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Housing Components
Studies of polyurethane-insulated one-family houses using new building components

FAVOURABLE RESULTS ACHIEVED OVER A THREE YEAR PERIOD IN LOW-ENERGY HOUSES WHILST STILL MAINTAINING HIGH STANDARDS

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Professor Höglund and his colleagues from the Department of Building Technology at The Royal Institute of Technology, Stockholm, describe their research and demonstration work concerning the construction and monitoring of 39 single family houses built at Sigtuna, 40km north of the city, where it was possible to build relatively simple, economical, well-insulated and airtight houses which have a low energy consumption.

Le Professeur Höglund et ses collègues du Département de la Technologie du Bâtiment à l'Institut Royal de Technologie, Stockholm, décrivent leurs recherches et leur travail de démonstration concernant la construction et la contrôle de 39 habitations individuelles construites à Sigtuna, à 40 km au nord de la ville, où il était possible de construire des maisons assez simples, économiques, bien isolées et étanches à l'air, ayant une consommation basse d'énergie.

Research project

Two almost identically constructed and situated houses were chosen for this project (Fig. 1). In one of them, the 'experimental house', some new construction methods were specially employed. The other house, the 'reference house', retained in all respects the construction methods originally planned for this residential estate. Evaluation of the project covers both the houses in their entirety and the above-mentioned new technical construction methods. During the three-year evaluation period all the houses have been occupied.

Among the interesting details and problems which have been studied more closely in the field were the use of energy (in detail for two of the houses and in general for all the 39 houses), exhaust air heat pumps using floor heating coils, floor surface temperatures, moisture content in wooden sills, wooden studs and the concrete slab, thermal resistance, airtightness and sound insulation in wall and roof elements insulated with polyurethane as well as ventilation in the whole building and in individual rooms. Complementary studies have also been carried out into thermal resistance and airtightness in two other similar (but older) houses, four-years and seven-years-old respectively. New construction methods which have been studied in the experimental house are: windows containing the new material, aerogel; windows with manoeuvrable and transparent low-emission plastic foil; and a new joint using a steel sill (allowing ventilation) between the wooden sill of the outer wall and the concrete slab. This paper is based primarily on a selection of the results (refs 1 and 2).

Description of the construction of the houses

The houses are two-storeyed, with foundations consisting of a concrete slab placed directly on the ground (Fig. 2). A carport and a small, unheated shed join the houses together, which were therefore built as link houses (Fig. 3). The houses are almost square in shape with a total floor space of 116 m^2. They are designed for four alternative extensions of the ground floor, which can add another 11–16 m^2 of floor space. The ceiling height is 2.3 m on both floors, which is somewhat lower than the standard 2.4 m.

The walls and roof consist of prefabricated sandwich elements insulated with polyurethane on a wooden frame. The wall elements are the same length as the sides of the house, i.e. about 8 m. The thickness of insulation is 120 mm for the walls and 195 mm for the roof (Figs 4 and 5).

The joints between the wall and roof elements and around the windows are sealed with polyurethane foam. The windows are triple-glazed, which is the normal

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Fig. 1. Single family houses at Sigtuna, Sweden

standard in Sweden. There is 70 mm of a polystyrene foam layer under the concrete slab, with 100 mm round the edges.

The houses are equipped with mechanical exhaust air ventilation, with supply air intakes in the outer walls. An exhaust air heat pump heats a 220 litre water-heater. When house heating is needed, a small pump will circulate water directly from the water-heater through the floor coils (copper tubes) placed in the concrete slab. The heat produced by the exhaust air heat pump is thus used both for hot water and for central heating. In addition the houses have thermostat-controlled electric radiators; in other words, the heating system consists of a combination of direct electric radiators and an exhaust air heat pump. Practically all electricity consumed by the heat pump (as well as the recovered heat) is utilized, which is also confirmed by our results.

Examples of results

Energy Balance

In order to determine in detail the energy consumption in the two houses, readings have been taken every month of a total of 13 different meters (for electricity etc.) in each house. These readings have been corrected with respect to deviations in the outdoor temperature from a normal year. The annual consumption of bought energy indoors is 12 300 kWh per year for the reference house and 13 200 kWh per year for the experimental house (the family in the experimental house kept a higher room temperature and used more hot water). Thus the amount of energy consumed in both houses is low. A computer calculation of the houses' energy balance corresponds closely with the consumption measured. Figure 6 shows the energy balance for the reference house. Of the total energy input for the house (family), 20 900 kWh per year, bought energy accounts for 59%, while heat recovered from exhaust air, utilized solar heat gain and body heat supplies the remaining 41%.

Fig. 2. Casting the concrete slab (March 1985)

The exhaust air heat pump contributes greatly to the low consumption of energy. The amount of energy retrieved from the exhaust air is about 5400 and 6800 kWh per year respectively. The heat pump's coefficient of performance is 2.2 in the reference house and 2.4 in the experimental house. The families' hot water requirements are provided for in both houses entirely by the heat pump. However, the greater part of the energy produced by the heat pump is used for the floor heating coils: 7900 and 8800 kWh per year respectively. This means that the floor heating coils account for over 60% of the energy provided for heating, while the electric radiators use less than 40%.

Of the 39 houses, 14 have extensions of 11 to 16 m^2, which makes the average floor space for all 39 houses 120.5 m^2. During a normal year the place has the mean outdoor temperature 5.5 °C and 4110 degree-days (assuming that the indoor temperature is raised to 17 °C until the outdoor temperature exceeds 11 °C). The average (and the mean) of all energy bought and used indoors (heating, hot water and household electricity) in all the houses (values corrected for a normal year based on two years' readings) is 14 500 kWh per year or

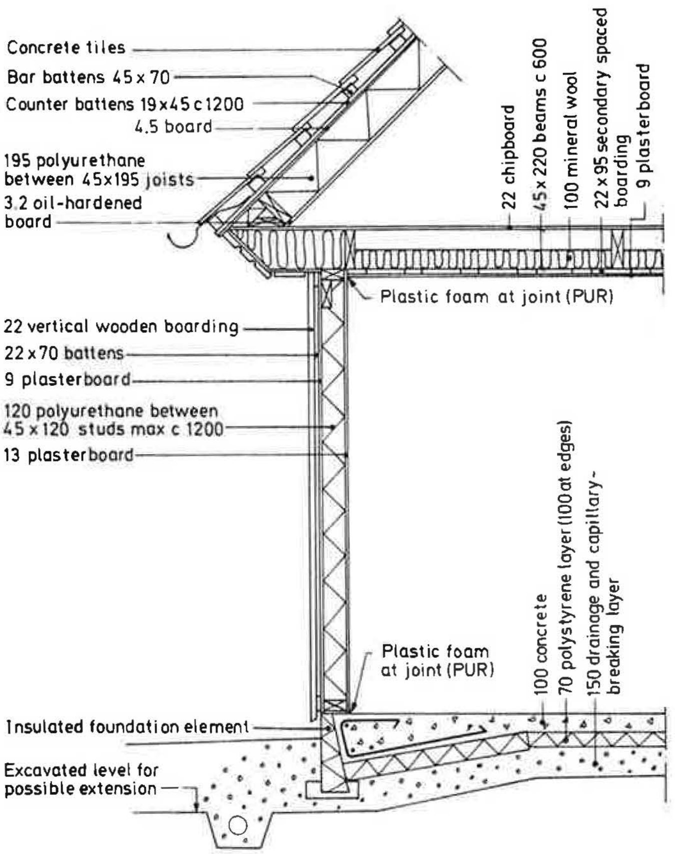


Fig. 3. The picture above shows the house facades facing the street. The facades are of vertical wooden boarding. On the left, a cross-section of the house construction. The houses are prefabricated to a fairly high degree. The foundation elements, which are left in position, act as forms for the concrete slab which is cast on the spot. These foundation elements consist of a core of polystyrene foam surrounded by an outer layer of concrete reinforced with steel fibre and glassfibre

121 kWh m^{-2} per year (52 300 MJ per year or 434 MJ m^{-2} per year). However, the differences between the various households (houses) are considerable. If the lowest consumption (8800) is compared with the highest (19 200 kWh per year) the ratio is 1:2.2. The fact that energy consumption varies greatly between equivalent houses owing to the households' different living habits has been documented in previous investigations. Lundstrom (ref. 3) gives the ratio of 1:2 for households with the lowest and the highest consumption.

In short, the houses built at Sigtuna are energy-economical, in spite of the fact that these houses were not planned in the first place to give low energy consumption. The potential for further energy saving by technical improvements (thicker insulation etc.) is relatively limited. For many families, however, the potential for energy saving by means of altering living habits is considerable.

Thermal resistance and airtightness

With the use of polyurethane foam (polyurethane insulation) very low thermal conductivity values can be achieved, thanks to the use of another gas than air in the cells of the material. Usually (as in the Sigtuna house) $CFCl_3$ (CFC-11) is used, which has a thermal conductivity of about 0.008 W/m·°C, i.e. about 1/3 of the value for still air. Using polyurethane foam makes it possible to have walls with the same thermal resistance much thinner than with mineral wool insulation. In the future, however, certain CFCs, including $CFCl_3$, will probably be completely banned because of their environmental effects and replaced with other gases.

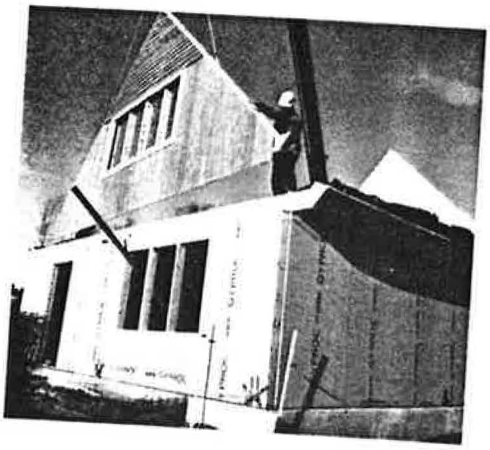
Thermal resistance and airtightness were determined for the two Sigtuna houses and two other similar houses which were four and seven years old when the measurements were made (1985–6). In every case the thermal conductivity refers to 110–70 mm of polyurethane foam in prefabricated wall elements between 9 or 13 mm sheets of plasterboard. The wall element joints etc. are made almost airtight with urethane foam.

The thermal conductivity determined lies within the range 0.018–22 W/m·°C. This low value (after up to seven years) suggests that the thermal conductivity of polyurethane foam in practice deteriorates very slowly due to gas diffusion. Another study (ref. 4) draws similar conclusions.

The air leakage rate in the four houses was 0.3–1.4 air changes per h at 50 Pa pressure difference (Fig. 7). All the houses easily meet the requirements of the Swedish Code of Practice (≤3.0 air changes per h). The very good airtightness in the seven-year-old house (0.3 air changes per h) indicates that the building envelope, including insulated joints between the various building elements, can hardly have aged to a noticeable degree as far as airtightness is concerned after seven years.

Ventilation and the indoor climate

The Sigtuna houses have mechanical exhaust air ventilation with supply air intakes in the outer walls. The total projected exhaust air flow rate is 162 m^3 h^{-1}, which corresponds to 0.64 air changes per hour. The total exhaust air flow rate was determined to be on average 12% lower in the reference house and 22% lower in the experimental house compared with the projected value. In practice there are often large deviations from the projected air flow, for which reason the Sigtuna house results are not surprising. However, a review and adjustment of the ventilation system seems to be warranted. Moreover, tracer gas measurements show that the air change for the whole house as well as the individual rooms is relatively constant regardless of wind and outdoor temperature, which is one favourable effect of



Figs 4 and 5. Both the wall and roof elements are prefabricated.

the exhaust air ventilation system in combination with the good airtightness of the houses.

Exhaust air ventilation leads on average to an underpressure of about 12 and 8 Pa in the reference and the experimental house respectively for the projected exhaust air flow. The underpressure varies more or less with the total airtightness of the buildings (including the supply air intakes), the exhaust air flow, the thermals (chimney effect) and the wind. At an outdoor temperature of −20 °C and 20 °C indoors the thermals make a

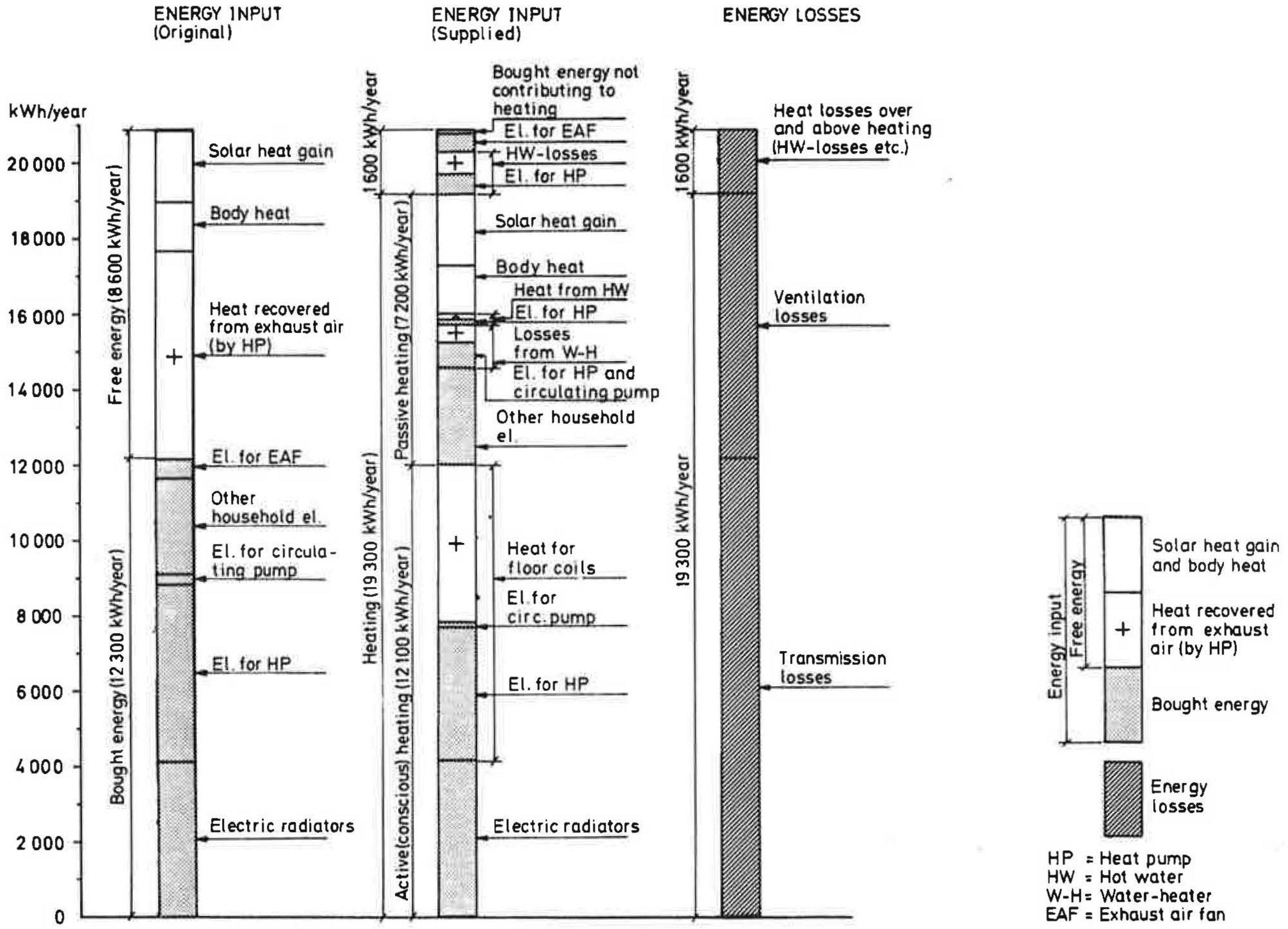


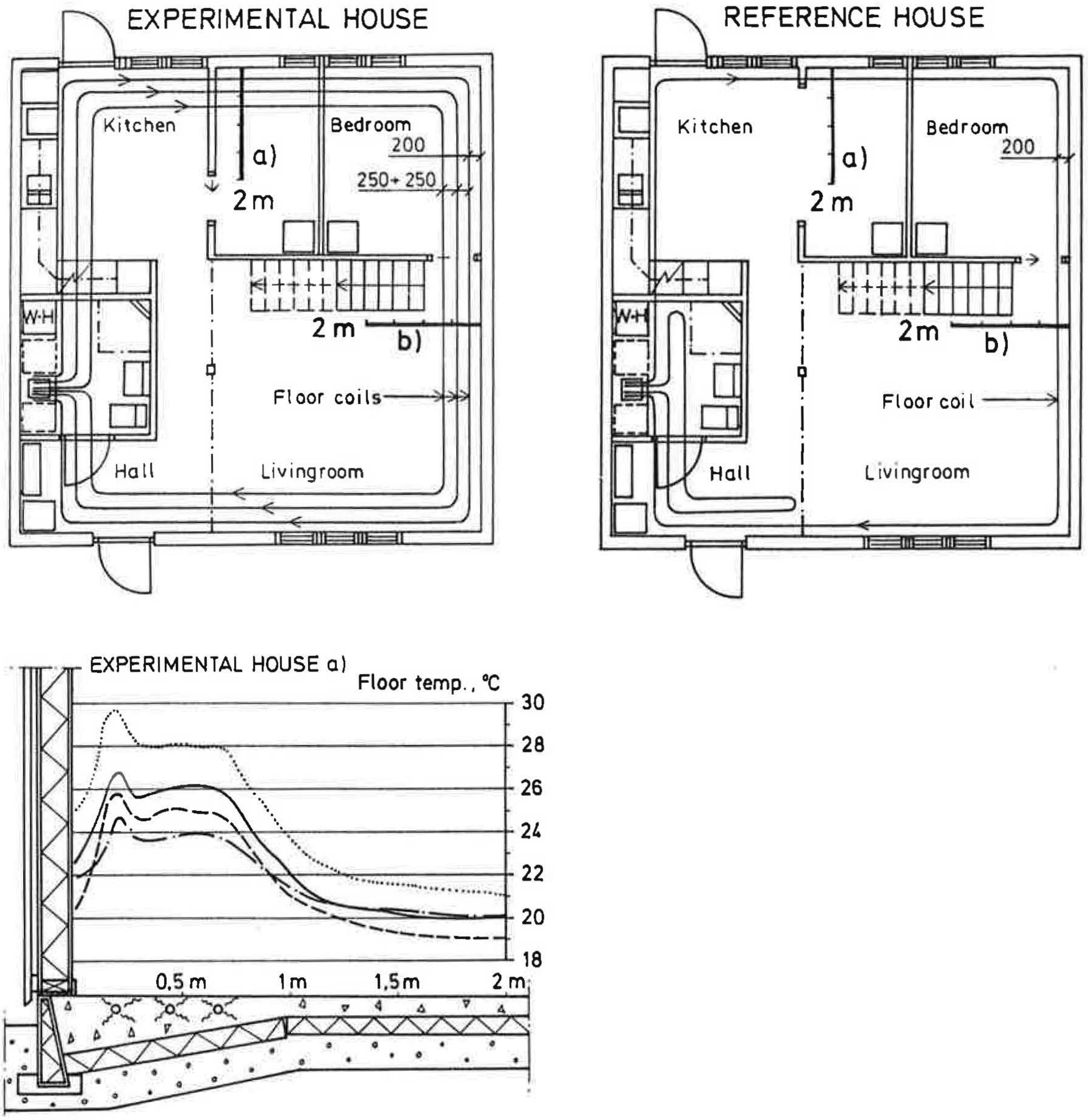
Fig. 6. Energy input and energy losses in the reference house. The values are based on a combination of measured consumption and calculations. The energy input is shown in two different ways, where the column on the left shows the source of the energy, while the middle column shows how the energy is provided.

Energy for heating (19 300 kWh per year) covers the whole year (including the summer) with an average indoor temperature of 21 °C. The bought energy used for active space heating is only 8 000 kWh per year. The total consumption of bought energy is 12 300 kWh per year, which means that the family in this house uses 2 000 kWh per year less than the average for the 39 houses

pressure gradient of 1.9 Pa m^{-1} or on average 4.8 Pa between the upper and lower storeys. Thus the thermals led to the two storeys having differing degrees of ventilation in the winter, with a smaller supply air flow rate to the upper storey. A calculation based on measurement data (related values for differences in pressure and air flow) has quantified this effect, which has proved to be significant. Both poorer airtightness and smaller exhaust air flow lead to lower air pressure indoors, which increases the relative effect of the thermals. In order to achieve a sufficiently constant supply air flow rate in a two-storeyed house with exhaust air ventilation, in spite of the effect of both thermals and wind, the underpressure indoors should not, at a rough estimate, be less than 10 Pa on average.

Fig. 7. Measurement of the air leakage rate.

Both measured air and surface temperatures and practical experience prove that the thermal climate in the houses is good. The temperature of the air indoors has, in the winter, usually been between 19–20 °C in the reference house and 20 and 21 °C in the experimental house. These values hold good for all the rooms except the shower/laundry room on the ground floor, where heat from the water-heater etc. has resulted in a temperature a few degrees higher. Close to the supply air intakes (three on each storey) there is, however, a small zone of somewhat colder air in the winter, which to some extent restricts the way in which the houses can be furnished. Measurements and practical experience also



—— 85-12-11 (−9°C) ---------- 86-02-07 (−7°C)
·-·-·-·-· 86-01-22 (−2°C) ·········· 86-04-01 (4°C)

Fig. 8. ***The floor temperatures were determined at one spot (a) on the ground floor of the experimental house on four different occasions. Alongside the date given is the outdoor temperature on that day. The indoor temperature was 19–20 °C (except for 1 April 1986, when it was 22 °C). The rise in temperature of the three floor heating coils is very evident. The occupants appreciated this higher temperature, which makes the floors more comfortable to walk on***

show that the ventilation and the air quality are on the whole good. It is, however, important that the ventilation system is well maintained, since the air quality in the relatively airtight buildings is highly dependent on how well the mechanical ventilation system functions.

Figure 8 shows examples of the surface floor temperature in the experimental house on four different winter days when the floor heating coils were in use. Measurements were taken at every dm 0–2 m away from the outer wall. It is generally true to say that houses with a concrete slab directly on the ground and without floor heating often have a relatively low floor temperature just inside the outer walls on the ground floor because of thermal bridge effects, in spite of having a relatively well-insulated construction. Thanks to the floor heating coils there is in the Sigtuna houses, by contrast, a higher temperature which is very favourable from the point of view of comfort and which makes it easier to make use of (furnish) the floor space right up to the outer walls. The rise in temperature inside the construction is also normally advantageous in order to avoid moisture problems.

Moisture in walls and the concrete slab

The risk of biological attacks on wood materials (rot, mould etc.) is to a large extent dependent on the moisture content. With a moisture content of less than 15% the risk is minimal. Just after the wall elements had been erected (March 1985) the moisture content was 20–29% in the pressure-impregnated wooden sills of the outer walls. The time it took for the wood to dry out to the average moisture content of 15% was 6 months for the reference house and 2.5 months for the experimental house. The rate of drying is shown in Fig. 9. The shorter time it took for the experimental house to dry out is mainly explained by the placing of a steel sill (of corrugated stainless steel) (Fig. 10) between the wooden sill and the concrete slab, while the reference house had the conventional construction generally used in the estate of polyurethane foam between the wooden sill and the concrete. A short drying-out period reduces the risk of attacks from mould etc.

The inner wall sills dried very quickly from, in some cases, a very high level of moisture. Throughout the period the outer wall studs have had moisture content (at the measuring points) of between 8 and 12%. The wall elements are, thanks to the polyurethane foai airtight themselves, which means that no plastic fil was used on the outer walls in this case. The dry out wall studs and the relatively good airtightness of tl houses indicate that the construction functions wє without plastic film, which is also confirmed by labor tory experiments by (Larsson (ref. 6). As far as tl concrete foundation slabs are concerned, both measur ments and practical experience show that the concre slab was sufficiently dry (with a moisture content corre ponding to a relative humidity of <90%) to avo: damage to, for example, the plastic floor covering.

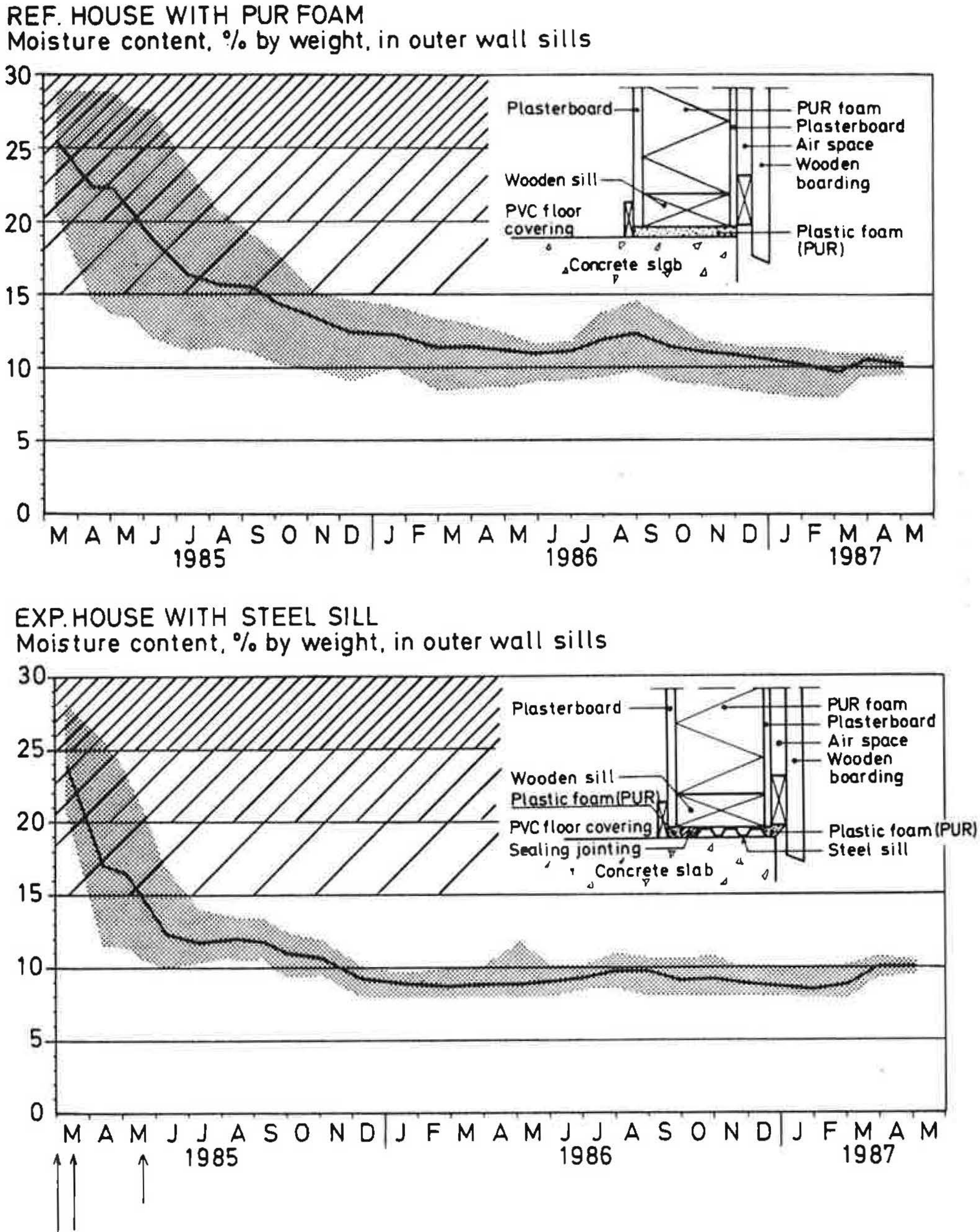


Fig. 9. Moisture content measured in the outer wall sills of pressure-impregnated wood. The mean value (broad line) and the spread from the lowest to the highest value from six measuring points. The risk of biological attacks on the wooden sills (rot and mould) is marked with shading, where close shading represents a greater risk. As can be seen, the period of drying-out (of damp after the erection) is considerably shorter thanks to the steel sill-system, where the moisture content alread after 2–3 months are below critical values. The steel sill is completely capillarity breaking betwee concrete and wood, and the wooden sills are ventilated (dried out) via air intakes in the corners of the house. After the short period of drying-out the air intakes are closed with special lids (ref. 7)

Fig. 10. A wall element is placed on the steel sill

Measurements of the air humidity show that the increase in moisture is relatively low, often about 2–3 g m^{-3} in the wet rooms and 1–2 g m^{-3} in the other rooms. This means that the relative humidity is fairly low indoors, and usually 20–40% in the winter.

Sound insulation

The outer walls of the Sigtuna houses consist, seen from inside, of 13 mm of plasterboard, 120 mm of polyurethane foam between 45×120 mm wooden studs, 9 mm of plasterboard, 22×70 mm wooden battens (i.e. 22 mm air space) and 22 mm wood panel on the outside. This construction is relatively light and at the same time fairly rigid, which implies that the sound insulation is poor. Conversations held inside the house can therefore be overheard outside the walls (Fig. 11).

After complaints had been made by the occupants, the wall towards the carport was insulated with an extra layer of mineral wool between 45×45 wooden studs, faced by 2×13 mm sheets of plasterboard. In addition, plasterboard was placed in the carport roof in order to reduce the flanking transmission. These simple improvements raised the apparent sound reduction index from R'_w30–35 dB to R'_w=50 dB.

These values do not directly say whether or not the sound insulation is now sufficiently good. In order to study this problem, speech intelligibility in the form of an 'articulation index', AI, was calculated in accordance with an American standard (ANSI 53.5–1969). The appropriate values for sound insulation and background level show that the additional insulation reduced the AI from 0.39 to 0.0. According to ANSI these values correspond to a speech intelligibility for sentences of 92% and 0% respectively. It is therefore evident that the additional insulation greatly raised the level of personal integrity.

The sound insulation of the original outer walls must thus be considered inadequate. However, both calculations and measurements show that a relatively simple improvement gives the walls an acceptable level of sound insulation.

Experiences and conclusions

On average during a normal year the 39 houses (households) used 14 500 kWh per year or 121 kWh m^{-2}, which includes all bought energy indoors (heating, hot water and household electricity). The average annual temperature at this location is 5.5 °C. Exhaust air heat pumps contribute greatly to the low level of energy consumption. When comparing the households with the lowest

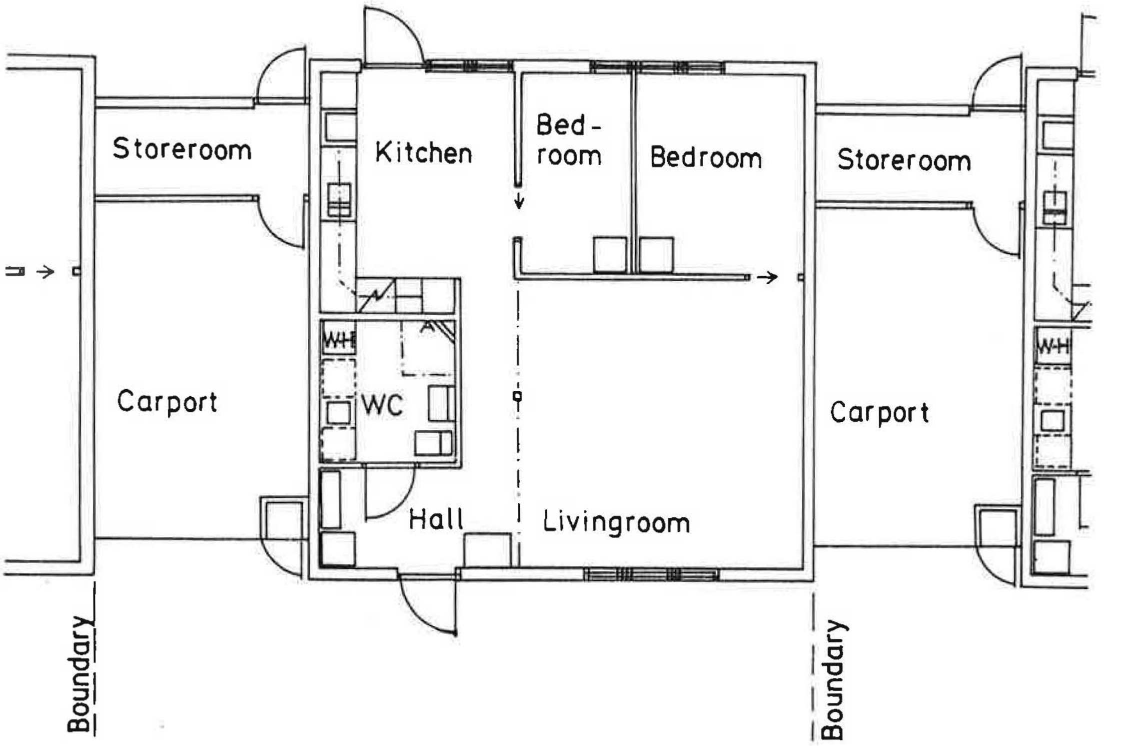


Fig. 11. Plan of the link houses in the project. This type of house plan obviously leads to the risk that conversations held in the bedroom or livingroom will be overheard in the neighbour's carport, particularly as there is no window in the wall concerned

and highest energy consumptions, however, the ratio is 1:2.2, although the differences between the technical quality of the house are relatively small. The fact that the consumption of energy varies greatly between equivalent houses as a result of the occupants' different living habits is thus confirmed (and quantified) in this study. The houses themselves are so energy-economical that the potential in economic terms for further energy saving by means of technical improvements (thicker insulation etc.) is relatively limited, but at the same time relatively high by means of altering the living habits of many families.

The determined coefficient of thermal conductivity of the polyurethane foam insulation in walls and roofs lies within the range of 0.018–22 W/m·°C. These low values (after up to seven years) indicate that the deterioration in the thermal conductivity of polyurethane foam in practice takes place very slowly.

The air leakage rate in four different polyurethane insulated houses was found to be 0.1–1.4 air changes per h at 50 Pa. The extremely good airtightness for a seven-year-old house (0.3 air changes per h) indicates that the building envelope including the joints between the various house elements, can hardly have aged noticeably as far as airtightness is concerned over a period of seven years.

One problem connected with PUR-insulated constructions is, however, that they are light and at the same time relatively rigid. This implies that the sound insulation will be poor if improvements are not made.

Houses with a concrete slab directly on the ground and without floor heating often have a low floor temperature close to the outer walls of the ground floor because of thermal bridge effects, in spite of a well-insulated construction. Thanks to the underfloor heating coils there is, in contrast, a raised temperature in these houses, which is very advantageous from the point of view of comfort. The fact that the thermal climate in other respects is also good is shown by the measured air and surface temperatures and by practical experience. No damage or problems caused by moisture have been noted in these two houses. Measurements also show that critical constructions are sufficiently dry and that the air humidity indoors is relatively low.

The mechanical system or exhaust air ventilation gives a relatively constant air change rate, but the exhaust air flow rate in these two houses was on average somewhat lower than the projected values. The exhaust air ventilation system gives for the projected exhaust air flow about 12 and 8 Pa underpressure respectively on average in the two houses. A combination of measurements and calculations, however, shows that the effect of the thermals (chimney effect] is considerable, so that the two storeys in the winter have different levels of ventilation, with a smaller supply air flow rate to the upper storey. In order to achieve a sufficiently constant flow of air in a two-storied house ventilated by an exhaust air system, in spite of the effect of the thermals and of the wind, the underpressure indoors should not at a rough estimate, be less than 10 Pa on average.

To sum up, the results are favourable. It has been proved possible to build relatively simple, economical, well-insulated and airtight houses which have a low energy consumption. At the same time problems connected with moisture, mould and poor air quality for example–in other words problems associated with so-called sick buildings–have been avoided.

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