INFRARED THERMOGRAPHY AND THERMAL INSULATION IN BUILDINGS

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Foreword

The present report gives a summary of the work in building thermography in the Scandinavian countries, especially Sweden. The report deals with the principles of thermography, how to detect thermal resistance deficiencies and air leakage. Application in building and the influencing factors are especially discussed. Test requirements in Scandinavia and the experience with the test technique is discussed.

The report is based on the work done at the Swedish National Testing Institute under a period of nearly ten years. During this time the main responsibility for developing the test method and making it suitable for field tests has been that of Bertil Pettersson, research scientist at the Institute. The report therfore presents parts from earlier work as well as not previously published results. Part of the material has been presented at various meetings at the ASTM, CIB etc.

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INTRODUCTION

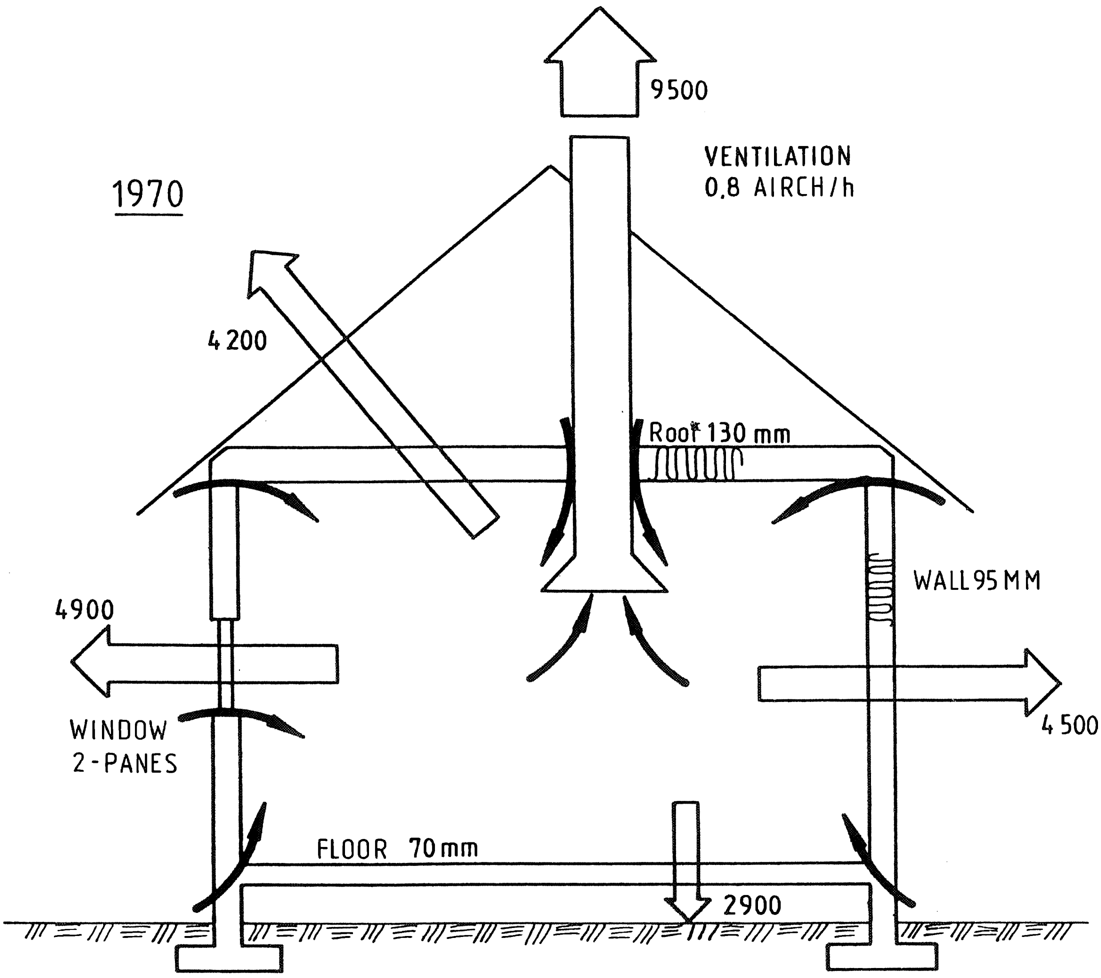
Heating of buildings constitutes nearly half of the total energy consumption in Sweden. Industrial progress, increased requirements of comfort and dwelling space has raised the energy consumption by 4-5 % a year to a present level of about 450 TWh. Changes in the price of energy in recent years and its availability have stressed the need for energy conservation especially in buildings.

Energy consumption in a building is mainly due to transmission losses through the building envelope and to ventilation, either through the ventilating system or through air leakages in the building envelope. The energy balance is also influenced by sonsumption of water, use of appliances, human beings, etc.

Fig. 1 shows examples of the energy loss in a one-family building according to common design practice at the beginning of 1970 and according to the 1978 requirements of the Swedish building code. The building is normally a light weight crossbar structure with insulation of mineral wool. The thermal standard is therefore indicated in mm mineral wool for walls, floors and ceilings.

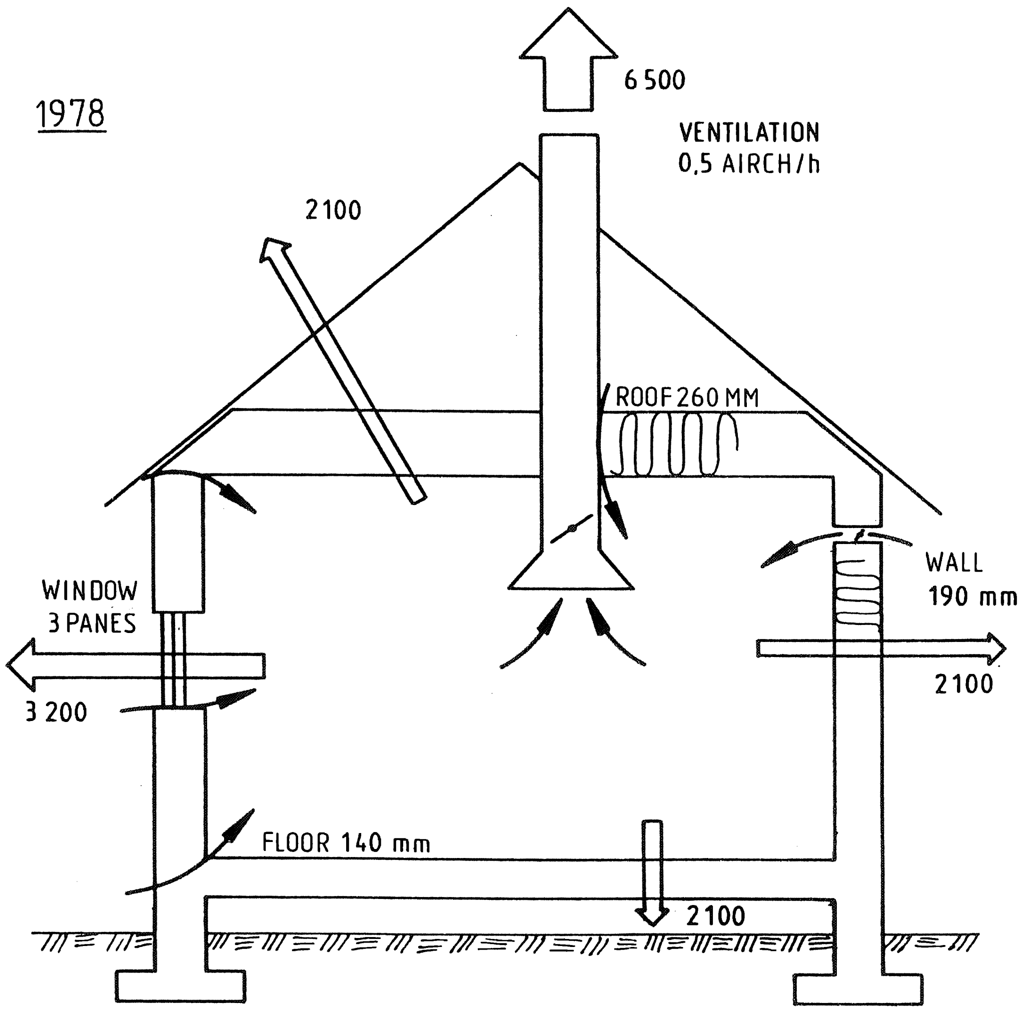
The figures show a marked increase in thermal insulation, triple glazed windows instead of double glazed, and a decrease in ventilation from 0.8 to 0.5 air changes per h. The heat losses due to ventilation and air leakages are the most difficult to evaluate. They normally correspond to 30 or 40 % of the total heat loss.

Basic conditions for achieving optimal thermal insulation and air tightness in practice are appropriate design rules and that the intended insulation and air tightness performance is really achieved in practice. This will depend upon the design solution, the choice of materials and the workmanship.



TRANSMISSION:	16 500 kWh
VENTILATION:	9 500 -"-
	26 000 kWh

FIG. 1A TRANSMISSION AND VENTILATION LOSSES IN A ONE-FAMILY HOUSE, 125 M^2, BUILT ACCORDING TO PRACTICE IN 1970



TRANSMISSION : 9 500 kWh
VENTILATION: 6 500 -"-
16 000 kWh

FIG 1 B TRANSMISSION AND VENTILATION LOSSES IN A ONE-FAMILY HOUSE, 125 M², BUILT ACCORDING TO PRACTICE IN 1978

In highly insulated structures and with high reguirements of air thightness it has been shown that it is especially important to avoid deficiencies in order to obtain the intended degree of energy consumption.

The importance of energy conservation in buildings has required development of testing methods for verifying the thermal performance of building elements and buildings, especially test methods to be used in field practice to take into account the influence of workmanship.

During the past years development and investigations in this direction have been made at the Swedish National Testing Institute (statens provningsanstalt). The work in the field has been based on infrared "thermography" of buildings. To this test is added facilities for measurement of air leakage and the thermal resistance value on part of the building envelope. Thermography is used mainly to investigate the thermal performance of the building. This is done by observing the temperature distribution over surfaces on the building envelope. The method gives a qualitative indication of insulation defects, cold bridges, points of air leakage and areas of moisture damage. The thermographic inspection does not give absolute values of the thermal resistance of the structure, only relative information. It also requires certain climatic conditions around the structure being tested. This depends on to what extent thermal irregularities are to be located.

The development of the thermography method was started in 1968. The purpose was to find rules for interpretation of the indicated temperature distribution. This was done by laboratory measurements. The next step was to find the application possibilities in practice and describe the measurement procedure. This work was later followed by a third part describing different effects influencing the evaluation of the measurements and presenting experience and results from practical thermography in existing buildings.

THERMOGRAPHY

Thermography is a method of indicating and representing the temperature distribution over a part of the envelope by means of an infrared sensing system. The thermal radiation, which depends on the surface temperature, is converted by the infrared radiation sensing system and a thermal image is produced.

The method is a qualitative test method for detecting thermal irregularities in building envelopes, and is used in the first place to find wide variation in the thermal insulation properties and the air tightness. The results obtained have to be interpreted and assessed by persons who are specially trained for this purpose. In order to quantify the degree of thermal insulation and air tightness of a structure, supplementary investigations by other means are required.

Determination of energi emitted by surface with a temperature of around 20 ^{o}C, i.e. in the temperature range which is of interest in building technology is possible with modern infrared cameras. They have a sensitivity range of 2-5.6 µm, which corresponds to temperatures much lower than those visible to the human eye (Fig. 2). The infrared camera is provided with a scanning system which continously scans and focusses several frames per second, each containing about 10000 picture elements. These signals are converted in a display unit to a monochrome image on the screen of an oscilloscope. In this way a detailed thermal image or thermogram is produced (Fig. 3). In the thermal image, the grey density is a function of the energy emitted and therefore also of the temperature of the different parts of the surface under examination. The temperature rang of the IR-kamera is approximately -30 ^{o}C to +2000 ^{0}C, and near +20 ^{o}C the camera indicates the temperature with a resolution that is better than 0.2 ^{o}C.

In order to facilitate measurement of differences in tempera-

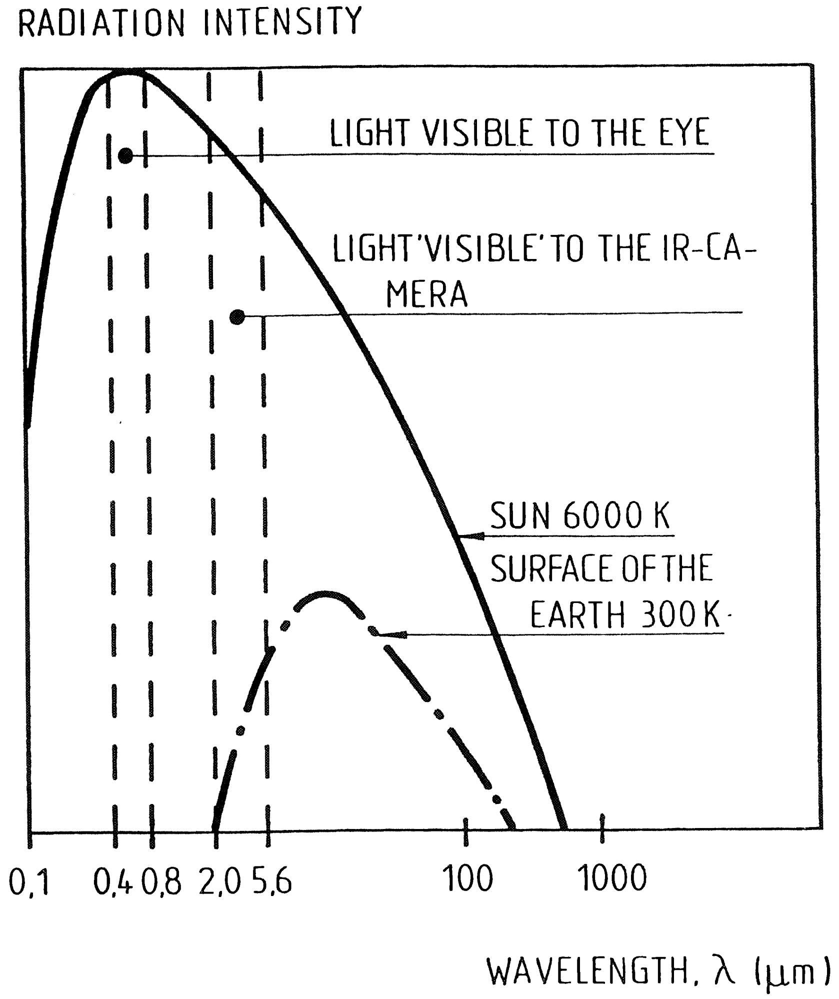
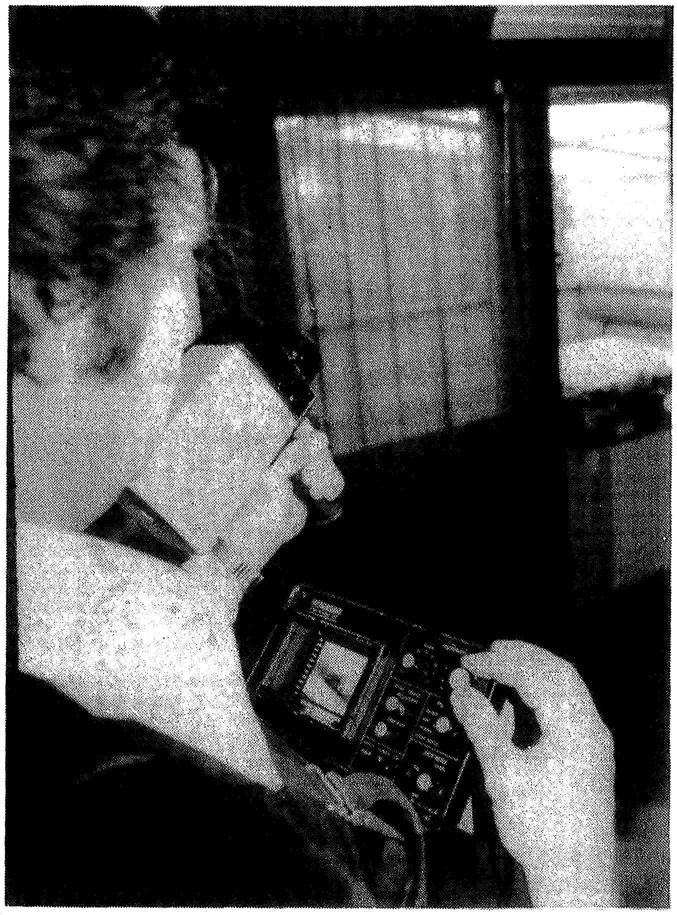
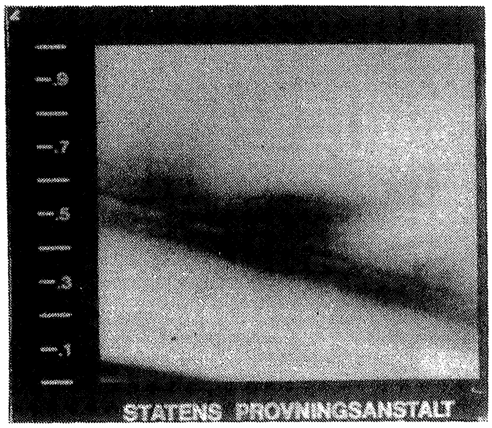


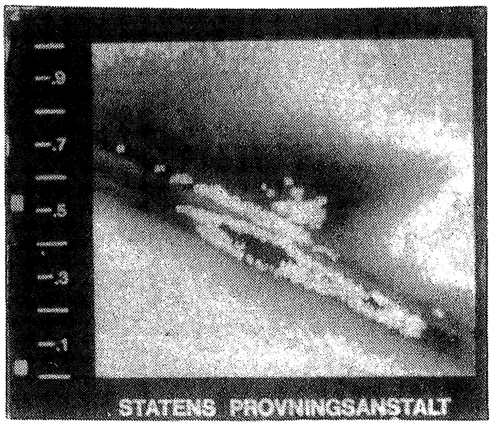
Fig. 2 Intensity of radiation emitted by an ideal black body at different temperatures as a function of the wavelength.



3 a) Thermographic inspection of wall and ceiling. The thermal image is presented on the display of the oscilloscope.



3 b) Thermogram of an area of wall/ceiling. No imposed isotherm (monochrome image).



3 c) Thermogram of the same area as in b with two isotherm markings (isotherm image).

Fig. 3 Thermography in building and thermograms.

ture between different parts of the surface, the IR-camera is equipped with an isotherm function. With the aid of this, parts of the surface which give the same radiation can be marked in the thermogram. An isotherm image is obtained (Fig. 3 c). The isotherms can be set at any temperature and a variable temperature range can be covered in the image. Some types of cameras are equipped with two isotherm functions. The method used to find the real temperature in °C is shown in Fig. 4.

The size of the field of view is determined by the optical system of the camera. Experience of field tests has shown that a measuring field of at least 0,3 x 0,3 m with a resolving power of at least 10 mm from a distance of 3 m is sufficient.

The Swedish National Testing Institute has mainly used two types of IR-cameras, THV 680 and THV 750, manufactured by the AGA company. The function of the two models is about the same. THV 750 is a small and portable equipment, suitable for field measurements. THV 680 is more suitable for laboratory work.

THERMAL RESISTANCE AND SURFACE TEMPERATURE

Considering one-dimensional heat flow between the warm (inside) and cold (outside) surface of a wall, it is easily shown that

$$t_{oi} = t_i - \frac{m_i \ (t_i - t_u)}{m_i + M + m_u}$$

$$t_{ou} = t_u - \frac{m_u \ (t_i - t_u)}{m_u + M + m_u}$$

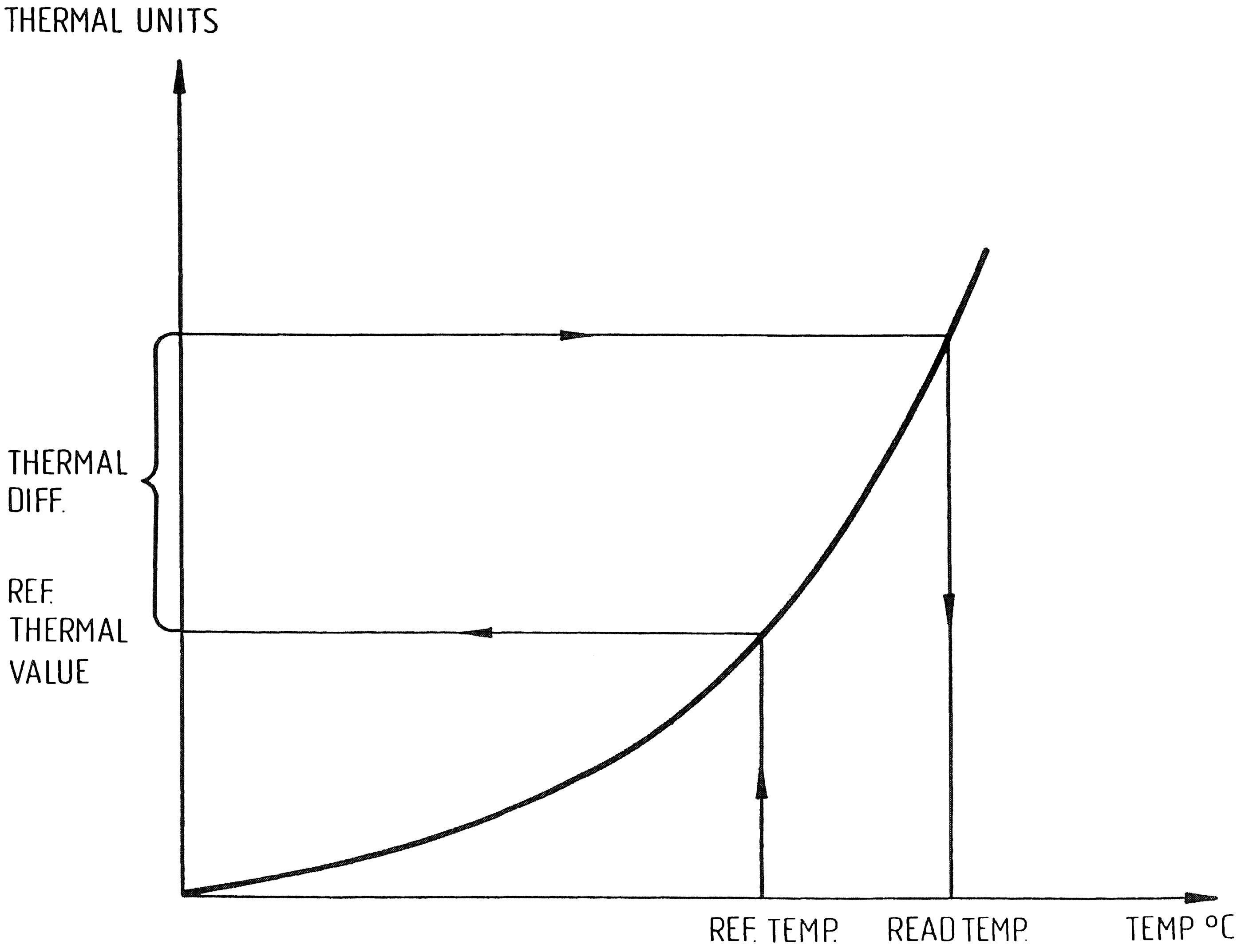


Fig. 4 Translation of measured "thermal" value into temperature value.

where

m_i surface resistance at the warm surface of the wall

m_u surface resistance at the cold surface of the wall

M thermal resistance of the wall

t_i air temperature on the warm side

t_{oi} surface temperature of the wall on the warm side

t_{ou} surface temperature of the wall on the cold side

t_u air temperature on the cold side

The temperature resolution of the IR-camera near room temperature is about 0.2^{o}C. On the basis of this information, it is possible to determine the least reduction in the thermal resistance of a wall which the IR-camera will detect under different conditions.

It is evident that there must always be a certain minimum difference in temperature between the air in the room and that outside, in order that the required resolution may be attained during thermography. The relation between the available temperature gradient across the wall and the lowest detectable reduction in thermal resistance is shown in Fig. 5. The figure shows the lowest detectable reduction in thermal resistance for different walls at different temperature drops across the wall. It is assumed in this figure that the surface resistance is 0.17 and 0.05 m^2 ^{o}C/W at the inside and outside of the wall, respectively.

AIR LEAKAGE AND SURFACE TEMPERATURE

During thermography of leakage defects, conditions are more favourable, particularly if the pressure in the room is lower

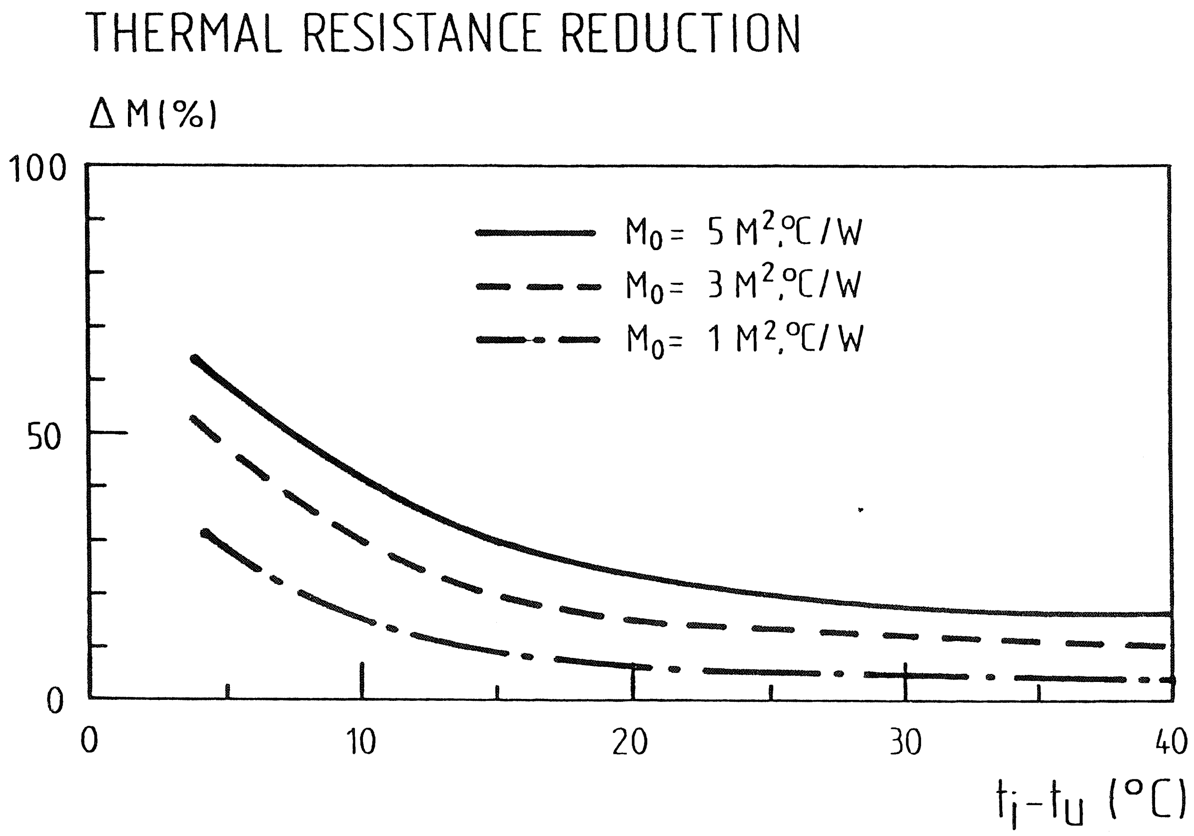


Fig. 5 Relation between lowest detectable reduction in thermal resistance and temperature drop over the wall.

than that outside. Since in this case external air comes into direct contact with the warm surface of the wall and cools this down, a difference in temperature of a few degrees between the air in the room and that outside is sufficient for a clear indication in the form of a lower surface temperature to be obtained.

THERMOGRAPHY IN BUILDINGS

Thermography of parts of buildings comprises the following operations:

- to determine the surface temperature distribution over a part of a building envelope with the aid of an infrared radiation sensing system
- to ascertain whether this surface temperature distribution is abnormal, that is to say, if it is due to e.g. insulation defects, moisture content and/or air leakage
- to estimate the type and the extent of such deviations

In order to find out whether the observed variations in the thermal insulation properties are abnormal, the thermograms obtained from tests are compared with the anticipated temperature distribution over the surface, determined by the design characteristics of the building envelope and by the environment at the time of measurement. The anticipated temperature distributions can be determined with the help of "reference thermograms", calculations or other investigations. This determination has to be based on drawings and other construction documents of the external envelope and the installations of the building under investigation.

Defects can be assessed by comparing the thermograms obtained from the actual measurements with reference thermograms relating to structures which are deliberately provided with thermal insulation defects and points of air leakage of various kinds. The general procedure in interpretation of thermograms is schematically represented in Fig. 6.

In practice the following procedure has been used.

On the basis of tests carried out in the laboratory (Fig. 7) a number of thermograms was prepared of typical walls including

- correctly built walls (examples see Figs 7 and 8)
- walls with deliberate defects (examples Figs 9 and 10)

The tests were made under certain climatic conditions and on typical external walls used in Sweden today: Crossbar walls with mineral wool insulation, sandwich wall with cellular plastics between concrete slabs and lightweight concrete blocks. The thermograms obtained were collected in a catalogue and used as reference thermograms.

An assessment of thermograms taken from a field measurement object is described in Fig. 11. Fig. 11a shows the thermograms of the wall surface taken on a site . On the basis of the drawing and of climatic conditions at the time of measurement (such as temperature and pressure gradient across the wall) an anticipated surface temperature distribution was established (Fig. 11b). This anticipated picture was compared with the previous thermograms. Differences appeared that were not explained by design and environment. They were noted as possible constructional defects.

The nature of insulation defects was determined by comparison with thermograms of commonly occuring typical insulation defects (Fig. 11c).

When interpreting a thermogram, the following features are

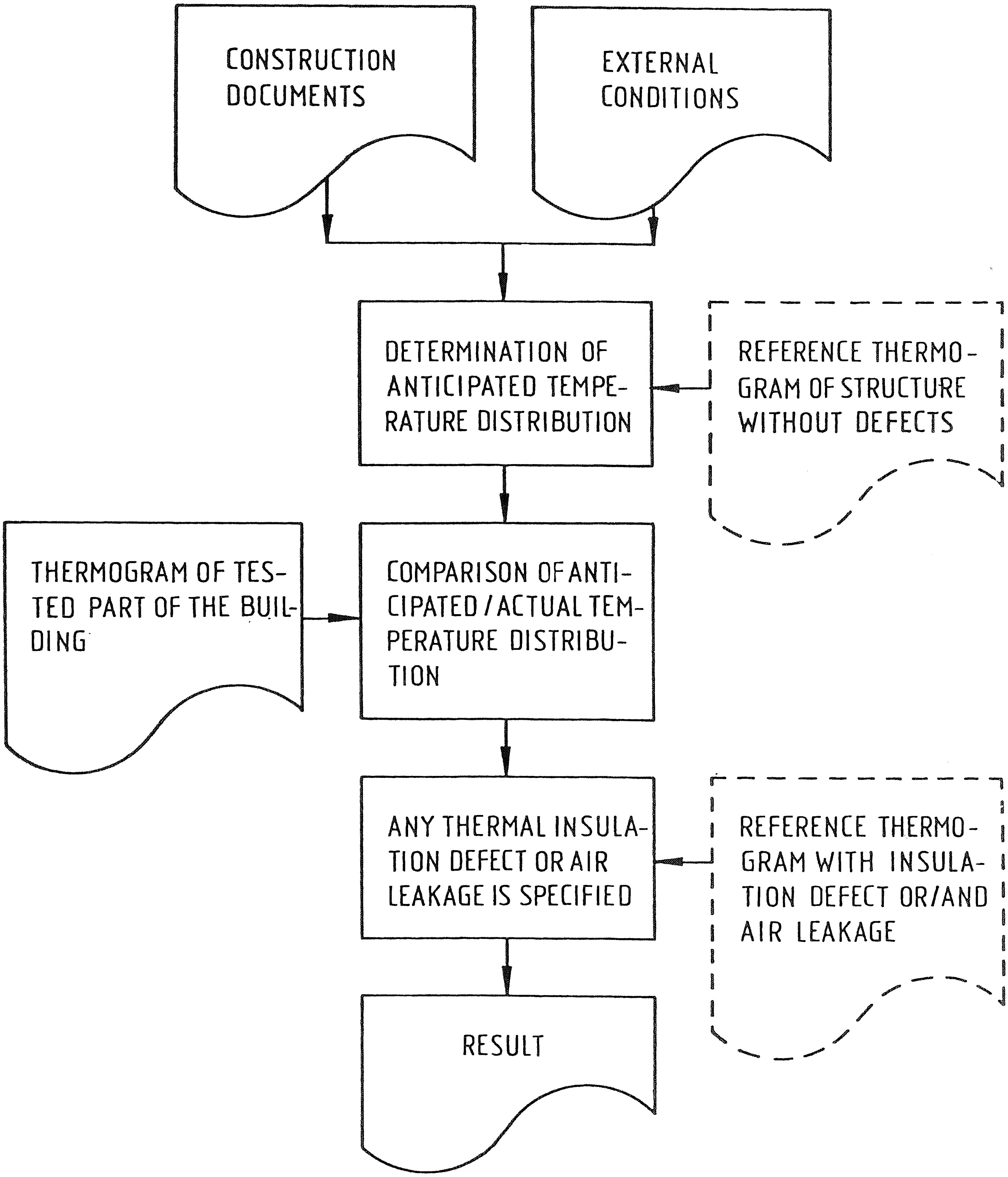


Fig. 6 General procedure in interpretation of thermograms. Dotted boxes indicate suggested use of reference thermograms.

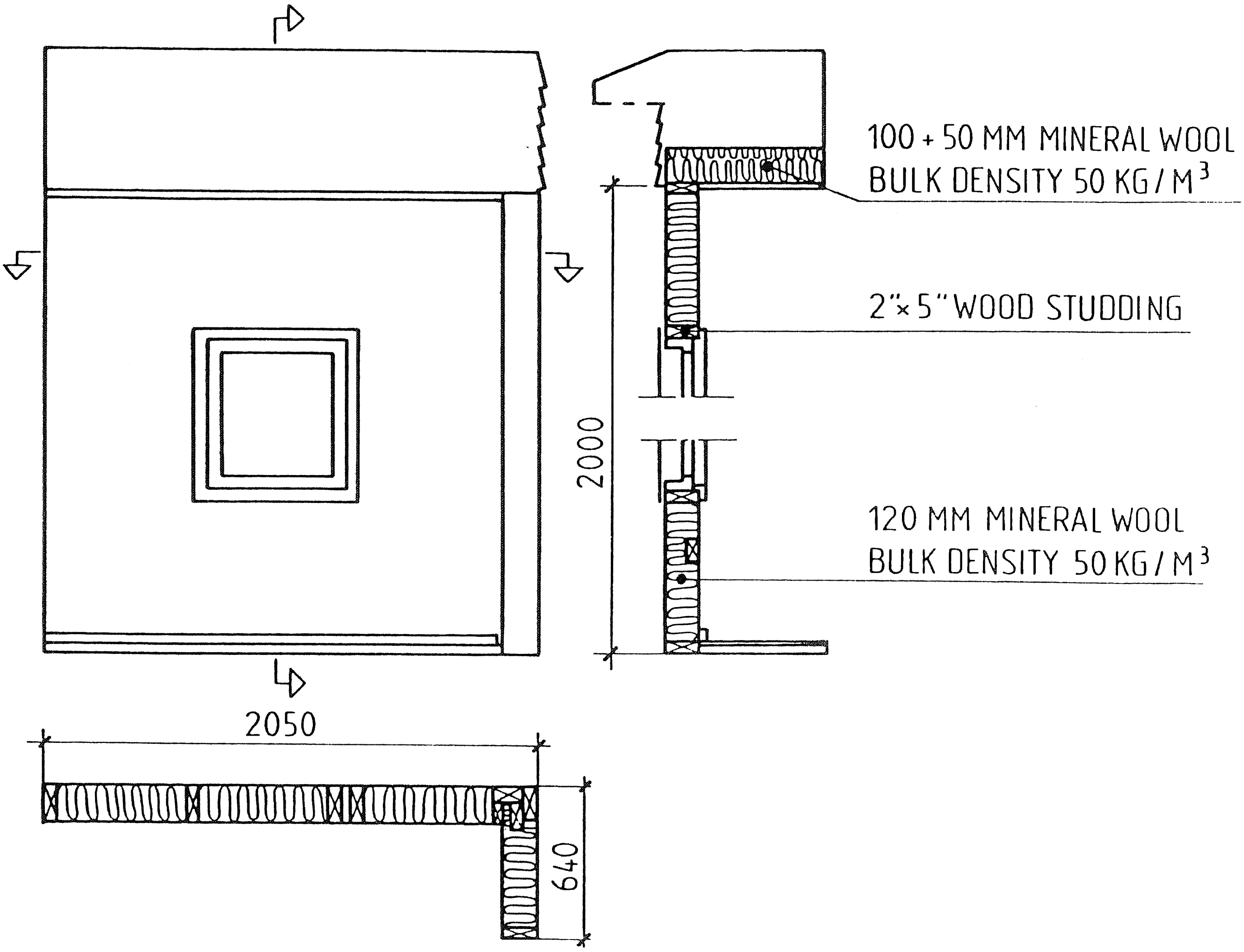


Fig. 7 Laboratory test wall

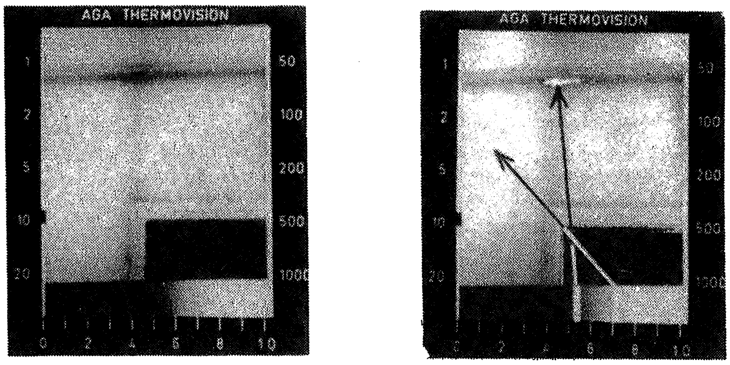


Fig. 8 Typical thermograms of portion of the test wall (fig.7) with correct design.

Difference in temperature (indoors-outdoors):
$t_i - t_u = 26^{\circ}C$
Difference in pressure (indoors-outdoors):
$P_i - P_u = -50Pa$

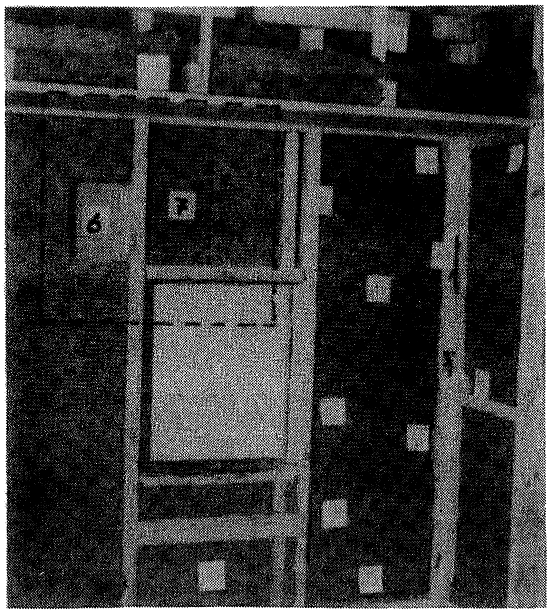


Fig. 9 Photograph of the test wall with plasterboard and plastic foil removed. The position of different types of insulation faults are shown. Notice faults 6 and 7 where 100 and 50% respectively of the original thickness is missing. The area shown in the thermograms (fig.10) are marked.

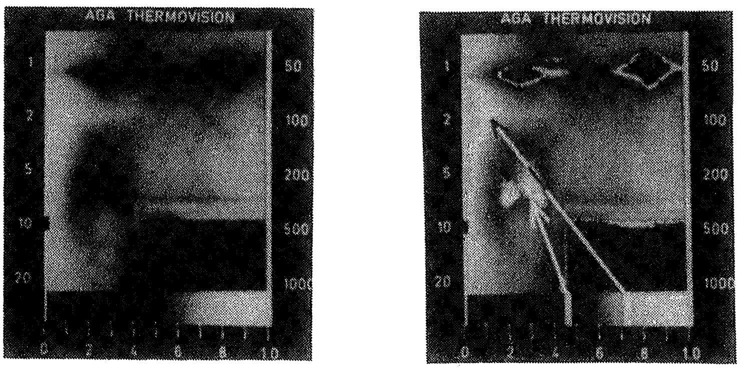
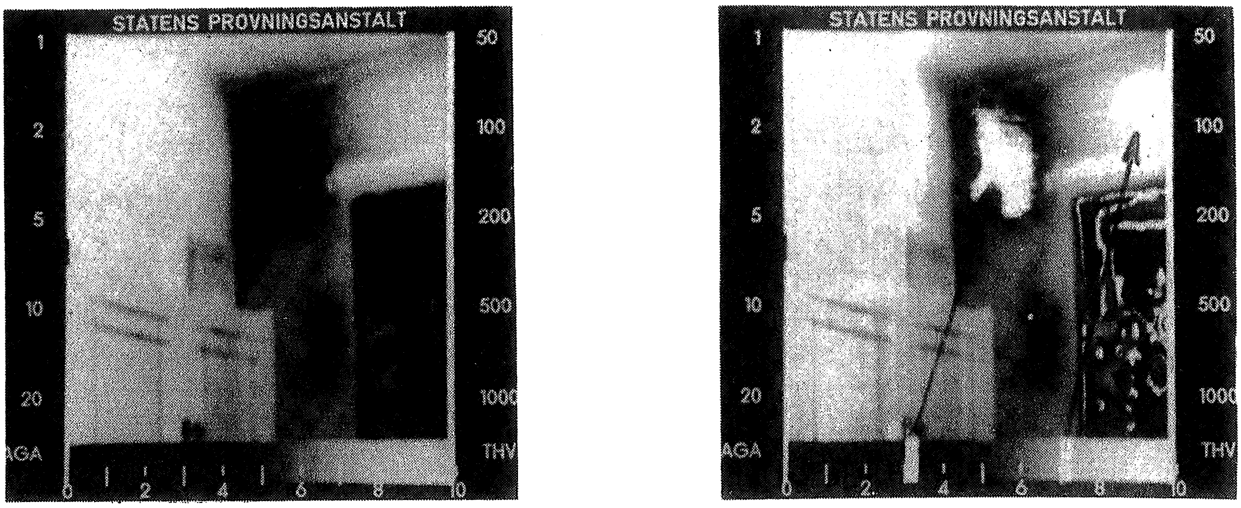
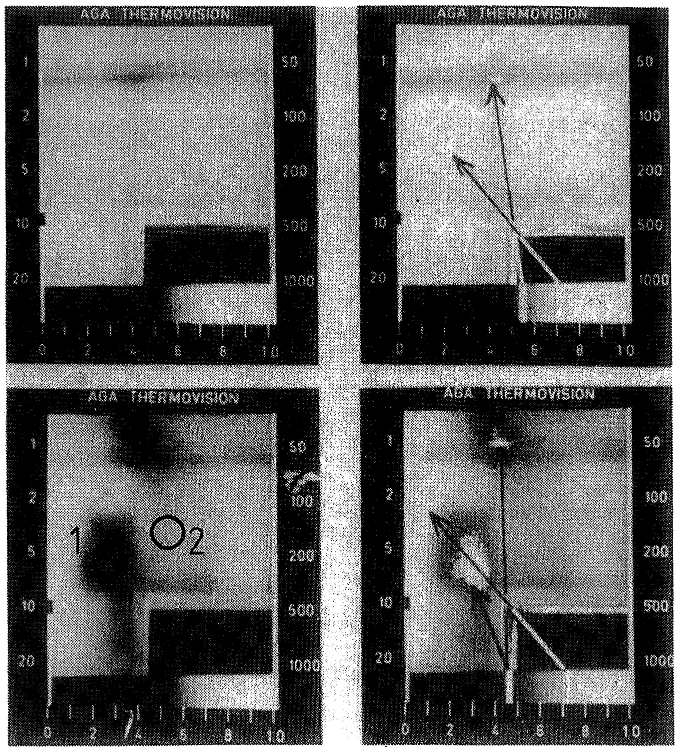


Fig. 10 Thermograms with deliberate faults (fig.9). Difference in temperature $t_i - t_u = 26^{\circ}C$. Difference in pressure $P_i - P_u = -50Pa$.



11a) Thermogram taken on part of an external wall near the corner. Cold (dark) areas are seen in the picture to the left of the window (monochrome image to the left, isotherm image to the right).
$t_i - t_u = 21^oC$, $P_i - P_u = -3$ Pa, $t_{ref} = 21^oC$, $\Delta t = 3.0^oC$ (difference in temperature on the surface.



11b) Typical thermograms of wall with correct design of the object of measurement

$t_i - t_u = 26^oC$
$t_{ref} = 20^oC$
$P_i - P_u = 0$ Pa
$\Delta t = 3.0^oC$

11c) Typical thermograms of building defect. Cf fig.11a

$t_i - t_u = 26^oC$
$t_{ref} = 20^oC$
$P_i - P_u = 0$ Pa
$\Delta t = 4.0^oC$

Fault No.1: 100% of the insulation missing
Fault No.2: 50% of the insulation missing

Fig. 11 Examples of assessment of a thermogram examined in the thermal image.

- The smoothness of the shade of grey in the image of areas where no cold bridges are present
- The regular shape and the place of cold areas where cold bridges are present in the building design and at the corners of the wall
- The contour and the characteristic form of the cold areas and the spread of the cold areas
- The difference in surface temperature between the cold area and the "normal" temperature of the wall surface
- The continuity and the pattern of the isotherm curves along the surface of the construction

A cold wall area caused by the absence of a whole insulation slab gives a regular shaped dark part of the thermogram as was shown in Fig. 11.

Air leakage through the structure often causes a local drop of surface temperature in the vicinity of the leakage point. The cooled area has often an uneven temperature distribution, giving an anomalous shape in the thermogram (Fig. 12).

Fig. 13 shows an example of cold air penetrating through an untight joint.

INFLUENCING FACTORS

When interpreting thermograms and determining the temperature distribution by the thermography method the emissivity of each material in depicted surfaces has to be considered. Laboratory investigations have been carried out in order to determine values of the emissivity applicable to the IR-camera

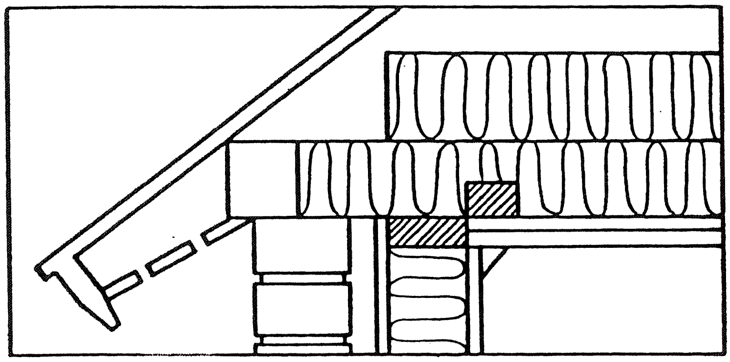


Fig. 12 a A framed wall with a 95 mm mineral wool insulation according to the construction drawing. The ceiling is insulated with 200 mm mineral wool slabs. In the figure below is shown what often happens in practice.

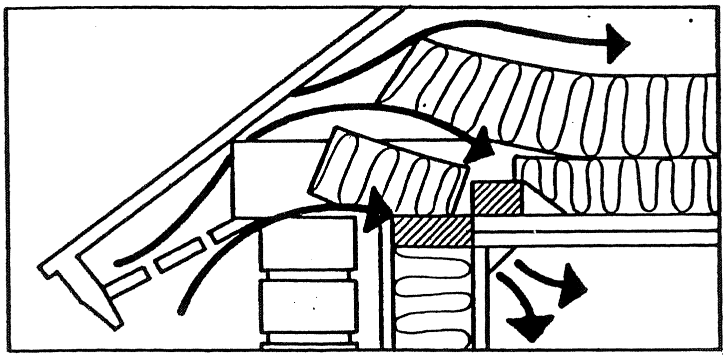


Fig. 12 b The insulation material at the eaves has not been properly fitted. Air enters between the mineral wool slabs, reducing the insulation capacity. The wall section and a portion of the ceiling become cold due to air leakage.

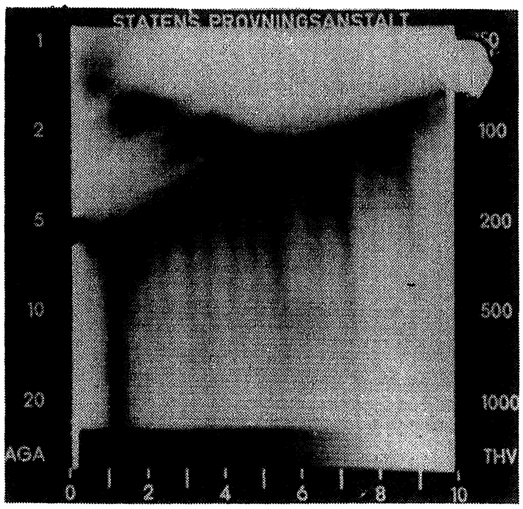


Fig. 12 c Thermogram from a section with defect. The measured difference between the "normal" surface temperature and the cold (dark) portion is about 3 °C. Air velocity measured at the ceiling is approximately 1.0 m/s.

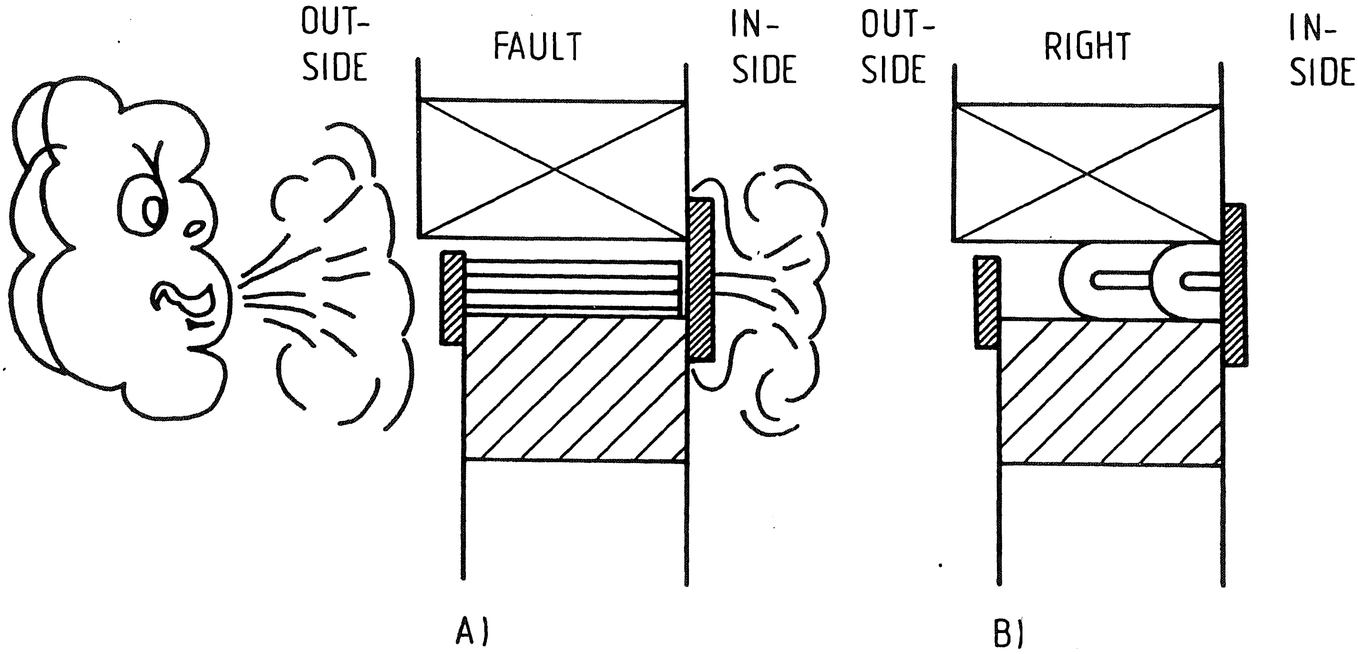


Fig. 13 a   Joint between door and wall section according to drawing (B), fitted in practice (A). Cold air leaks through the untight joint. The wall section near the door becomes cold due to air leakage.

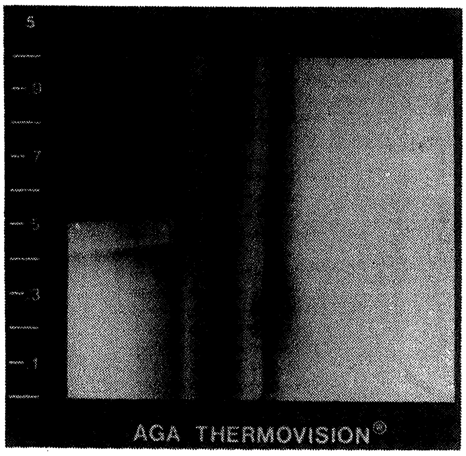


Fig. 13 b   Thermogram near the door. The measured difference between the "normal surface temperature and the cold portion is about 4^{o}C. Air velocity measured near the point of leakage is approximately 1.0 m/s.

for a number of common building materials. Most of the values of the emissivity were in the range 0,85 - 0,95.

The emissivity of glossy metal surfaces is low, 0,04 - 0,08. Measuring on such surfaces is difficult as most of the measured radiation is reflected radiation from the surroundings. If it is suspected that the variation of the radiation intensity is due to reflection, the surface in question may be studied from different positions of measurement. A reflection then changes its position on the surface. A cold area caused by a cold bridge or an insulation defect remains in the same position.

Measurement on glass give special problems. Normal window glass is transparent to radiation within the wavelength range 0 - 5 μm. Therefore, if thermography is carried out in the normal way, the thermogram of a window will also contain thermal radiation transmitted through the glass. This problem of measurement is best solved by fitting a radiation filter to the camera which screens incident radiation within the wavelength range 0 - 5 μm.

Thermography measurements from the outside are generally disturbed by outdoor atmospheric factors (rain, sun and wind). The surface coefficient of heat transfer at the outside of the structure is usually higher than that at the inside. This results in a greater surface temperature variation on the inside than on the outside.

When assessing a building by thermography the pressure gradient across the structure is an important factor. Pressure differences across a building component may be due to indoor - outdoor temperature difference, wind or ventilation system. In reality the pressure difference is generally caused by a combination of these.

The thermograms in Fig. 14 a - e show different distributions of the surface temperature caused by fluctuating wind acting on an external wall.

TEST REQUIREMENTS

Thermography has to be carried out so as to ensure that the disturbing effects produced by outdoor and indoor climatic factors are as small as possible. Therefore, the test in most cases is made indoors.

Outdoor thermography may be valuable e.g. in preliminary examinations of large areas of external surfaces, in cases of low thermal resistance or when detecting air leakage at high indoor pressure.

Thermography is made so far as possible at constant temperature and pressure drops across the envelope. This implies, among other things, that thermography can not be carried out when the outside air temperature is liable to wide variations, or when the structure is exposed to solar radiation, or when the wind varies markedly. Furthermore, the temperature drop across the envelope has to be sufficiently great to make possible the detection of thermal irregularities.

These general requirements have to be considered when a thermography test is made. The actual requirements may be varied depending on the thermal properties of the building envelope under investigation and the characteristics of the infrared radiation sensing system. They may also be varied to meet the local climate. The conditions under which the thermography is carried out must be taken into account when carrying out the test and when evaluating the thermograms.

Example of actual test requirements is given in the following.

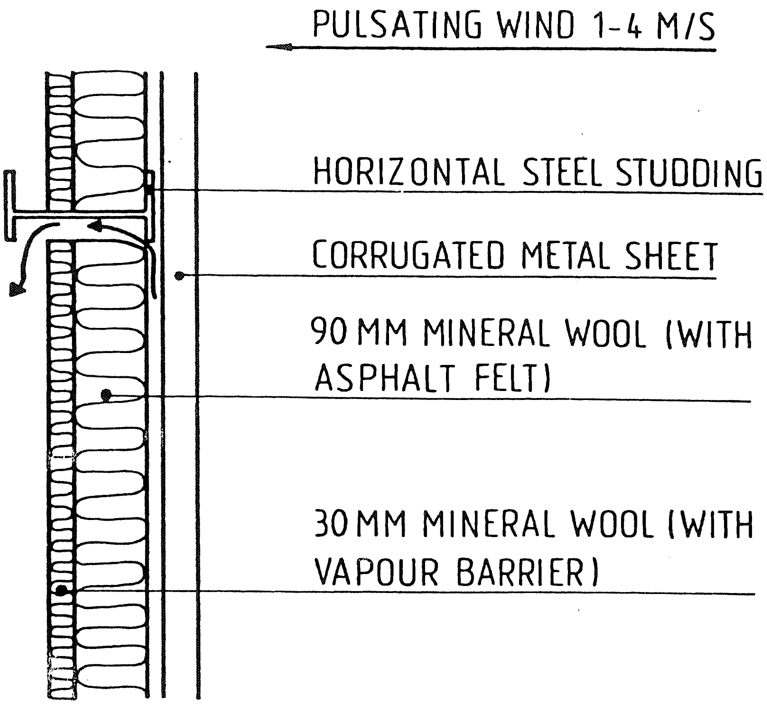
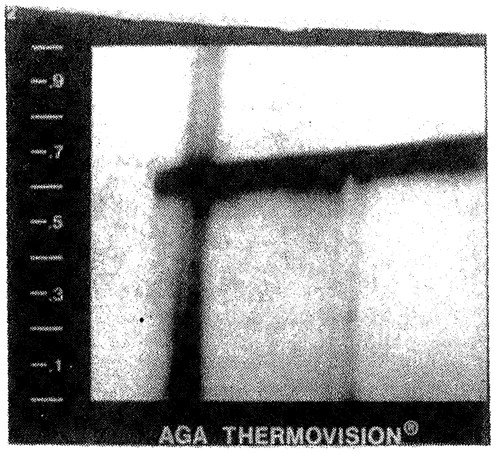


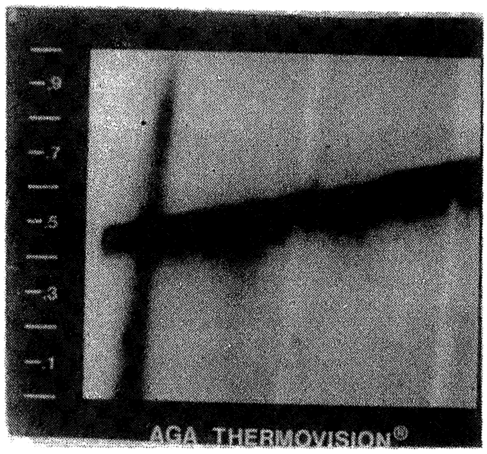
Fig. 14 Design drawing of an external wall

Conditions:

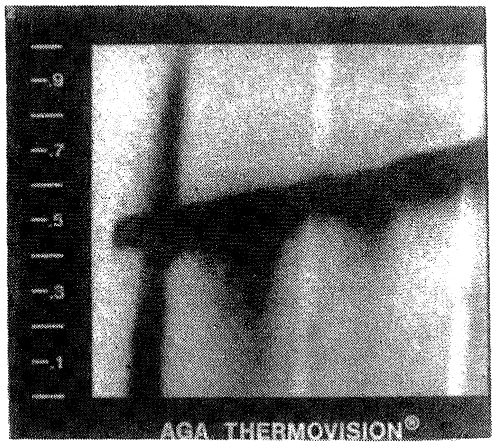
cloudiness:	cloudy
air temp.outside	$-1^{o}C$
air temp.inside	$+19^{o}C$
wind:	1-4 m/s (against the facade)
$P_i - P_u$:	-10 to 0 Pa (pulsating wind)



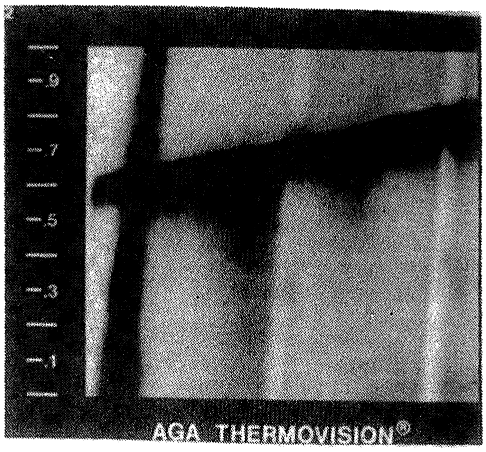
a) After 0 minutes. The horizontal bar looks like a cold line in the thermogram



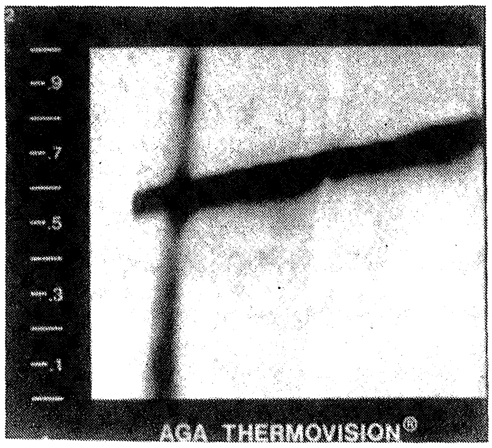
b) After 1 minute. Dark areas due to air leakage.



c) After 2 minutes. The dark areas are here bigger than in b)



d) After 3 minutes. The cold air is still leaking thorugh the structure.



e) After 4 minutes. The thermogram looks like that in a)

"During at least 24 hours before the start of the test, as well as during the test, the air temperature drop across the building envelope shall be at least 10°C. During the same period the air temperature drop shall not vary more than ±30 per cent of its actual value at the start of the test. During the test the indoor air temperature shall not vary by more than ± 2°C.

During at least 12 hours before the start of the test, as well as during the test, the surfaces of the envelope under investigation shall not be exposed to solar radiation.

The minimum and maximum temperature at the place of measurement shall be known for a period of 24 hours before the thermography e.g. with min-max thermometer or by information from a weather station. The solar radiation conditions at the place of measurement shall be known for a period of 12 hours before the thermography"

Detailed information on the test method can be found in "Thermal insulation - infrared method for qualitative detection of thermal irregularities in building envelopes" draft proposal ISO/TC163/SC1/WG4.

EXPERIENCE FROM MEASUREMENTS IN EXISTING BUILDINGS

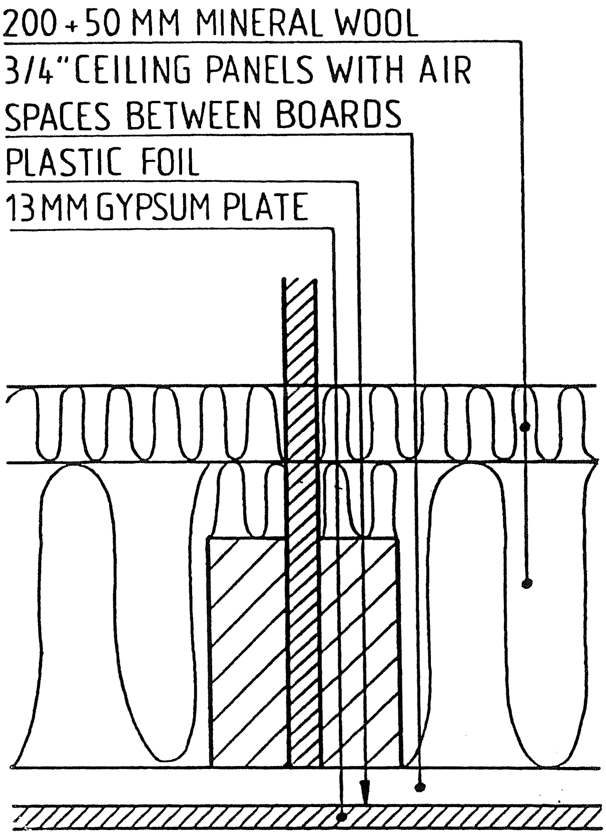
Since 1970 about 500 building projects have been examined by thermography method. Each one of these projects has included up to 300 houses or flats of the same building design.

The investigations have shown that air leakage thorugh joints is the most serious defect in Swedish buildings nowadays. Defects only due to missing portions of insulation in the middle of a wall section are not so common. Furthermore, an insulation defect can be caused not only by poor workmanship but also by unsuitable design of building elements or the use of unsuitable materials. Some material-saving designs are e.g. very sensitive to air leakage. An example is shown in Fig. 15. Some constructions are difficult to insulate in practice so that the intended thermal resistance can be achieved. In Fig. 16 common areas of air leakage or insulation defects are marked for a one-family and a dwelling house. Statistics of building defects based on the results of these investigations have been collected. The measurements have shown that some types of building designs generally have a poor thermal performance.

Thermographic inspections have been used in cases of reinsulation where the inspection is done first to locate the deficiencies and then to check the reinsulation result. Fig. 17 shows an example of this.

In about 100 cases where insulation defects have been located by means of thermography, the results have been verified in detail either by disassembling and visual examination Fig. 18, or by means of other test methods, e.g. heat flow measurements (Fig. 19). In all the cases where a building defect was checked by other means, the result from thermography test was verified. The test method has been used in cases of dispute. The Testing Institute has been called in for building inspections in about 50 such cases, some of which have been brought to court. In these cases the court has stressed the importance of the thermographic inspection as a basis for deciding the dispute.

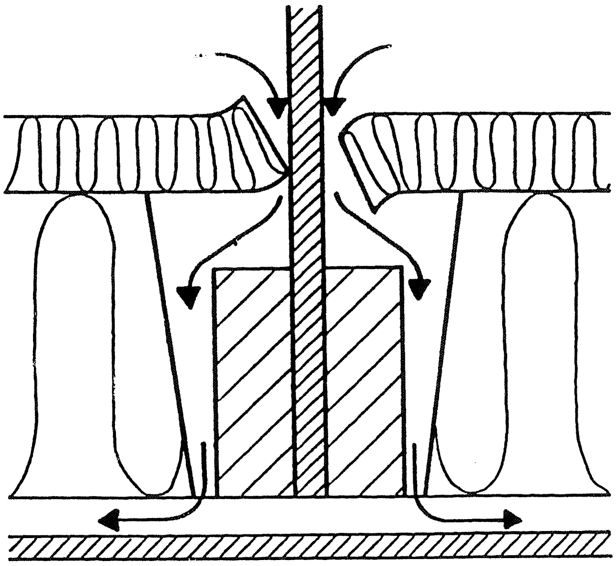
It is important that the thermography test is carried out and that the results obtained are evaluated by persons who are specially trained and educated for this purpose. The concept in interpretation of the thermal irregularities requires personel with special knowledge and experience in the areas of building technology, building physics, heating and ventilation techniques and measurement techniques.



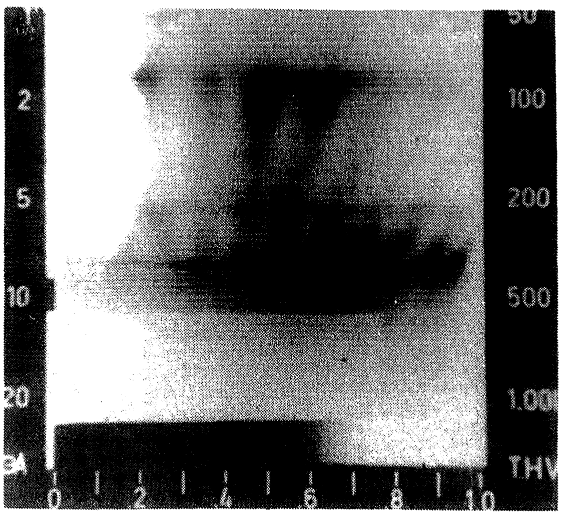
a) Design drawing of attic floor joists.

Conditions:

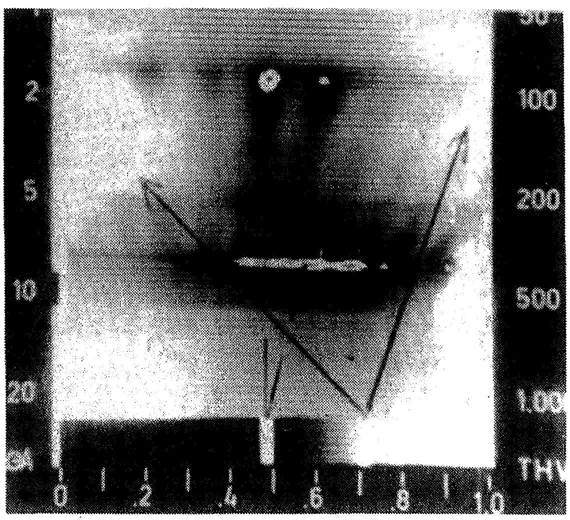
cloudiness:	cloudy
Air temp. outside:	$-4^{\circ}C$
-"- -"- inside:	$+21^{\circ}C$
Wind speed:	0,5 m/sec



b) Badly fitted insulation. Cold air from outside enters the spaces and spreads into the air spaces between the boards.

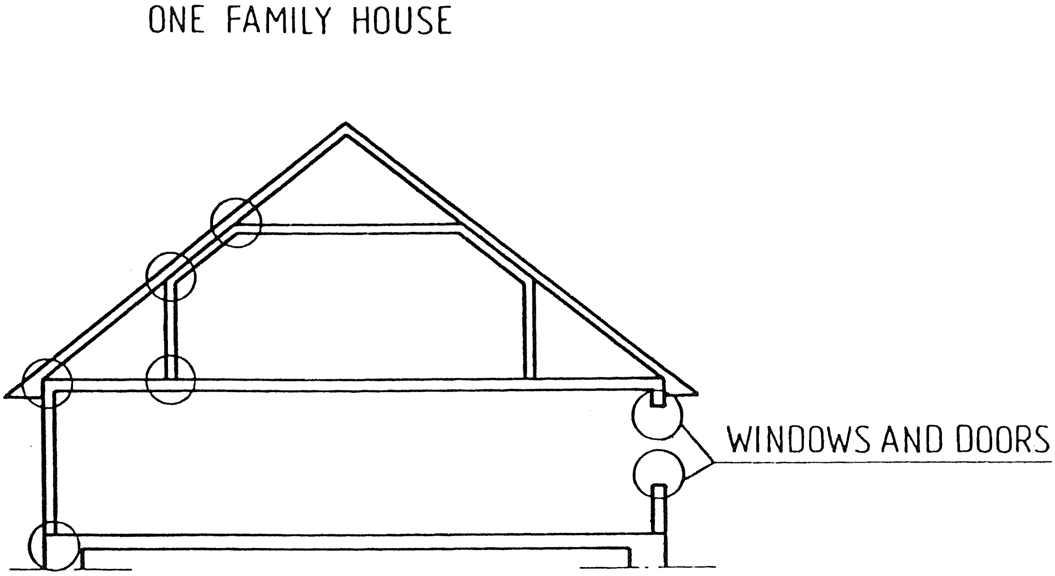


c) The cold portions of the ceiling are depicted in the thermogram. The spaces between the panels are seen as stripes due to defect described in b).



d) Difference in pressure indoors-outdoors, $P_i - P_u = -5$ Pa.
Reference temperature $= 20^{\circ}C$.
Difference in surface temperature $t_i - t_u = 3.5^{\circ}C$

Fig 15 Insulation defect at attic floor joists.



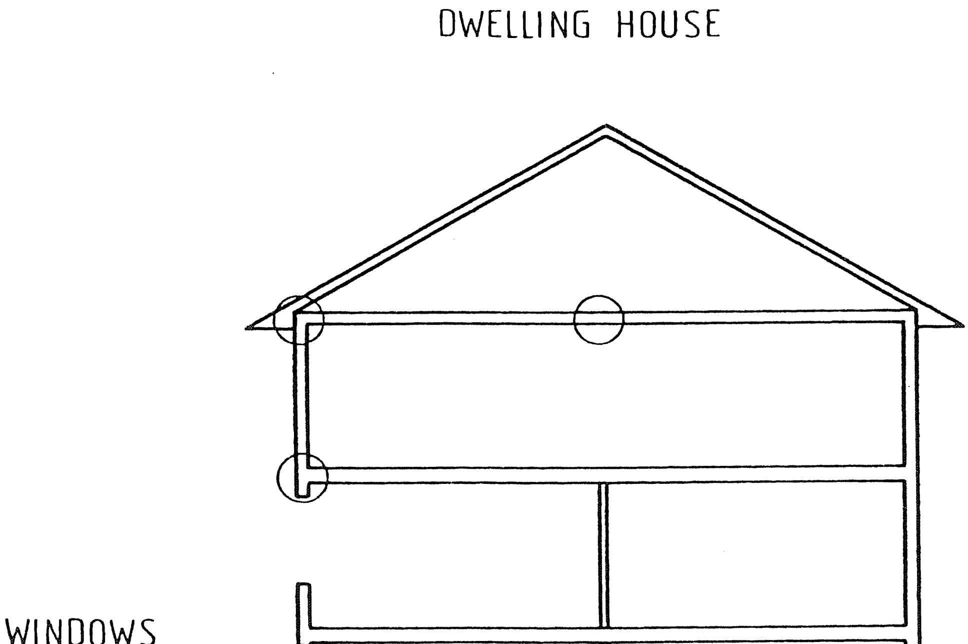
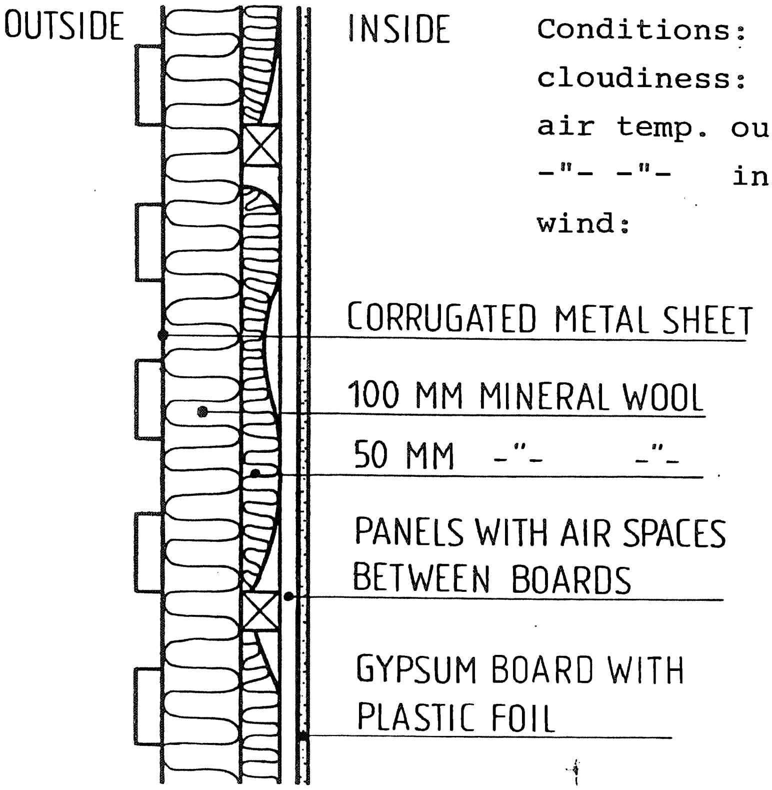


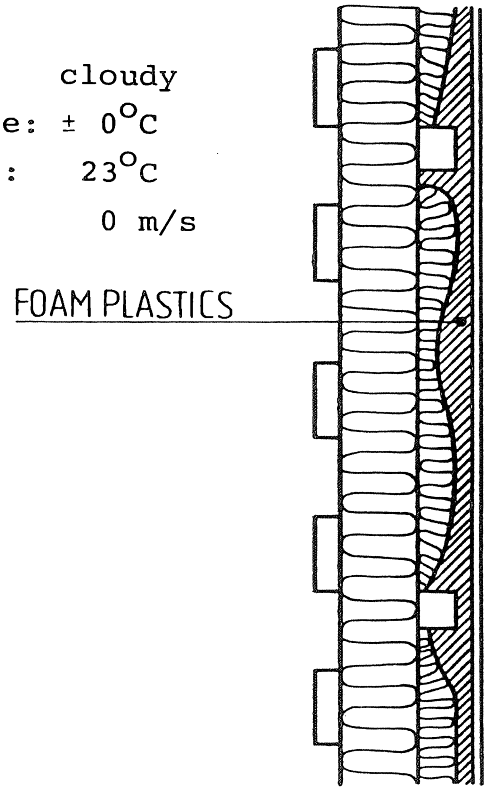
Fig. 16 Critical areas of thermal insulation and air leakage performance.



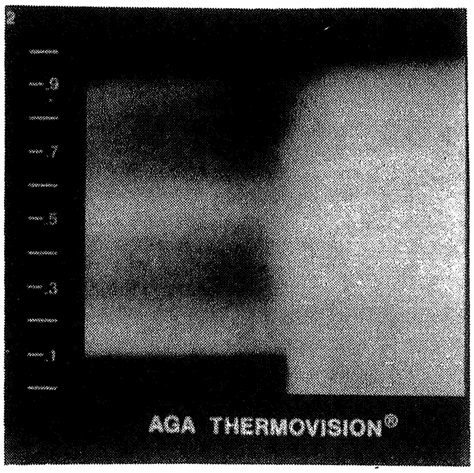
Conditions:

cloudiness:	cloudy
air temp. outside:	± 0°C
-"- -"- inside:	23°C
wind:	0 m/s

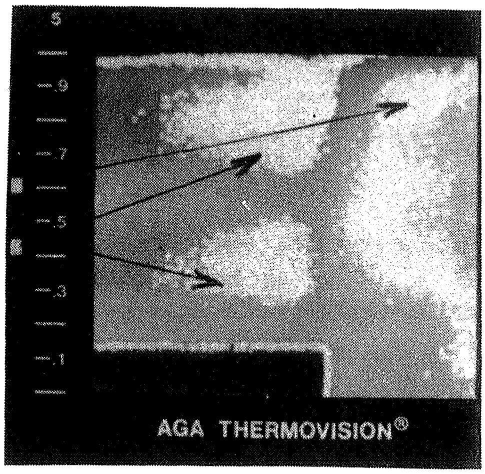
a) Horisontal section of external wall. The insulation slab on the warmer part of the wall is badly fitted.



b) The external wall is here repaired by injecting foam plastics.



c) The thermogram shows the portion of the wall where the section to the right in the image is reinsulated as described in b). The wall section to the left in the image is not repaired.



d) Difference in pressure indoors-outdoors, $P_i - P_u = -8$ Pa

Reference temperature = 22°C

Difference in surface temperature $t_i - t_u = 1.5$°C (measured by the IR-camera).

Fig. 17 An example of a thermographic inspection of an external wall section where the part to the right in the thermogram is repaired and the part to the left is not repaired.

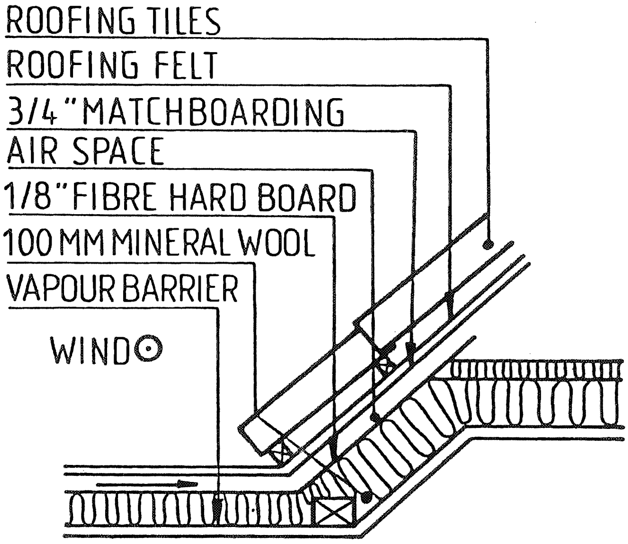
Conditions:

cloudiness: clear

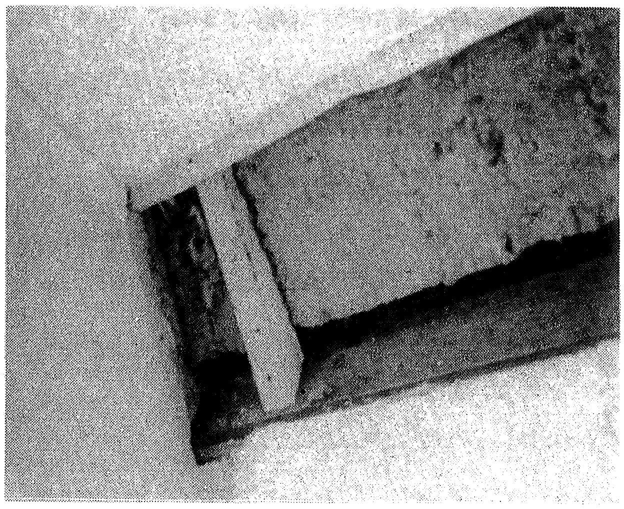
air temp. outside: ±0°C

-"- -"- inside: 20°C

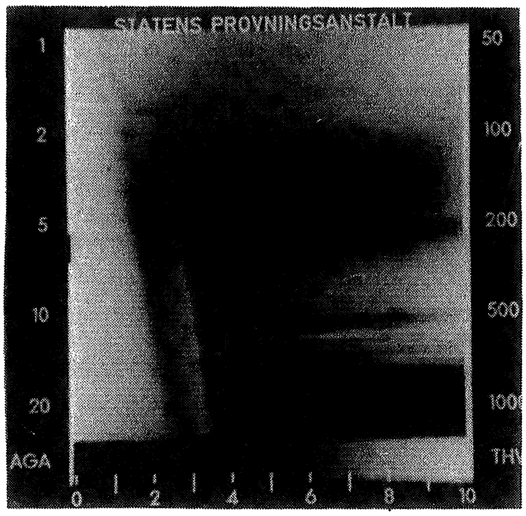
wind: 2-3 m/s (parallel to the roof)



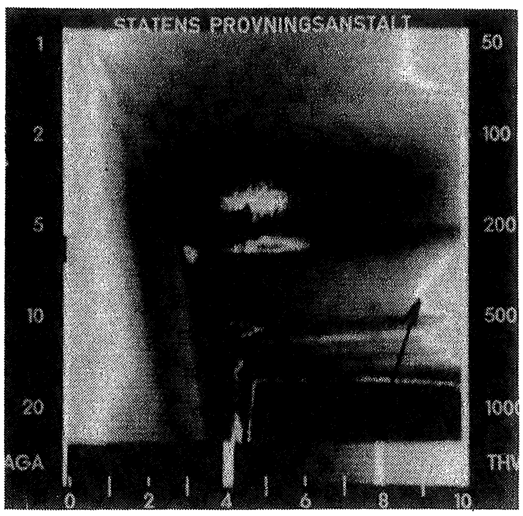
a) Design drawing of insulated roof



b) A photograph from inside of an opened wall section. The insulated slabs are badly fitted. Strong air currents can arise in the spaces as a result of faulty fitting of the insula-tion and local air leakage.



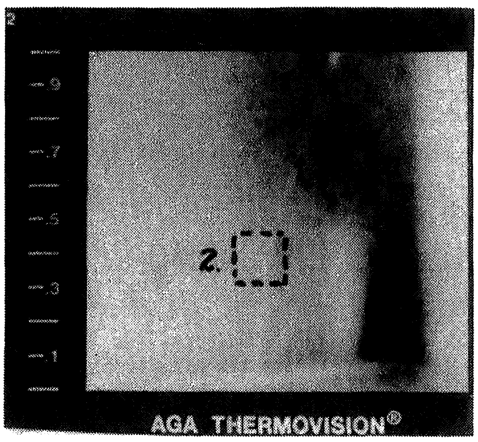
c) The thermogram shows the cold portion of the sloping ceiling. The cold area is due to cold air entering between the mineral wool slabs and the internal board plate, thus reducing the insulating capa-city.



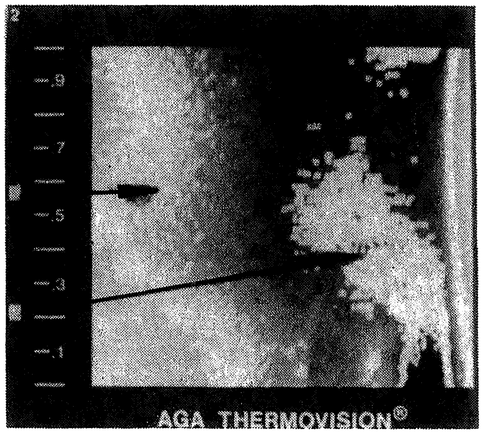
d) Difference in pressure indoors-outdoors, $P_i - P_u = -4$ Pa
Reference temperature = 19°C
Difference in surface temperature measured by the IR-camera, $t_i - t_u = 3.0$°C

Fig. 18 Insulation defect in a sloping ceiling.

Fig. 19   a) Testing of external wall by means of thermography and heat flow meters.



b) A thermogram from portion of the external wall. The corresponding area is marked in the photograph.



c) Difference in temperature on the surface

$\Delta t = 1.0\,^{o}C$

Thermal conductance measured at

point 1: 0.6 $W/m^2\,^{o}C$
point 2: 0.4 - " -

PRESENT TRENDS

Investigations have shown that thermographic inspection of buildings effectively locates insulation defects and air leakages in the envelope. Therefore, this method makes it possible to assess the thermal performance and find out whether the structure being examined possesses the specified properties. In a few cases supplementary measurements and investigations have to be made e.g. to find the thermal resistance value of an area of the insulated structure.

In Sweden the basis of such evalutions is afforded by the Swedish building code, which states that heated buildings shall be so thermally insulated and air tight that satisfactory climatic conditions can be achieved in the building. Furthermore the building elements must be made air tight in order to prevent air leakage thorough the structures as well as air movements inside the structure, which are mostly responsible for a decrease of the thermal resistance. The code also redommends that the thermography methods is used for field inspection and verification.

A general plan in Sweden for thermally upgrading od buildings has furgher emphasized the need for field test methods, the main such method being the thermography method. The Swedish National Testing Institute has introduced a certification for organizations doing thermographic inspections. This includes special education of engineers and regular check of the work performed.

A Swedish standard for the thermography methods has also been accept as a "NORDTEST" standard method for the Scandinavian countries. This standard has formed the basis for the ISO draft proposal by ISO/TC163/SC1/WG4.

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