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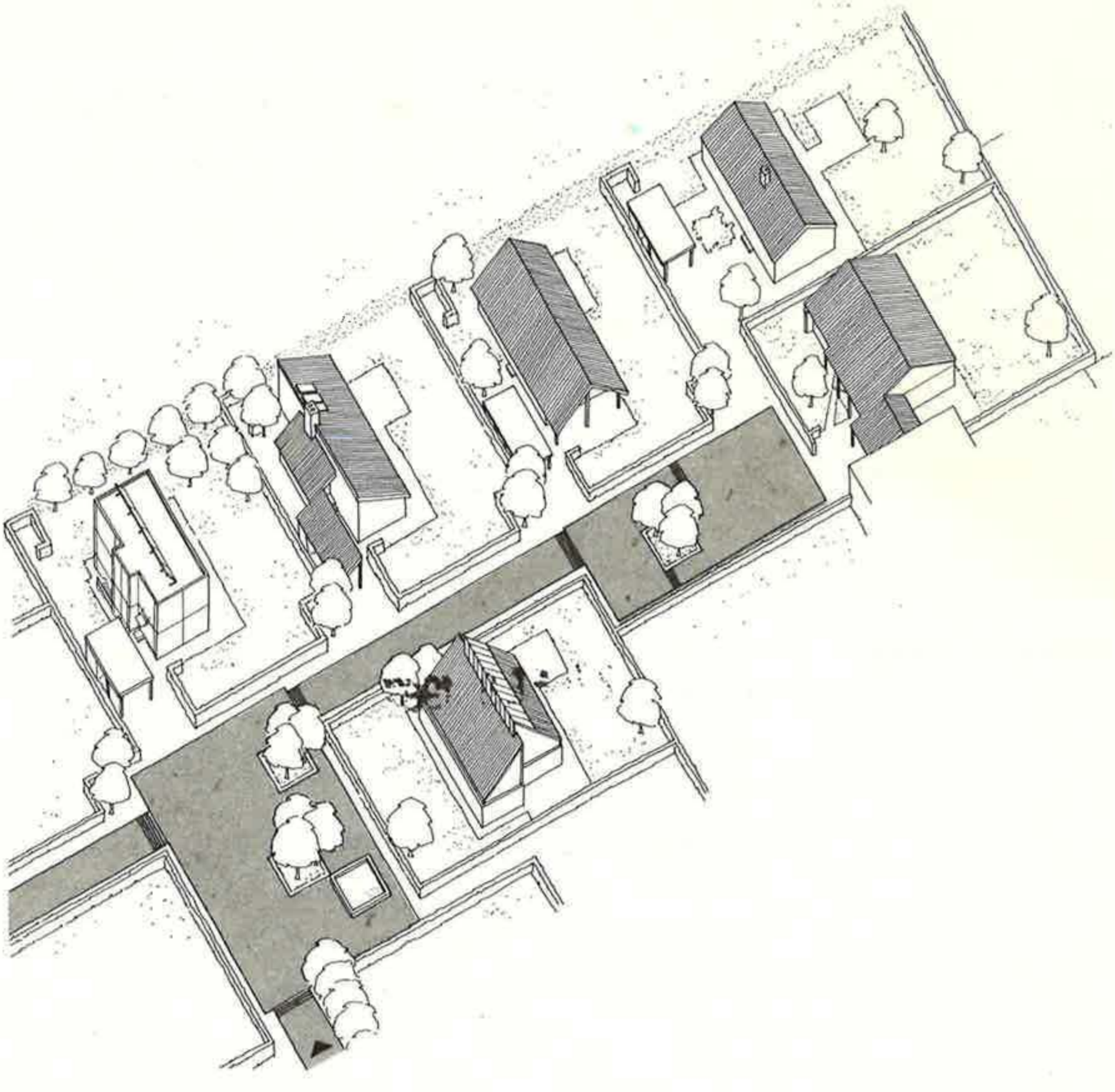
The Low-Energy House Project, The Danish Ministry of Energy



INSULATION AND AIR TIGHTNESS OF SIX LOW-ENERGY HOUSES AT HJORTEKÆR, DENMARK

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PREFACE

The main part of the results in this report was presented at the Third International Symposium on CIB Working Commission W-67 held in Dublin, Ireland, March 30-April 1 1982, orally or in our conference paper. The material has been reedited and new experimental results and some supplementary analyses as well as new illustrations have been added.

The Low-Energy House Project is carried out by the Thermal Insulation Laboratory at the Technical University of Denmark. The project is part of the National Energy Research Programme and is funded by the Danish Ministry of Energy.

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ABSTRACT

In 1978-79 six detached single-family houses were built at Hjortekær, north of Copenhagen, as six different prototype low-energy houses.

Throughout 1979 and 1980, continuous energy measurements as well as limited investigations of specific problems were carried out by a research team from the Thermal Insulation Laboratory.

In this report, a few typical construction details are described, some details having been chosen to illustrate solutions to the problem of cold bridges, others to demonstrate ways of obtaining airtight constructions.

The infiltration air change rate has been measured a number of times by the tracer gas decay method, showing results ranging from 0.02 to 0.12 a.c.h. Also, pressurization and depressurization tests have been made - the results of these tests and the possible correlation with the air change rate are discussed.

For a few weeks, the ventilation systems of the houses have been sealed, and the houses have been heated by electric resistance heaters. For selected stationary periods, the total heat loss is worked out from the meter readings, allowing for the solar heat gain. The transmission heat loss (ranging from approx 70 to 155 W/C) is found by deducting the infiltration heat loss (mostly less than 10% of the total), and the result is compared to the calculated heat loss, based on the actual temperatures and the theoretical U-values. The calculated and the measured transmission heat loss differ less than 15%.

By means of regression analysis of the thermal calibration data three different models for heat loss equations are tested. Two very simple models show good agreement with the

corresponding calculated heat loss, and very low standard errors. The present analyses are considered a pilot study for working out a short term calibration test procedure for low-energy houses.

INTRODUCTION

About 20-25 years ago there was a change in the Danish building methods for detached houses. Earlier, most houses were brick-built (solid or cavity walls), and internal surfaces were plastered. In the late fifties timber structures became prevalent, often with a brick facing, and internal surfaces were panelled. In the following years the use and misuse of vapour barriers were introduced and widely adopted. Up till now, however, too little emphasis has been given to the joining of the vapour barriers. Consequently, on the average, the change in building methods caused an increase of air change by infiltration. During the past few years the air tightness of houses has been improved, mainly through introduction of weather stripping of doors and windows.

The six low-energy houses at Hjortekær, built as part of the Danish Energy Research and Development Programme, offer a diversity of architectural and technical solutions as to design, choice of building materials, heating systems, energy sources etc, [1]. Each house has a living area of about 120 m^2 and a design energy supply of approximately 5000 kWh/year, covering space heating, ventilation and domestic hot water. The low design energy supply is achieved through an interplay of a low energy demand and utilization of alternative energy sources, the greater importance being attached to the former, [2]. All six houses are extremely well insulated (typical U-values for walls 0.13-0.20 W/m^2C - and for roofs 0.09-0.12 W/m^2C), [3], and an attempt has been made to keep the air leakage at a negligible level.

SELECTED CONSTRUCTION DETAILS

Six construction details from the low-energy houses have been selected for presentation in this context. A detailed description of the constructions is given in [4].

It must be emphasized that the main reason for the extreme care given to the use of and the joining of polyethylene or aluminium foils in this project is not to prevent moisture transport by diffusion, but to prevent air leakage through the constructions. The air tightness is important for two major reasons. First of all, the possible moisture transport by convection considerably exceeds the moisture migration by diffusion, and condensation in the timber structures can cause severe damage (rot and dry rot). Secondly, controlled ventilation with heat recovery is only energy efficient if the infiltration heat loss is kept low, as illustrated in Figure 1 by simple calculations for a heat exchanger with 50% efficiency. All six houses at Hjortekær have commercially built cross-flow plate type heat exchangers.

Infiltration rate	[a.c.h.]	0.10	0.50	1.00
Controlled ventilation	[a.c.h.]	0.50	0.50	0.50
Total air change	[a.c.h.]	0.60	1.00	1.50
Thermal net air change	[a.c.h.]	0.35	0.75	1.25
True recovery efficiency	[%]	42	25	17

Figure 1. Example, heat exchanger with 50% efficiency.

The first construction detail, Figure 2, shows a horizontal section of the corner of a prefabricated house, built of concrete sandwich building elements. The elements are insulated with 200 mm mineral wool (the term mineral wool being used for rockwool as well as for glass fibre wool). In this new building unit the insulation thickness has not been reduced at the edges of the elements. The concrete facing and the inner leaf are connected with stainless reinforcement steel (approx 350 mm^2/m^2) which causes an increase of the U-value of less than 6%. No vapour barrier is shown - the painted interior surface of the concrete acts as vapour barrier. The inner leaf joint between two elements is concreted as usual, except that cement mortar has been used for the inner 20 mm, to be replaced with mastic, if necessary. The house was completed in March 1979, and up till now the mortar joints have proved satisfactory.

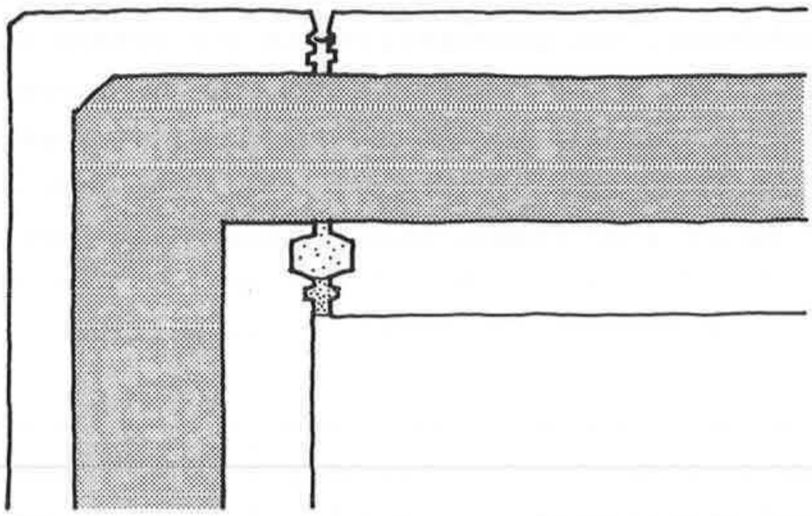


Figure 2. Horizontal section of corner.

Figure 3 shows a vertical section of a foundation for a house with a slab-on-ground construction, traditionally a weak point, thermally speaking. In this case the 200 mm wall insulation is adjacent to the 225 mm foundation insulation (both mineral wool), the only thermal bridge being the concreting at the bottom connecting the two prefabricated concrete elements. This foundation construction has since been further developed into a U-shaped precast and pre-insulated unit. A thermal analysis of this and the other foundation constructions at Hjortekær is given in [5]. To prevent water suction a bituminous millboard is placed between the foundation slab and the brickwork. The interior surface of the lightweight concrete wall is puttied and painted and serves as vapour barrier. The polyethylene foil on the concrete floor slab is fastened between the lightweight concrete wall and the skirting board, sealed with mastic to compensate for warping.

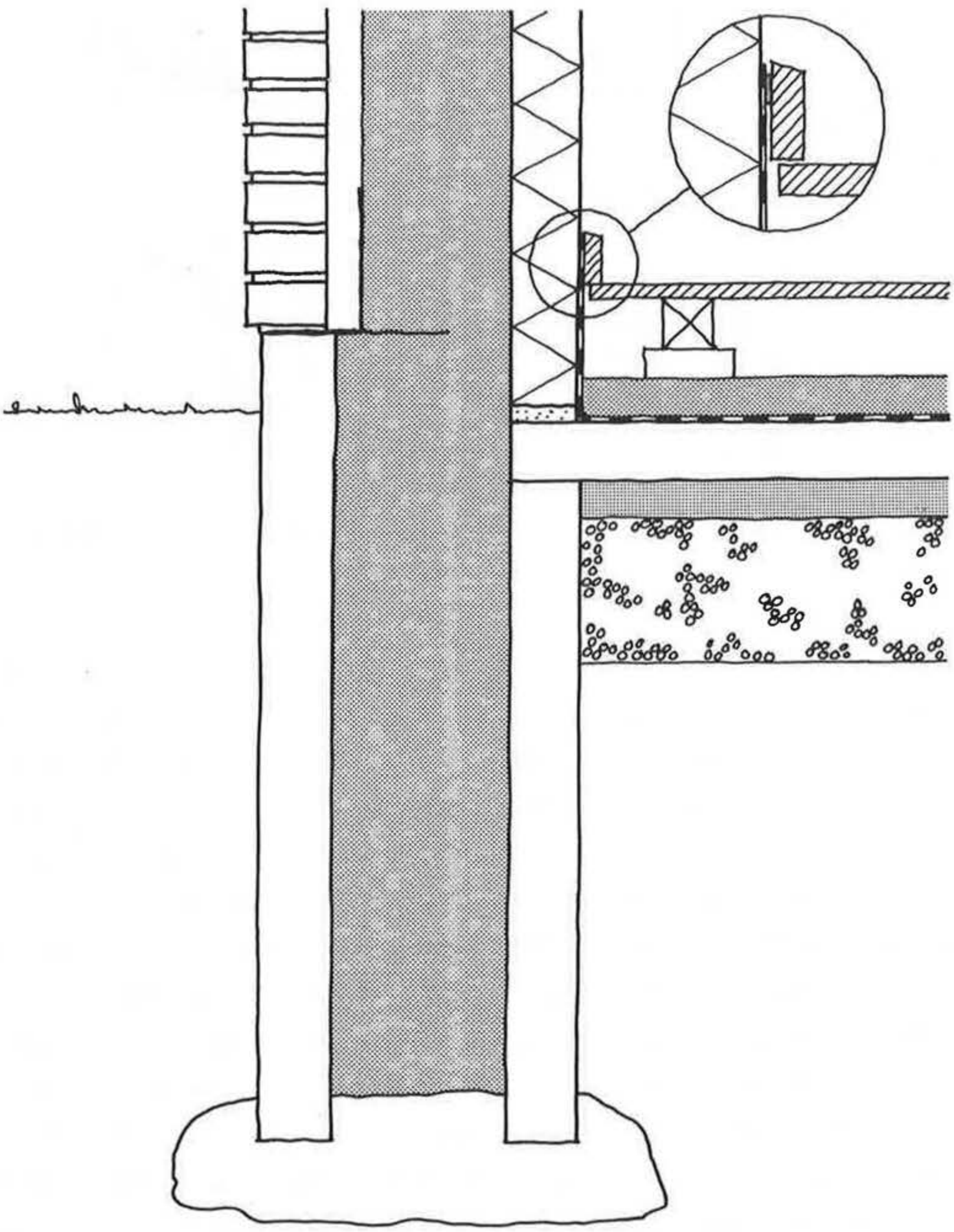


Figure 3. Vertical section of foundation.

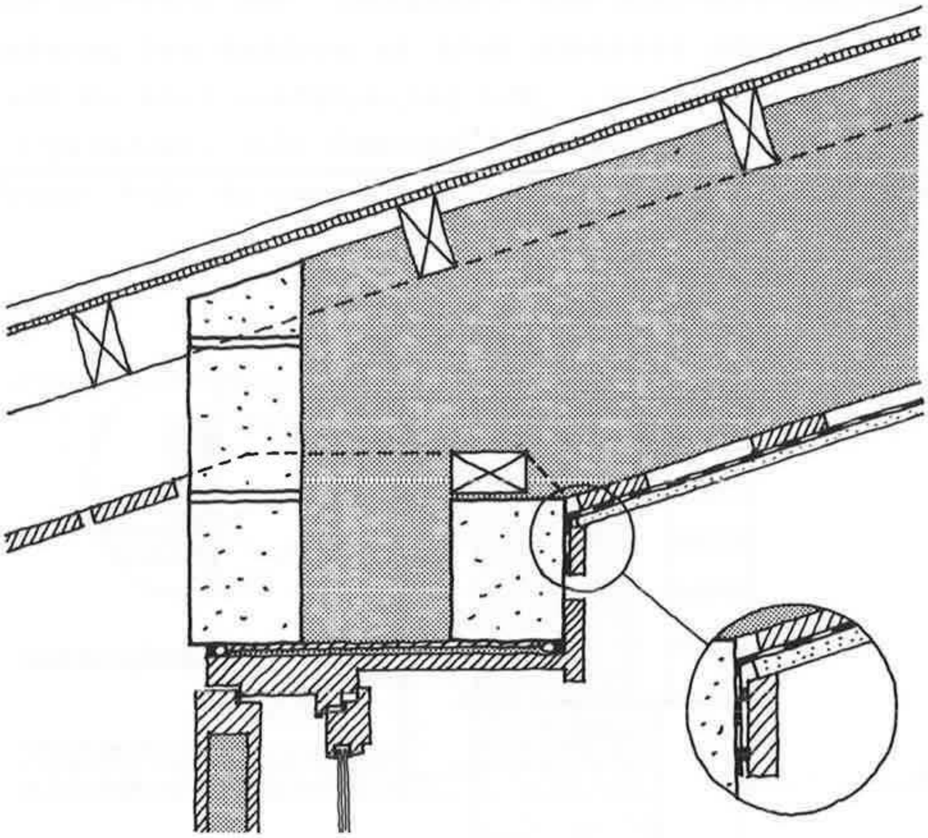


Figure 4. Vertical section of roof and connecting wall.

Figure 4 shows a vertical section of the connection of a sloping roof to the upper part of the lower wall. The outer and inner leaf of the sandwich wall are built from blocks of aerated concrete, a special insulating mortar being employed for the joints. Very few binders - and only plastic binders - have been used, causing but infinitesimal thermal bridges. The exterior and interior wall surfaces have been plastered and painted, the internal wall surface acting as vapour barrier. The mineral wool insulation of roof and walls measure 400 mm and 200 mm respectively. The 65 mm wide laminated rafters (indicated by dashed lines) form a thermal bridge of minor importance, causing an increase of the mean U-value for the roof of less than 7%. In the roof the vapour barrier consists of polythene sheeting between the lathing and the gypsum ceiling panels. Along the edges a wooden board is screwed onto the wall, squeezing the foil - two strips of foam plastic compensate for warping of the board. The wide window casing is preassembled, nailed and glued to the window frame to form an airtight box, open to the room. The joint between the casing and the aerated concrete is sealed with mastic. The exterior silicone mastic shown should be replaced by a weather strip.

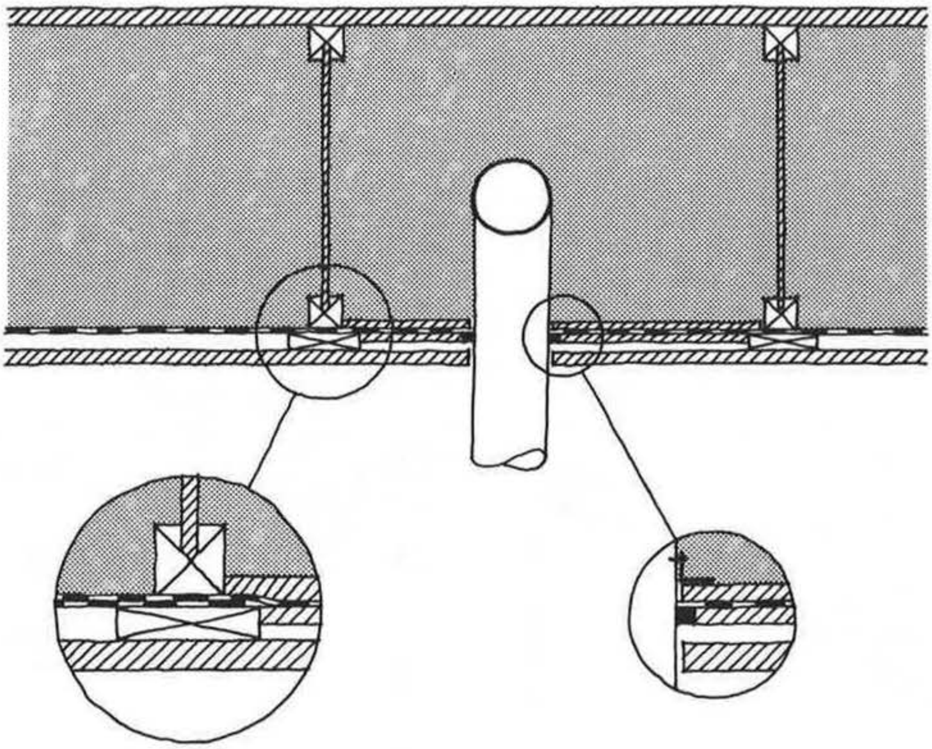


Figure 5. Vertical section of insulated storey partition.

The vertical section of a ceiling construction shown in Figure 5 demonstrates one way to take ducts, tubes or wires through the vapour barrier without introducing a leakage. The normal cross section of the storey partition is seen to the left of the masonite beam (the first floor is a one-room loft, designed for a later enlargement of the house). Certain specific areas are predesigned for perforations - then the polythene sheeting is squeezed between two plywood boards, and the lead-in is sealed with mastic. The mastic sealing can be carried out from below, as shown, or from above, if that is preferred. The structural beam has a depth of 400 mm, and its only 8 mm wide web plate of hard fibre board minimizes thermal bridges. The enlargement to the left shows the squeezed lap joints of the polyethylene foil.

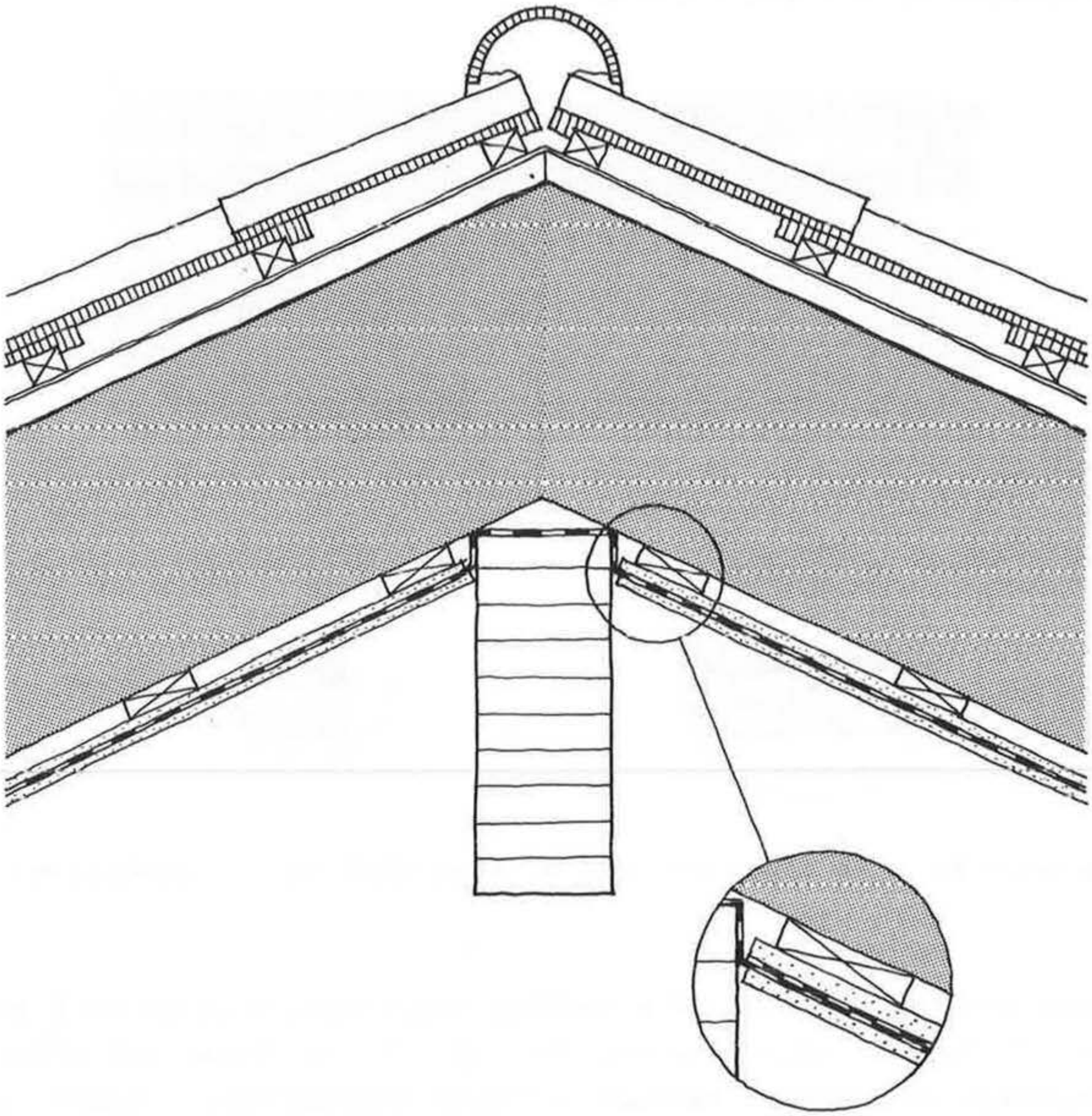


Figure 6. Vertical section of roof, at the ridge.

Figure 6 shows a vertical section of a roof construction, at the ridge. The rafters are 400 mm masonite rafters as in Figure 5 - thus the cold bridges are minimized. In this case the vapour barrier is placed between two layers of plaster boards. Other construction details not included in this report suggested this solution. As everywhere else in the six houses joints between polythene sheets are squeezed lap joints. As soon as the laminated girder is in position a sheet of heavy polyethylene foil is rolled out on top of it and stapled to its sides temporarily. When the rafters, the lathing and the first layer of gypsum ceiling panels have been put up the foil is unstapled and a lap joint can be established (as indicated in the enlargement).

A new type of structural element, a post without any thermal bridges, is shown in Figure 7. It consists of two strips of wood glued to a hard core of mineral wool. Two posts glued and nailed to a thin plywood panel form a strong beam, as shown to the right in Figure 7.

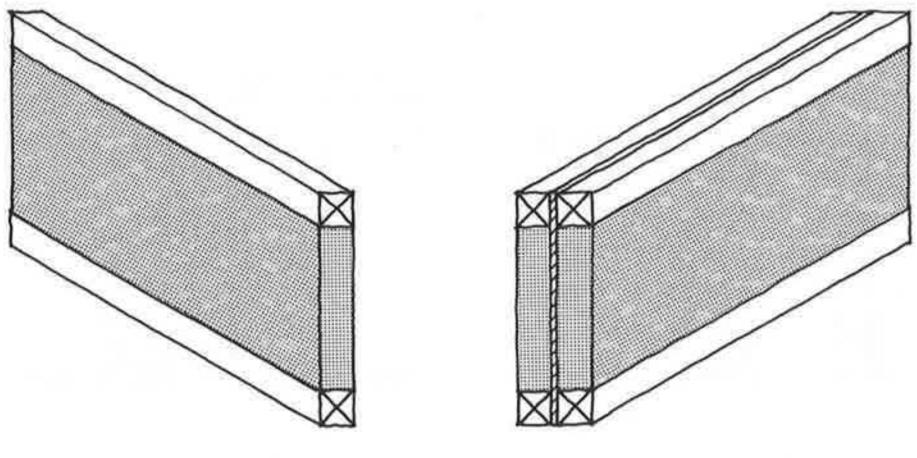


Figure 7. Mineral wool post (left) and mineral wool beam (right).

The post and the beam are used as structural parts in the building elements of a prefabricated thermally light house, the post being used in the roof and walls, and the beam in the floor. A vertical cross section of two such floor elements is shown in Figure 8, before and after the joining. No vapour barrier has been indicated in the illustration. The idea was to use 15 mm plywood boards with aluminium foil integrated in the panels. This is not a standard product, and to keep within the time limits it was decided to use polythene sheeting (between the 15 mm plywood and the 300 mm mineral wool insulation) for this first house. However, it is reasonable to assume that the plywood panels alone would be sufficiently tight. The joints between elements are sealed with mastic. Through the use of large units (only 6 floor units, 6 roof units and 6 external wall units for the house) the total length of joints is kept low. As shown to the right in Figure 8 the matched floor boards rest directly on mineral wool, the fibre plane of the mineral wool being vertical. In the space between the floor boards and the plywood panels rectangular ventilation ducts, pipes and (as indicated) wire tubes can be placed, above the vapour barrier.

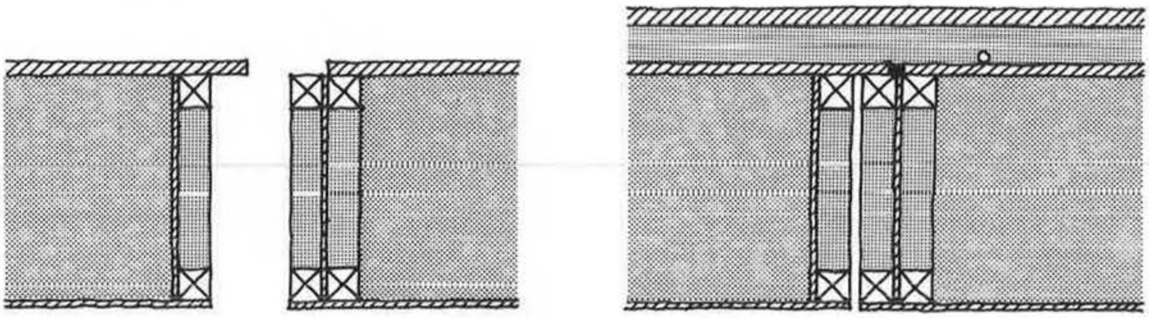


Figure 8. Vertical cross section of two floor elements, before and after joining (vapour barrier not shown).

GENERAL INFORMATION ON THE HOUSES

To facilitate the reading of the subsequent sections on infiltration rates and transmission heat loss some basic information on the geometry of the houses is summarized in Figure 9.

House		A	B	C*	D	E**	F**
Volume	[m^3]	247.0	291.9	268.3	345.2	359.3	349.2
Gross floor space	[m^2]	122.9	143.2	130.6	137.9	135.8	176.1
Living area	[m^2]	105.1	122.6	114.9	112.1	116.6	126.2
(1) Windows/doors	[m^2]	25.6	19.7	24.7	20.5	22.0	31.0
(2) Do, transparent area	[m^2]	17.0	11.0	12.4	11.0	10.4	19.9
(3) Of (2) south facing	[m^2]	9.2	5.5	7.1	8.6	7.3	18.8
(4) Product of (3) and solar factors	[m^2]	6.2	4.9	5.8	8.6	5.4	16.9
Number of storeys		1	1	1	1	1	2
Slab-on-ground		Yes	No	Yes	Yes	Yes	No
Crawl space		No	Yes	No	No	No	No
Basement		No	No	No	No	Yes	Yes
Insulated shutters		No	No	No	Yes	Yes	Yes
*) ground floor only **) excl basement							

Figure 9. General information on the geometry of the houses.

MEASURED AIR CHANGE RATES

Normally the controlled ventilation provides an air change of approx 0.5 per hour. To determine the air leakage of the houses, ie through the constructions, the ventilation ducts were sealed during the test periods, as described in [6]. When the first tests were carried out the houses were about 18 months old and had been heated all the time. The weather data were recorded locally as part of the continuous monitoring programme of this project.

Infiltration Measurements by the Tracer Gas Method

No equipment for constant-concentration measurements was available. The tracer gas was injected in all rooms until the concentration reached a fixed level. A uniform distribution was obtained by means of transportable fans. The concentration was then monitored as a function of time, and the assumedly constant air change rate derived as the reciprocal of the time constant of the exponential decrease function.

The first measurements were carried out simultaneously in all six houses, using N_2O as tracer gas. The results are shown in Figure 10. The later tests were performed in one house at a time, using a radioactive tracer, Kr-85. These results are also shown in Figure 10.

Measurements of Air Leakage by Pressurization and Depressurization

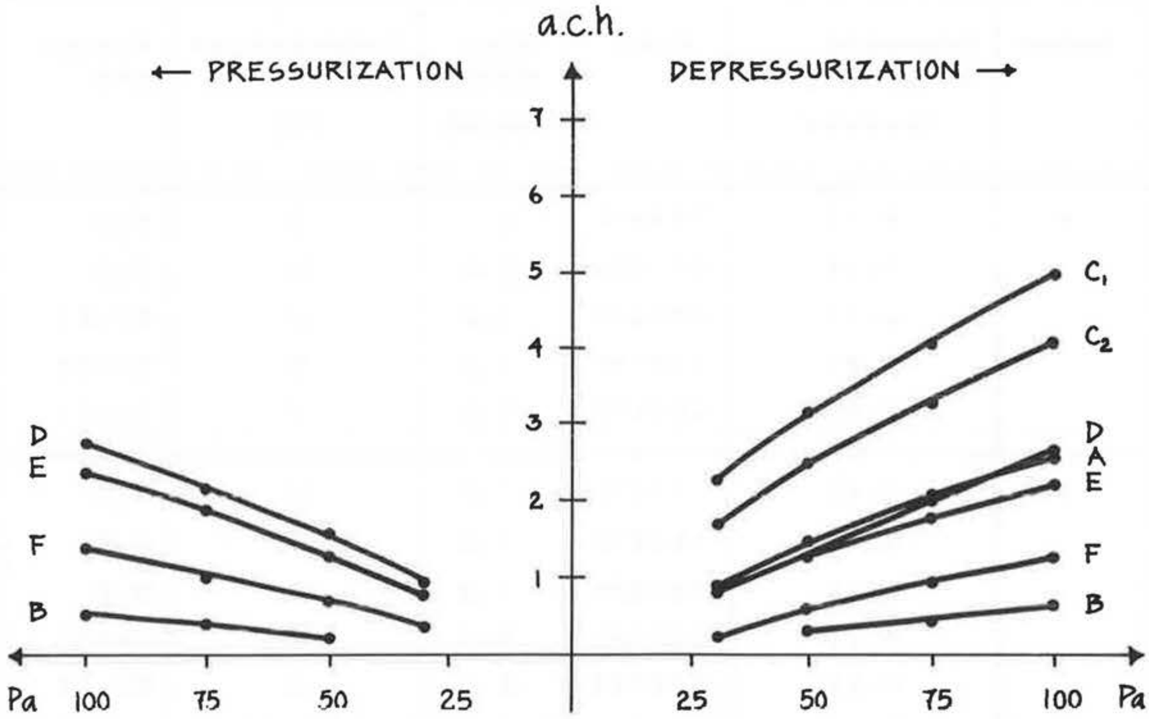
The results quoted are based on two series of tests performed in the summer of 1980 and 1982 respectively, ie almost two and four years after the houses were built, [7]. In 1980 depressurization measurements were made in all six houses - in four houses, additional pressurization tests were carried out. In 1982 both types of tests were carried out in all houses. The normal operating conditions of the houses result in a slight depressurization.

The results are shown in Figure 11 and Figure 12. House C is represented by two leakage curves for reasons discussed later. In the same Figures the air change rate at a differential pressure of 50 Pa is listed. DS, ES and FS represent measurements in three houses with external shutters - in these measurements the shutters have been closed, but the windows behind them opened.

House	Measured infiltration [a.c.h.]	Date	Wind speed [m/s]	Temperature difference [C]	Tracer gas
A	0.10	791218	5.9	18	N_2O
	0.07	800429	2.0	14	N_2O
	0.05	800429	1.8	13	Kr-85
	0.05	810619	1.5	6	Kr-85
	0.04	820824	2.5	4	Kr-85
B	0.03	791218	5.6	23	N_2O
	0.02	800218	1.6	23	N_2O
	0.02	800428	3.4	16	N_2O
	0.02	800428	3.1	15	Kr-85
	0.03	820804	0.6	-4	Kr-85
C	0.12	791218	5.9	20	N_2O
	0.07	800429	1.6	8	N_2O
	0.05	800429	1.9	10	Kr-85
	0.11	820615	3.4	5	Kr-85
D	0.09	791218	5.9	17	N_2O
	0.08	800423	3.2	16	N_2O
	0.08*)	800423	4.1	11	Kr-85
	0.02	820713	2.0	3	Kr-85
E	0.08	791218	5.9	18	N_2O
	0.11	800424	4.5	13	N_2O
	0.10	800424	4.6	12	Kr-85
	0.02	820623	1.8	8	Kr-85
F	0.07	791218	5.9	19	N_2O
	0.07	800422	2.2	11	N_2O
	0.08	800422	2.3	13	Kr-85
	0.04	820722	1.6	5	Kr-85

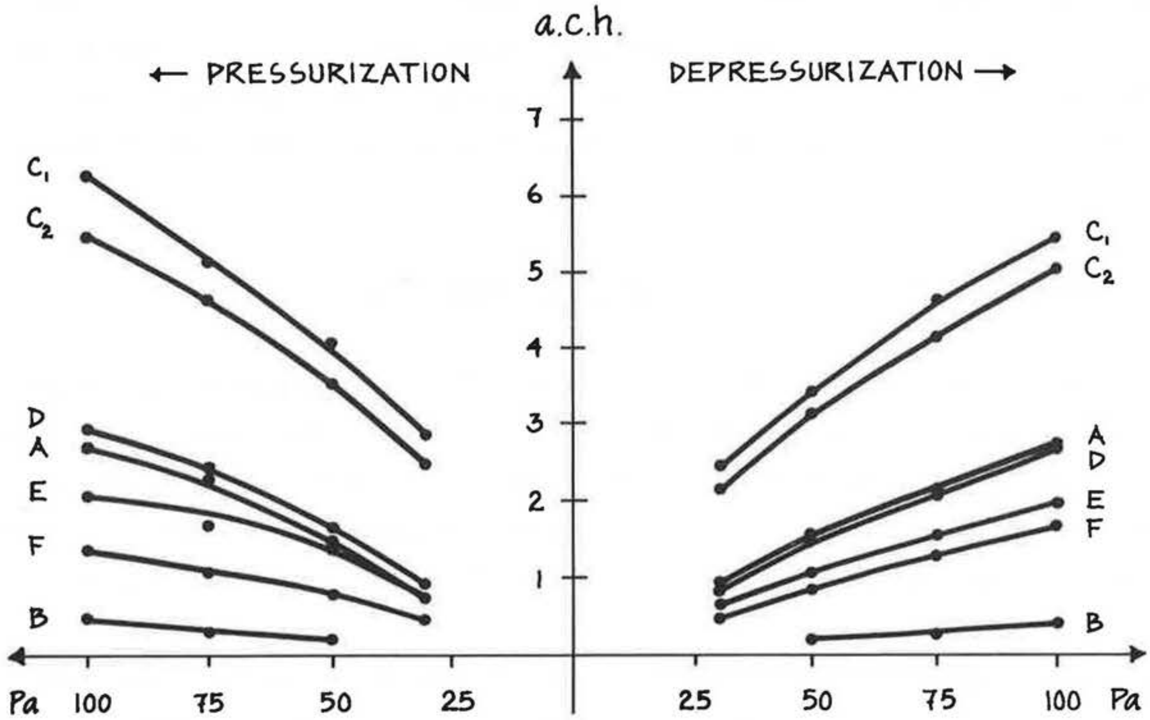
*) Insulating shutters closed

Figure 10. Air change rates measured by the tracer gas decay method.



Measured air change rates at 50 Pa differential pressure		
Pressurization [a.c.h.]	House	Depressurization [a.c.h.]
-	A	1.4
0.21	B	0.31
-	C1	3.2
-	C2	2.5
1.6	D	1.5
1.3	E	1.3
0.64	F	0.62
-	DS	2.1
-	ES	1.3
-	FS	0.66

Figure 11. Air change rates measured in 1980 at different differential pressures. DS, ES, FS: Houses with insulating shutters closed but the windows behind them open.



Measured air change rates at 50 Pa differential pressure		
Pressurization [a.c.h.]	House	Depressurization [a.c.h.]
1.5	A	1.5
0.20	B	0.14
4.1	C1	3.5
3.6	C2	3.2
1.7	D	1.6
1.4	E	1.1
0.79	F	0.86
2.0	DS	1.7
1.6	ES	1.2
0.85	FS	0.65

Figure 12. Air change rates measured in 1982 at different differential pressures. DS, ES, FS: Houses with insulating shutters closed but the windows behind them open.

In each test an exterior door was replaced by a plywood panel with a fan, and a venturi tube for air flow measurement. An attempt was made to replace the tightest door of each house, mostly from a choice between two possibilities.

Discussion of the Air Change Measurements

It is obvious from the results by the two measurement techniques that all six houses must be considered tight. Judged by the depressurization tests, however, they can be divided into three groups: 1) the extremely tight (B and F), 2) the very tight (A, D and E) and 3) the fairly tight ones (C).

B and F are prefabricated houses built from large elements, while the others are site constructions. C has a porch, and due to some misunderstanding the builder put weather strips on the exterior porch door, but used interior doors (without plastic strips and without sills) between the porch and the house. In Figure 11 the curve C2 shows the air leakage values when the porch doors and a leaking loft hatch had been sealed with tape. In 1981 the new owner rebuilt the staircase and replaced the leaky loft hatch by an even leakier door - C2 in Figure 12 represents an attempt to seal this door as well as the porch doors. In B, the windows and doors open inward, and the results from 1980 illustrate that the weather stripping, though good, is the weak point in this connection. One of the openings has two separately operated glass doors - an internal sliding door and an external outward opening door. During the tests in 1980 the sliding door was closed (in fact screwed to the casing). During the tests in 1982 the internal door was open, and some air leakage was detected at the external door.

The results DS, ES and FS indicate that the external insulating shutters are effective, ie that their effect on the transmission heat loss is not diminished by unexpected air leakage. It is not surprising that the pressurization tests for the shutters show the larger air change as the shutters are all external.

The results show no general indication of age dependant deterioration of the air tightness of the houses. It must be stated though that the latest results of the tracer gas measurements are not very informative as the tests had to be performed in the summer, and at very low wind speeds. These conditions do not affect the differential pressure tests, however, and the major differences in the results from 1980 and 1982 are due to changes in the constructions or the test conditions as mentioned above. Only house F deviates from this pattern - the change in air tightness is mainly caused by an air leak at the hinge side of one of the windows. It should be emphasized that the degree of accuracy on these measurements is approx 10%, and maybe even up to 20-25% for the extremely tight houses.

The results quoted so far, and other measurement values not included in this report, have not demonstrated any significant relations between the infiltration air change of tight houses and the wind speed. It must be emphasized that so far too few tests have been made, considering the low infiltration rates measured. The work will be continued, but unless this relation is established, no special effort will be made to correlate the wind speed and wind direction to the differential pressure ruling the air leakage.

TRANSMISSION HEAT LOSS MEASUREMENTS

Test Procedure

As for the air change measurements the ventilation ducts were sealed for these tests. The tests, usually referred to as thermal calibrations, were performed during the winter 1979-80 in two houses at a time, for periods ranging from 7 to 24 days. House D, E and F were tested twice, the shutters being closed the first time and open the second.

Each room was heated by a thermostat-controlled electric resistance heater, and meter readings were generally logged twice a day. Room temperatures as well as weather data were recorded every ten minutes (solar radiation data were measured every ten seconds, and the sums were recorded every ten minutes).

Calculation Method

From each test two periods were selected: Firstly, the longest period beginning and ending with approx the same internal and external temperatures (to minimize the problem of heat accumulation in the constructions) - secondly, a short stationary period (approx 24-48 hours) with a minimum of insolation. For the chosen periods, the following heat balance applies:

Transmission heat loss + Infiltration heat loss
equal
Electricity for heating + Solar heat gain

The transmission heat loss is calculated from the theoretical U-values, the actual average temperature difference and the transmission areas, as prescribed in [8]. The lower sky radiation temperature is taken into account through a 15% increase of the transmission heat loss through the roof, in accordance with [8]. This one-dimensional model is slightly modified regarding the heat flow at the foundation. An additional heat loss is calculated, using a model for two-dimensional heat flow, [9]. The transmission heat loss coefficients listed in Figure 13 are obtained by dividing the calculated heat losses with the average internal to external temperature difference for each period. In this case the house average temperature is derived from the room temperatures, each room temperature being weighted with respect to the room's design transmission heat loss, [3].

The solar heat gain is obtained as the product of the measured solar radiation, the window area and standard solar transmission factors, [10]. The infiltration heat loss is calculated from the measured air change rates - the values obtained from the first N_2O measurements were chosen for this calculation. The measured transmission heat loss is found as the sum of the solar heat gain and the electricity meter readings with the subtraction of the infiltration heat loss. As before, the heat loss coefficient is obtained by division with the average internal to external temperature difference.

The results are listed in Figure 13 and graphically illustrated in Figure 14. In 1979 the Building Regulations now in force introduced strict demands to the insulation level of new buildings, [11]. In [12] the permitted heat loss by transmission according to the Regulations is defined - the calculation is based on the temperature differences from [8], fixed U-values and the actual internal surface areas of the thermal envelope. Figure 14 also indicates the degree of insulation for the six houses by comparison to the corresponding allowed transmission heat losses, [13].

Sensitivity of Measured and Calculated Transmission Heat Loss (TM and TC)

The sensitivity of TM and TC to deviations in the input data has been analysed in [14] chiefly to find out if any single factor could cause the differences between the calculated and the measured values. The windows are obvious suspects - they are responsible for about 50% of the transmission heat loss from the house and are determinative for the solar heat gain. Other possible sources of error such as the fixed infiltration rate, the standard thermal conductivities (λ-values) for the insulation materials and the definition of the transmission areas are examined as well as erroneous measurement of the internal to external temperature difference Δt.

House	LP	Δt	I	EL	TC	TM	TMV	$\frac{TC-TM}{TC} \cdot 100$
	[h]	[C]	[kWh]	[kWh]	[W/C]	[W/C]	[W/m³C]	[%]
A	119.3	21.9	6.5	214.5	83	76	0.31	8
A	22.8	22.5	0.3	40.6	83	71	0.29	14
B	119.2	22.1	5.4	195.8	79	73	0.25	8
B	46.8	22.5	0.4	77.0	78	70	0.24	10
C	516.2	23.3	124.0	1077.2	88	89	0.33	-1
C	44.8	21.3	1.1	97.7	89	93	0.35	-4
D	328.2	21.6	172.9	592.6	97	97	0.28	0
D	47.7	20.4	6.7	89.2	97	88	0.25	9
D*	454.0	21.3	0.0	765.6	68	66	0.19	3
D*	49.3	22.3	0.0	86.4	68	68	0.20	0
E	424.6	21.8	195.6	732.2	82	88	0.24	-7
E	47.7	20.9	4.2	87.0	82	80	0.22	2
E*	334.4	22.8	0.0	560.5	60	62	0.17	-3
E*	93.9	22.8	0.0	162.0	60	65	0.18	-8
F	410.7	22.6	550.0	966.5	145	155	0.44	-7
F	24.5	21.1	5.9	66.7	145	132	0.38	9
F*	311.8	23.3	0.0	788.8	92	100	0.29	-7
F*	23.1	20.9	0.0	55.7	95	107	0.31	-13

LP	Length of period
Δt	Average temperature difference during LP
I	Insolation during LP (solar heat gain)
EL	Electricity for heating during LP
TC	Calculated transmission heat loss coefficient
TM	Measured transmission heat loss coefficient
TMV	TM per m^3 house volume

Figure 13. Results from transmission heat loss measurements. D*, E*, F*: Houses with insulating shutters closed.

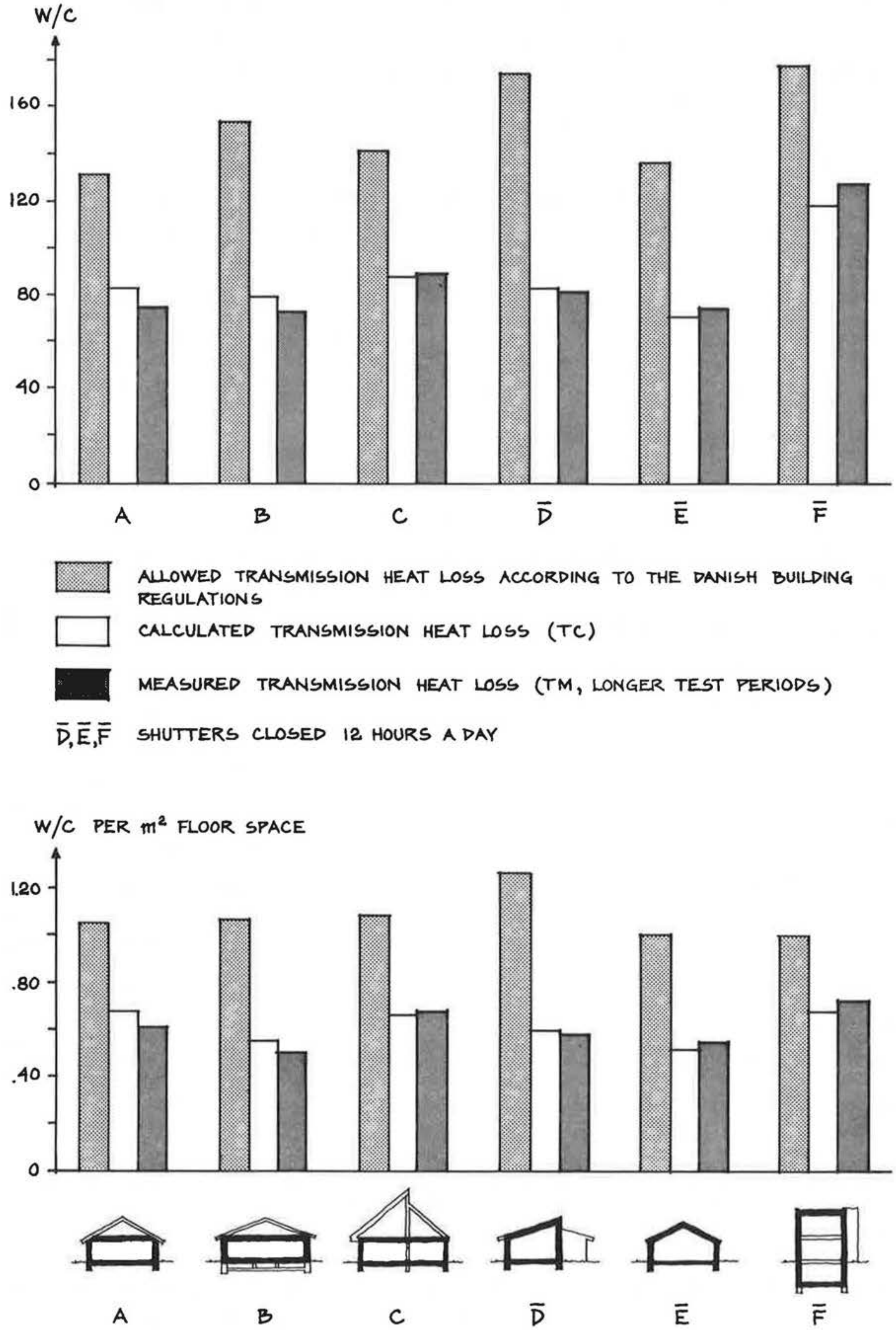


Figure 14. Transmission heat loss for the six houses.

The main results are listed in Figure 15 and an example is graphically illustrated in Figure 16. In [14] a few other possibilities are examined or ruled out.

All figures given in [W/C]									
House	A	B	C	D	D*	E	E*	F	F*
TM	76	73	89	97	66	88	62	155	100
ΔTM(1)	-0.8	-1.0	-0.9	-1.2	-1.2	-1.4	-1.4	-1.2	-1.2
ΔTM(2)	0.3	0.2	1.0	2.4	0	2.1	0	5.9	0
ΔTM(3)	-1.0	-1.0	-1.1	-1.3	-0.9	-1.2	-0.8	-2.0	-1.3

ΔTM(1) Increase of TM at a 0.01 a.c.h. increase of the infiltration rate (about 8-50%, cf Figure 10)

ΔTM(2) Increase of TM at a 10% increase of the insolation

ΔTM(3) Increase of TM at a 0.3 C increase of Δt (about 1%, cf Figure 13)

House	A	B	C	D	D*	E	E*	F	F*
TC	83	79	88	97	68	82	60	145	92
ΔTC(1)	2.1	2.1	2.5	2.5	2.5	1.7	1.7	3.4	3.4
ΔTC(2)	2.6	2.0	2.5	2.1	0.6	2.2	0.5	3.1	0.5
ΔTC(3)	2.3	2.7	2.6	3.1	3.2	2.6	2.8	2.4	2.8

ΔTC(1) Increase of TC at a 5% increase of the insulated surface areas

ΔTC(2) Increase of TC at a 0.1 W/m^2C increase of the U-values for doors and windows (about 4-6%)

ΔTC(3) Increase of TC at a 0.003 W/mC increase of the λ-value for insulation materials (about 8%)

Figure 15. Sensitivity of measured and calculated transmission heat losses. D*, E* and F*: Houses with insulating shutters closed.

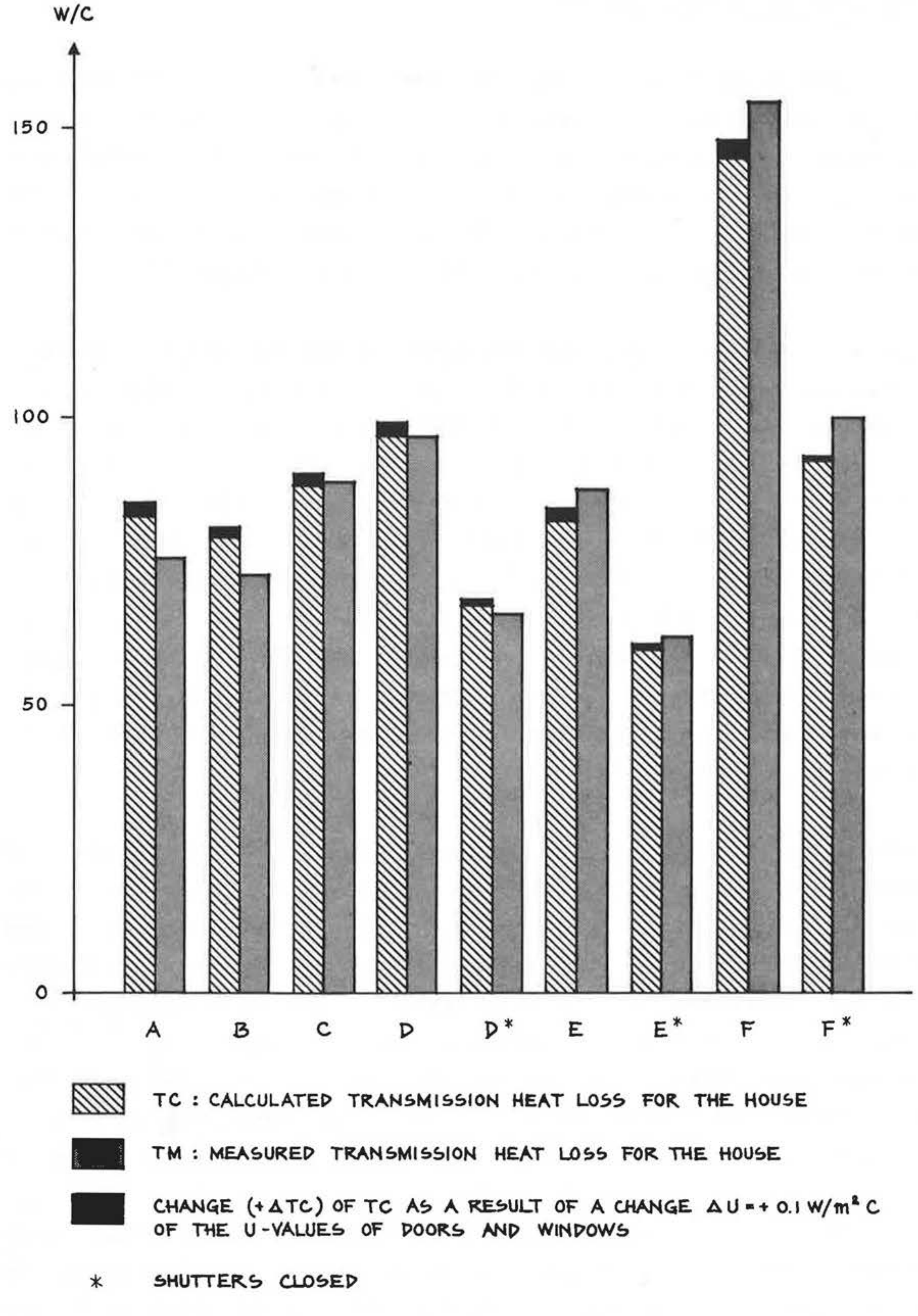


Figure 16. Transmission heat loss, calculated and measured. Sensitivity of calculation (example).

Discussion of the Results

The agreement between the theoretical and the experimental values is good, considering the simplicity of the model applied. The longer test periods show the better agreement (measured coefficients range from 8% below to 7% above the calculated values - the similar percentages for the shorter periods are 14% and 13% respectively), cf Figure 17.

The effect of introducing the two-dimensional heat flow calculation model for the slab-on-ground houses is illustrated in Figure 18. For house A, C and D the effect is seen to be negligible, and in fact the one-dimensional model from [8] yields the larger heat loss in these cases. That is because the Danish Standards prescribe a higher U-value and the use of the internal to external air temperature difference in a 1.0 m wide perimeter zone of the floor. For house E the more realistic two-dimensional model yields the larger heat loss, partly because of the geometry of the house and partly because the insulated sandwich foundation of house E is thermally inefficient, [5].

Generally, the product of the heat loss coefficient and the number of heating degree hours is used as an estimate of the annual transmission heat loss. Denmark has approx 70000 heating degree hours (17 deg C base) in a year. The simple product, however, will not necessarily be in agreement with the measured annual transmission heat losses. Some of the houses have been designed to utilize a large part of the free heat (especially house F, which was designed as a passive solar house), and the steady state model does not take this into account, except that the stipulation of a 17 deg C base to some extent does compensate for this free heat effect. It must be emphasized that the main achievement of this experiment has been to verify the calculation of U-values, and thus the standard design procedure, for low-energy houses.

Some of the differences between calculated and measured heat losses are considered to be due to the difficulties of assessing the solar heat gain. The standard solar transmission factors have been determined from experiments with clean windows. The windows at Hjortekær were not cleaned immediately before the house calibrations, and their glass might be different from that of the reference windows (eg with respect to the concentration of iron oxide). Some preliminary solarimeter measurements of the solar transmission do indicate that the solar heat gain derived from the standard factors was too high.

However, the sensitivity analysis suggests that no single factor is responsible for the differences. The same type of windows (double glazed coated sealed units), [14], has been used in house A and E, but the measured heat loss is 8% lower and 7% higher than the calculated in A and E respectively. Uncertain assesment of the solar heat gain (as mentioned above) may contribute to the differences in general, but hardly for house A and B (almost no insolation during the test period) and not at all for house F (the same percentual difference between TC and TM is found with the shutters opened and closed respectively).

For a group of houses the definition of transmission areas can only cause one-sided errors and thus cannot explain the actual differences. The internal surface areas defined in [8] must be considered minimum transmission areas. The 'practical λ-value' prescribed in [8] could be too high in connection with constructions as well insulated and as airtight as those in the Hjortekær houses, and it may well be, but the influence would be one-sided especially as only two main insulating products were used for all six houses.

As fixed infiltration rates were used for the calculations the actual average infiltration rate may very well differ from the fixed rate, but a difference of more than 0.01 or maybe 0.02 a.c.h. is unlikely and the influence would tend

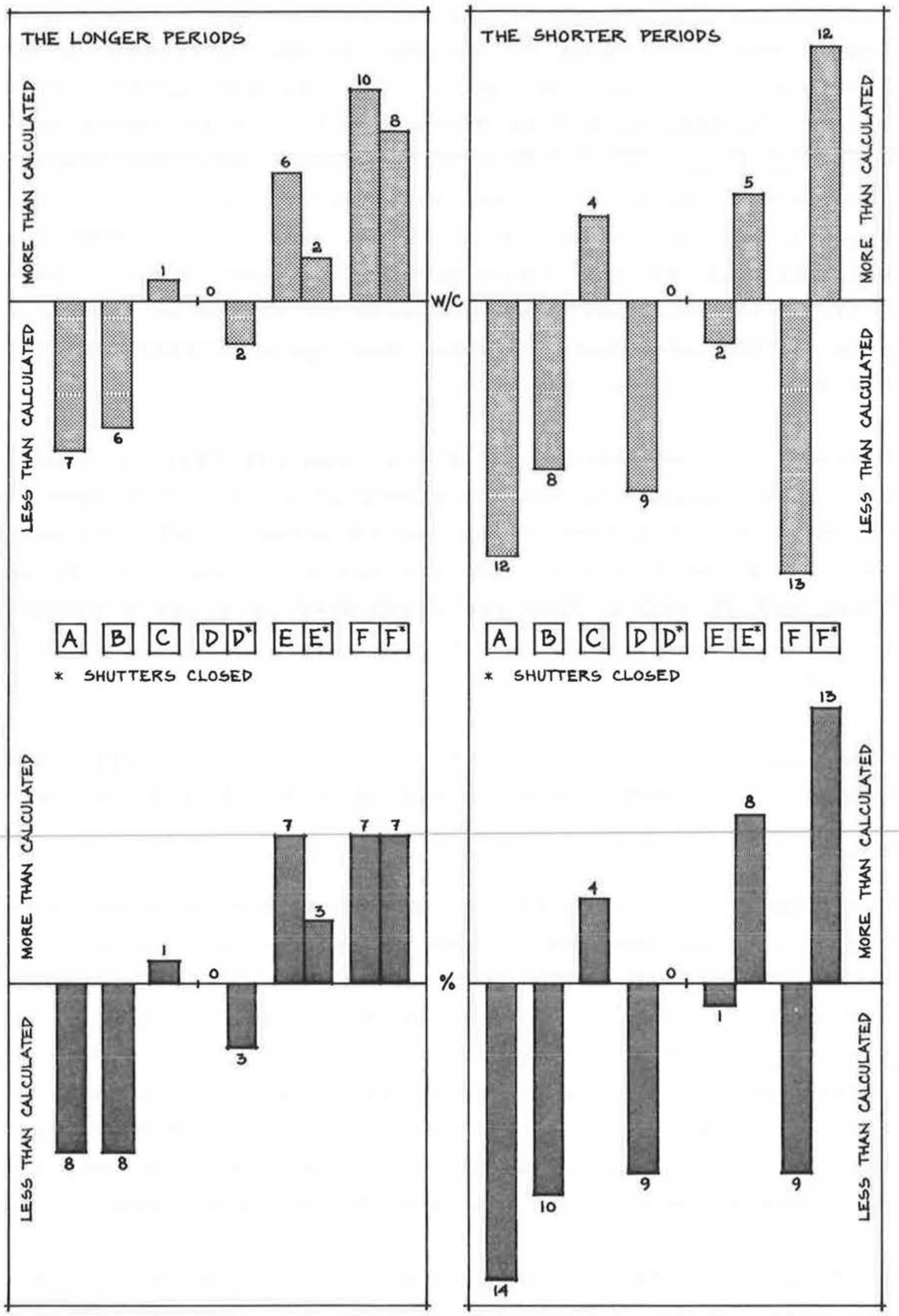


Figure 17. Measured transmission heat loss, Deviations from calculated values.

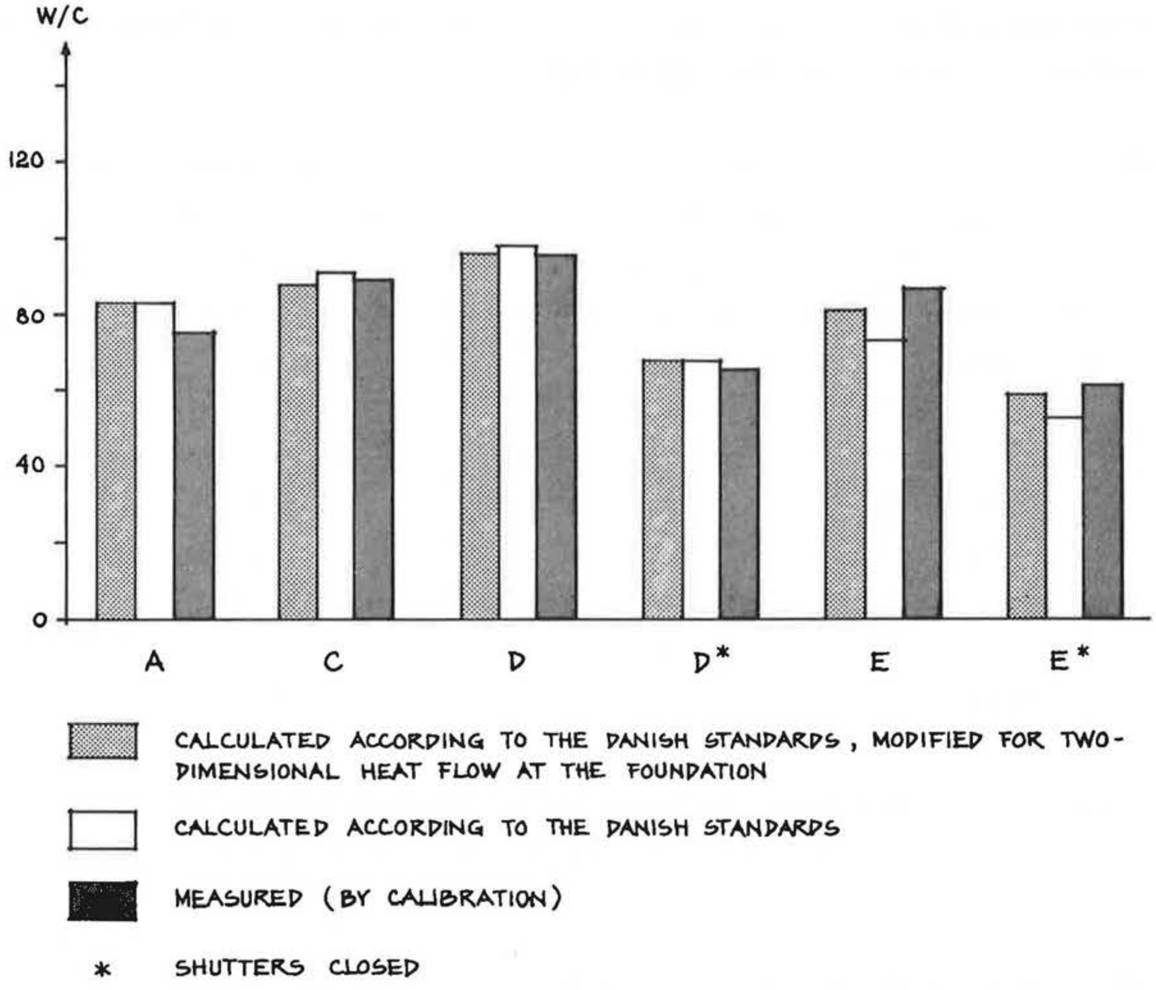


Figure 18. Slab-on-ground low-energy houses. Transmission heat loss, calculated and measured (the longer 'total' test periods).

to be one-sided as the fixed rates were values measured on a cold and windy day.

The differences between calculated and measured heat loss must be attributed to sums of small quantities some of which due to unknown irregularities in the building process (in the workmanship or - mainly - in the materials).

A comparison between the transmission heat loss coefficients derived from the longer test periods, of house D, E, and F respectively, with and without shutters, verifies that the expected energy savings from use of insulated shutters is obtained, Figure 19. The shorter periods all indicate smaller energy savings than expected.

House	Calculated effect [W/C]	Measured effect [W/C]
D(sp)	29	20
D(lp)	29	31
E(sp)	22	15
E(lp)	22	26
F(sp)	50	25
F(lp)	50	55

Figure 19. Energy saving effect of shutters - sp = the shorter period, lp = the longer period.

REGRESSION MODELS FOR HEAT LOSS

When energy conserving measures have been carried out in a building the actual effect of these steps is very often not known. In many cases the effect is never measured, in other cases a simple comparison is made between the energy consumption in the last year before changes and that of the first year after changes, maybe allowing for differences in outdoor conditions (eg by means of the degree day method). A more direct and time saving way of measuring the effect - if possible at all - is to carry out a short term thermal calibration of the building (as described earlier) before and after the retrofit. A regression analysis performed on the data obtained could then render a heat loss equation with two sets of coefficients, one pre- and one post-changes. The differences in coefficients in this equation assess the effect of the energy conserving measures.

In an early work by Korsgaard, [15], this method was used to derive heat loss equations for three different moderately - or by today's standard even poorly - insulated houses. Whether the procedure would be suitable for energy conservation houses was difficult to tell. As a pilot study recognizing and introducing problems and possible solutions the authors decided to do the analysis on the Hjortekær data, [16].

It must be emphasized that the calibration procedure used at Hjortekær was planned for the comparison to the calculated heat loss as described earlier.

Thermal Data

As mentioned in the section on the thermal calibration test procedure very detailed information on weather data and room temperatures was available, but there was no automatic data logging of electricity meters. Visual meter readings were intended twice daily, but in some periods they were carried out only once a day or - in weekends - not at all. Consequently the observations are few and the observation periods are not of equal length, ie one observation represents from 3.9 to 48.3 hours. These conditions are unfavourable for the regression analysis, but a consequence of the test procedure having been planned for another purpose. Figure 20-24 show the outdoor temperature, solar radiation on a south-facing surface and the indoor temperatures of the houses in the test periods with an indication of the time of the meter readings. Some readings have been omitted because other data necessary for the regression analysis were missing.

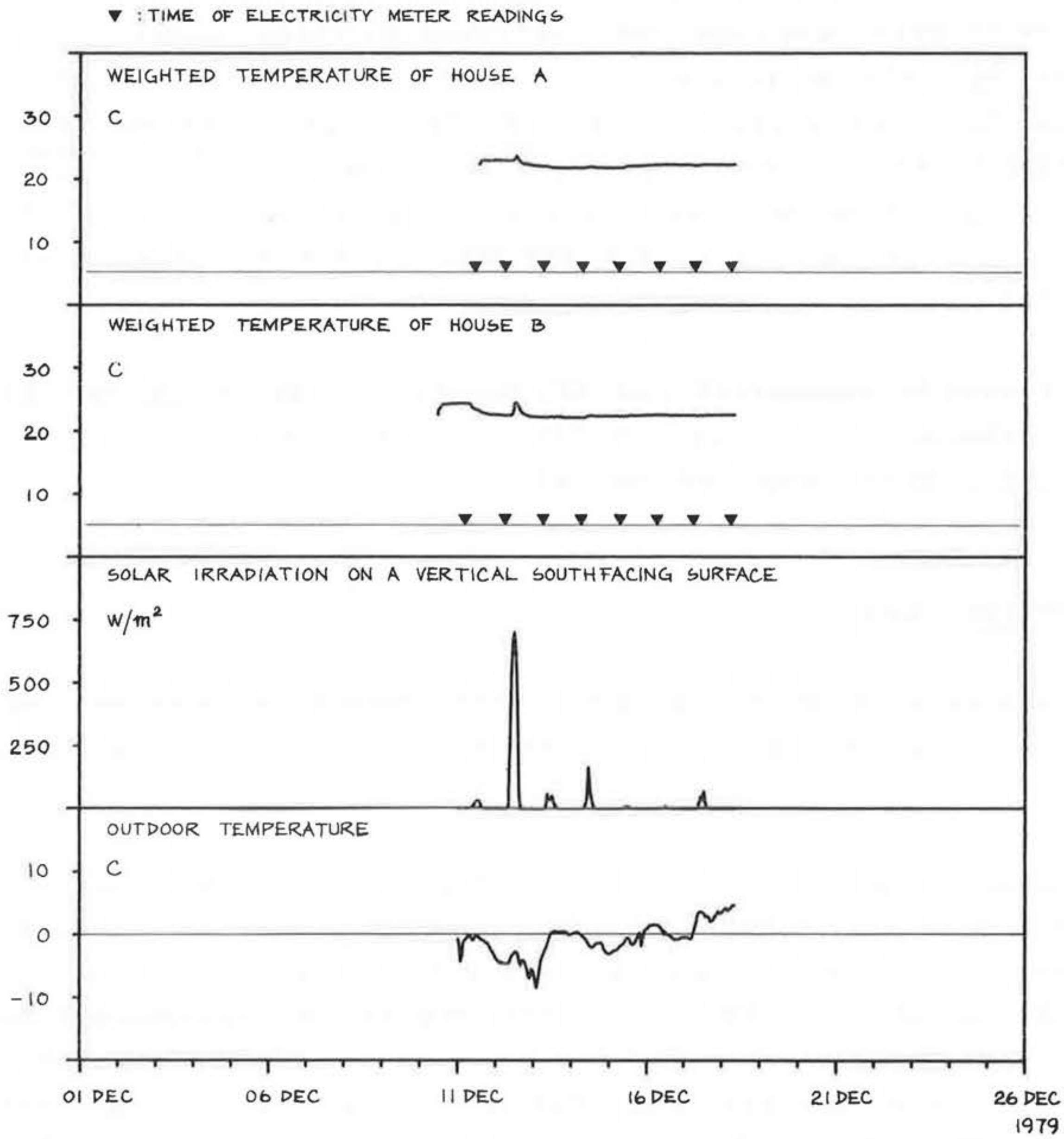


Figure 20. House A and B. Thermal data from calibration period.

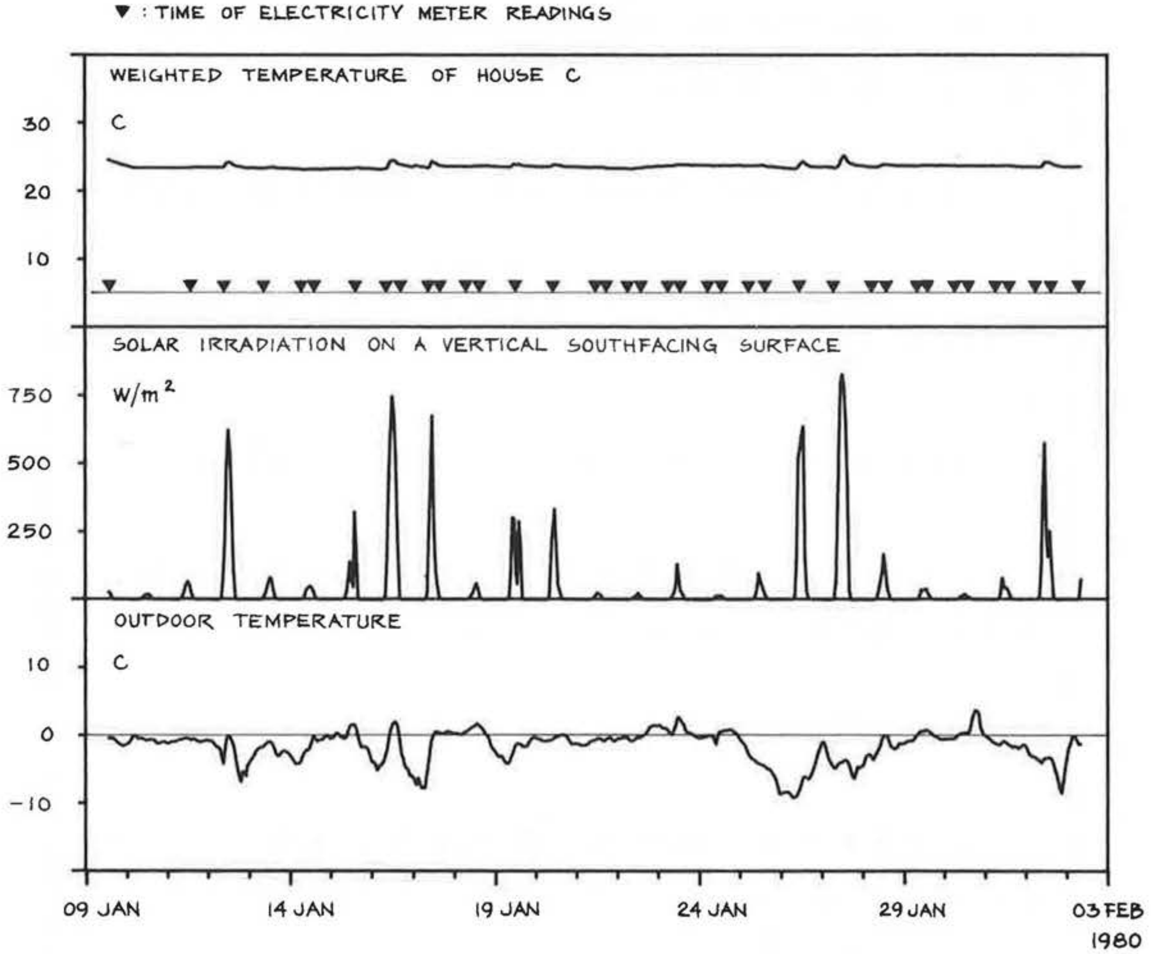


Figure 21. House C. Thermal data from calibration period.

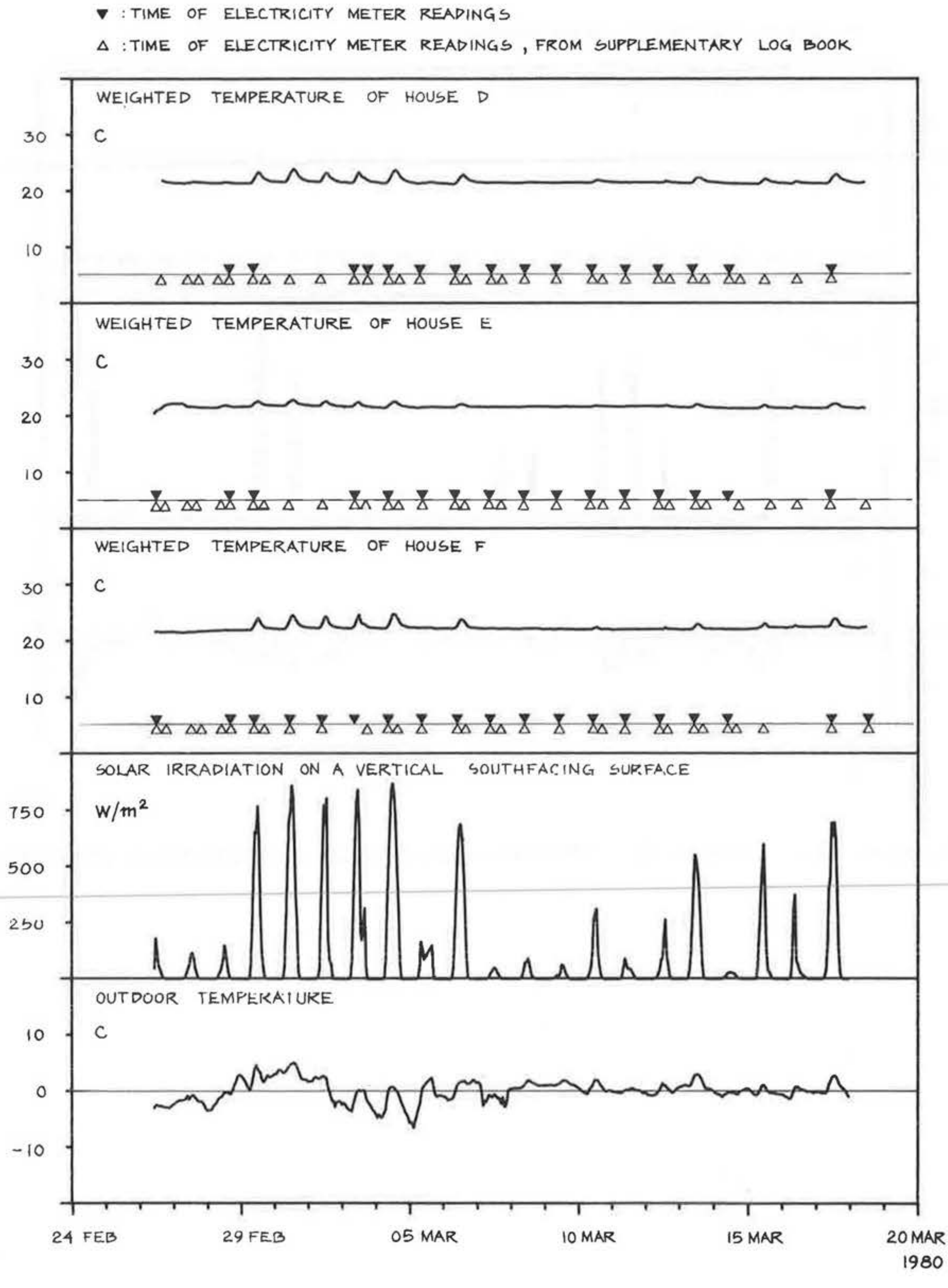


Figure 22. House D, E and F. Thermal data from calibration period.

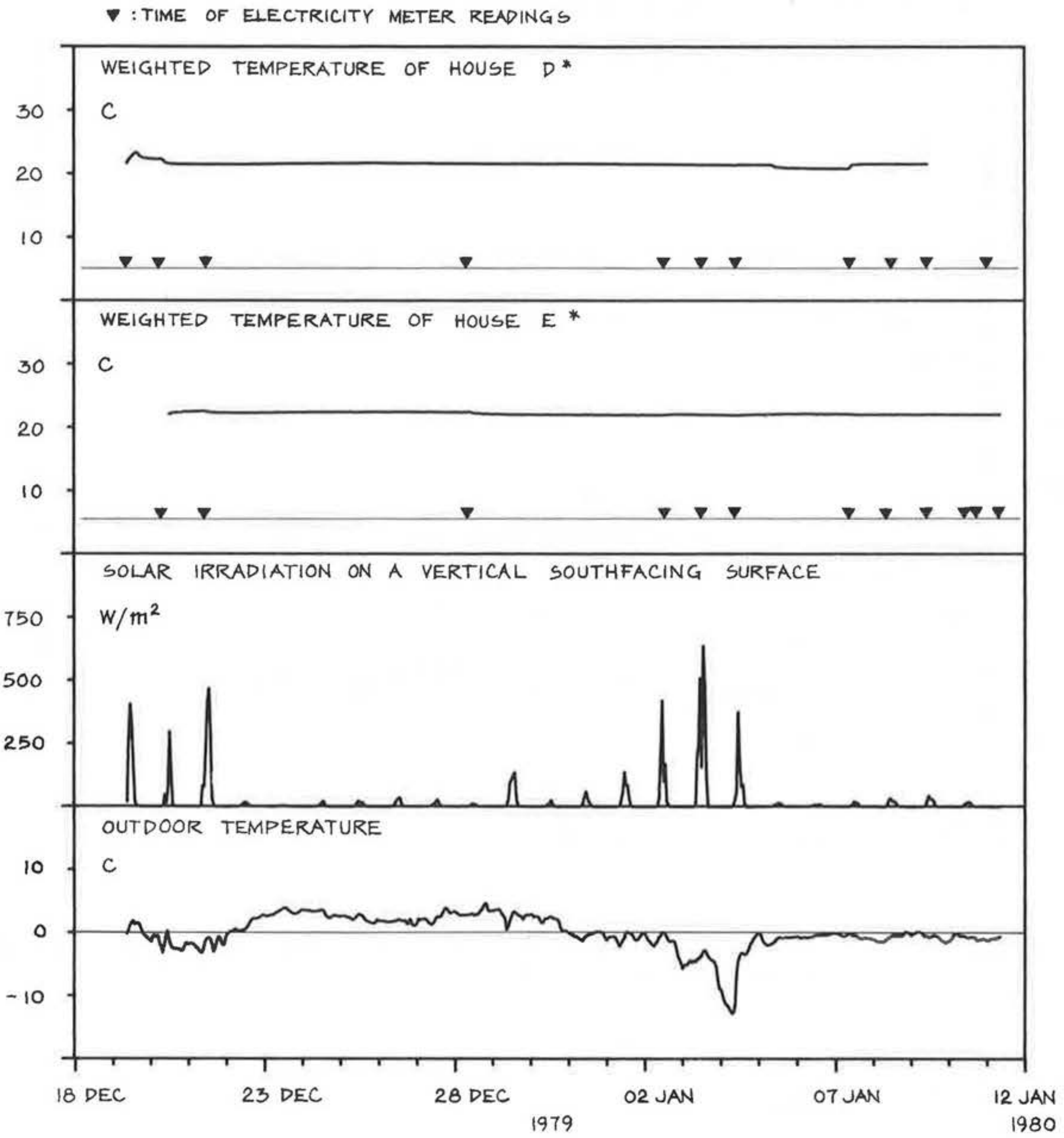


Figure 23. House D and E. Thermal data from calibration period (shutters closed).

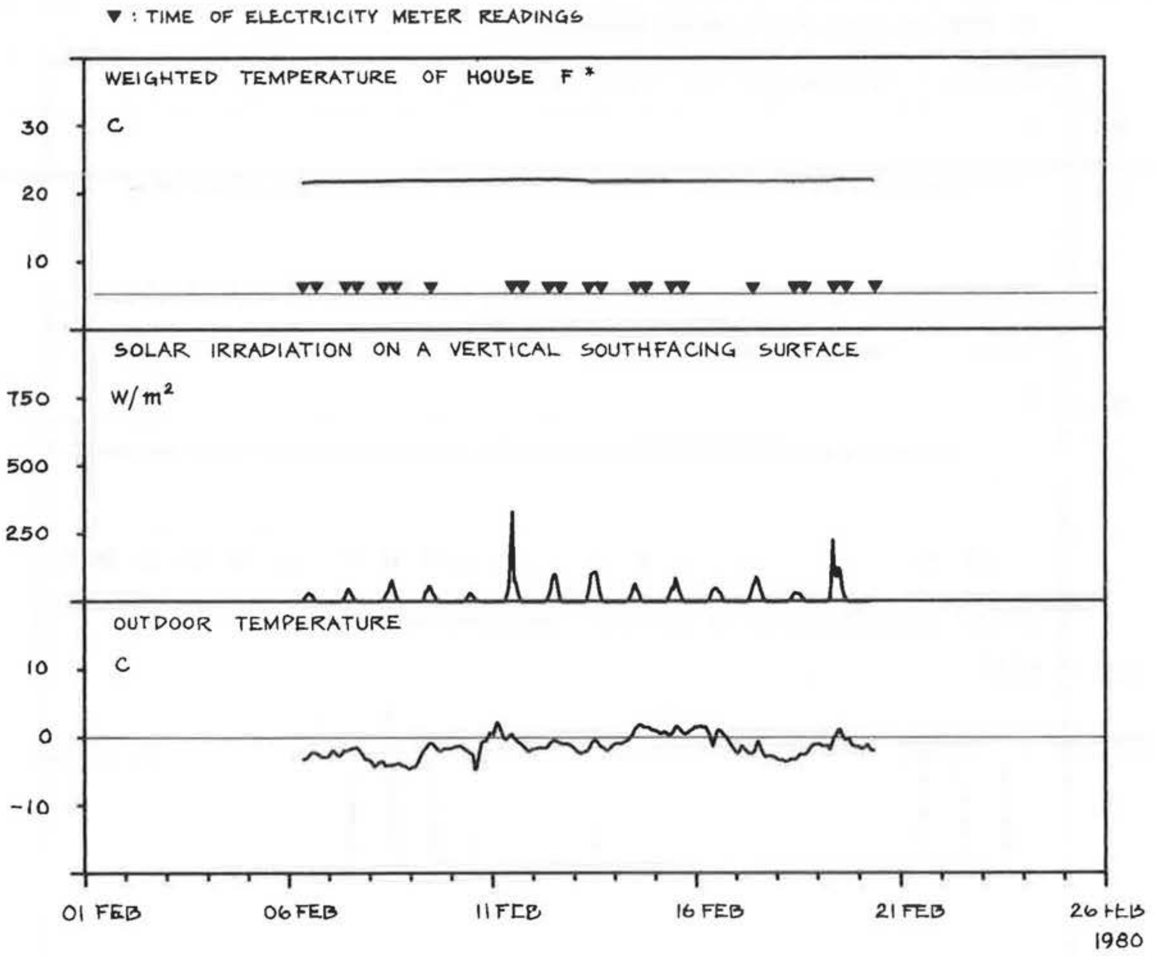


Figure 24. House F. Thermal data from calibration period (shutters closed).

Regression Models

The first model to be tried in the analysis, Model 1, is a detailed model taking into account most of the relevant parameters, ie the parameters that influence the heat loss from buildings. The wind direction is considered a negligible factor in connection with very tight houses. The solar heat gain is treated in two alternative ways in the model. As solar parameter is used either the calculated average total insolated effect or the average intensity of solar radiation on a vertical exterior south-facing surface. In the first case the solar heat gain is calculated in each of the directions north, east, south and west as described earlier. In the second case an attempt is made to use the radiation data directly - the south-facing surface was chosen because 45-88% of the window area in each house is south-facing.

<u>Model 1:</u>

average electric effect [kW] =

      a x temp.diff. to outside air [C]
    + b x temp.diff. to ground [C]
    + c x temp.diff. to basement or crawl space [C]
    + d x speed of wind [m/s]
    + e x average insolated effect into the house [kW]

or

    + e x average intensity of solar radiation on a south-facing surface outside the house [kW/m^2]

Acknowledging that the number of observations available for the analysis was low it was decided to test a simpler regression model too, Model 2. From a physical point of view the determinative parameters for tight well insulated houses (with sealed air ducts) like the Hjortekær houses are the temperature difference to outside air and the solar radiation. The solar radiation data are treated in two alternative ways as in Model 1.

<u>Model 2:</u>

average electric effect [kW] =

      a x temp.diff. to outside air [C]
    + e x average insolated effect into the house [kW]

or

    + e x average intensity of solar radiation on a south-facing surface outside the house [kW/m^2]

When most of the calculations for the regression analysis were completed a supplementary log book for the houses D, E and F was discovered, thus making it possible to subdivide the three test periods and more than double the number of observations. From the results of the previous analyses it was decided to use Model 2, alternative 2 (direct use of solar radiation data), for the supplementary analysis. Because of the increased number of observations available it was decided to make an attempt to take the heat accumulation into account by introducing a solar radiation lag value as a third parameter, Model 3.

Model 3:

average electric effect [kW] =

a x temp.diff. to outside air [C]
+ e x average intensity of solar radiation on a south-facing surface outside the house [kW/m^2]
+ f x value of previous observation of average intensity of solar radiation on a south-facing surface outside the house [kW/m^2]

The calculations were executed by means of the SAS computer system (Statistical Analysis System) and the results are shown in Figure 25, 26 and 27.

Discussion of the Results

Physically speaking 'e' is the only coefficient in Model 1 that should be negative. However, several of the others including 'a' turn out negative - in fact, for house E all coefficients but 'b' are negative. From the values of the coefficients and the standard errors (mostly several times the actual coefficient) and from the Student's t-tests (not

House	Obs.	a [kW/C]	b [kW/C]	c [kW/C]	d [kW/(m/s)]	e [kW/kW]	e [kW/(kW/m^2)]
A	7	.083	.0030		-.0098	-1.10	
		.032	.052		.069	.40	
		.087	.0023		-.017		-6.00
		.033	.053		.072		2.25
B	8	-.052		.15	.036	-.29	
		.059		.081	.081	.49	
		-.046		.14	.031		-1.70
		.059		.080	.078		2.27
C	37	.041	.067		-.00046	-.24	
		.017	.023		.041	.066	
		.042	.065		-.00066		-1.24
		.017	.024		.041		.35
D	15	-.0094	.12		-.014	-.39	
		.023	.029		.032	.030	
		-.0045	.12		-.0075		-3.06
		.023	.029		.032		.24
D*	9	.031	.079		-.13		
		.020	.033		.13		
E	15	-.017	.021	-.23	-.066	-.53	
		.030	.056	.074	.037	.091	
		-.017	.21	-.23	-.062		-2.75
		.030	.056	.073	.037		.46
E*	11	.055	.095	-.21	.090		
		.018	.058	.12	.13		
F	19	.069		.23	.0042	-.40	
		.056		.24	.089	.063	
		.069		.23	.0063		-5.81
		.056		.24	.089		.90
F*	22	.10		-.0098	.13		
		.016		.080	.082		

Shows coefficients calculated by regression analysis according to Model 1. In the Figure each model is represented by two lines the first of which contains the values of the coefficients; the second line contains the standard errors of the coefficients immediately above (in absolute figures).

Figure 25. Heat Loss Equation Coefficients, Model 1.

House	Obs.	a [kW/C]	e [kW/kW]	e [$kW/(kW/m^2)$]	TC+inf [kW/C]	TM+inf [kW/C]
A	7	.087	-1.07		.091	.085
		3%	22%			
		.086		-5.69	.091	.085
		3%		23%		
B	8	.073	-.86		.082	.076
		7%	55%			
		.073		-4.44	.082	.076
		6%		47%		
C	37	.091	-.23		.099	.100
		2%	31%			
		.090		-1.19	.099	.100
		2%		31%		
D	15	.091	-.39		.107	.108
		3%	11%			
		.091		-3.08	.107	.108
		3%		11%		
D*	9	.077			.079	.077
		4%				
E	15	.093	-.71		.093	.099
		3%	14%			
		.093		-3.66	.093	.099
		3%		14%		
E*	11	.076			.071	.074
		3%				
F	19	.126	-.36		.153	.163
		4%	14%			
		.126		-5.18	.153	.163
		4%		14%		
F*	22	.109			.100	.109
		2%				

Shows coefficients calculated by regression analysis according to Model 2. Figures quoted in percent are standard errors of coefficients immediately above. Sums of infiltration heat loss coefficients and calculated and measured transmission heat loss coefficients are also shown, TC+inf and TM+inf respectively.

Figure 26. Heat Loss Equation Coefficients, Model 2.

House	Obs.	a [kW/C]	e [kW/(kW/m^2)]	f [kW/(kW/m^2)]	TC+inf [kW/C]	TM+inf [kW/C]
A	7	.086	-5.69		.091	.085
		3%	23%			
	6	.084	-5.22	-.33	.091	.085
		4%	22%	320%		
B	8	.073	-4.44		.082	.076
		6%	47%			
	7	.074	-5.24	2.60	.082	.076
		2%	13%	25%		
C	37	.090	-1.19		.099	.100
		2%	31%			
	34	.092	-1.31	-.12	.099	.100
		2%	22%	250%		
D	32	.086	-2.05		.107	.108
		2%	11%			
	30	.093	-2.31	-.82	.107	.108
		2%	7%	20%		
E	33	.090	-2.04		.093	.099
		3%	13%			
	31	.093	-2.17	-.63	.093	.099
		3%	11%	40%		
F	32	.123	-3.85		.153	.163
		3%	11%			
	30	.134	-4.21	-1.51	.153	.163
		3%	8%	23%		

Shows coefficients calculated by regression analysis according to Model 2, alternative 2, and Model 3. Figures quoted in percent are standard errors of coefficients immediately above. Sums of infiltration heat loss coefficients and calculated and measured transmission heat loss coefficients are also shown, TC+inf and TM+inf respectively.

Figure 27. Heat Loss Equation Coefficients, Model 2, alternative 2, and Model 3.

quoted) this model is seen to be dissatisfactory which is not surprising as the number of observations in most of the houses is much too low to set up a model with five parameters. The house with the largest number of observations, house C, also shows the lowest standard errors (except for the shuttered houses where 'e' does not appear in the equations). Even then the wind speed parameter 'd' turns out negative - with a very large standard error. This mainly reflects that the physical influence of the wind speed on very tight houses is extremely low and thus almost impossible to quantify by measurement. Judged by the standard errors 'e' appears to be equally well assessed in the two alternatives.

This is confirmed in Figure 26 by the results from Model 2, ie for these strictly south-oriented houses it is not necessary to calculate the solar heat gain and it would only be necessary to measure the solar radiation on a south-facing surface to set up a heat loss regression model for the houses. It should be noticed that this also indicates that no error has been introduced into the assessment of the measured transmission heat loss TM by calculation of the insolation. The values of the standard errors for 'a' and 'e' (and the Student's t-tests, not quoted) show Model 2 to be far better than Model 1, and the standard errors for 'a' ranging from 2-4% are very satisfactory. If the standard errors of 'e' are compared to the solar radiation data the houses with high standard errors (22-55%) correspond to the test periods with a low average solar radiation, Figure 28.

The sums of the infiltration heat loss coefficients and the calculated and the measured transmission heat loss coefficients (TC+inf and TM+inf) show a reasonable agreement with the regression model coefficients to the parameter 'temp. diff. to outside air', 'a'. The difference between 'a' of the simple model and TM+inf should be very little as they represent two ways of treating about the same group of measured data.

House	A	B	C	D	E	F
E(e) [%] I(ave) [W]	24 55	55 45	31 220	11 530	14 460	14 1340

Figure 28. Model 2. Comparison of E(e), the standard error on the coefficient 'e' (by alternative 1) and I(ave), the average solar heat gain during the test period.

In Figure 29 the resulting regression model coefficients for house D, E and F, Model 2, alternative 2 (direct use of solar radiation data), from Figure 26 and 27 are compared. The subdivision of the test periods (about doubling the number of observations) is seen to lower the standard errors, mainly on 'a'. However, the figures also contain a warning against relying too much on the standard errors for evaluation of the models. The subdivision of the test periods yield about the same standard errors on 'e' but distinctively different values for 'e'. Another point of interest is that the increase in the number of observations in all three cases results in a decrease in the 'a'-value although the higher value is equal to or smaller than the corresponding calculated and measured values (TC+inf and TM+inf).

The values of the standard errors (and the values of R-square as well as the Student's t-tests, neither quoted) in Model 3, Figure 27, show that the introduction of the solar radiation lag value increases the goodness of the fit for most of the houses. House A and B form an exception which is not surprising as the number of observations available for the model is as low as 6 and 7 respectively. The standard errors on 'a' and 'e' in house B are certainly lowered from 6% and 47% to 2% and 13%, but the lag value parameter is positive which is physically impossible. It should be noticed that the value of the coefficient 'a' approaches the value of TM+inf (and TC+inf).

House	Test period [h]	Obs.	a [kW/C]	e $[kW/(kW/m^2)]$	TC+inf [kW/C]	TM+inf [kW/C]
D	424.6	15	.091 3%	-3.08 11%	.107	.108
	498.3	32	.086 2%	-2.05 11%	.107	.108
E	477.8	15	.093 3%	-3.66 14%	.093	.099
	503.7	33	.090 3%	-2.04 13%	.093	.099
F	504.3	19	.126 4%	-5.18 14%	.153	.163
	504.3	32	.123 3%	-3.85 11%	.153	.163

Figure 29. Results from Model 2, alternative 2, and Model 3.

It is obvious that a low number of observations is a problem in connection with regression models, and so is an irregular data logging pattern. However, it is hardly possible from the material in this report to establish the necessary or minimum number of observations for a regression model, cf Figure 29. The introduction of a simple lag function improved the model, but as indicated in Figure 20-24 the observations were made with irregular and rather long intervals, the longest span for one house being from 5.8 hours to 48.3 hours. It is quite natural that a lag function operating with heat accumulated during several hours and 'influencing' an even longer period must result in a very rough estimate. A more suitable data logging pattern operating eg with hourly values would certainly increase the goodness of the model considerably.

It is also important to remember that as only average values of the thermal data within each observation period can be used long observation intervals reduce the parameter variation and thus the goodness of the model.

CONCLUSIONS

It has been shown in this project that it is possible to build well insulated airtight houses, and mainly that it can be done in various ways using many different building materials.

The designer must pay attention to the two- and three-dimensional character of the tightness problems, and he must make the builders aware of the importance of a properly sealed structure. During a period of transition intensified supervision may be necessary.

Air change measurements have illustrated that the chosen solutions perform well two and even four years after the houses were built. The weather stripping of doors and windows is subject to wear and tear and will eventually have to be replaced, but otherwise the air tightening is not expected to deteriorate with age.

Although no direct correlation has so far been found between the tracer gas measurements and the depressurization tests for very tight houses it is advisable to apply both methods to assess and/or improve the air tightness of a house. The tracer gas decay method gives the level of the weather dependant air infiltration at the specific time of the measurements, and the depressurization tests supply information on the physics of the building. Under depressurization it is possible to find air leaks, as they cause cold draught. Air leaks can also be detected by combining a pressurization/depressurization test with a smoke test or infrared thermography.

The thermal calibration of the houses shows good agreement between the measured transmission heat loss and the transmission heat loss calculated according to the present simplified design procedures. A simple sensivity analysis indicates that no single parameter can account for the difference - or rather, the pattern of differences. They must be attributed to sums of small quantities some of which due to unknown irregularities in the building process. However, it must be emphasized that a maximum disagreement of 8% (the longer test periods) is a very low figure especially as the absolute heat loss is low. Most of the uncertainty factors would have the same influence on the transmission heat loss (in absolute figures) for normal new houses with a transmission heat loss about 2-3 times that of the low-energy houses at Hjortekær.

Thermal calibration test periods should have a length of not less than 10 days. It has been found that results based on shorter extracts of the test periods, eg 24 hours, are more dispersed even if the data are selected from a quasi-stationary period.

Regression analyses of the data from the thermal calibration periods have shown that it is possible to set up simple satisfactory heat loss equations for conservation houses. The present analyses are considered a pilot study for working out a short term calibration procedure for low-energy houses.

The results indicate that it is feasible to develop such a test procedure. The authors are of the opinion that the combination of regression analysis and a thermal calibration with regular and frequent logging of all relevant parameters (eg hourly values) may limit the necessary calibration period to 3-4 days.

Experiments in a low-energy experimental house at the Technical University have been planned, mainly to elucidate the influence of thermal mass and climate parameter variation on the scanning frequency and the minimum test period.

ACKNOWLEDGEMENT

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