Designing houses for energy conservation

by Arne Elmroth and Ingemar Höglund

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Domestic demands account for about 40 per cent of total energy supplies in Sweden. This article reviews research by the Building Technology Division of the Swedish Royal Institute of Technology over many years into the thermal behaviour of houses. It highlights the importance of effective insulation and of solar heat gains in particular situations, entailing modifications to conventional design calculations.

This paper summarises investigations which show that the waste of energy can be largely prevented by such simple means as good heat insulation in combination with well designed heating and automatic control systems. A higher degree of insulation in the external structure forms the basis for a lower room temperature without any detrimental effects on the living comfort. Both these factors imply a great saving in energy in the heating of dwellings. Well designed automatic control systems for regulating the heat supply are a prerequisite for utilising solar energy radiation through the windows, and result in more uniform and comfortable room temperatures. Even in very northerly latitudes a considerable quantity of free heat can be obtained in this way.

The background

The 'energy crisis' which is a rapidly growing international problem, is developing into a menacing reality in Sweden also. A considerable portion of the energy supply in Sweden goes into the heating of dwellings, ie in round figures about 40% of the total supply. Converted into fuel oil consumption, the heating of dwelling houses would require between 10 to 12 million cubic metres of oil which corresponds to an average consumption of between 3 and 3.5 cubic metres per dwelling/year. Thus a restriction of energy consumption for heating purposes is of great interest both for the national economy and for environment protection.

With the aim of illustrating the factors which affect, in the first place, the heat balance in a single-family house, investigations into the energy consumption in single-family houses have been conducted by the Division of Building Technology at the Royal Institute of Technology, Stockholm, since the end of the 1950's. In this connection, the heat balance during the entire heating season has, among other things, been determined for five different single-family houses, whereby the outdoor and indoor climate has been carefully controlled and regulated. Houses of different design and type have been investigated, ie houses erected in bricks, cellular concrete and wood with a timber-frame structure and mineral wool insulation. Two of the houses have a basement, two have a crawl-space and in the fifth a concrete foundation slab has been placed directly on the ground. All five houses have been unoccupied during the time of investigation. In this way it was not necessary to determine the effect of the usually varying living habits of the occupants, which are both difficult to determine and uncontrollable. Instead, this effect is being investigated in a current research project, including 7000 single-family houses. This project attempts to assess the effect of the increase in heat from the occupants, from radiators, warm water, lighting, etc. With the help of a statistical analysis it is hoped that it will be possible to determine the effect of different living habits on energy consumption.

Building structures and testing methods

The test house most recently investigated is a single-storey building with an attic which, if desired, can be fitted out so as to add to the living space of the house. The house is situated in Nälsta, outside Stockholm (latitude c. 60° N). The living space amounts to about 104 square metres. The house is a timber-frame structure. In the outer walls heat insulation consists of 12 cm thick mineral wool slabs and in the attic floor of 2 × 10 cm mineral wool slabs plus 2 × 2.5 cm mineral wool matting (see fig 1). The outer

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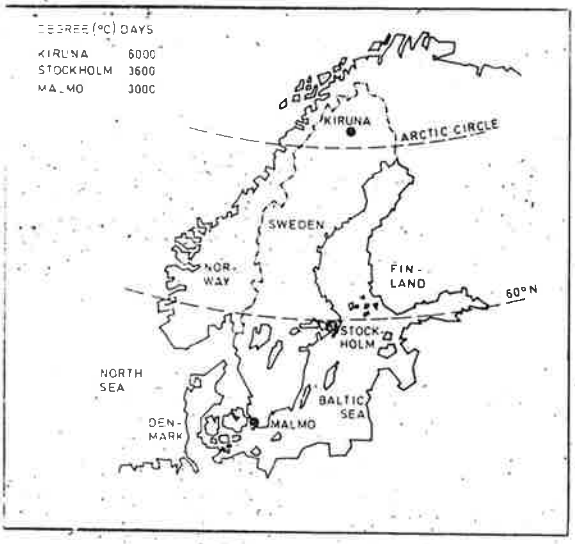
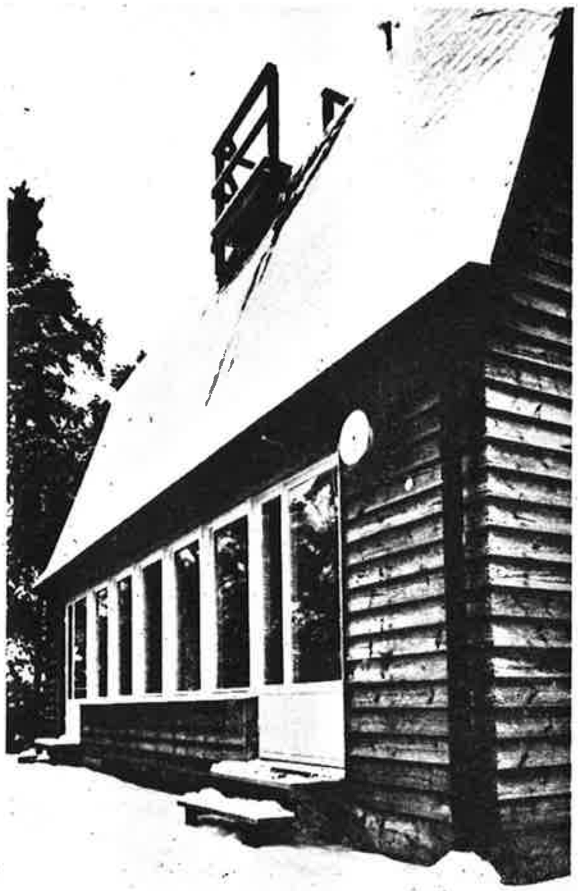
Much of Sweden lies in the same latitudes as Hudson Bay and Siberia, though the climate in the south is tempered by the Gulf Stream. A timber frame house at Nälsta, near Stockholm, was the subject of these experiments. The vertical section shows the wall construction. In all cases insulation consisted of mineral wool.





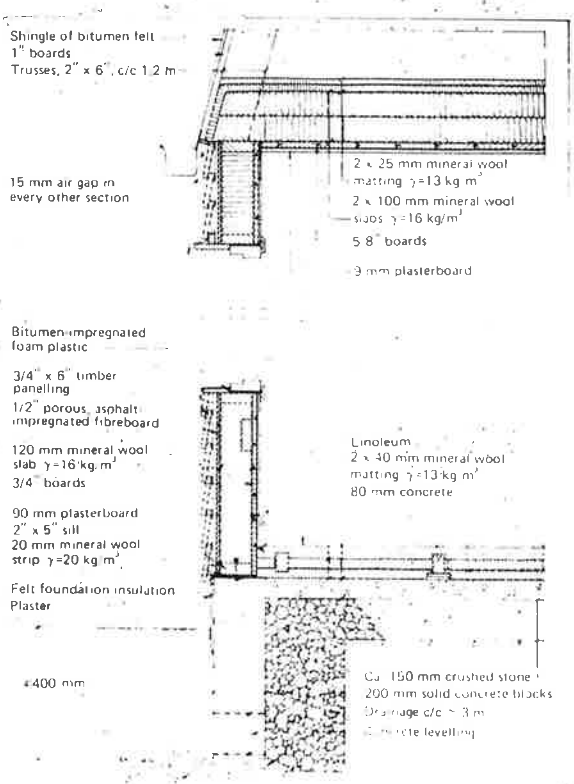


Fig 1

edge zone of the floor – within 1 m of the outer wall – is insulated with 2 × 4 cm mineral wool mattings, while the rest of the floor has an insulation of only one layer of 4 cm mineral wool matting. All windows are triple-glazed. At the time of construction in 1963, this house had an almost optimum degree of insulation with regard to heating economy. In designing this house, the aim has been to make the best possible use of the thermal insulation capacity of the mineral wool. Special care was taken to seal the house in the best possible way.

The investigation comprised a careful determination of the weather data both indoors and outdoors. The energy consumption in each room has been determined both for the night and day as well as for full 24-hour periods throughout the heating season. The heat flow through external walls, floors and roof has been continually recorded. In addition, natural ventilation under different weather conditions has been determined.

Room temperatures and energy consumption

The investigations made possible a careful determination of the heat balance of the houses. The heat balance is composed of heat losses and heat gains. The heat losses consist of transmission losses through all peripheral parts of the building and natural ventilation losses. The heat gain consists of heat emission from the heating system and solar heat gains through the windows. The difference between the calculated and recorded energy consumption has been small in the case of the timber-frame house in Nälsta.

In fig 2 the total calculated heat losses are shown divided into transmission and natural ventilation losses. In addition, the heat gain due to solar radiation through windows is given. The recorded energy consumption for each month during the heating season is also accounted for. The investigations and calculations on which the figure is based have been made for a constant room temperature of +22 °C, which is usual in Sweden and which is even exceeded in winter. With a view to limiting energy consumption, a lower indoor temperature could possibly be chosen during the heating season. The saving in energy which would be possible when reducing the temperature from +22 °C to +20 °C and +18 °C respectively can be seen from fig 3. A temperature reduction by 2 °C indoors implies for the test house that the transmission and ventilation losses are reduced by approximately 11%. A reduction of 4 °C reduces the losses by about 22%.

Room temperatures and comfort

A lower room temperature implies, however, a risk of less comfort. This can be counteracted to a certain extent if the outer shell of the building has a high degree of insulation. As is known, good thermal insulation in our dwellings results in a good climate indoors, ie the rooms become hygienic and comfortable. In well-insulated dwellings there are no draughts and 'cold sides', as the difference between the temperature of the air indoors and the temperature of the room surfaces is small. In addition, there is no great variation in temperature between the various parts of the surfaces. Even with a low outdoor temperature in winter the residents experience a feeling of warmth in the rooms.

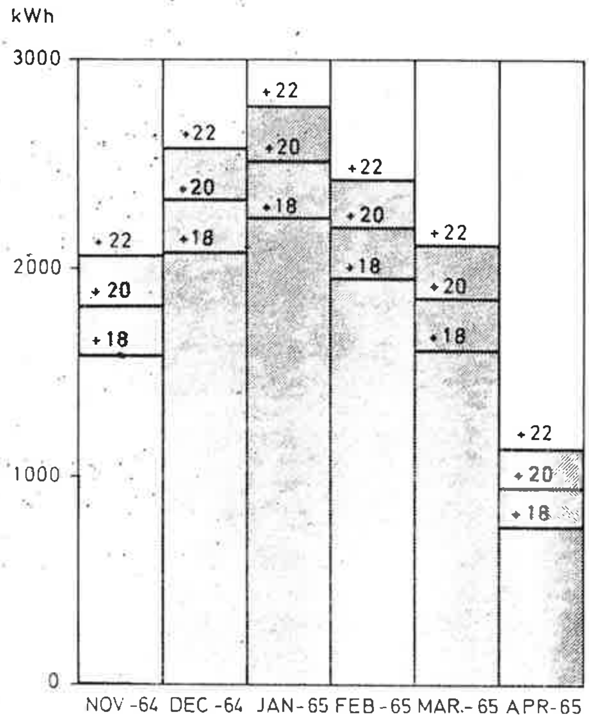
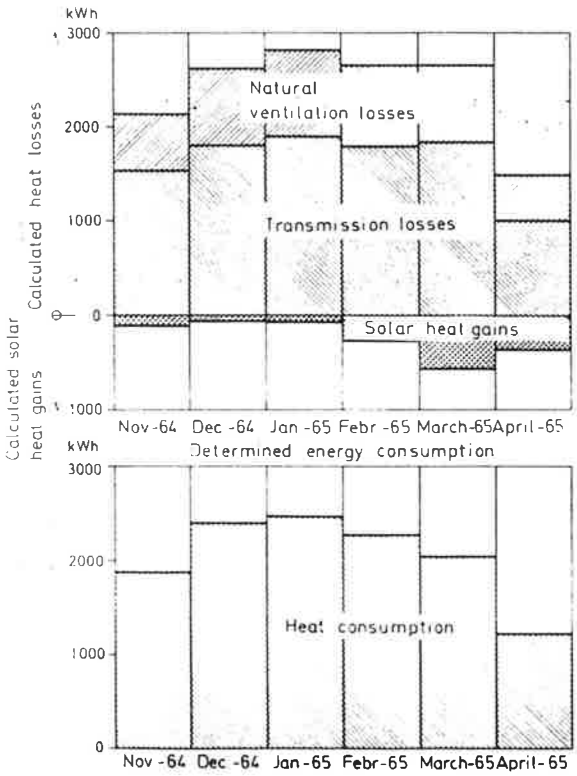


FIG 3. *Calculated energy consumption at different room temperatures (22 C, 20 C and 18 C) in the test house.*



To obtain the same feeling of comfort it is therefore not necessary to increase the room temperature so as to compensate for 'cold sides', provided the external structure is properly constructed. This implies, among other things, that the properties of the insulation material must be fully utilised so as to avoid irregular surface temperatures which cause asymmetrical heat emission from the body, which in turn may result in discomfort. For the same reason, connections between, for example, walls and ceilings, windows, etc., must be made sufficiently tight against air leakage and designed in such a way that no unnecessary cold-bridges arise. A higher degree of insulation thus provides the prerequisites for a lower room temperature which does not interfere with comfort. Both factors result in a saving of energy in the heating of dwellings, offices, hospitals, etc.

FIG 2 (*left*). *The total calculated heat requirement divided between ventilation and heat losses. In March and April, solar heat gain compensated for most of the ventilation losses.*

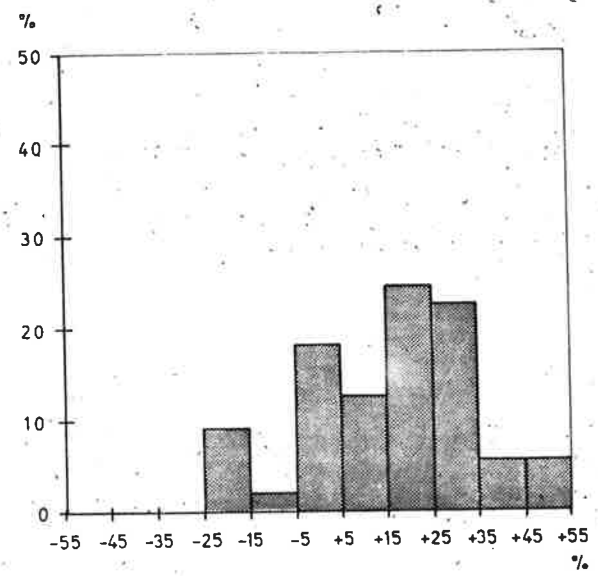


FIG 4. *Frequency diagram shows the difference between recorded and estimated thermal resistance expressed as a percentage of the latter. Procedures followed the relevant Swedish code of practice.*

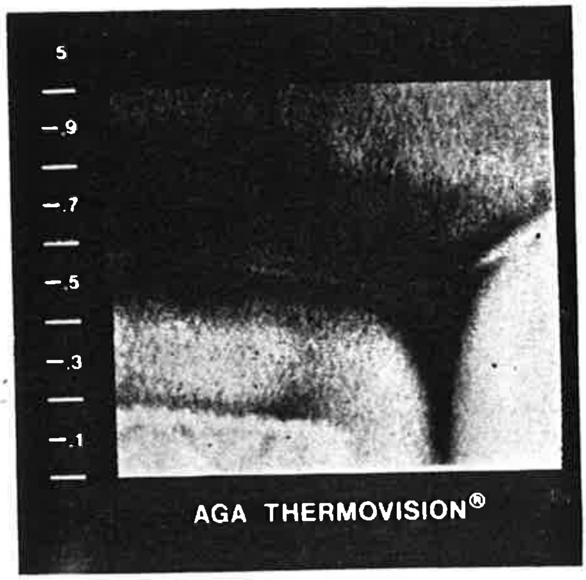


FIG 5. *A thermal picture showing cold (dark) ceiling and wall areas inside a room. A hand-held infra-red camera and battery-operated thermal picture display unit were used for the purpose.*

Good workmanship and thermal resistance

An earlier project at the Division of Building Technology involved determination of the thermal resistance found in a large number of external multi-layer wall types (Höglund 1964). These studies, which together may be regarded as a total investigation of multi-layer walls in blocks of flats, mainly in the Stockholm region, erected between 1954 and 1958 and incorporating high-grade insulation, cover a total of 74 different wall designs. 56 of these were insulated with mineral wool slabs. The frequency diagram shows the difference between determined and calculated thermal resistance in these walls insulated with mineral wool expressed as a percentage of the determined thermal resistance (fig 4). The mean was 16% better than the calculated values and the standard deviation was 18%. For the purpose of the calculations, the coefficient of thermal conductivity was for mineral wool assumed to be 0·040 kcal/m h °C according to the Swedish code of practice of 1960. The coefficients of thermal conductivity for other materials in the walls were also taken from the Swedish code of practice.

However, approximately 23% of the thermal resistance values determined were lower than those calculated, primarily due to faulty workmanship. The mean of all the thermal resistance values is equivalent to a k value for mineral wool slabs of approximately 0·035 kcal/m h °C assuming that other materials in the walls have the coefficient of thermal conductivity recommended in the Swedish code of practice as being practically applicable. Measurements on more traditional types of external walls – in the same Stockholm area and with the same measuring instruments – yielded not only lower mean values but also a smaller standard deviation. In fact, the average thermal resistance of each type was about 4% more than the calculated value and the standard deviation was about 10%, depending, for example, on the moisture content and density of wall materials. *The rather high standard deviation for the multilayer walls was, on the other hand, mainly due to the fact that their thermal resistances are more sensitive to constructional imperfections than the more traditional walls.*

Summarising, these and subsequent investigations have shown that a good thermal insulation in building structures is dependent on

- insulating materials having suitable technical and physical properties
- design properly adapted to the design aspects of the building and to its installations
- skilled workmanship and meticulous control.

The location of defects in insulation and points of air leakage are nowadays thermographically determined by infra-red camera techniques (figs 5a, 5b).

The effects of solar radiation

With the help of continuous registration of solar radiation at the timber-frame house in Nälsta, the solar heat gain through windows could be determined quantitatively for the periods of investigation. By means of a special method of analysis, due consideration has been paid to, among other things, cloud conditions and screening. This special method of analysis formed a necessary prerequisite for a careful determination of the heat balance over a longer period of time.

Solar radiation affects energy consumption in several different ways. As the sun only shines during the day, energy consumption will differ between day and night, which is of interest particularly as regards the efficiency of electric heating. Studies conducted in the timber-frame house in Nälsta have shown that during November, December and January, energy consumption was almost identical during day- and night-time. In the remaining months of the heating season, day-time consumption has, however, been smaller. During the first half of March, for example, day-time consumption amounted to only about 70% of night-time consumption (compare table 1 and fig 6). This is due to the fact that during that time of year the weather is frequently very clear which, in addition to a considerable solar radiation during the day, implies a considerable net emission during the night, resulting in large heat losses and even low outside temperatures. In occupied houses, the calculated quota may be expected to shift somewhat as lower room temperatures are usually accepted during the night. It should also be stressed that, *in order to make use of the positive effect of solar radiation, the heating and regulating system should not be too inflexible.* Otherwise solar radiation could lead to uncomfortably high room temperatures during a large part of the year, which in turn implies a risk of the solar heat gain being wasted unnecessarily through ventilation.

The effect of solar radiation varies in rooms with different orientation. To illustrate this, the heat consumption in two corner rooms of approximately the same size has been compared (fig 7). One of the rooms lies towards the SE with windows only in the wall facing south, while the other room lies towards the NE with windows only in the wall facing north. Table 2 shows the monthly heat consumption in the two rooms together with other details. The room facing SE has a somewhat larger peripheral surface,

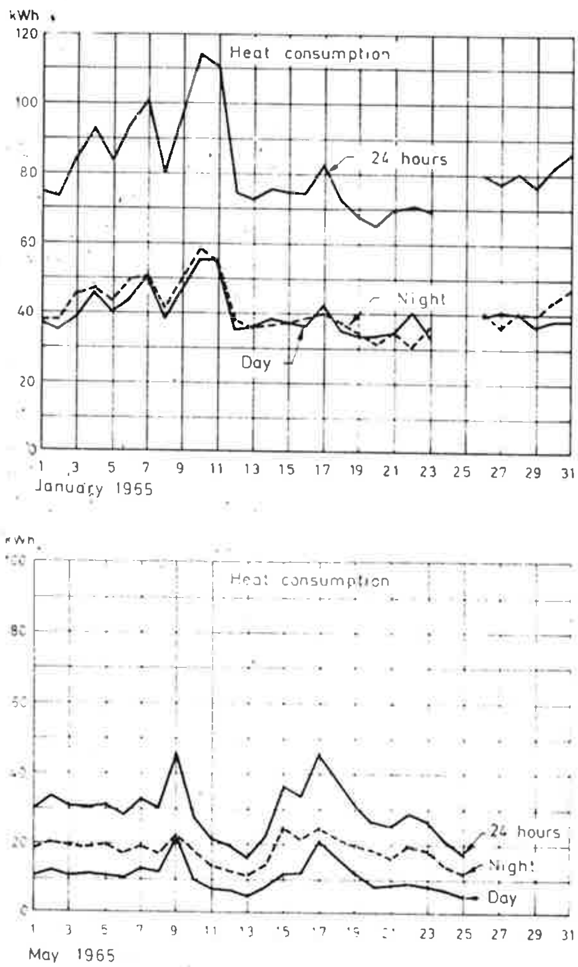


FIG 6. *Diagrams of total consumption and respective day and night-time consumptions on each day in January and May 1965. Note divergent pattern during sunnier days of May.*

both as regards floor and ceiling as well as walls. The window surface is a good 50% larger in the room facing SE.

During the winter, the heat consumption in the room facing south has been considerably larger than in the room facing north, ie 32% larger in December and January. During March and April heat consumption has, on the other hand, been smaller in the room facing south than in that facing north. Heat consumption in April has for example only amounted to 91% of that recorded for the room facing north. This illustrates once again the great importance of solar radiation, in the first place, in the autumn and spring. It also shows *that rooms with different orientation should of necessity have separate regulation devices for heat supply if all rooms are to have the same temperature and if the solar heat gain is to be best utilised.*

FIG 7A (right). *Monthly records of energy consumption in a room with a south facing window (see also Fig 7b overleaf for a north facing window). The solar heat gain effect is sharply illustrated.*

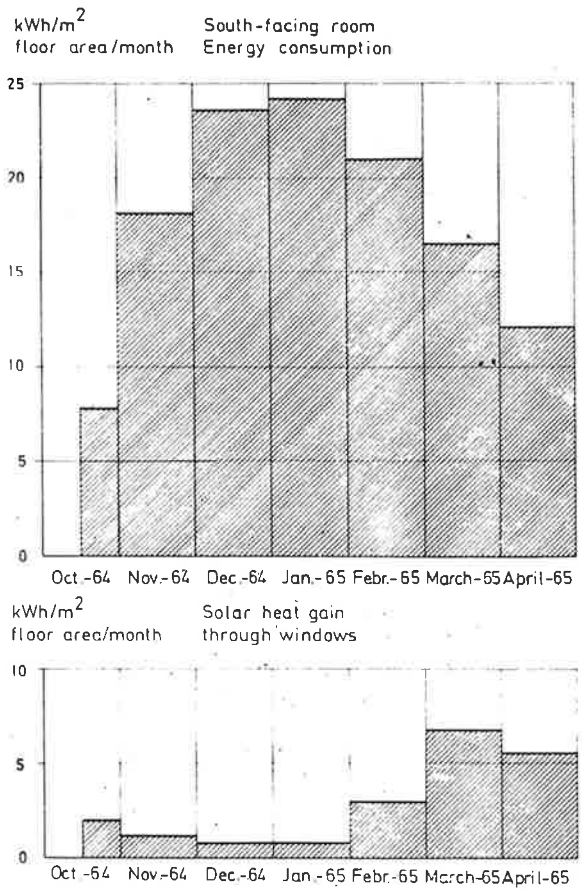


Table 1 Day and night consumption

Test period	Heat consumption during the day 06–18 kWh	Heat consumption during the night 18–06 kWh	Ratio day to night
Oct. 15–31	362.6	438.3	0.83
Nov. 1–15	417.3	469.8	0.89
16–30	484.3	516.0	0.94
Dec. 1–15	512.6	530.1	0.97
16–31	—	—	—
Jan. 1–15	634.4	662.9	0.96
16–31	—	—	—
Feb. 1–15	549.1	635.4	0.87
16–28	491.5	611.5	0.80
Mar. 1–15	450.0	644.0	0.70
16–31	417.5	545.8	0.76
April 1–15	355.3	406.1	0.88
16–30	287.5	382.1	0.75
May 1–15	158.9	271.2	0.59
16–25	105.0	186.4	0.56

The heat balance of windows

In calculating the heat transfer coefficient (British U-value) of the windows, due consideration has been paid to heat transmission, which is high compared with, for example, that of an outer wall. However, a considerable amount of heat gain is obtained through windows, as has been shown in the above. This should be taken into account when determining the effect of windows on the annual heating requirement. However, when calculating the necessary heating effect of a building, a heat gain from solar radiation cannot be expected in cloudy conditions. In this case a heat transfer coefficient which only takes into account transmission losses should be used.

In the calculation of the annual heating requirement it is necessary to make a reduction in the computed transmission losses, as solar heat radiation results in a heat contribution which cannot be neglected. To illustrate the relation between heat contribution and heat losses in the various months of the heating season an 'equivalent U-value' has been determined. For the timber-frame house in Nälsta, 'equivalent U-values' have been calculated for the months of

The tables on right give the characteristic features of the rooms in Figs 7a and 7b and the recorded heat consumption.

Table 2a Consumption of different rooms in timber-frame house at Nälsta

	South-facing room kWh	North facing room kWh	S-room / N-room %
1964			
Oct. 15–31	100.2	87.0	115
Nov. ,,	235.6	192.5	122
Dec. ,,	306.8	233.0	132
1965			
Jan. ,,	314.3	238.2	132
Feb. ,,	272.0	226.9	120
Mar. ,,	217.2	225.0	96
April ,,	157.7	174.3	91
15 Oct., 1964 – April 1965	1 603.8	1 376.9	117

Table 2b Features of the rooms

	Floor area, inner size, m^2	Glazed area, m^2	External wall incl. window inner size, m^2
South-facing room	13.0	2.7 S	8.6 S +8.6 E
North-facing room	12.0	1.7 N	6.9N +9.7W

October 1964 to April 1965 (table 3). In this calculation, heat contributions on account of solar radiation have been deducted from conventionally calculated transmission losses through the glazed surface. The U-value which would have directly given these net losses is the 'equivalent U-value'.

The heat gain from solar radiation varies with the orientation of the windows (table 3 and fig 8). Thus, windows in facades facing in different directions have different 'equivalent U-values'. In March 1965, for example, the solar heat gain through windows in the differently facing external walls calculated per square metre of glazed surface during the whole of March, which was a relatively sunny month, has amounted to 14 kWh, 29 kWh and 44 kWh for the windows facing north, east and south respectively, resulting in an approximate ratio of 1:2:3. During the same month the transmission losses were 34 kWh per square metre glazed surface (U-value=1.7 kcal/m² h °C for the triple glazed surface). If the 'equivalent U-values' are calculated for each direction during March, for example, an 'equivalent U-value' of 1.0, 0.3 and —0.5 is obtained for the windows facing north, east and south respectively, (table 3). Thus *in that month there was, on average, a greater gain in heat on account of solar radiation through the windows facing south than was transmitted through these windows due to the temperature difference indoors-outdoors.*

The investigations show that the greater part of the solar heat gain through the windows during the main part of the heating season can be utilised for heating purposes with the help of adequately designed automatic control systems for heat supply. As far as

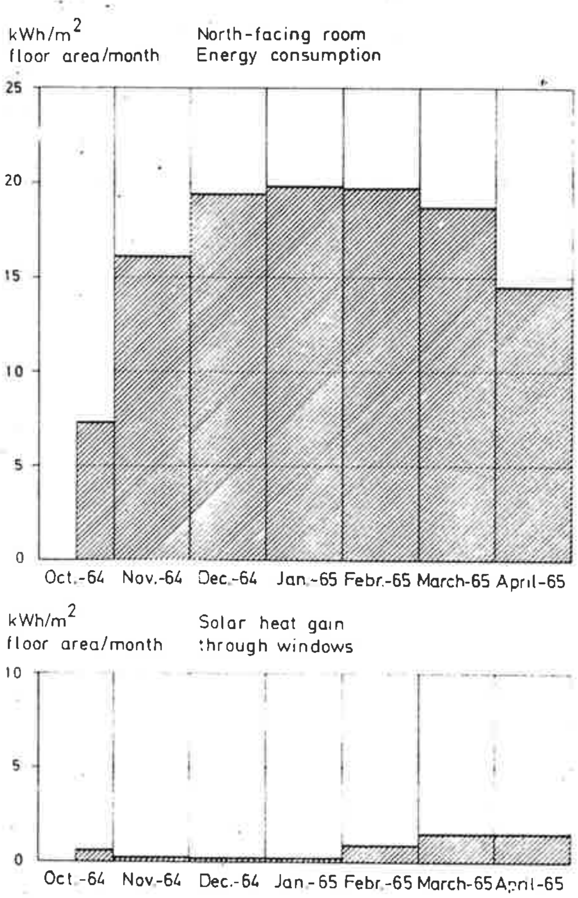


FIG 7B. *Behaviour of the room with a north facing window, both slightly smaller and with a smaller glazed area than its south-facing counterpart, where solar heat gains in Spring were especially marked.*

Table 3 Adjustment for 'Equivalent U-values'

Month	Trans-mission losses	Solar heat gain Windows facing S(36°)	N(—144°)	E(—54°)	'Equivalent U-values' Windows facing S(36°)	N(—144°)	E(—54°)
1964							
October	22·0	18·0	5.7	10.6	0.3	1.3	0.9
November	28.3	8.2	2.4	5.2	1.3	1.6	1.4
December	33.5	4.0	1.3	2.9	1.5	1.6	1.6
1965							
January	35.5	3.9	2.1	4.5	1.5	1.6	1.5
February	34.9	19.5	9.0	15.3	0.8	1.3	1.0
March	34.4	44.4	14.1	29.1	—0.5	1.0	0.3
April	27.0	36.8	14.5	25.7	—0.6	0.8	0.1

Calculated transmission losses, solar heat gain and 'equivalent U-values' in kWh per m² of glazed area/month in Nälsta house. Triple glazed windows (U = 1.7 kcal/m²h°C). Monthly means for 'equivalent U-values'.

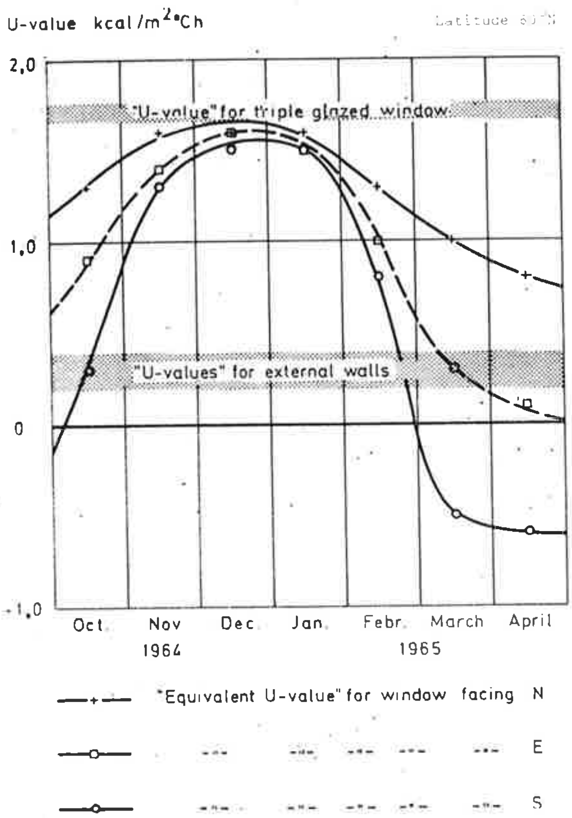


FIG 8. *'Equivalent U-values' for different facades. These take account of the varying solar heat gain resulting from different orientations of the windows and are deduced from conventionally-calculated transmission losses. They are compared with U-values for windows and external walls when solar heat gain has not been taken into account.*
The actual calculations are listed in table 3.

windows are concerned, this implies that considerably lower heat transfer coefficients can be used in calculating the energy requirement than is the case if only transmission losses are taken into consideration. For the calculation of such equivalent coefficients of thermal conductivity, methods are available which take into consideration the type of window construction (transmission properties) and orientation, the extent of solar radiation, cloudiness factors, the length of the heating period and the temperature difference indoors-outdoors during that period.
The great importance of solar radiation through windows on the total heat balance is illustrated in fig 2. The gains in solar heat during the months of November, December and January have been relatively small, while in the spring the gain was so large as to have an important effect on the heat balance of the entire house. In March and April, the heat contribution on account of solar radiation has thus been almost as large as the heat losses due to natural ventilation.

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