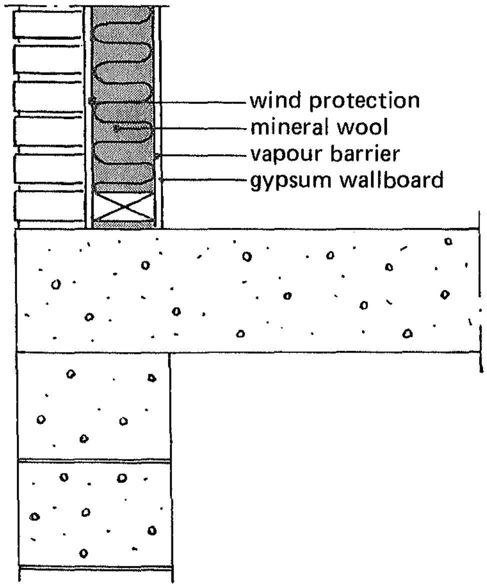


Table 10. Total number of buildings/dwellings in the investigated projects. Single-family houses: 41. Blocks of flats: 0.

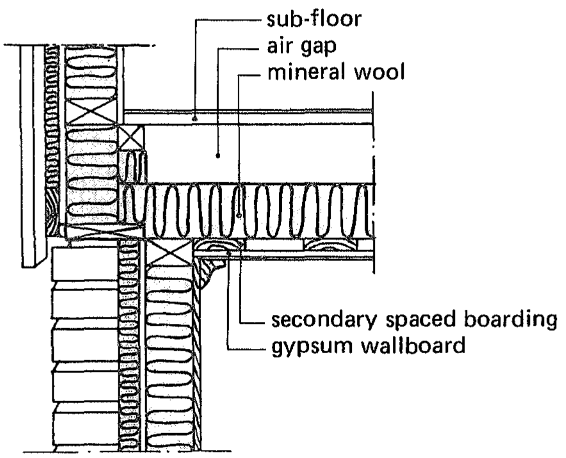
BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	6	41	100	17	0	83
Blocks of flats	–	–	–	–	–	–

Intermediate floor of timber, mb 2, partly filled with thermal insulation material.

This construction mainly occurs in single-family houses, which is the reason why these constitute the greatest proportion of the projects comprised in the investigation.

Defects in this type of construction are generally due to incorrectly sealed junctions between the floor construction and the external wall, and to incorrect placing of the insulation material at the edge of the floor, with leakage of air into the construction as a consequence. In this way, comparatively extensive areas in the ceiling and floor may become colder. The air leaking into the floor may also spread into internal walls and, through incorrectly sealed joints and junctions (electric sockets), into the room.

The results indicate a relatively high frequency of defects.



It must be pointed out how important it is that the insulation material should cover the whole of the space at the edge of the floor construction, for an approximate distance of 1 m from the external wall.

Table 11. Total number of buildings/dwellings in the investigated projects. Single-family houses: 1906. Blocks of flats: 0.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	37	380	21	10	79	90
Blocks of flats	–	–	–	–	–	–

Intermediate floor of concrete, mb 3.

The investigation material is dominated by floor constructions in blocks of flats.

In this type of construction, leakage of air at the junction of the floor and external wall occurs with relatively great frequency. Leakage of air has an effect on floor and ceiling temperatures in the vicinity of the point of leakage.

Defects due to incorrect insulation do not occur here as a result of design faults. Owing to the relatively low thermal resistance of the floor construction, floor temperatures over an unheated basement can be relatively low.

In this type of construction, there is a certain thermal bridge effect at the junctions between floor and wall.

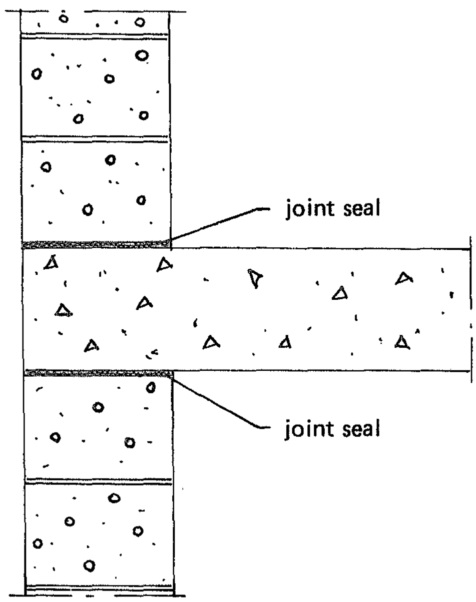


Table 12. Total number of buildings/dwellings in the investigated projects. Single-family houses: 0. Blocks of flats: 33/805.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	–	–	–	–	–	–
Blocks of flats	14	19/155	100/100	21/21	0/0	79/79

Loft ceiling beams, vb 1, with mineral wool insulation and secondary spaced boarding construction, in a building with gable roof.

The defects found here are located at the junction at the eaves, and at sections of the attic floor adjacent to roof trusses and constructional timber.

At the eaves junction, insulation material in the wall and floor is generally discontinuous. Insulation material is often incorrectly placed in the spaces intended for it. Continuity in the inner and outer windproof layer is often neglected. The result is penetration of air into the construction, with a reduction in thermal resistance and leakage of air into the room as a consequence. Air may also spread along the ducts formed by the secondary spaced boarding construction, resulting in colder areas at a comparatively long distance from the edge of the floor construction.

Owing to the fact that insulation material is often incorrectly placed near roof trusses, etc, insulation defects in the attic floor occur relatively frequently. When pressure conditions over the construction vary, air in the attic spaces can penetrate into gaps and cavities and spread along the above ducts.

The investigation has shown that it is generally much easier for the air to spread in the construction when the vapour barrier is placed between the secondary spaced boarding and the ceiling than when it is placed tightly against the insulation material.

It was also found that the shape and quality of the insulation material used has a marked effect on the insulation and airtightness of the construction. It was noted that when the insulation material is highly permeable and of low quality, placing and fitting of the insulation material requires workmanship of higher quality in order that insulation and airtightness may be satisfactory.

Electric installations in the floor often make good workmanship difficult, and thus give rise to defects in insulation and airtightness.

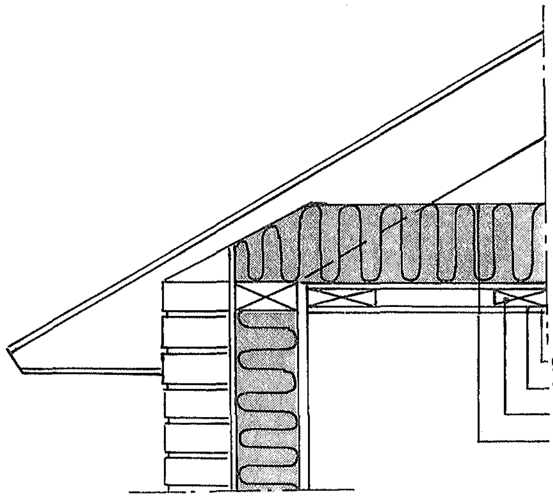


Table 13. Total number of buildings/dwellings in the investigated projects. Single-family houses: 1352. Blocks of flats: 29/553.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	47	243	30	27	70	73
Blocks of flats	13	18/106	61/55	61/55	39/45	39/45

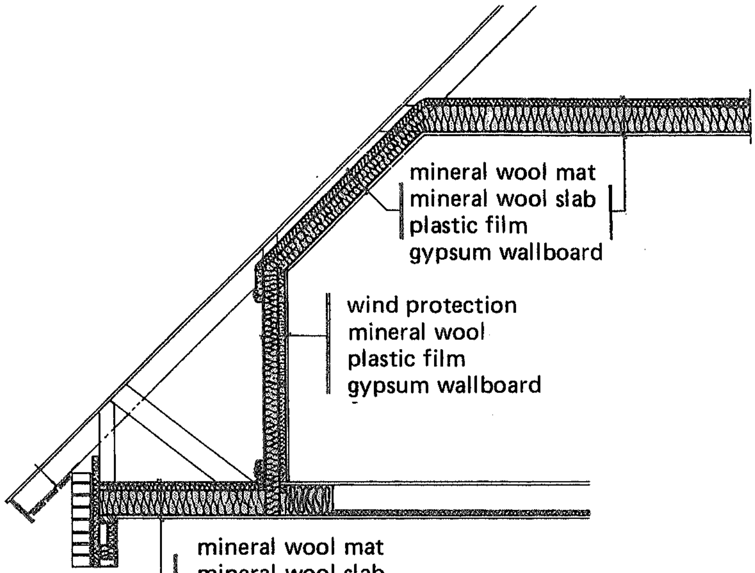


Table 14. Total number of buildings/dwellings in the investigated projects. Single-family houses: 1077. Blocks of flats: 0.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance		buildings/dwellings of defective performance	
			floor	floor junct	floor	floor junct
Single-family houses	20	246	16	11	84	89
Blocks of flats	–	–	–	–	–	–

Loft ceiling beams of concrete with mineral wool insulation underneath flat roofs, vb 4.

This construction is mainly found in blocks of flats. The investigations have shown that the defects found are generally located around the edges of the loft ceiling beams. Insulation material is often badly fitted, with a considerable thermal bridge effect as a consequence. Some defects have also been noted adjacent to ventilation ducts and installations on the loft ceiling beams, owing to the difficulty of fitting the material satisfactorily.

Leakage of air through improperly sealed joints between the floor and the external wall appears to occur to some extent where the external wall and the floor construction are of different materials.

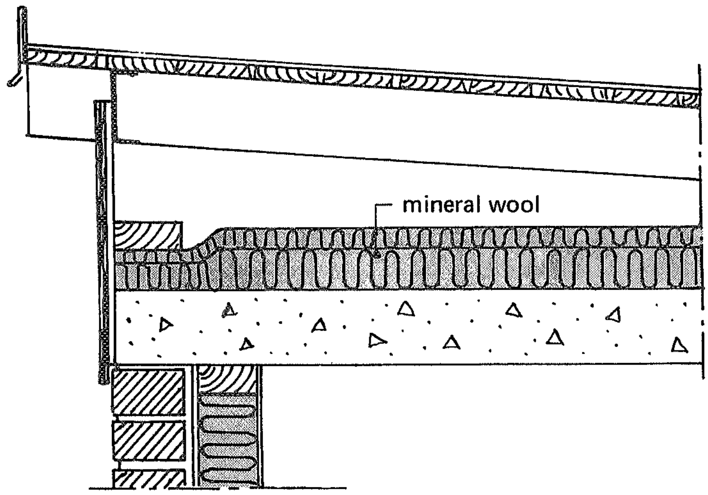


Table 16. Total number of buildings/dwellings in the investigated projects. Single-family houses: 81. Blocks of flats: 33/778.

BUILDING TYPE	NUMBER		PROPORTION, %			
	projects	investigated buildings/ dwellings	buildings/dwellings of acceptable performance floor	floor junct	buildings/dwellings of defective performance floor	floor junct
Single-family houses	3	18	22	17	78	83
Blocks of flats	5	23/170	52/54	52/54	48/46	48/46

9 Experiences

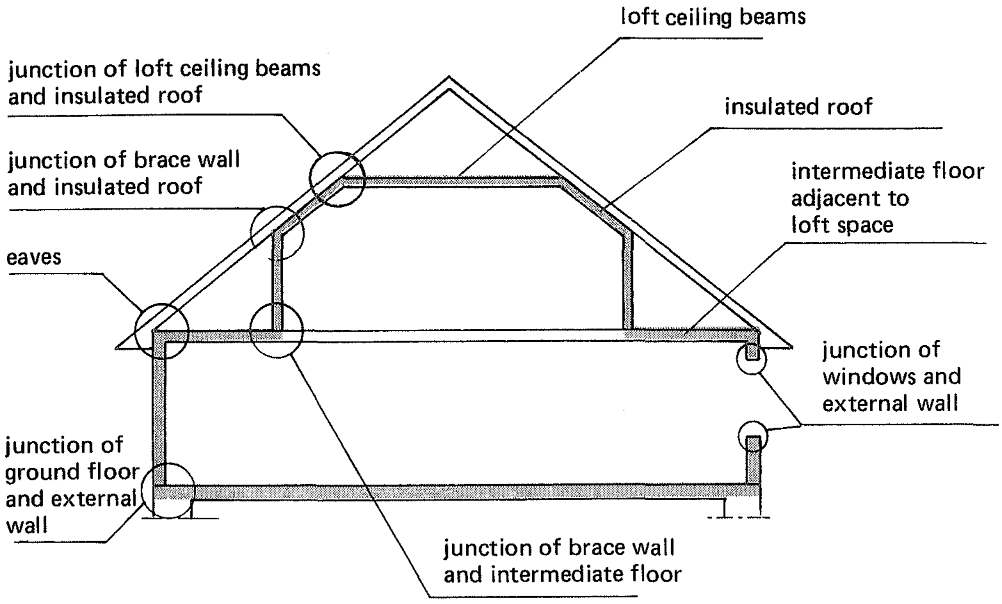
9.1 Structural experiences

The investigations have shown that defects in insulation and airtightness are very common, even in newly constructed buildings. The design and the choice of material, as well as workmanship, are of critical importance. These factors generally act in combination. Simplified explanations such as that defects are due only to careless workmanship are generally without foundation. The defects found have often been of a systematic character. They have occurred with great regularity in certain constructions and materials.

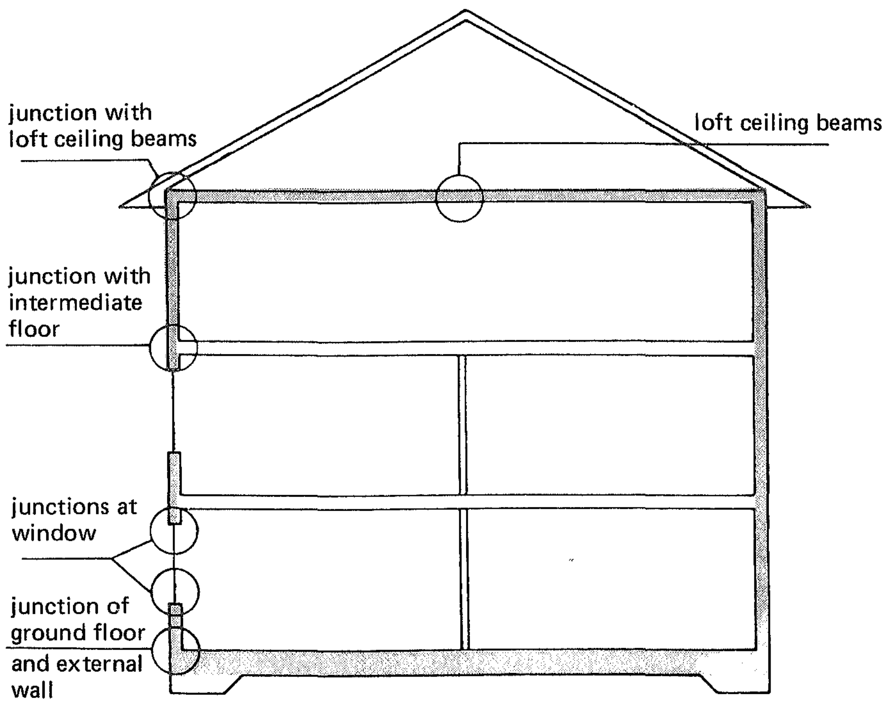
Certain constructional elements in a building are more prone to defects than others. Such elements are the junctions of floors and walls and junctions at the eaves, certain isolated parts of floors and inclined ceilings, and joints between different building elements.

Leakage of air through improperly sealed joints and junctions, and incorrect placing of the insulation material at the points indicated in FIG. 123 a)–b), appear to be the types of defect of the greatest frequency. Such defects may give rise to unsatisfactory temperature distribution and unpleasant air movements (draughts) in the occupation zones of the rooms, and to local reductions in temperature on the surfaces of the construction, with the attendant risk of condensation and deposition of dirt. Defects in the inner or outer airtight layer of the construction involve the risk that movement of air will occur right through the construction, and may cause moisture to collect.

New designs which aim at an economical use of materials have often been found sensitive from the airtightness and thermal insulation standpoint, resulting in difficulties in maintaining an adequate indoor temperature, especially in windy weather. Points of defective airtightness in multilayer constructions can often short-circuit extensive portions of insulated building elements, with local reductions in temperature over parts of the surface.



a) Single-family house



b) Block of flats

Fig. 123. Single-family house and block of flats with constructional elements sensitive from the thermal insulation and airtightness standpoint marked.

The investigations have also shown that prefabricated buildings generally have better insulation and airtightness than buildings constructed in situ. However, there are variations in each group.

The scope which the infrared camera provides for the checking of the insulation and airtightness of a building has been found to have a great preventive effect, and even exerts an influence on construction which is not directly subjected to tests.

A summary of the results obtained during the investigations, from about 2000 single-family houses, about 1000 dwellings in blocks of flats and about 50 other buildings (offices, hospitals and industrial buildings), which have been referred to in Section 8.2, shows that.

- certain insulation and sealing materials are more suitable than others from the points of view of insulation and airtightness
- certain types of constructions are very sensitive from the point of view of airtightness
- certain forms of construction have been found unsuitable from the points of view of insulation and airtightness
- leakage of air through improperly sealed joints and junctions is the dominant type of defect
- leakage of air into the construction at certain critical points (for instance, at the eaves), with convective air movements in the construction as a consequence, occurs very frequently
- recommendations for improvements have been given in about 80% of the investigated cases.

The final standard of construction depends on the following factors:

- the design of the building
- the choice and knowledge of materials
- the occurrence of pipes and installations, for instance electric conduits and holes for pipes through the construction
- working method and workmanship.

9.1.1 Design

As mentioned previously, Section 33:4 of Swedish Building Code SBN 1975 /16./ lays down requirements of increased stringency for the thermal insulation and airtightness of buildings.

A construction must naturally be designed in such a way that satisfactory thermal insulation and airtightness can be achieved, even in view of present working methods and fast rate of work. It appears desirable that well tried typical constructions should be used to an increasing extent in order that satisfactory conditions may be attained with regard to both energy consumption and comfort requirements.

Certain constructions have been found to have a high frequency of defects. This applies, for instance, to slatted panel constructions. In constructions which incorporate slatted panels in floors and walls (attic walls), it has been found that the vapour barrier is often placed between the slatted panel and the outer skin. The vapour barrier should be laid directly against the thermal insulation material. This will cut the risk of air leaking into the construction and spreading along the ducts formed between the boards in the slatted panel. Investigations have shown that the thermal insulation has a more satisfactory performance if the vapour barrier is placed in this way. This may however necessitate some additional work since extra sealing is required near electrical installations, etc.

In single-family houses with a habitable attic storey, air often leaks into the attic wall construction at the corners, particularly if there is a slatted panel on the inside of the thermal insulation. In this type of construction, it is important that junctions at gable walls, ceiling and the floor should be properly sealed. Attic walls should be provided with a satisfactory windproof layer on the outside. The junction with the floor construction must be made with great care. Defects also occur at the junction between the attic wall and the inclined ceiling. Owing to the design, there are difficulties in ensuring complete airtightness and proper placing of the insulation material at this point.

The eaves are very sensitive from the insulation and airtightness standpoint. It is often difficult to achieve continuity of the insulation material and airtight layer. Different methods of designing this constructional detail have been found to give rise to large variations in the insulation and airtightness performance. Special designs in the form of prefabricated eaves units have been found to simplify work and, generally, to result in improved performance.

9.1.2 Materials

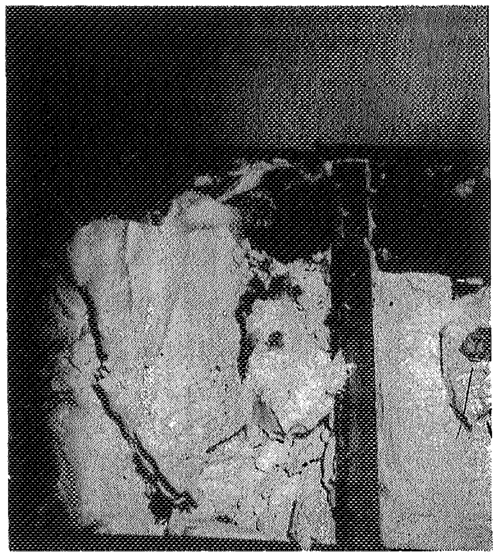
High-grade insulation materials are available at present. The thermal insulation properties of these are relatively well known. Comparatively extensive tests and checks, such as VIM checks, are carried out by means of laboratory measurements. The performance of a construction is determined by the properties of the individual materials. It is essential that the materials comprised in the construction should be compatible, so that the intended performance is achieved even under the stresses which occur in practice.

The investigations have shown that mineral wool insulation of high quality (quality A) has a better performance than a lower quality. In general, material of quality A appears easier to place properly in the construction. When a lower grade of material (quality B) is used, workmanship must generally be of a higher standard. Results of measurements on lightweight attic floor constructions insulated with quality A and quality B material were considerably different with regard to both insulation and airtightness.

Insulation with flocculated mineral wool is employed both for the insulation of floors (general approval of the Swedish National Board of Physical Planning and Building) and as additional insulation to improve the insulation and airtightness performance of floors. The material is relatively easy to apply, fills the spaces around constructional elements properly, and provides satisfactory insulation provided that the airtight layer is properly installed. However, the experience of this material in this investigation is of comparatively limited extent.

Urea-formaldehyde foam is most suitable for use as additional insulation in walls and floors where the original insulation consists of some other material. The results of measurements show that insulation and airtightness performance is satisfactory provided that material and workmanship are kept under close supervision. Serious damage has occurred in cases where the material did not have the correct composition or was not applied in the correct way (the spray equipment was not kept clean). In

a) Satisfactory placing of foam.



b) Defective placing of foam (shrinkage and cracking).

Fig. 124. Part of floor construction opened-up one year after injection of plastics foam. Two different qualities had been used.

such cases, both moisture damage in building elements and extensive shrinkage of the insulation material have been found, FIG. 124.

Wood shavings are mostly found in older buildings as insulation material in external walls and floors. It has been found during investigations that this material has settled to a certain extent. The insulation provided by this material is relatively poor. Compaction and airtightness properties have been found satisfactory, and for this reason the material is very useful as additional insulation, for instance in attic floors. The investigations include a large number of projects in which this application has shown good results.

Material of lower quality is more permeable to air, and is thus more dependent on the provision of a satisfactory airtight layer. This is often disregarded, for instance at the eaves.

The availability of special insulation products, such as "eaves slabs" and "ceiling slabs" may considerably simplify installation. The risk that undesirable air gaps and ducts will occur in the construction is reduced in this way. Development and use of such special products provides better conditions for satisfactory installation.

Generally speaking, the airtightness of heavy constructions (lightweight concrete and concrete) is relatively satisfactory. Certain problems occur at joints and junctions between building elements of different materials. Points of reduced airtightness often occur here, with leakage of air and moisture in consequence. This is due to the differences in the properties of the materials which expand differentially when the temperature changes, often with cracking as a result.

In the case of concrete walls with an insulation of mineral wool on the outside, it is shown by the investigations that the quality of the insulation material is of critical importance. In order that insulation performance may be satisfactory, a high grade mineral wool is required, so that the material may be glued onto the concrete wall, or that the concrete may be cast against it.

Lightweight concrete constructions often give relatively good airtightness. The investigations show, however, that considerable cracking may occur both in the precast units and in the joints between these.

9.1.3 Airtight layer

The performance of the internal and external airtight layer is essential for the insulation and airtightness of the construction. Different airtight layers have been tested during this investigation.

The most common windproofing material, sheathing felt placed on the outside of the insulation material, has in certain cases been found to have a not entirely satisfactory performance. When building elements have been opened up, it has been found that damage in the form of torn pieces, defective adhesion and insufficient overlapping often occurs in the felt. When air movements were measured in constructions in which defects had been found, it would appear that the felt can in certain cases give rise to a pumping effect, i.e. air currents in existing gaps and cavities when the wind pressure on the construction varies. When the felt is placed on the inside of the external insulation layer, such an effect does not seem to occur.

Windproofing consisting of sheets of wood fibre (masonite) does not appear to have a satisfactory performance, due to the difficulty of sealing the joints between the sheets and between the sheets and the framing, especially if the material has been exposed to damp. Taping of joints has not had the intended effect.

In general, windproofing in the form of bitumen impregnated wood fibre board appears to provide satisfactory results. Even in this case, the importance of ensuring that the material is placed tightly against the framing must be emphasized. Additional nailing of the boards may be necessary if the material has become wet.

Investigations have also been made in order to elucidate the windproofing effect of sheets of mineral wool of high density placed in different types of thermal insulation. The results of measurements indicate that the thermal insulation performance of constructions provided with this type of windproofing does not call for adverse comment, provided that the insulation material is placed tightly against the framing and the sheets are properly fitted together. If installation is in conformity with the instructions of the manufacturer, the windproofing performance of this material appears to be equivalent to that of other windproofing materials. The measurements have shown a relatively high frequency of defects in cases where the installation instructions have not been observed.

The adverse effect of defects in the external windproofing layer on insulation and airtightness is smaller if the internal windproofing layer in the construction is quite intact. A vapour barrier (plastics film) with an overlap of 20 cm at all joints, corners, etc generally provides satisfactory performance. A wall material covered with plastics film does not appear to have the same satisfactory performance, due to the risk of improper sealing of the joints between the sheets of material.

Placing of the vapour barrier in the roof, the junction of the attic floor and gable wall, etc, should receive special attention. Defective sealing at these points may permit leakage of warm air into the construction, with the risk that condensation will occur at these points. Moisture damage in combination with rotting and mould damage has been noted in conjunction with these defects.

9.1.4 Joint sealing

Leakage of air through improperly sealed joints and junctions often occurs. In designing constructional details of this type, care must be taken to ensure that a sufficient gap is provided, so that effective sealing of the joint can be carried out. It has been found that a joint width of 15 ± 5 mm is appropriate.

In sealing joints, the choice of material is of great importance for the performance of the seal. Certain types of material are unsuitable with regard to both performance and workmanship. When sealing strips of mineral wool are used, it is essential that the strips are folded prior to placing in the joint, and that there is sufficient sealing material in the joint (2–4 strips as a rule), see FIG. 97. It would appear that sealing performance is best when foamed polyurethane, sole plate seal of EPDM rubber, or the Gullfiber "Fogfiber" system is used. See FIG. 99–101.

9.1.5 Installations

Electrical installations and holes for pipes passing through the construction often give rise to problems with regard to the insulation and airtightness performance. Air movements often occur both in the conduits provided for electric cables, and in the ducts formed between the conduits and the insulation material. Electric cables laid in the vicinity of the eaves are particularly sensitive. In cases where electrical installations have been placed not in the external wall but in an inner wall, the insulation and airtightness performance has generally been better.

9.1.6 Workmanship

Untrained personnel is sometimes employed for the installation of insulation and joint sealing material. This often gives rise to inferior workmanship due to lack of knowledge concerning the performance and properties of the different materials. Those engaged on insulation work must also know which are the "sensitive" parts of the construction, and must also know what purpose the different layers of material in the construction perform. Training and information are factors of great importance in this respect.

When a construction is being insulated, it is essential that the insulation material is properly placed both around studs and against the "warm" side of the construction. If there are gaps or ducts at these places, air may leak into the construction, for instance through improperly sealed joints, with the consequence that insulation performance is adversely affected due to convective air currents inside the construction. If there are also defects in the vapour barrier, air may enter the room directly. The insulation performance of external walls appears to improve when high-grade insulation material (quality A) is used, and when unbroken sheets of insulation material are used which fit into the bays between the framing members. Thermal insulation material mounted in the wall in different layers often compensates for local defects in workmanship.

It has been found in connection with measurements in the field that insulation in floors is generally laid from the centre of the floor towards the edges of the floor. As a result, the insulation material and airtight layer are often fitted badly at the eaves and the edges of the floor.

9.2 Recommendations regarding measurements

9.2.1 Preparations

Before thermography is carried out in a building, information concerning the design of the building, for instance drawings and specifications, must be obtained. External conditions such as air temperatures, wind and sunshine, must also be noted.

Thermography may be performed when the measuring conditions are as required. In order to eliminate interference due to external climatic factors, etc, measurements are generally made from the inside of a building element. Measurements outdoors may also be employed, for instance in conjunction with preliminary measurements on large facade surfaces. When thermal insulation and airtightness are defective, or when the pressure indoors is higher than that outdoors, outdoor measurement may be advantageous.

The following must be determined and noted on the site during thermography:

- The maximum and minimum temperature of the air over a 24-hour period prior to measurements, e.g. by means of a maximum-minimum thermometer, or by data provided by the Swedish Meteorological and Hydrological Institute.
- Sunshine conditions over 12 hours prior to measurements.
- Wind conditions (direction and intensity) during measurements.
- Orientation of the building, as well as surrounding buildings and the nature of the country (layout plan).
- Air temperature outdoors at the time of measurement.
- Cloud conditions (precipitation) and information concerning the presence of moisture on the surface of the building element.

- Pressure difference across the surfaces enclosing the building, measured with e.g. a U-tube manometer. Measurements should be made on every floor on both windward and leeward side. (If possible, the pressure inside the building should be made lower than that outside, for instance using the existing fans.)
- The emissivity (ϵ-value) of the surface materials.
- Air movement and thermal radiation conditions in the room.
- The presence of warm radiators and pipes cast into the wall (if possible, radiators should be turned off before commencement of thermography.)
- Air temperature indoors during the measurements.
- Reference temperature for determination of temperature differences in the thermal image.

9.2.2 Thermography

The IR camera is set up and put into operation (it should be allowed to warm up for a few minutes before measurements are started). The function and settings of the camera are to be checked, the instructions of the manufacturer being observed.

A cursory examination of the warm surface of the building element is carried out. The appropriate sensitive range is selected for the IR camera. In order that comparisons may be made easily between different parts of the same building, the same range of sensitivity should be retained as far as possible. When detailed studies are made of selected sections of the surface, however, the sensitivity selected must be such as to give detectable contrasts in the thermal image. Selected parts of the object (both parts free of defects and parts in which a defect is suspected) are documented by taking a photograph of the thermal image (thermograms are made). As a rule, one monochrome image and one isotherm image is taken for each section of surface. Isotherms are imposed both on the section free of defect (surface of "normal" surface temperature) and on the section in which a defect or thermal bridge is suspected. The lower isotherm value should then correspond to the characteristic section of the colder surface (not always the lowest surface temperature). The extent of the colder surface should be noted. The position of the thermograms taken is noted, for instance on a sketch plan. Interpretation and assessment of the thermograms are carried out according to the method outlined in Section 4.2.

If the appearance of the thermogram indicates air leakage, this is verified by measurement of air velocity. The velocity of the air leaking into the room is measured near the point of entry, using, for instance, a hot-wire anemometer. The measured values should be characteristic of the leakage in the thermal image. The proportion of the joint or junction over which leakage occurs is estimated.

In order to facilitate the preparation of reports, the thermograms obtained can be mounted on sheets produced for this purpose, as in the example shown in the Appendix, p. 218.

9.2.3 Report

A thermography report should contain the following:

- Construction of the building (walls, floors, junctions)
- Type of surface material (ϵ-value)
- Orientation of the building (layout plan) and description of surrounding buildings and the country
- The object of the investigation
- Air temperature conditions at the time of measurement and over 24 hours prior to thermography
- Sunshine conditions over 12 hours prior to thermography, and during the measurements
- Wind conditions during measurements
- Pressure drop across the building element
- A sketch plan of the inverstigated building, indicating the positions of the surfaces included in the thermograms
- Thermograms of selected parts of the investigated surfaces in the building, with indication of location and comments
- Interpretation of the thermograms, and an assessment of the insulation and airtightness of the different elements of construction
- A brief analysis of the type and extent of the defects in insulation found in the different constructional elements.

A report concerning a thermographic investigation normally comprises thermograms with the appropriate readings, an analysis and interpretation of the thermograms, and an assessment of the insulation and airtightness of the building elements.

The results of measurements can be subdivided as follows:

1. *Thermograms* showing the distribution of surface temperatures over the different building elements. Certain ambient data such as air temperatures, pressure differences, reference temperatures, air velocities, etc are given in conjunction with the thermograms. A brief assessment is made of the type and extent of the defect in the building element concerned. The extent can be portion of the surface in question which is colder or indicated in terms of a percentage which shows the proportion of the joint/junction through which air leakage occurs. This percentage may refer to a certain

room. The surface temperatures or air velocities must be representative of the building element for which thermography has been carried out.

2. *Comments* are given as to whether the measured temperature distribution is as expected, or abnormal. An assessment is made as to whether the lack of uniformity found in the temperature distribution is due to a constructional thermal bridge, defect in insulation or air leakage. The type and extent of the defect are specified.
3. *A summary* is given concerning the performance of the insulation and airtightness of the different building elements, and a qualitative assessment is made of the insulation and airtightness performance of the building. An opinion is given concerning the standard of workmanship.

The report should also include an assessment of the effect which the defects have on the energy consumption of the building and on the indoor climate, and whether any measures should be taken to remedy the situation. The reasons on which such an assessment is based should be given.

10 The development of thermography

The first investigations in the field with an infrared camera were made in 1968. The Co-operative Building Organization of the Swedish Trade Unions and the Swedish National Testing Institute carried out certain preliminary measurements in order to gain further information on the usability of the method. At the Swedish National Testing Institut, development was carried out with the object of elucidating in greater depth the conditions governing thermography of buildings, and to put forward proposals for the interpretation of thermal images. Some of this work has been described in the Report "Thermography of buildings" /12./, published in 1972.

This investigation was performed with the object, among others, of determining the usability and reliability of the IR camera in the field, and to lay down a procedure for the thermography of buildings so that it may be used in the field in a routine manner.

There has been a marked increase in recent years in the interest shown in thermography. It has become increasingly common for thermography to be specified in contract documents, and for the method to be used for the settling of disputes between buyer and seller. Swedish Building Code SBN 1975 recommends the use of the IR camera for special checks regarding the insulation and airtightness of buildings.

Thermography has been found to be a useful and reliable method for the investigation of the insulation and airtightness performance of a building, provided that it is applied in the correct manner. By using thermography in conjunction with building control, building owners and building firms can make large savings. The method can be used in connection with the development of new products and materials. Thermography gives the owner of a property an opportunity to obtain evidence that the building possesses the promised insulation and airtightness properties.

The method will probably attain great importance as part of the evidence in legal disputes. Owing to new requirements concerning the economic use of energy in buildings, and developments in the energy sector, it is likely that the method will be increasingly used in the future.

In 1978, the Swedish National Testing Institute and the Co-operative Building Organization of the Swedish Trade Unions each had 4 groups for work in the field. Each group comprises two persons (group leader and assistant), and is provided with an IR camera and the necessary auxiliary equipment. It is intended that a few more field groups should be formed over the next year or two. At present there are about 15 firms of consultants engaged on the thermography of buildings in Sweden.

The increased need for tests and checks by means of thermography places stringent demands on the method and its application. See Section 10.1, Swedish Standard. Rules have been laid down for the authorization of companies engaged on the thermography of buildings. See section 10.2.

Thermography has also been introduced in other countries, and interest in the method has been great. This has brought about international contacts with both research institutions and State authorities and companies, for instance in the US, Canada, France, Germany, Italy, Poland and the Soviet Union.

10.1 Swedish standard

In order to create the basis for uniform and correct application of the method of thermography, the Swedish National Testing Institute has collaborated in the preparation of a Swedish Standard (SIS 02 42 10). This Standard defines, inter alia, the instrument and its field of application, and the conditions which must be satisfied during the thermography of buildings. Rules for the interpretation and assessment of thermograms are also given. This Standard has been based on material obtained in our investigations.

As pointed out before, requirements need not be as stringent as those laid down in the Standard when the IR camera is used only for the location of points of air leakage. Investigations with the IR camera may be divided into two methods – one very accurate and the other less so – as follows:

A. Thermography with the object of investigating the insulation and airtightness performance of buildings according to the Swedish Standard.

B. Investigation with the IR camera with the object of locating only points of air leakage in the climatic envelope of a building. The fundamental requirement for this is that there should be sufficiently large differences in temperature and pressure in order that leakage of air through the construction may be detected. Such a method of lesser accuracy has also been referred to in the Standard.

It should be pointed out that the Standard is not compulsory, and that, in practice, thermography will be used in different types of commissions, such as:

1. In special control of the airtightness and thermal insulation of buildings in accordance with the guide lines laid down in the Comments to Swedish Building Code, SBN 1975, 1977:3.
2. As a result of clauses to this effect in contract documents, etc.
3. In legal disputes between the buyer and seller of a building.
4. In continuous checks on the insulation and airtightness during the construction stage. Detailed checks. Checking the effect of remedial measures, etc.
5. For the location of points of air leakage only, e.g. in combination with pressure measurements.
6. In existing buildings where improvements are to be carried out as a result of the requirement concerning economic use of energy, and in conjunction with modernization measures.

Thermography in conformity with the Swedish Standard should primarily be carried out in cases 1, 2 and 3. Deviations from the Standard can naturally be made, for instance in special measurements according to 4, 5 and 6.

10.2 Authorization for the thermography of buildings

The staff carrying out thermography must possess special competence. The method comprises stages where judgment must be exercised, needing specialist knowledge and experience in the fields of building technology, building physics, heating and ventilation technique, and the technique involved in thermography. Application of the method may also necessitate supplementary investigations, chiefly for the quantitative determination of the thermal resistance of building elements, and for determination of the airtightness of buildings.

In order to lay the foundations for correct application of the method of thermography, the Swedish National Testing Institute has drawn up rules for authorization in conjunction with the thermography of buildings. The exact formulation of the authorization rules is given in publication SPFS 1978:2 of the Institute, "Regulations concerning authorized test sites for the thermography of buildings".

It is the task of the Swedish National Testing Institute to exercise supervision of work performed at authorized test sites.

Authorization imposes demands concerning training and the attendance of courses. The Institute has therefore organized courses with the object of training team leaders for thermography at authorized test sites. The aim is to provide the requisite information in the areas concerned.

The aim of the authorization procedure is to increase the use of thermography in checking the insulation and airtightness of buildings, and to enhance confidence in the method. The authorization is also of value in assessing the competence of thermography consultants.

The Institute granted the first authorizations in the autumn of 1978.

10.3 Work within the framework of Nordtest and ISO

In the Nordic countries, the above Swedish Standard has been adopted as a Nordtest method.

At an ISO meeting in Stockholm in April 1976, a proposal was put forward to make the thermographic method described above an international standard. The method and principle of thermography should be described, the measuring conditions specified, and rules drawn up for the interpretation and assessment of thermograms.

At an ISO meeting in Berlin in May 1977, a Working Group was set up to examine thermography. This working group includes representatives from Austria, Canada, France, Germany, Italy, USA and Sweden. The working group has prepared a draft international standard, and this was discussed at an ISO meeting in the autumn of 1978.

11 Appendix

FIG. 125 shows the appearance of the thermograms obtained with different IR camera settings.

FIG. 126 shows the calibration diagram over the temperature range + 5°C to + 25°C for the AGA THV 750 camera, including an application example. This diagram has been specially prepared for the IR camera used in these investigations.

FIG. 127 shows a diagram for the saturation temperature of air at different air temperatures and relative humidities.

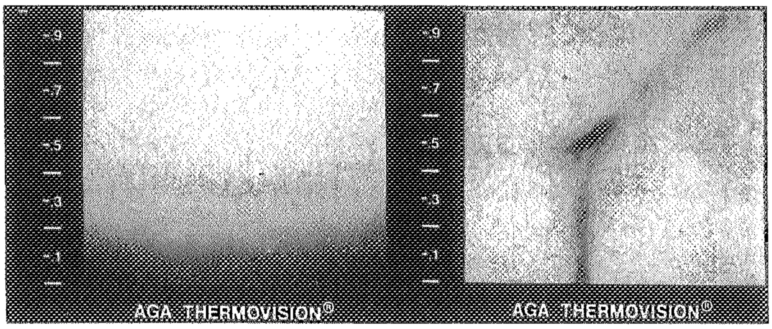
FIG. 128 shows the transmissivity in air as a function of distance.

On p. 218, a form is shown on which thermograms can be mounted when a report is drawn up.

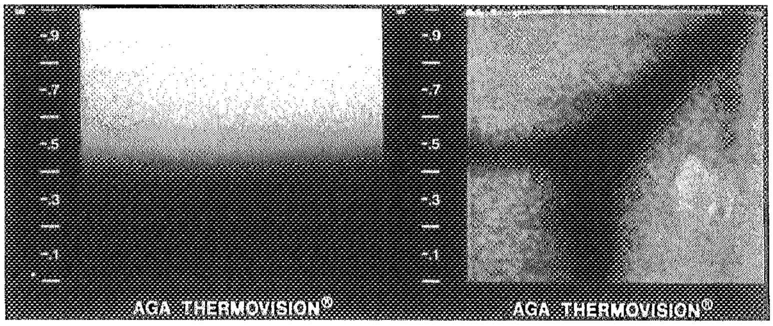
TABLE 17 a gives values of the emissivity of some common surface materials. The emissivity has been determined with the IR camera.

Data concerning some building materials are given in TABLES 18–20.

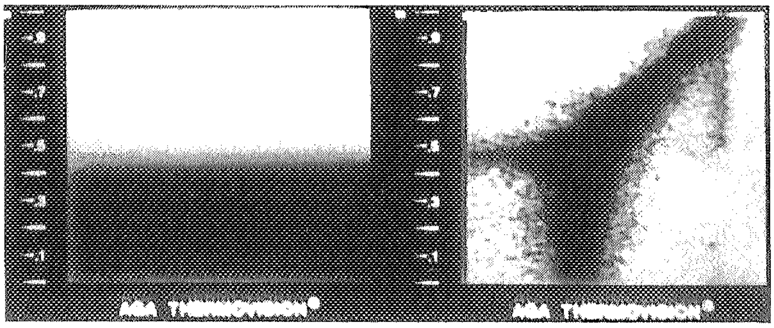
Fig. 125. Examples of variation in appearance of thermogram depending on different settings of the grey scale.



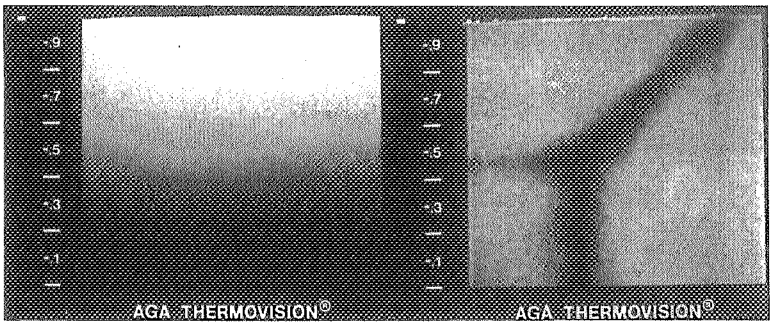
a) Contrast too low.



b) Contrast too high.

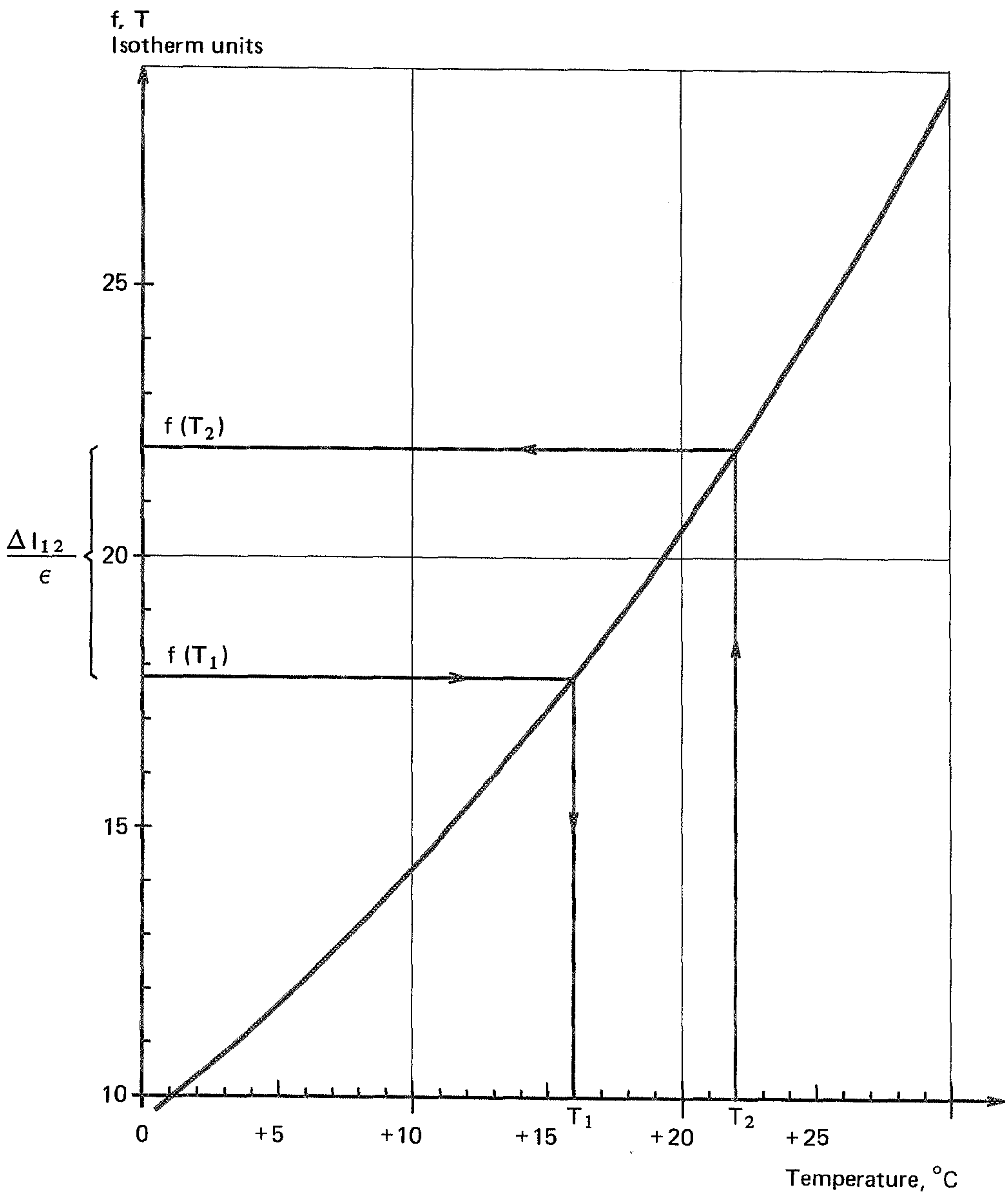


c) Contrast and brilliance too high.



d) Correct setting and grey scale.

Fig. 126. Calibration diagram in the region 273–303 K (0–30°C) for AGA THV 750 (aperture f/1:8) with application example.



Example (see Equation 3.2)

T_2	= 295 K (= 22°C), temperature at point 2 (reference temperature)
$f(T_2)$	= 22.0 isotherm units
$\Delta I_{1,2}$	= 3.8 isotherm units
ϵ	= 0.9
$f(T_1)$	= 17.8 isotherm units
T_1	= 289 K (= 16°C), temperature at point 1

Fig. 127. Saturation temperature of air at different relative humidities and air temperatures.

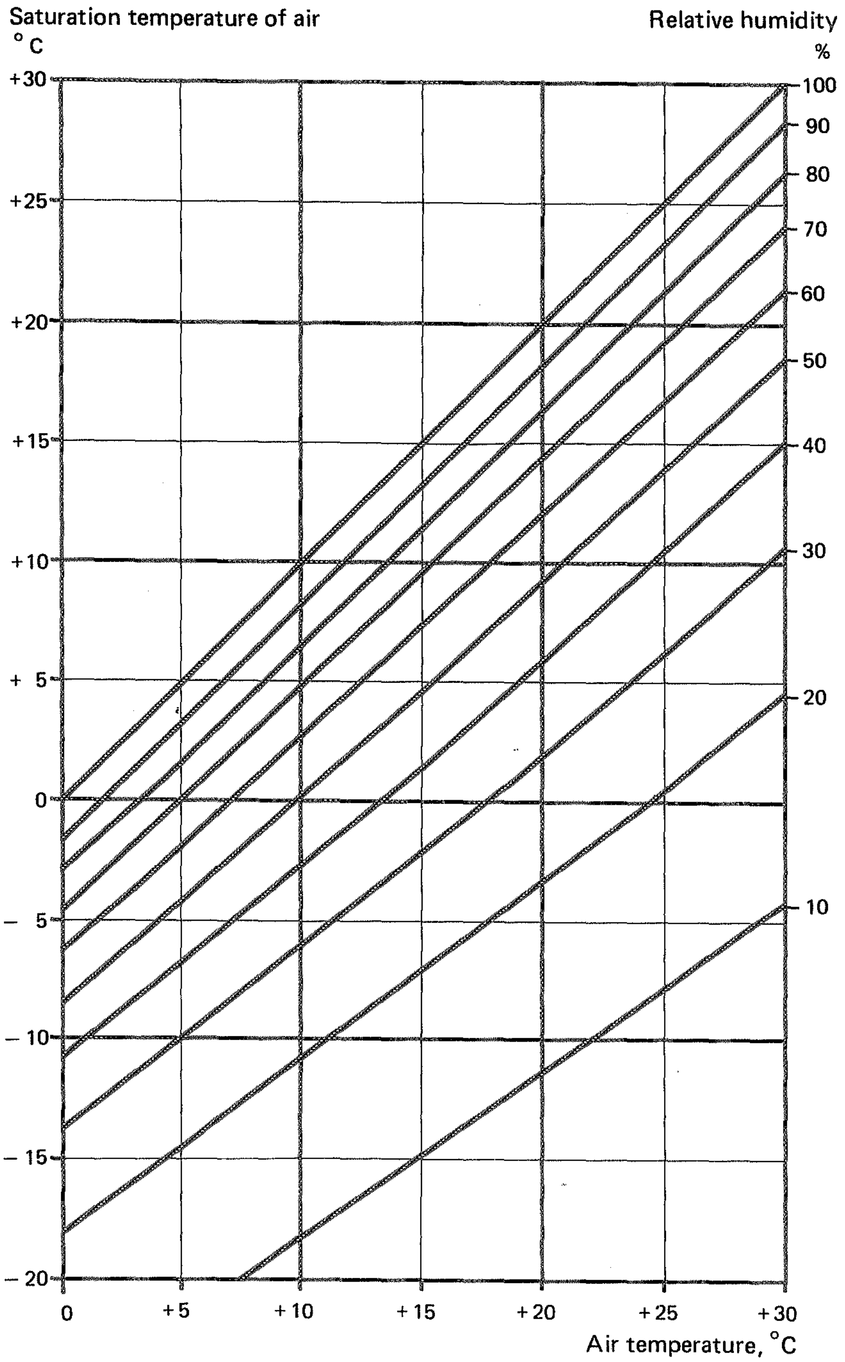
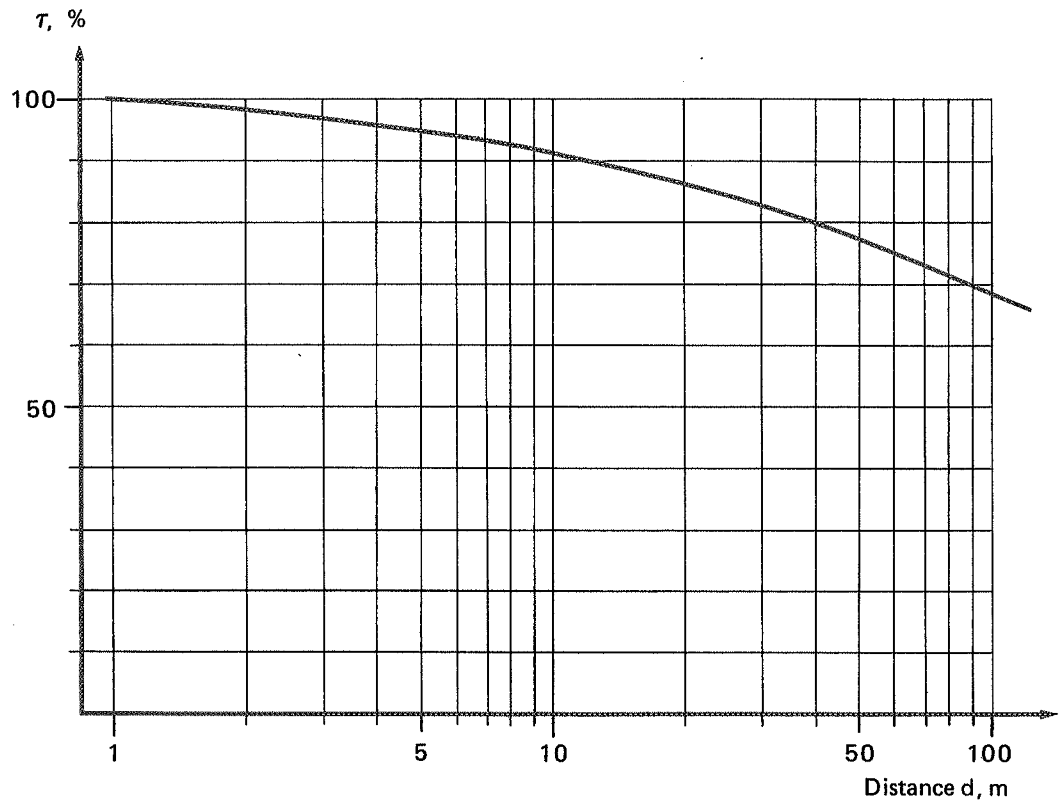


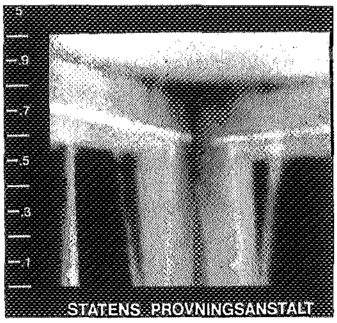
Fig. 128. Transmissivity (τ) for radiation in air as a function of the distance (Typical curve).

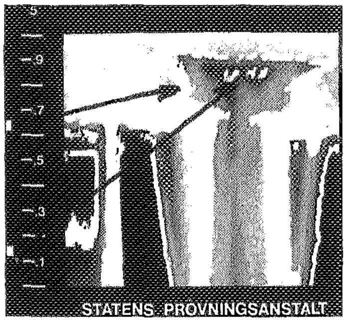


OBJECT SINGLE-FAMILY HOUSES — APPENDIX 1

REPORT NO. ______

MONOCHROME IMAGE No. 1 — ISOTHERM IMAGE No. 2





HOUSE/~~FLAT~~ 1
CORNER OF CEILING IN LIVING ROOM

P A

t_u -6 t_i +25 t_r +24

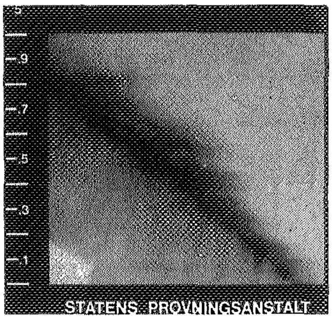
$t_i - t_u$ 31 Δp -5

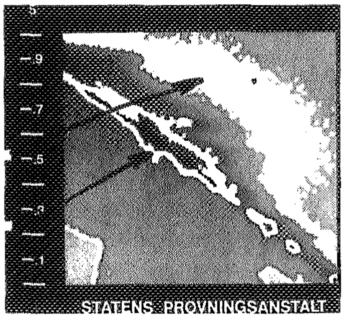
ΔI -2.5 Δt 3.5

v ≈ 0,2 (AT CORNER OF CEILING)

- [ ] EXPECTED TEMPERATURE DISTRIBUTION ON THE SURFACE AT ______
- [x] COLD SECTIONS AT CORNER OF CEILING (AIR LEAKAGE) (≈30 %)
- [ ] COLD SECTIONS AT THE JUNCTION ______ (%)
- [ ] AIR LEAKAGE THROUGH LEAKING JOINT AT ______ (%)

MONOCHROME IMAGE No. 3 — ISOTHERM IMAGE No. 4





HOUSE/~~FLAT~~ 1
CORNER OF CEILING IN LIVING ROOM

P B

t_u -6 t_i +25 t_r +24

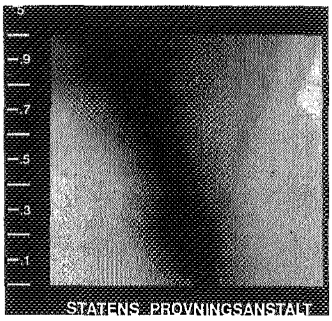
$t_i - t_u$ 31 Δp -5

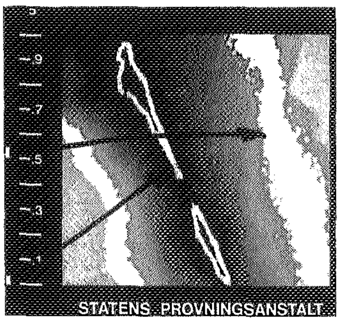
ΔI -1.4 Δt 2.0

v 0

- [ ] EXPECTED TEMPERATURE DISTRIBUTION ON THE SURFACE AT ______
- [x] COLD SECTIONS AT CEILING (AT JUNCTION WITH THE FLOOR STRUCTURE) DUE TO AIR LEAKAGE (≈30 %)
- [ ] COLD SECTIONS AT THE JUNCTION ______ (%)
- [ ] AIR LEAKAGE THROUGH LEAKING JOINT AT ______ (%)

MONOCHROME IMAGE No. 5 — ISOTHERM IMAGE No. 6





HOUSE/~~FLAT~~ 1
CORNER OF FLOOR IN LIVING ROOM

P C

t_u -6 t_i +25 t_r +23

$t_i - t_u$ 31 Δp -5

ΔI -2.5 Δt 4.0

v 0.2 - 0.3 (AT CORNER OF FLOOR)

- [ ] EXPECTED TEMPERATURE DISTRIBUTION ON THE SURFACE AT ______
- [x] COLD SECTIONS AT CORNER OF FLOOR (AIR LEAKAGE) (≈40 %)
- [ ] COLD SECTIONS AT THE JUNCTION ______ (%)
- [ ] AIR LEAKAGE THROUGH LEAKING JOINT AT ______ (%)

Table 17. Values of the emissivity over the wavelength region 2–5.6 μm for some common surface materials. /12./

Surface material	Emissivity
Fibre board (porous), untreated	0.85
Fibre board (hard), untreated	0.85
Plywood, untreated	0.83
Redwood (wrought), untreated	0.83
Redwood (unwrought), untreated	0.84
Gypsum wallboard, untreated	0.90
Chipboard, untreated	0.90
Filler, white	0.88
Oil paint, grey flat	0.97
Oil paint, grey gloss	0.96
Oil paint, black flat	0.94
Oil paint, black gloss	0.92
Plastic paint, white	0.84
Plastic paint, black	0.95
Varnish, flat	0.93
Wallpaper (slight pattern), light grey	0.85
Wallpaper (slight pattern), red	0.90
Plastic wallpaper, white	0.84
Plastic wallpaper, red	0.94
Hessian fabric, uncoloured	0.87
Hessian fabric, green	0.88
Facing bricks, red	0.92
Facing bricks, yellow	0.72
Plaster, grey	0.92

Table 18. Extract from Comments on SBN, 1977:3.

Table B 33. 1c. Practical values of thermal conductivity λ_n for some other building materials.

Material	Density ρdry kg/m³	Average thermal conductivity of dry material $\lambda 10$ W/m °C	Moisture ratio u_n %	Practical value of thermal conductivity λ_n W/m °C
1	2	3	4	5
Asbestos cement sheets	1 800	0.40	2	0.60
Asbestos silicate sheets	800	0.13	4	0.19
	660	0.12	4	0.18
Mastic asphalt	2 100			0.8
Bitumen	1 050			0.18
Window glass	2 600			0.8
Wood (heat flux perpendicular to fibres)				
pine, spruce	500	0.12	16	0.14
beech, oak	700	0.14	18	0.16
Chipboard	600	0.13	10	0.14
	400	0.11	10	0.12
Wood wool slabs, internal with impervious surface layer	151–200		8	0.075
	201–300		8	0.075
	301–350		8	0.080
without impervious layer, installed horizontally, heat flux downwards	151–200		8	0.075
	201–300		8	0.075
	301–350		8	0.080
without impervious layer, other applications	151–200		8	0.095
	201–300		8	0.075
	301–350		8	0.085
Fibre board				
hard	1 000	0.12	8	0.13
semi-hard	600	0.075	9	0.080
porous	300	0.045	10	0.050
bitumen impregnated	400	0.055	10	0.065
Cork slabs, expanded	200	0.040	3	0.046
	140	0.035	3	0.040
Cork parquet	500	0.075	10	0.080
Straw slabs, internal	300	0.085	10	0.090
Cellular glass	180	0.060		0.065
Cellular glass	150	0.055		0.060
Cellular glass	130	0.050		0.055
Sheets of mineral fibre	400	0.040	1	0.050
Mineral wool	15–200		0.5	0.055
Expanded polystyrene	12–40		2	0.055
Expanded polyurethane	30–50			0.040

Table 19. Extract from Comments on SBN, 1977:3.

Table B 33. 1 d. Practical values of thermal conductivity λ_n for fill material

Material	Density	Average thermal conductivity of dry material	Moisture ratio	Practical value of thermal conductivity
	ρdry kg/m³	λ10 W/m °C	u_n %	λ_n W/m °C
Fill				
sand	1 700		0.5	0.40
shale ash	1 000		2	0.25
clinker	700		3	0.25
crushed gas concrete	400		4	0.15
Expanded clay				
in floor, unventilated	450	0.10	0.5	0.13
	330	0.09	0.5	0.10
	280	0.08	0.5	0.09
in floor, ventilated	330	0.09	0.5	0.12
on ground, unventilated	330	0.09	6	0.13
	280	0.08	6	0.12
Granulated blast-furnace slag	250		0.5	0.12
	150		0.5	0.10
Sawdust, loosely packed	120		12	0.12
compacted	200		12	0.18
Wood shavings, loosely packed	80		12	0.14
compacted	120		12	0.08
Expanded polystyrene, compacted pellets on floor	10–20		2	0.06
Urea-formaldehyde foam	7–14			g

Table 20. Extract from Comments on SBN, 1977:3.

Table B 33. 1 e. Practical values of thermal conductivity for thermal insulation materials subject to official quality control.

Material Type of construction	Quality group for insulation material	Average thermal conductivity of dry material $\lambda 10$ W/m °C	Moisture ratio u_n %	Practical value of thermal conductivity λ_n W/m °C
1	2	3	4	5
Cellular glass		*k*		
sheets laid in	C		–	0.052
bitumen, joints	D		–	0.057
max 1 mm	E		–	0.062
Expanded polystyrene		*k*		
sheets glued or cast	A		2	0.038
onto impervious	B		2	0.043
material layer above ground	C		2	0.048
other use above	A		2	0.040
ground	B		2	0.045
	C		2	0.051
sheets laid between concrete floor tile and drained soil	A		2	0.042
Mineral wool				
hard sheets glued or cast onto impervious material layer above ground[h]	A	*k*	0.5	0.038
other use above	A		0.5	0.040
ground	B		0.5	0.045
	C		0.5	0.051
hard sheets placed between foundation wall and drained soil[i]	A		1.0	0.060
hard sheets placed between concrete floor tile and drained soil[i]	A		0.5	0.042
Gas concrete				
insulation slabs	400	*k*	4	0.10
internal and external	450		4	0.12
with rain protection	500		4	0.14
	600		4	0.17
external above	400		6	0.11
ground	450		6	0.13
	500		6	0.15
	600		6	0.18
external below	500		30	0.24
ground[a]	600		30	0.27

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