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WELL INSULATED AIRTIGHT BUILDINGS
DESIGN AND CONSTRUCTION

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SUMMARY

A new Building Code came into force in Sweden on 1st January 1977 and contains considerably more stringent requirements concerning the thermal insulation of buildings and an entirely new requirements dealing with the airtightness of buildings. It has been shown that design and workmanship must be changed if these requirements are to be complied with. This paper illustrates ways and means whereby the new more stringent requirements concerning airtightness and thermal insulation can be satisfied. For example, pressure tests showd that for the seven buildings investigated the number of air changes per hour at an overpressure of 50 Pa varied between 0,67 and 0,86. These are considered to be very low values for that type of building. The buildings are mechanically ventilated by an exhaust air system. Measurements have shown that ventilation rate is almost entirely governed by the exhaust fan. Theoretical calculations also show that the ventilation in airtight buildings is independent of wind velocity under 6 - 8 m/s. In permeable houses, on the other hand, the ventilation increases rapidly as wind velocity increases.

Measurements indicate that the annual energy consumption of the house considered will be about 18 000 kWh in the Stockholm climate, while that for comparable houses erected at the beginning of the seventies is around 26 - 28 000 kWh. These results thus indicate that the improved thermal insulation and better airtightness results under normal conditions in an annual energy saving of some 8 - 10 000 kWh.

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Background

In Sweden, specifications concerning thermal insulation and airtightness of buildings are contained in the Swedish Building Code. In previous codes specifications pertaining to thermal insulation were mainly based on hygienic and comfort requirements to provide acceptable indoor climate. However, both in terms of economic as well as the energy conservation policy the insulation provided exceeded the minimum requirements of the building code.

In 1975, an energy policy decision was taken in Sweden in an attempt to reduce energy consumption. To realize this, among other things, the energy used for the heating of buildings was to be reduced on the average by 0,9 % annually up to 1985. As a result of this energy policy decision, new specifications concerning the energy management in buildings were drawn up. They come into force on January 1st 1977, containing considerably more stringent requirements concerning the thermal insulation of buildings as well as entirely new requirements pertaining to the airtightness of buildings.

In the Swedish Building Code, SBN 75, the highest permitted values for thermal transmittance (k-values) are specified for different components of a building. These vary depending on the geographical location of the building as well as on the temperature to which the premises are to be heated. Table 1 gives examples of the highest permissible k-values for building components enclosing premises which are to be heated to 18 ^{o}C or more. Temperature zone I + II includes northerns Sweden, entailing somewhat more stringent requirements than those for zone III + IV covering southerns Sweden. Space which is to be heated to temperatures above 18 ^{o}C is considered to include dwellings, offices, schools and shops. The Code also contains rules limiting the permissible window area.

Table 1. Maximum permitted thermal transmittance coefficients (k-values), $W/m^2\ ^oC$ for building components for rooms intended to be heated to temperatures higher than +18 ^oC

Building Component	Requirement in temperature zone	
Description	I + II	III + IV
Walls directly against the open air or throug earth to the open air	0,25	0,30
Roofs or attic floors and roof above facing the open air	0,17	0,20
Floor construction above crawle space	0,30	0,30
Floor structure on ground	0,30	0,30
Non-glazed portions of doors (including frame)	1,00	1,00
Windows	2,00	2,00

For premises which are to be heated to temperatures not exceeding 18 ^oC, the k-values specified in the table may be exceeded. The k-values may also be exceeded, within certain specified limits, for individual components of a building provided it can be shown that the total energy consumption of the building is thereby not increased. In other words, if the thermal insulation of one part of a building is reduced, this must be compensated by a corresponding increase of the insulation in another part.

A large proportion of the energy consumed in buildings is used for the heating of the ventilation air. In an attempt to reduce the total number of air changes, SBN 75, established requirements for airtightness. These are specified for different building components in terms of the maximum permissible infiltration at various over and under pressures.

Table 2. Maximum permitted air-leakage m^3/m^2 h

Building components	Pressure difference Pa	Building: number of storeys		
		1-2	3-8	8
External walls	50	0,4	0,2	0,2
External windows and doors (relates to absence of leakage in the gap between frame and window lintel or door)	50	1,7	1,7	1,7
	300	5,6	5,6	5,6
	500	-	-	7,9
Roof and floor in contact with the open air or floor in contact with ventilated room	50	0,2	0,1	0,1

The requirements in this table relate only to infiltration through the actual building components including joints which are a part thereof.

The airtightness of the completed building is to be determined by means of a special pressure test in which the total number of air changes is determined at a pressure difference of 50 Pa. According to the recommendations given in SBN 75, the number of air changes should not exceed the values specified in Table 3. After a transitional period which ends on 1st July 1978, the highest permitted number of air changes is reduced.

Table 3. Maximum permitted number of air changes in a completed building

	1 July 77 - 30 June 78 change/h	After 1 July 78 change/h
Detached house or linked house	4,5	3,0
Other building of at least 2 storeys	3,0	2,0
Building of 3 or more storeys	1,5	1,0

As already mentioned, the requirements concerning air infiltration are new. The values for the transition period up to 30 Juni 1978 have been specified keeping in mind the standards which could be achieved to date in a well constructed building employing techniques which do no require special provisions for airtightness or special design procedures.

Investigations have shown that only a small proportion of housing production conforms to the more stringent requirements regarding airtightness. Both design as well as workmanship must therefore be changed if the more stringent requirements are to be satisfied. The main reasons for increasing the airtightness of buildings are set out below. Examples are also given of construction methods which meet stringent requirements concerning airtightness and good thermal insulation. Finally, climatic conditions - mainly ventilation - and energy consumption in well insulated airtight buildings will be analysed.

The Reasons for the Construction of Airtight Buildings

In well insulated buildings about 30 - 40 % of the energy consumed is used to heat the ventilation air. From the point of view of energy conservation, it is of interest to study ways whereby the energy consumed by ventilation can be reduced. This can be achieved in two ways: the number of air changes can be reduced and/or a heat recovery unit can be built into the ventilating system. Many buildings have natural ventilation and depend on a certain amount of air leakage. In such cases ventilation is thus primarily governed by the external climate and not by the need for fresh air, being greatest in the winter when it is cold. A natural ventilation system is thus uncontrolled with ventilation largely left to chance. In order to better control ventilation, mechanical exhaust ventilation has been introduced. However, for such systems to work in a satisfactory manner, it is essential that uncontrolled or unintentional air leakage into the building be small. It must thus be possible to control the inflow of air.

Unintentional and uncontrolled ventilation of a building results in an increase of the energy needed for heating. The reasons are as follows:

a) the outside air must be heated to room temperature,

b) air leakage may lead to draughts. To compensate for the resulting discomfort room temperature must be raised, which in turn results in higher energy losses,

c) uncontrolled infiltration may cool down the inside surfaces of the building envelope, calling for higher room temperature to compensate for the lack of comfort due to the cold surfaces and

d) airflow through the thermal insulation will deminish its effectiveness.

In airtight buildings the control of ventilation is largely independent of the external climate. This means that the desired air quality can be set and maintained regardless of the external climate. For systems with heat recovery from the ventilation air, it is essential that the building be airtight if the system is to function in a satisfactory manner and its full economic potential be realized.

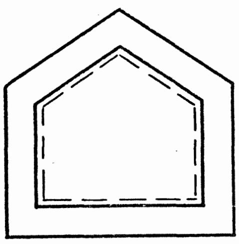
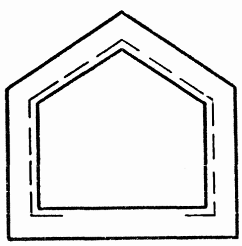
Design for Airtightness

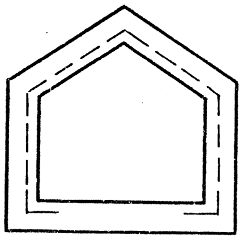
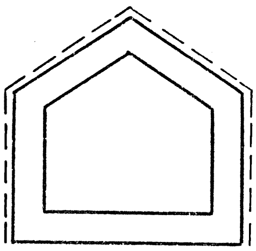
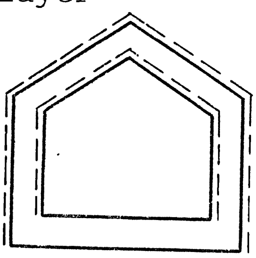
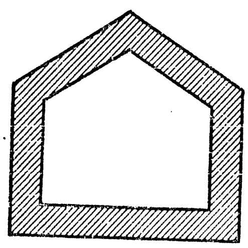
Careful detailing during the design process is essential if buildings are to be airtight. Moreover, this will also greatly simplify the contruction process. It is essential that suitable details be developed for junctions between external and internal walls, at the sill, between external walls and the attic floor, between external walls and the attic ceiling as well as joints around windows and, last but not least, for points where services for electricity, water, space heating and ventilation penetrate the building envelope.

Some of the most common causes for the lack of airtightness can be attributed to faulty or inappropriate design, incomplete drawings (the way in which junctions are to be made airtight is not specified), wrong working sequences on the site, substandard sealants and poor workmanship, and far too many and incorrectly insulated penetrations for services.

Depending on materials and construction details, there are a number of ways in which a building can be made airtight. Table 4 outlines conceiveable ways whereby airtightness can be achieved. The approach chosen should be applied as consistently as possible over the entire building envelope. This means that not only the walls and roofs must conform to this principle, but that it must also be carried out consistently at all joints and connections.

Table 4. The main principles for the design and placement of airtight layers in stuctures

Construction principle	Advantages	Drawbacks
Internal airtight cladding, e.g. plasterboard 	makes use of the properties of ordinary board material can be checked and repaired relatively easily	the layer is unprotected risk of puncturing joints must be carefylly sealed sensitive to movement and consequent cracking
Internal airtight layer (polyethylene sheet 	the vapour barrier can naturally also be used as airtight layer sheets of large size can be used	certain constructior details are difficult to deal with needs accuracy in lapping penetrations for services lead to problems

Recessed airtight layer (felt, polyethelene sheet) 	the airtight layer is protected from mechanical damage electrical installations possible without damage to airtight layer good chance of achieving high degree of airtightness	unknown risk of damage at high RH and low outside temperatures effect of joinery and furniture on moisture conditions at airtight layer, especially at outside corners, is unknown requires a double stud wall
External airtight layer (windproofing) 	easy to apply the airtight properties of the windproof layer can be utilised	great risk that airtightness is so great that there will be condensation layer affected by outside climate risk of damage during construction material must have high degree of weather resistance places high demands on external vapour barrier
Combination of internal and external airtight layer 	double safety	a double airtight layer is uneconomical an aritight windproof layer may cause moisture damage
Homogeneous constructions, e.g. gas concrete 	simple	limited choice of materials junction details must be designed separately all parts of the building should be constructed according to the same system, and this restricts the choice of method and material

Examples of Design Solutions for Detached Houses

To illustrate ways and means whereby airtightness can be achieved the design, construction and evaluation of single family dwellings in a Stockholm suburb will be considered. The 1 1/2 storey dwellings were built to comply with SBN 75.

The principle adopted during design was that the internal vapour barrier consisting of polyethylene sheet be applied consistently to provide an impermeable envelope. The goal was to achieve a level of airtightness exceeding that specified by SBN 75.

General Description of the Buildings

The study comprised seven bungalows with attic storeys, each having a floor area of 138 m^2. The foundations consist of concrete slabs on ground while the wood-frames are loadbearing. Wood panels are used for cladding and the roofs are covered with corrugated metal decking.

The concrete slab is laid on a fill of blasted rock covered with a capillary breaking layer of crushed rock. The frame is made up of a double stud system, with the vertical studs on the inside and the horizontal ones on the outside. All framing lumber was pre-cut to a high tolerance. The wall frame sections were assembled on the concrete slab and one by one tilted into position. The roof trusses were assembled on the site in a template and lifted into place. The horizontal studs as well as the doors and windows were then attached. The stud systems were carefully designed to maintain a 60 cm stud spacing throughout. This made it, to a very large extent, possible to use standard sizes of insulation materials and boards without the need for cutting, thereby facilitating the achievement of good workmanship.

Mineral wool for thermal insulation was provided in the thicknesses of: 10 + 5 cm for the exterior walls, 19,5 cm for the sloping parts of the attic roof, 19,5 + 5 cm for the attic ceiling and 10 cm on the floor slab. Roof insulation was applied from the inside, making it possible to provide weather protection to the building and especially the insulationsmaterial at an early state of construction. The roof itself consisted of fibre board covered with nailing strips and corrugated metal decking.

Insulation between the horizontal studs in the external walls was applied from the outside and covered with a windproof layer of sheathing felt. The sloping roof was insulated from the inside, while the attic ceiling was insulated from the top after the polyethylene sheet vapour barrier and strapping had been applied.

The vapour barrier was applied first to the gable walls of the upper floor, then to the ceilings of the upper floor, and finally to the walls on the ground floor.

Chipboard on the gable walls, and plasterboard in the remaining locations was used for internal wall covering. The chipboard also serves as wind bracing.

The floor on the slab on grade consists of chipboard sheets or laminated oak boards laid on wooden sleepers with intermediate mineral wool insulation. A polyethylene sheet was first laid down to cover the concrete slab.

Construction Details

Some details which require a great del of attention during design to ensure that the building is sufficiently airtight are shown in FIG 1.

External Wall - Ground Floor

Complaints about draughts at the floor and cold floors are common. This is often due to faulty construction of the junction between the wall and the floor. In order to avoid this, the sill must be made airtight, and the inner and outer airtight layers must be applied properly.

In this example, a sealing strip of EPDM rubber was laid on the steel floated concrete surface. The sill was then placed in the

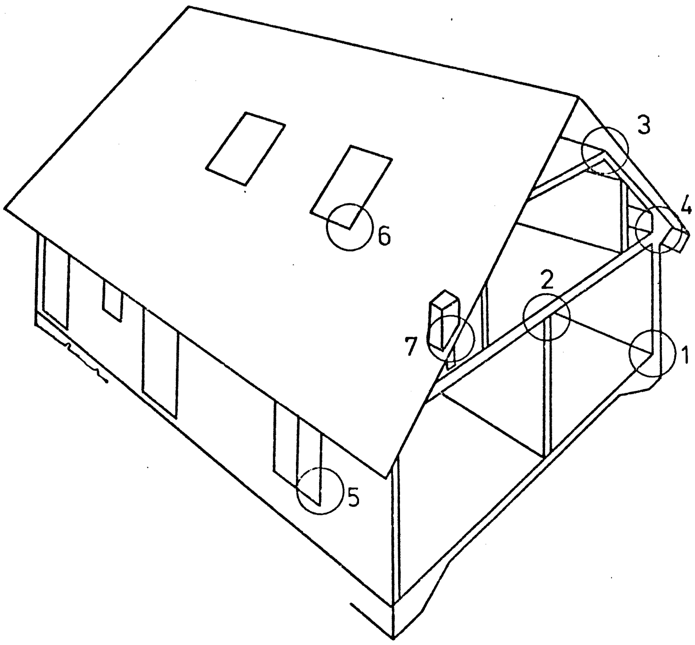


FIG 1. Conncetion and joint details to which a great deal of attention must be paid in order to achieve satisfactory airtightness.

1 External wall - ground floor

2 Loadbearing partition - gable wall/attic floor

3 Attic roof - sloping roof

4 Eaves

5 Joints around windows

6 Joints around windows in the roof

7 Penetrations for services

correct position and fixed to the concrete with expansion bolts. The wall frame was then tilted into position.

From the point of view of airtightness, this detail is well thought out. Three components are used to achieve aritightness:

1 a continuous windproof layer of sheathing felt is carried over the sill and down onto the edge of the floor slab,

2 a sealing strip of EPDM rubber is clamped underneath the sill and

3 an inner airtight layer of polyethylene sheet is applied. The polyethylene sheets on the wall and floor being overlapped and taped.

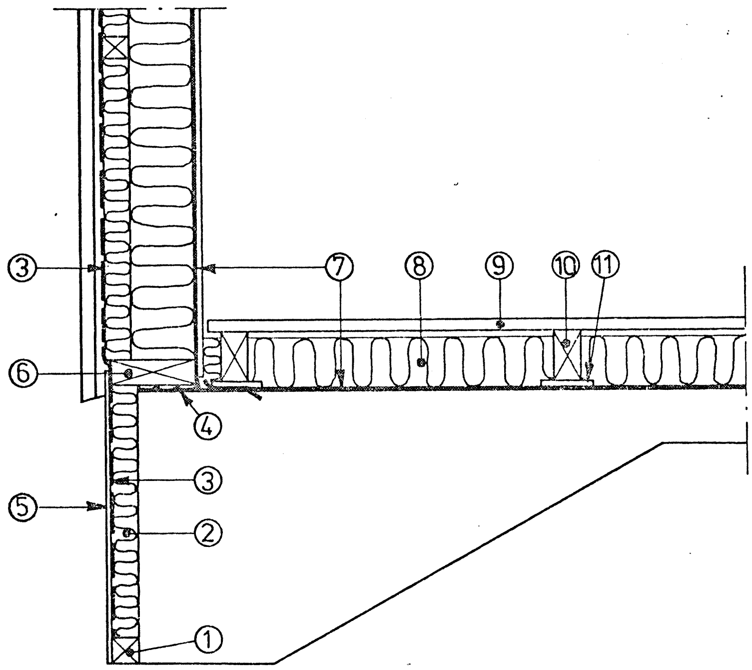


FIG 2. Junction between the external wall and the ground floor

1 50 x 50 mm pressure impregnated batten
2 50 mm mineral wool
3 sheathing felt
4 sealing strip of EPDM rubber under the sill
5 5 mm "Steni interior" glassfibre reinforced concrete
6 48 x 160 mm sill
7 0,20 mm transparent polyethylene sheet vapour barrier
8 100 mm mineral wool
9 22 mm floor grade chipboard or 22 mm laminated oak boards
10 45 x 95 mm sleepers
11 100 mm wide strip of 12,7 mm asphalt-impregnated wood fibre board

This detail is relatively easy to complete while the risk of failure i minimized.

In order that this solution function as intended it is essential that the concret be placed with reasonable care, steel trowel finishing being usually required. It has been found that it is possible to achieve the required degree of accuracy with this detail.

Loadbearing Partition, Attic Floor - Gable Wall

Preparations are made during erection of the frame for application of the vapour barrier by placing strips of polyethylene sheet underneath the loadbearing partition wall, between the load bearing partition wall and the gable wall, and between the gable wall and the attic floor (see FIG 3). These strips make it possible to provide for continuity of the inner airtight layer. These strips should be about 60 cm wide to provide sufficient overlap.

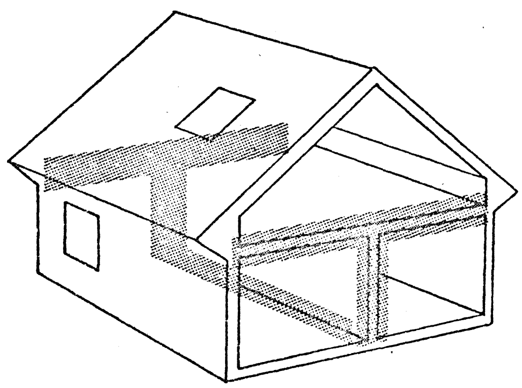


FIG 3. During erection of the frame strips of polyethylene sheet vapour barrier are placed underneath the loadbearing partition wall, between the loadbearing partition wall and the gable wall as well as between the gable wall and the attic floor.

Figurs 4 and 5 show details of the junctions between the loadbearing partition wall and gable wall, and between the gable wall and the attic floor. The strips of polyethylene sheet are applied during the erection of the frame.

Erection of the frame and application of the polyethylene sheet to walls and ceilings take place at different stages. As the frame is erected at a fast pace, it is easy to forget to install the above mentioned polyethylene strips. In order to prevent this, the strips should be clearly marked on the framing drawings, and the stage at which they are to be applied should be specified in the working instructions.

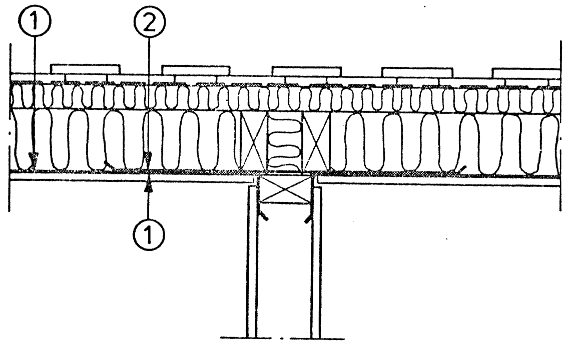


FIG 4. Horizontal section, gable wall - loadbearing partition wall

1 0,20 mm transparent polyethylene sheet

2 60 cm wide strip of polyethylene sheet

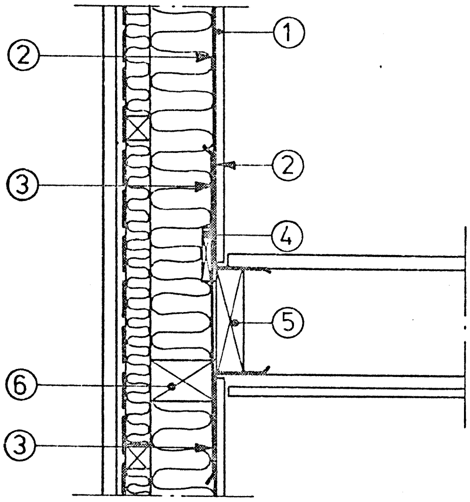


FIG 5. Vertical section through the junction between the gable wall and the attic floor

1 13 mm plasterboard

2 0,20 mm transparent polyethylene sheet

3 60 cm wide strip of polyethylene sheet

4 25 x 100 mm blocking

5 48 x 195 lower chord member of roof truss

6 73 x 120 mm top plate

Attic Ceiling - Gable Wall

If the airtight layer is not applied properly at the junction between the wall and the ceiling, cold air can spread out in the joist spaces between the floor and the ceiling, thereby "short circuiting" the insulation. Warm moist air can also flow outwards into the thickness of the building enclosure where damage due to moisture can result. It is therefore essential that both the outer and inner airtight layers be properly installed.

Airtightness is ensured by overlapping the polyethylene sheet at all joints and carefylly taping it. In the attic ceiling the vapour barrier sheet is laid above the strapping to ensure good contact between the mineral wool och the vapour barrier. This will reduce the risk of loss of effectiveness of the insulation due to convection.

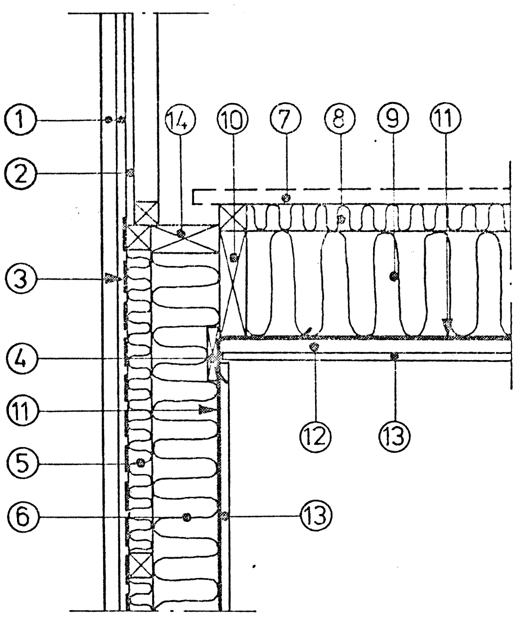


FIG 6. Vertical section through junction of the attic ceiling and the gable wall

1 Chipboard panel
2 12,7 mm asphalt-impregnated wood fibre board
3 Sheathing felt
4 25 x 100 mm blocking
5 45 mm mineral wool
6 120 mm mineral wool
7 25 x 125 mm walkway plank
8 50 mm mineral woll slab with felt
9 195 mm mineral wool
10 50 x 195 mm tie beam
11 0,20 mm transparent polyethylene sheet
12 23 x 95 mm strapping
13 13 mm plasterboard
14 48 x 120 mm top plate

Eaves

The most difficult detail from the point of view of airtightness in 1 1/2-storey houses is the point where the polyethylene sheet passes through the floor at the eaves. Owing to the large number of penetrations for services and the rectangular floor joists, application of the plastics foil becomes both difficult and time consuming. In view of this, the design of this detail merits careful attention.

In principle, there are two methods of applying insulation and the vapour barrier at the junction of the attic floor. These are illustrated in FIG 7.

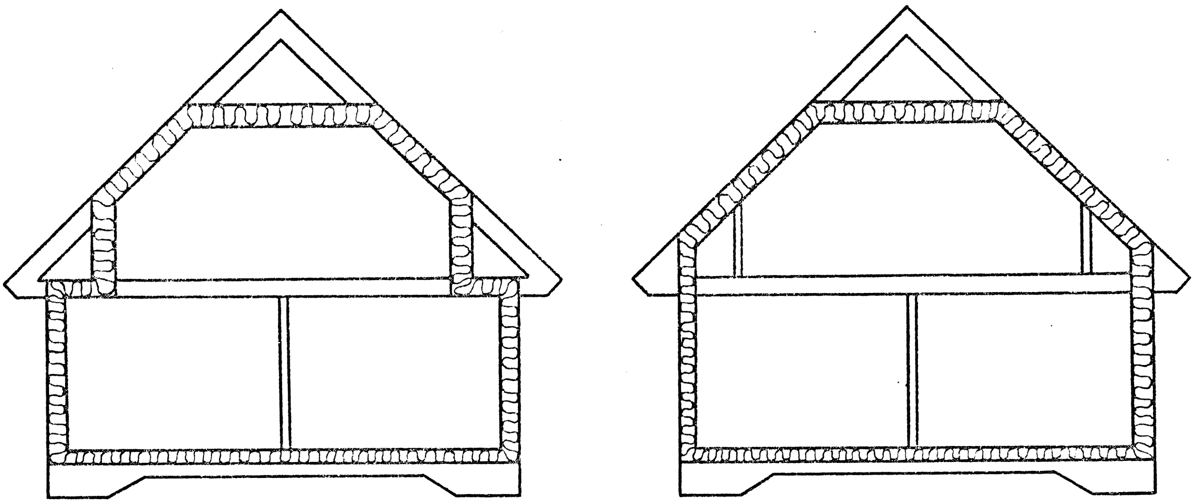


FIG 7 a. Roof truss with insulated walls along the truss supports.

FIG 7 b. Roof truss with the supports in line with the external walls and with lightweight stud walls.

The conventional roof truss of a 1 1/2-storey house has the insulated wall set back some 1 to 2 m from the exterior wall (see FIG 7 a). The application of insulation and vapour barriers is both difficult and time consuming, often leading to the leakage of cold air into the joist space. However, by moving the vertical support members of the trusses together with the vapour barrier and insulation into the plane of the exterior wall two right angle corners with associated vapour barrier and insulation application problems were eliminated (see FIG 7 b).

The space left behind the lightweight stud wall but inside the insulation and vapour barrier can now be used to advantage to house various electrical and mechanical installations. In this way, there is no need to utilise any of the dwelling space for pipes and ducts nor to make difficult to seal penetrations through the vapour barrier.

In order to ensure a good seal at the point where the attic floor joins the external wall polyethylene sheet was clamped onto the joists. It was clamped between the plasterboard and pieces of blocking (marked 9 and 10 on FIG 8) which were nailed to the joists and the top wall platt after erection of the frame. Jointing compound was used as a supplement to the clamping of the joints.

Joints Around Doors and Windows

Around doors and windows there is naturally a joint between the vapour barrier and the frame. The overall lenght of this joint in the houses studied is about 80 m, while the total joint length where the airtightness function of the polyethylene sheet is taken over by some other building material amounts to about 100 m (including junctions at floors and around ventilation ducts). This means that about 80 % of the total joint length is at doors and windows. It is therefore essential that simple yet reliable details be developed for such joints.

Here the outside dimension of the window frames were made to suit studs spaced at 60 cm centres which reduced the number of studs in walls and facilitated the installation of insulation.

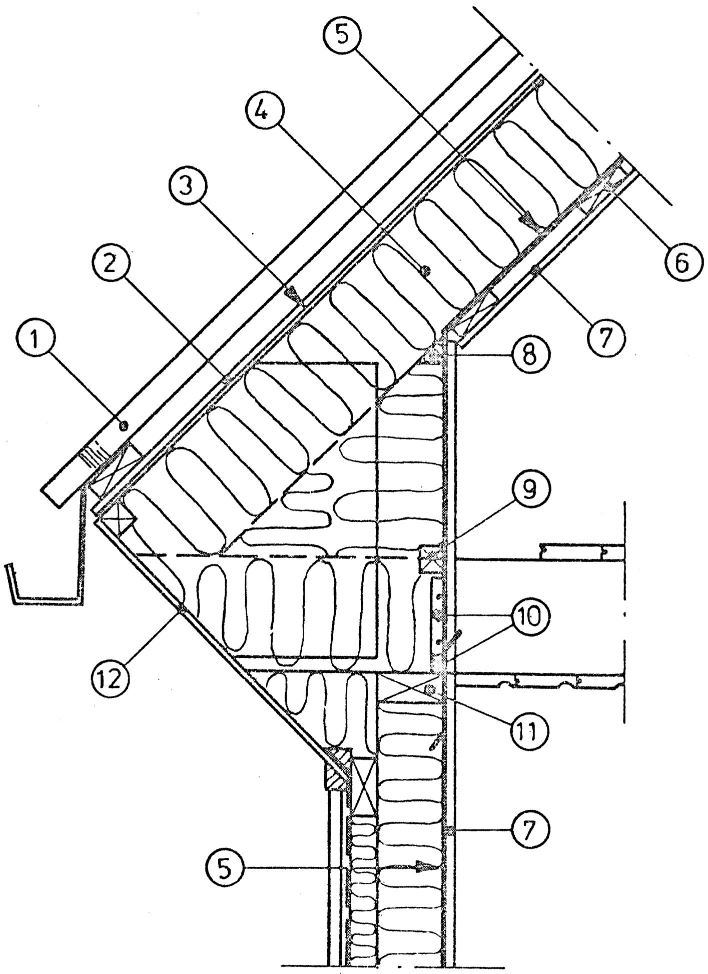


FIG 8. Vertical section through the eaves

1 Corrugated metod decking
2 13 x 50 mm battens
3 6,3 mm wood fibre board
4 195 mm mineral wool
5 0,20 mm transparent polyethylene sheet
6 23 x 95 mm strapping
7 13 mm plasterboard
8 45 mm triangular batten
9 45 x 45 mm blocking
10 25 x 25 mm blocking
11 48 x 120 top plate
12 9 mm wood fibre board

Door and window frames were also provided with a rebate to facilitate the clamping of the plastics foil against the frame. This was accomplished by nailing a strip of chipboard (No 1 in FIG 9) to the frame and the studs.

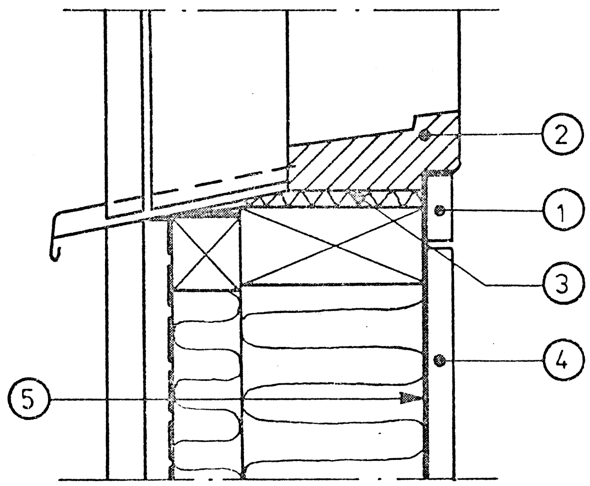


FIG 9. Detail at window sill
1 12 mm chipboard
2 Window sill
3 Mineral wool caulking or expanded polyurethane
4 13 mm plasterboard
5 0,20 transparent polyethylene sheet

Chipboard was used as it is stiffer and stronger than plasterboard, and can thus be expected to proved better clamping action.

Mineral wool caulking or one - component expanded polyurethane foam was used to seal the space between the frame and the surrounding studs.

Penetrations for Services

To satisfy the new code requirements it is essential that the effect of various penetrations of the building envelope on airtightness be taken into consideration at the design stage.

The most obvious measure is to cut the number of such penetrations to the bare minimum. For instance, electric cables can be located in interior walls in special baseboard conduits. Unavoidable penetrations should be made so that they can be easily sealed. For instance, ventilation ducts can be fitted with soldered-on sheetmetal collars or have butyl rubber collars stretched onto them.

In the buildings studied, most of the electric cables were located in interior walls, the attic floor and between the strapping of the attic ceiling. Consequently, only four penetrations of the building enclosure were necessary (for outside lighting, the bell circuit, external kWh meter and the antenna cable). These penetrations as well as those for the ventilation pipe were sealed with tape. At the ventilation outlet (FIG 10), the plastics foil was clamped between the flashing at the bottom of the outlet and the strapping of the attic ceiling.

Here the cover sheet was screwed to the strapping after which the 2 holes for the ventilation pipes through the cover sheet were sealed with a sealing compound. If the sheetmetal cover had been located underneath the slats (see FIG 10), the airtightness around the holes would have been further improved.

Installation of the Polyethylene Sheet

Polyethylene sheet, 0,20 mm thick and of two sizes was used. A sheet of width 2,70 m, i.e. exceeding the height of a wall, was placed on the walls, while in the roof a sheet 1,35 m wide was used which covered the space between two roof trusses (at 1 200 mm centres).

Top Floor

The polyethylene sheet was first of all attached to the gable walls (FIG 11). It was rolled out on the floor along the wall and cut to be about 80 cm too long. The sheet was then attached to the underside of the attic ceiling, after which it was folded down and stapled to the rest of the wall. After completing

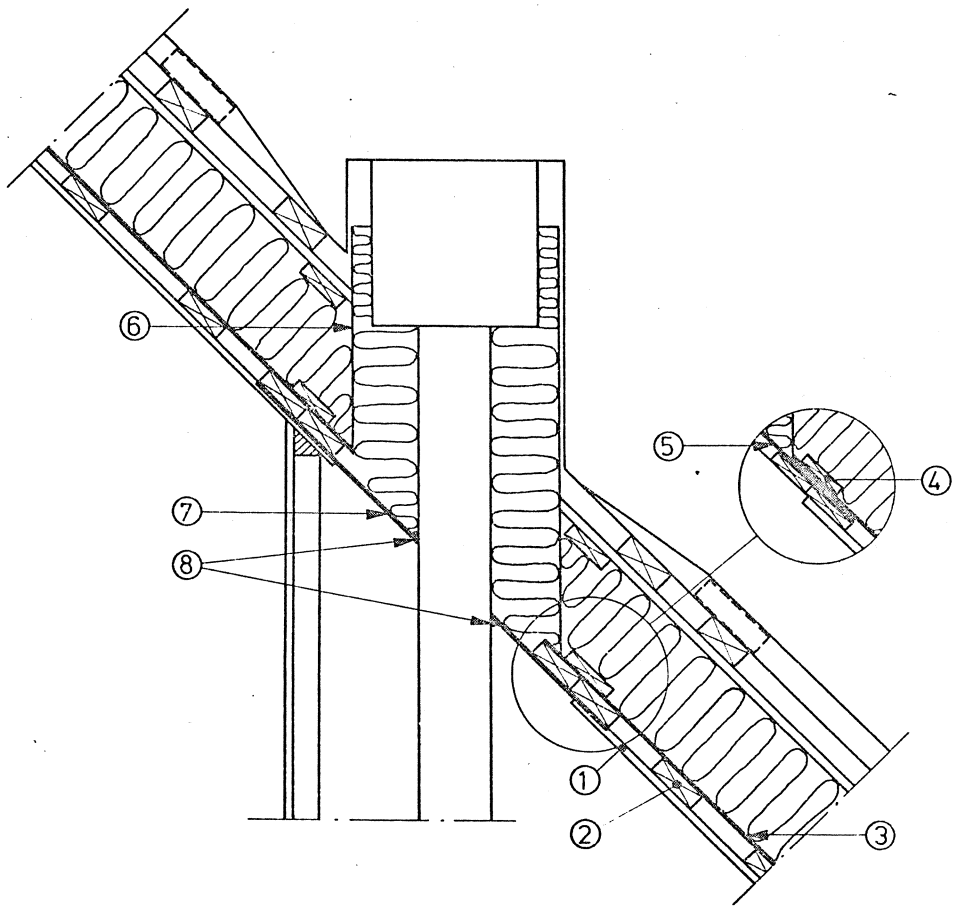


FIG 10. Roof Ventdetail

1 13 mm plasterboard
2 23 x 95 mm strapping
3 0,20 mm transparent

Proposed modification:

4 23 x 95 mm blocking
5 Cover sheet moved
6 Bottom flashing
7 Cover sheet
8 Sealed with compound

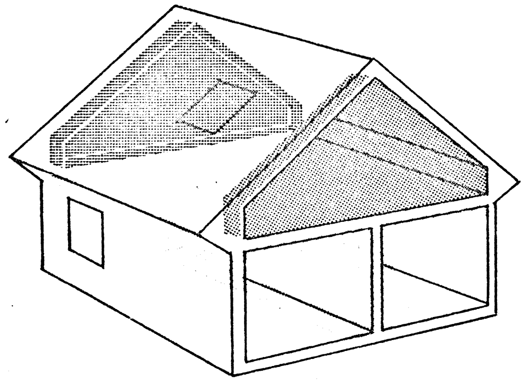


FIG 11. Line the gables on the top floor with polyethylene sheet

the gable wall the sheet could be applied to the ceiling (FIG 12). Here it was first fixed at one of the eaves, after which the sheet was secured along the sloping roof and then down to the eaves on the opposit side. At each eaves the sheet was cut about 40 cm too long, so that it could pass through the attic floor and be overlapped with the vapour barrier for the lower wall. The sheet had to, however, be cut where it passes each joist in the attic floor. Each portion of the sheet was then folded down through the floor and attached to the joists, the blocking pieces and the top plate.

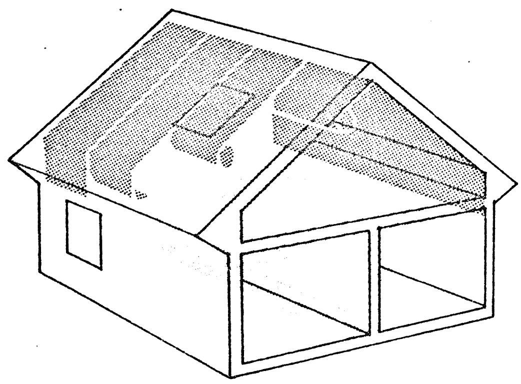


FIG 12. Line the ceiling with polyethylens sheet parallel to the roof trusses. Pass the rolls through an opening at the edge of the attic floor. The joints are to be laid over the supports with a good overlap and clamped with strips of plywood, or taped.

The sheet for the ground floor walls was placed last (FIG 13). Use was made of the fact that the width of the sheet exceeded somewhat the height of the wall, whereby it could be applied horizontally, thus reducing the number of vertical joint - preferable to one.

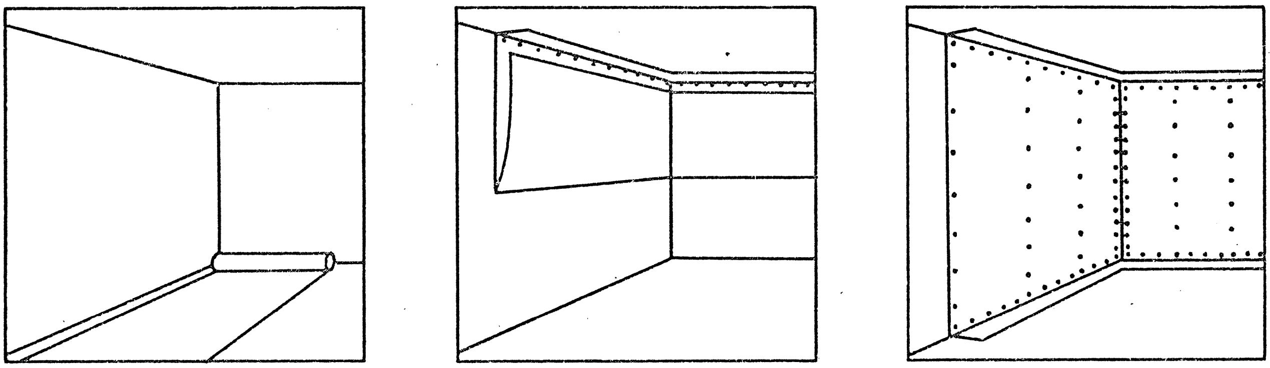


FIG 13. Principle of operation in placing the 2,70 m wide polyethylene sheet

a roll it out around the external wall

b lift it up, fold the narrow piece up against the ceiling and attach to the wall underneath the ceiling

c fold down the rest of the sheet and attach it to the wall.

Checkning the Airtightness

When construction of the buildings was finished, the airtightness was shecked by the pressure test method. The results from these tests are presented in FIG 14 in terms of the number of air changes per hour for an overpressure of 50 Pa. The number of air changes per hour were found to vary between 0,67 and 0,86 for the 7 buildings. These values are very low for this type of building, and are well below the code requirements, as shown in FIG 14.

The investigation shows thus that it is feasible to construct this type of building so that it is very airtight. The good results can be first of all attributed to the following:

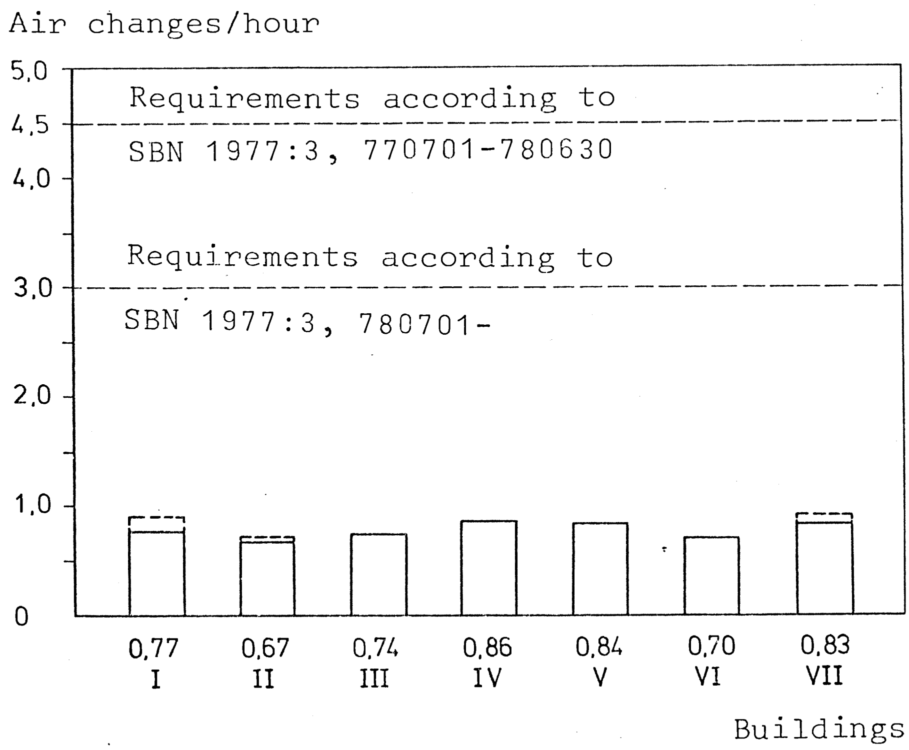


FIG 14. The results of pressure tests.

careful and systematic design,

careful workmanship and

the availability of materials for the airtight layer which were fit for the purpose.

Some of the significant factors which contributed to the results were that detailed drawings had been prepared for practically every construction detail, that the sizes of the wallboard were made to fit the frame spacing, and that the number of penetrations for services was cut to a minimum - for instance, all the electricity cables were laid in the interior wall and joist spaces, and that a high grade polyethylene sheet was used.

Study of Climatic Conditions and Energy Consumption

Ventilation

As mentioned above, the buildings are ventilated mechanically by an exhaust air system. The fan capacity can be varied between three positions - basic rpm, 50 % fan capacity and 100 % fan capacity. Intake air is obtained through slot vents at the top of the 11 windows. The slot openings can be regulated but cannot be closed completely.

Air changes measured at different intake vent settings and fan capacities are presented in Table 5. It is evident from the results that it is the fan setting which has the decisive influence on ventilation.

Table 5.

Fan setting, % of capacity	Air changes m^3/h when slot vents are		
	closed	40 % open	fully open
basic rpm	78	81	82
50 %	168	172	160
100 %	276	285	304

This means that ventilation is governed almost entirely by the exhaust fan. Supplementary pressure difference measurements also show that the outside climate has only a modest effect on the difference in pressure between outside and inside. Nor could changes in air flow,attributable to changes in the outside climate be detected.

In 1977 Nylund calculated with the aid of a theoretical model the effect of the airtightness of the building, the capacity of the ventilation system itself as well as outside weather on ventilation. FIG 15 gives an example of expected results for a detached house. Here it was assumed that ventilation is by an exhaust fan adjusted to provide 0,5 air changes per hour when there is no wind. In practice, ventilation will thus depend on the airtightness of the house, expressed in terms of the number o air changes at an overpressure of 50 Pa (n^{50} in the figure) and thereby primarly on wind velocity. It can be seen from the figure that the ventilation in airtight houses (n_{50}= 1 change/hour or less) is independent of wind when its velocity is below 6 - 8 m/s. It is only at higher wind velocities that ventilation is increased. This result agrees well with measurements for the test houses. In permeable houses, on the other hand (n_{50}= 5 changes/hour), ventilation increases rapidly

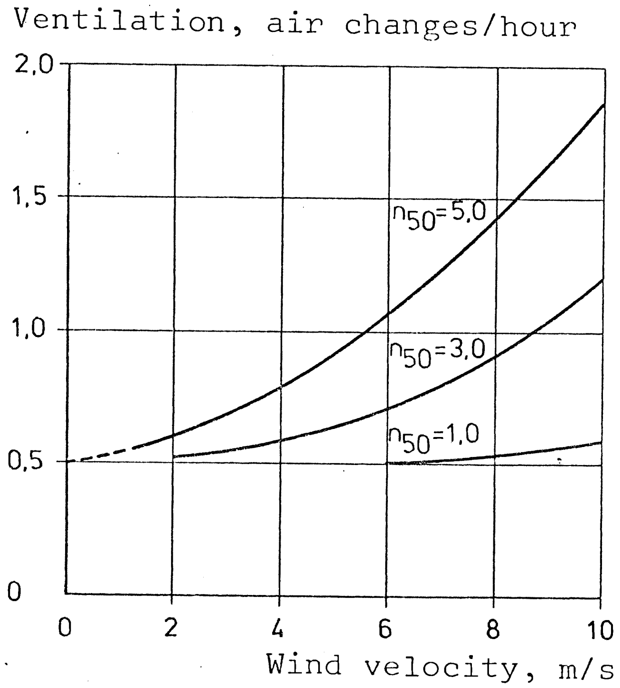


FIG 15. Relationship between ventilation and wind velocity for different degrees of airtightness (n_{50}) of the building. It is assumed that ventilation is by an air exhaust system which is set to provide 0,5 air change/hour when there is no wind.

as wind velocity rises. Already at a wind velocity of 6 m/s, ventilation is doubled.

Nylund´s calculated values for average annual ventilation for detached houses of varying airtightness are presented in FIG 16. It is assumed that the average wind velocity is 4 m/s, that the mean outside air temperature during the heating season is +2 °C, and that the house has an exhaust air system set to 0,5 air change per hour when there is no wind and the temperature inside and outside is the same. Energy losses due to ventilation can also be determined from this figure. The results show that in very airtight houses with an exhaust system, ventilation is entirely dependent on the setting of the exhaust fan and that there is no increase in energy consumption when wind velocities are high.

Air velocities in the houses have been low. There is however some risk of inconvenience due to draughts in the vicinity of the slot vents. At a distance of 1 m from these, air velocities were however never above 0,2 m/s. It should however be possible to enhance comfort somewhat by improving the way whereby supply air is provided.

To sum up, the results of the ventilation and air velocity measurements show that in airtight houses the flow of ventilation air can be accurately controlled by means of the exhaust fan.

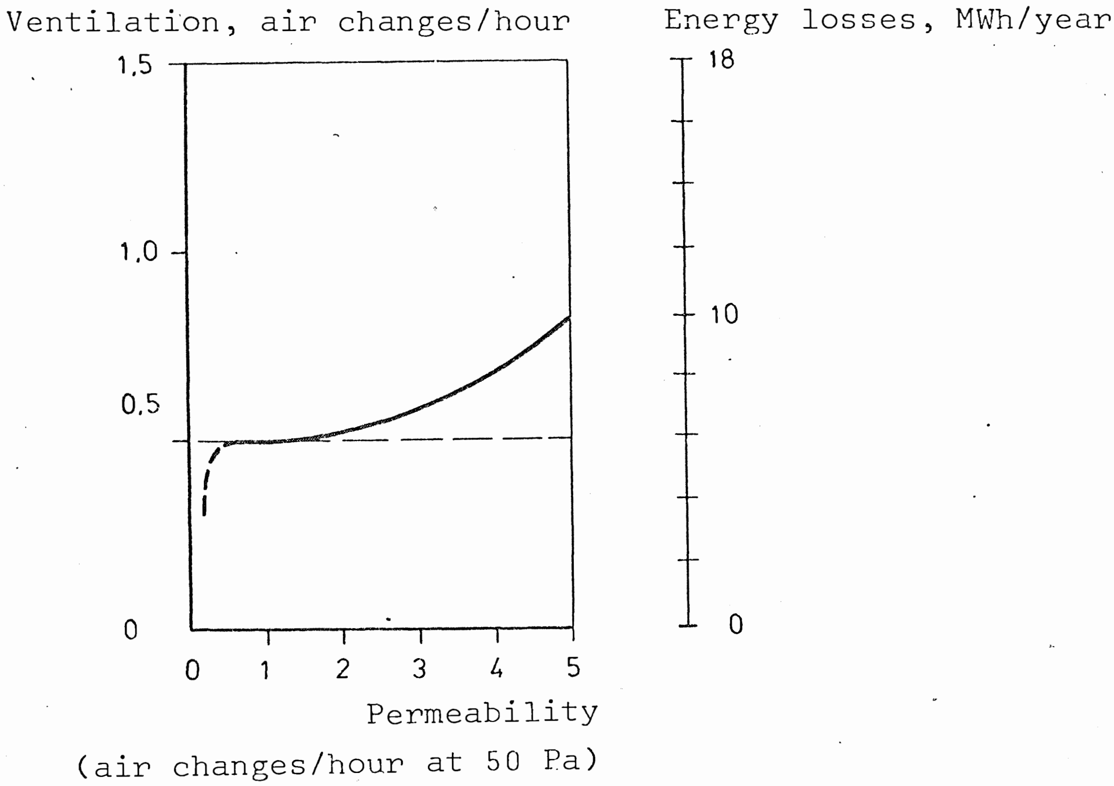


FIG 16. Calculated annual average ventilation in a building eqipped eith an exhaust system,as a function of the permeability af the building (number of air changes per hour at 50 Pa). The scale to the right shows the energy losses owing to ventilation at a climate equivalent to 110 000 °C h (Stockholm climate).

Energy consumption

Energy consumption was measured over short periods during the winter of 77 - 78. During these periods the exhaust fan was operated at about 50 % of its capacity, and all slot vents were about 40 % open. Air was exhausted of a rate of about 170 m^3 per hour, corresponding to about 0,5 air change per hour. Energy consumption was measured on cloudy days when the variations in the outside temperature were small. During the course of measurements the house was uninhabited, and the inside temperature was kept constant at +20,5 ^{o}C. On the average, 0,177 kWh/^{o}C h was supplied during the measuring period. Of this 0,058 kWh/^{o}C was attributed to ventilation losses, and 0,119 kWh/^{o}C to transmission losses. It is of course difficult to reliably predict the annual energy consumption on the basis of measurements taken over short periods. (It is intended to continue to measure energy consumption over a period of at least 1 year).

The number of degree hours based on an inside temperature of 20 ^{o}C is about 110 000 in Stockholm. The energy consumption due to ventilation losses for one year is then about 6 400 kWh, and that due to transmission losses about 13 100 kWh. Based on information by Munter 1974, an annual energy balance can then be drawn up as follows.

It is considered probable that the exhaust fan setting will be kept at the minimum level consistent with acceptable air quality in order to conserve energy.

Energy losses kWh/year	No of air changes per hour 0,5	0,25
transmission losses	+13 000	+13 000
ventilation losses	+ 6 400	+ 3 200
domestic hot water	+ 5 000	+ 5 000
domestic electricity	+ 3 500	+ 3 500
waste heat from domestic hot water	- 1 500	- 1 500
waste heat from domestic electricity	- 2 500	- 2 500
heat generated by occupants	- 1 500	- 1 500
solar radiation	- 3 200	- 3 200
forced ventilation	+ 300	+ 300
total annual energy requirement kWh	19 600	16 400

It may be assumed that the number of air changes will be 0,5 per hour for half the heating season, and 0,25 per hour for the remainder. This means that the annual energy consumption will be about 18 000 kWh.

Munther, 1974, and also Adamsson & Källblad, 1975, show that houses in the Stockholm climate of comparable size constructed at the beginning of the seventies have an annual energy consumption of around 26 - 28 000 kWh. These values relate to houses constructed before the "energy crisis" and before the new Swedish Building Regulations came into force. The results thus indicate that the improvement of thermal insulation and airtightness in these houses should result in an annual energy saving of about 8 - 10 000 kWh under normal operating conditions. This is a considerable saving which has been achieved only by construction measures, which can therefore be expected to have a very long life and which do not give rise to any additional maintenance expenditures.

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