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Insulation and Air Tightness of six Low-Energy Houses at Hjortekær, Denmark.

PREPRINT

Paper submitted to the Third International Symposium on CIB Working Commission W-67, Dublin March 30 - April 1, 1982.

December 1981

Insulation and Air Tightness of six Low-Energy Houses at Hjortekær, Denmark.

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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 paper, 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 suction 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%.

Isolation et étanchéité à l'air de six maisons à faible énergie à Hjortekær, Danemark.

RESUMÉ

En 1978-79 six maisons individuelles à faible énergie étaient construites à Hjortekær au nord du Copenhague, faisant partie du programme danois de recherche et de développement de la consommation d'énergie.

Au cours de 1979 et 1980 des opérations de mesurages continues, ainsi que des investigations limitées aux problèmes spécifiques ont été exécutés par un groupe de rechercheurs du Laboratoire de l'Isolation Thermique.

Dans la présente contribution quelques détails de construction typiques sont décrits, quelques uns choisis pour illustrer des solutions quant aux ponts thermiques, d'autres pour démontrer des constructions étanches à l'air et à la vapeur. Le taux du renouvellement de l'air a été mesuré quelques fois par la méthode de décomposition des gaz traceurs et nous a donné des résultats allant de 0.02 jusqu'à 0.12 de renouvellement de l'air par heure. De même des tests de pression et d'admission ont été faits - les resultats de ces tests et la correlation possible avec le taux du renouvellement de l'air sont discutées.

L'installation d'aérage a été scellée pendant quelques semaines, où les maisons étaient chauffées par des fours électriques à résistance. Pour des périodes stationaires choisies la perte de chaleur est obtenue d'après la lecture des indicateurs, en prenant en considération le gain d'énergie par ensoleillement. La perte thermique de transmission (allant de 70 à 155 W/C approx.) est trouvée par déduction de la perte thermique de l'infiltration (souvent moins de 10% du total), et le résultat est comparé avec la perte thermique calculée, qui est basée sur les températures actuelles et les coefficients K théoriques. La perte thermique de transmission calculée et mesurée diffèrent moins de 15%.

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), and an attempt has been made to keep the air leakage at a negligible level.

SELECTED CONSTRUCTION DETAILS

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 heat loss by infiltration is kept low as illustrated by the simple calculations in Figure 1. 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 heat 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 joint between two elements is cast with cement mortar, except that lime 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.

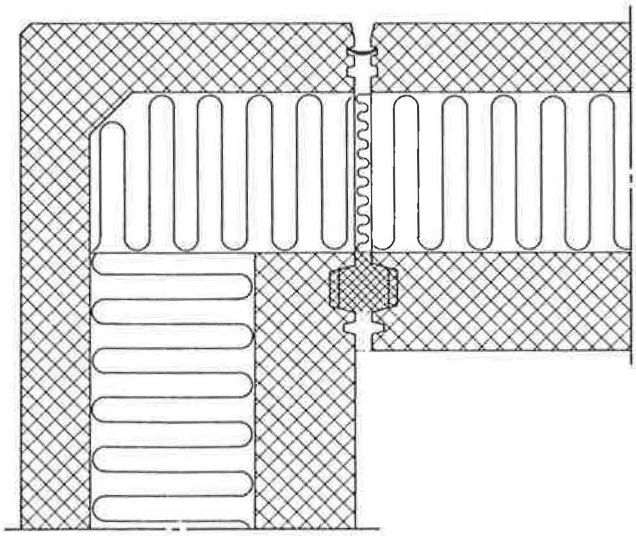


Figure 2. Horizontal section of corner.

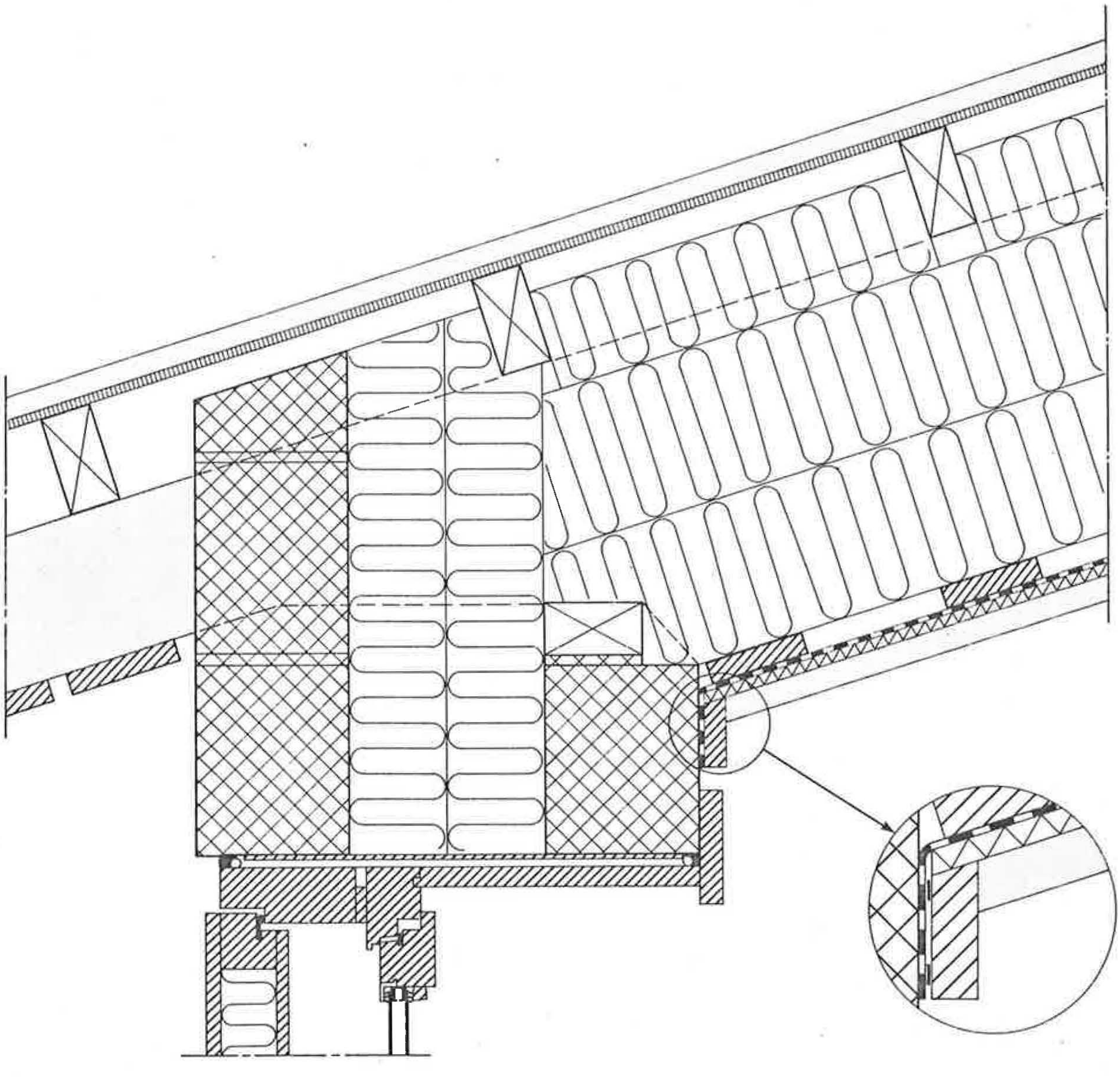


Figure 4. Vertical section of roof and connecting wall.

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.

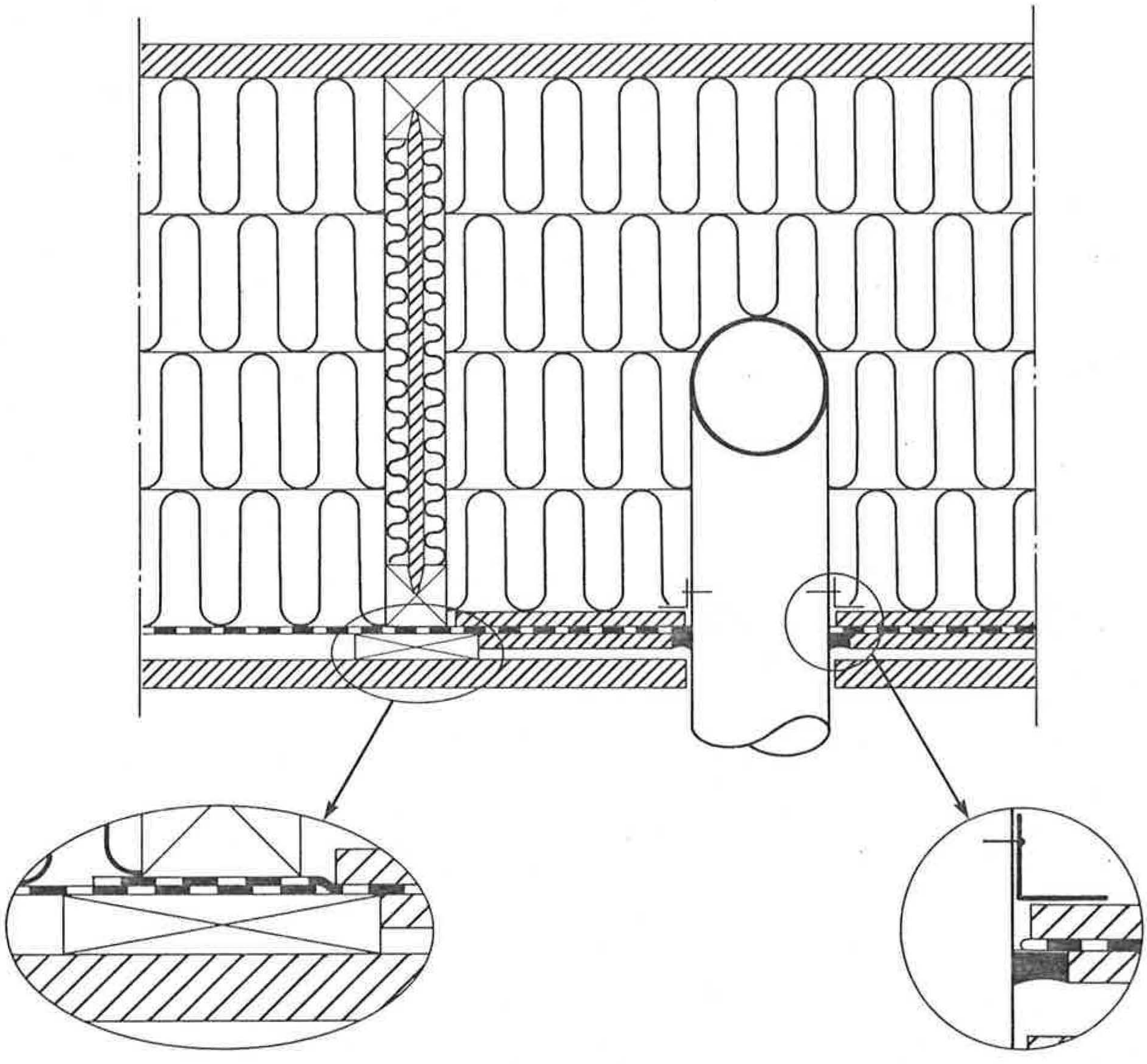


Figure 5. Vertical section of insulated storey partition.

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

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. 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.

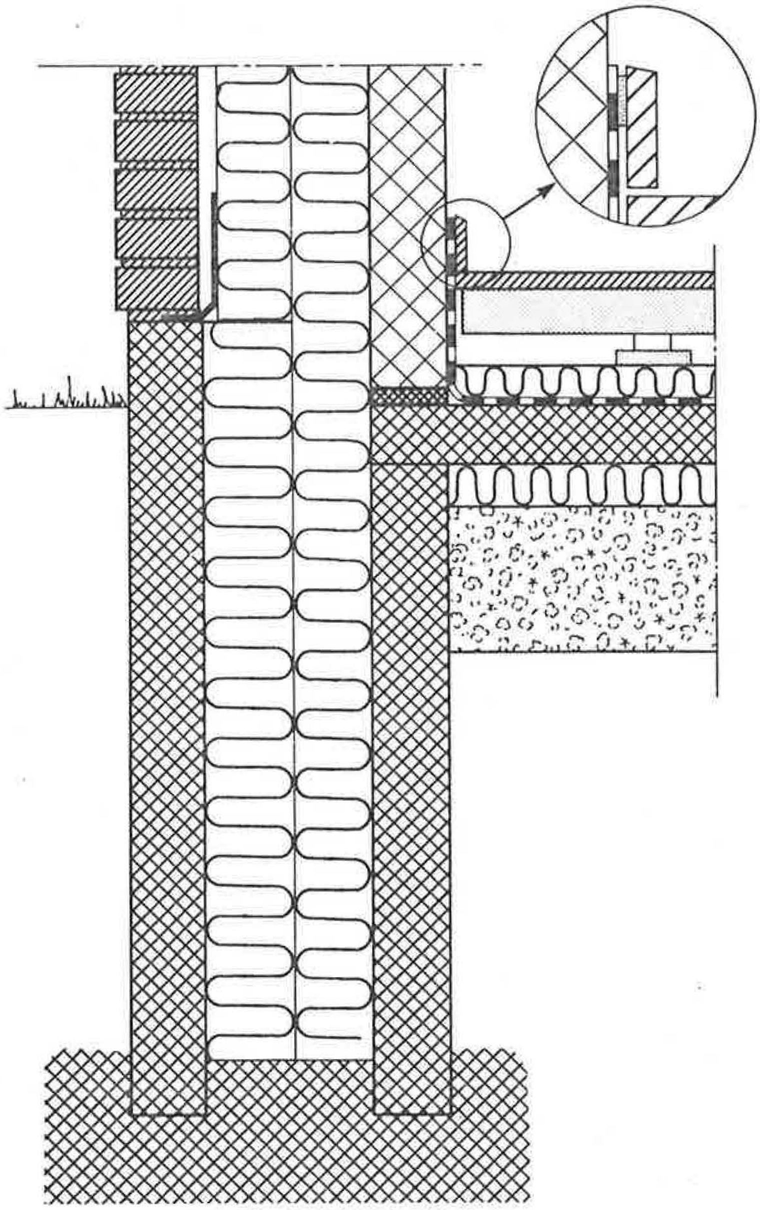


Figure 3. Vertical section of foundation.

Figure 4 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 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.

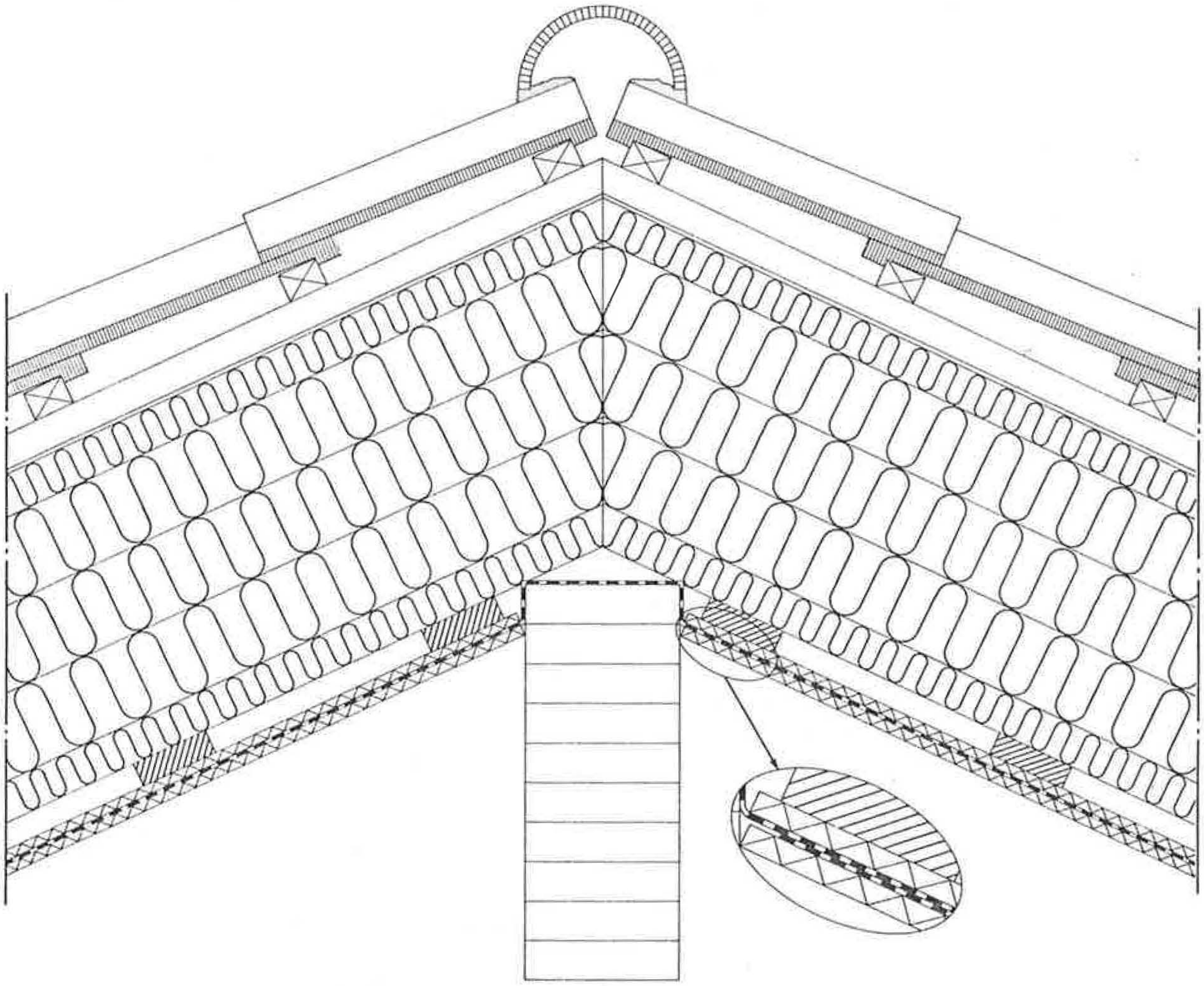


Figure 6. Vertical section of roof, at the ridge.

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 paper 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

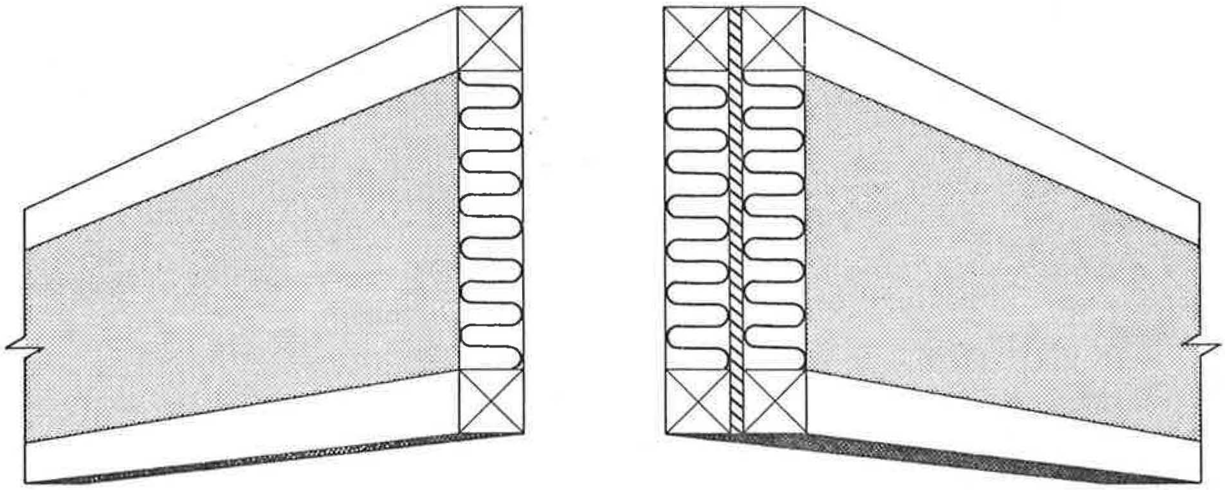


Figure 7. Mineral wool post (left) and mineral wool beam (right).

strong beam, as shown to the right in Figure 7. 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.

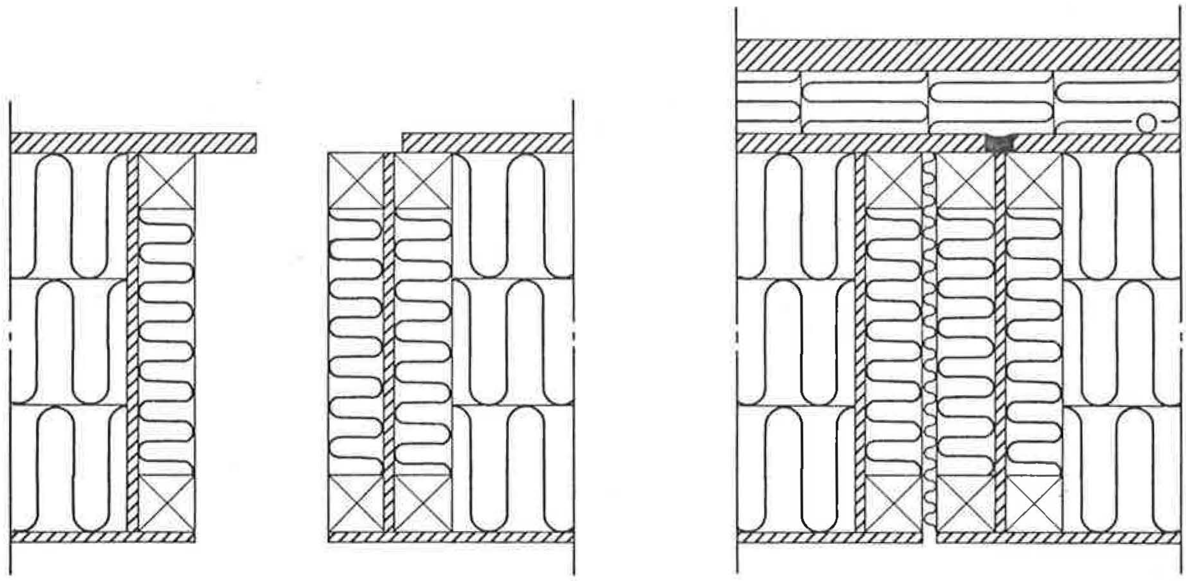


Figure 8. Vertical cross section of two floor elements, before and after joining.

MEASURED AIR CHANGE RATES

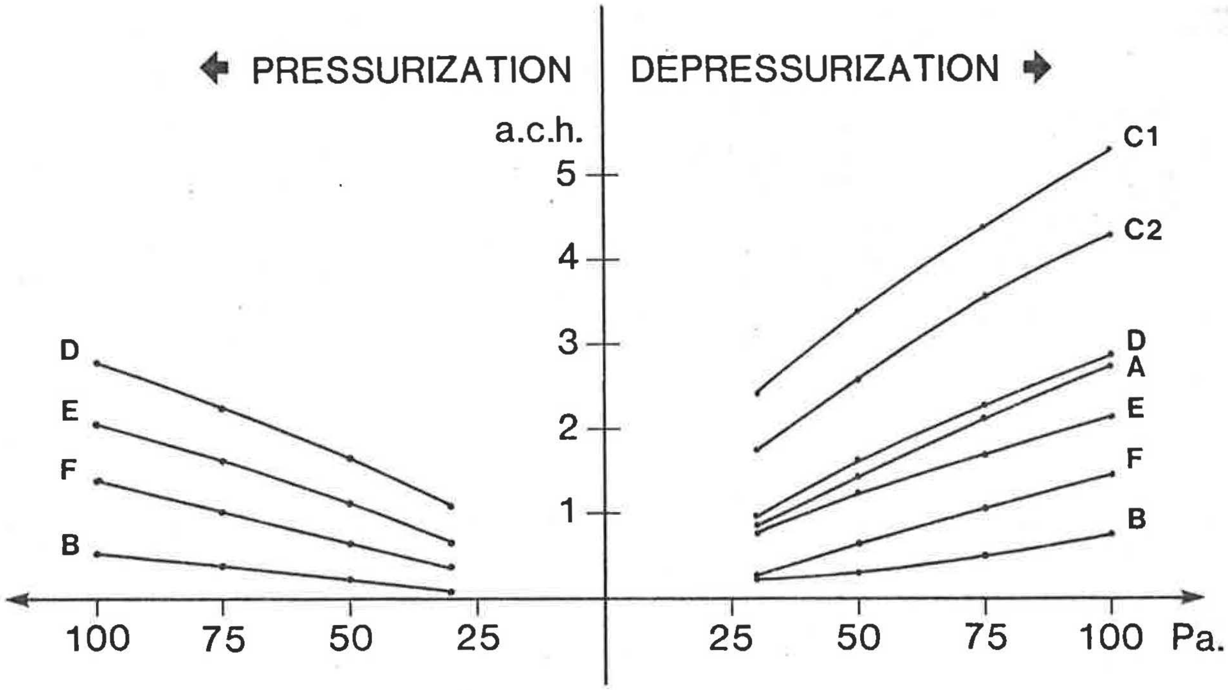
Normally the controlled ventilation provides an air change of approx. 0.5 per hour. To determine the air leakage of the houses, i.e. through the constructions, the ventilation ducts were sealed during the test periods. When the first tests were carried out the houses were about 18 months old and had 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.

House	Measured infiltration [a.c.h.]	Wind speed [m/s]	Temperature difference [C]	Tracer gas ($N=N_2O$, K=Kr-85)
A	0.10	5.9	18	N
	0.07	2.0	14	N
	0.05	1.8	13	K
	0.05	1.5	6	K
B	0.03	5.6	23	N
	0.02	1.6	23	N
	0.02	3.4	16	N
	0.02	3.1	15	K
C	0.12	5.9	20	N
	0.07	1.6	8	N
	0.05	1.9	10	K
D	0.09	5.9	17	N
	0.08	3.2	16	N
	0.08*)	4.1	11	K
E	0.08	5.9	18	N
	0.11	4.5	13	N
	0.10	4.6	12	K
F	0.07	5.9	19	N
	0.07	2.2	11	N
	0.08	2.3	13	K
*) Insulating shutters closed				

Figure 9. Air change rates measured by the tracer gas decay method.



Measured air change rates at a differential pressure of 50 Pa		
House	Pressurization [a.c.h.]	Depressurization [a.c.h.]
A	-	1.42
B	0.21	0.29
C1	-	3.39
C2	-	2.59
D	1.65	1.61
E	1.12	1.24
F	0.64	0.64
D*	-	2.22
E*	-	1.23
F*	-	0.72

Figure 10. Measured air change rates at different differential pressures.

indicate that the external insulating shutters are effective, i.e. that their effect on the transmission heat loss is not diminished by unexpected air leakage.

The results quoted so far, and other measurement values not included in this paper, 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 until this relation is established, no special effort is 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 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 calibrated 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 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 [3]. The lower sky radiation temperature is taken into account through a 15% increase of the transmission heat loss through the roof, in accordance with [3]. 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, [4]. The transmission heat loss coefficients listed in Figure 11 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.

The solar heat gain is obtained as the product of the measured solar radiation, the window area and standard solar transmission factors, [5]. 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 11.

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).

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.

House	LP	Δt	I	EL	TC	TM	$\frac{TC-TM}{TC} \cdot 100$	TMV
	[h]	[C]	[kWh]	[kWh]	[W/C]	[W/C]	[%]	[W/m³C]
A	119.3	21.9	6.5	214.5	83	76	8	0.31
A	22.8	22.5	0.3	40.6	83	71	14	0.29
B	119.2	22.1	5.4	195.8	79	73	8	0.25
B	46.8	22.5	0.4	77.0	78	70	10	0.24
C	516.2	23.3	124.0	1077.2	88	89	-1	0.33
C	44.8	21.3	1.1	97.7	89	93	-4	0.35
D	328.2	21.6	172.9	592.6	97	97	0	0.28
D	47.7	20.4	6.7	89.2	97	88	9	0.25
D*	454.0	21.9	0.0	765.6	68	66	3	0.19
D*	49.3	22.3	0.0	86.4	68	68	0	0.20
E	424.6	22.1	195.6	732.2	82	88	-7	0.21
E	47.7	20.9	4.2	87.0	82	80	2	0.19
E*	334.4	22.8	0.0	560.5	60	62	-3	0.15
E*	93.9	22.8	0.0	162.0	60	65	-8	0.16
F	410.7	22.6	550.0	966.5	145	155	-7	0.44
F	24.5	21.1	5.9	66.7	145	132	9	0.38
F*	311.8	23.3	0.0	788.8	92	100	-7	0.29
F*	23.1	20.9	0.0	55.7	95	107	-13	0.31

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

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 (e.g. with respect to the concentration of iron oxide). However, some preliminary solarimeter measurements of the solar transmission indicate that the solar heat gain derived from the standard factors was too high.

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 12. The shorter periods all indicate smaller energy savings than expected.

	D(sp)	D(lp)	E(sp)	E(lp)	F(sp)	F(lp)
Calculated effect [W/C]	29	29	22	22	50	53
Measured effect [W/C]	20	31	15	26	25	55

Figure 12. Energy saving effect of shutters - sp = the shorter period, lp = the longer period.

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.

Although no direct correlation has so far been found between the tracer gas measurements and the depressurization tests 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, and a pressurization/depressurization test can furthermore be combined with a smoke test.

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. 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, e.g. 24 hours, are more dispersed even if the data are selected from a quasi-stationary period. Future work will show if it is possible to derive a simple heat loss equation for each low-energy house from regression analysis of the experimental data, an equation based on the three variables: temperature difference, solar radiation and wind speed, [6].

ACKNOWLEDGEMENT

We should like to thank our colleagues in the research team, Mogens R. Byberg (project manager), Rolf G. Djurtoft, Gad Nissenbaum, Johannes Poulsen, Kirsten E. Poulsen and Niels Henrik Rasmussen, who have participated in either the planning or the execution of the experiments and calculations reported in this paper.

The Low-Energy House Project is funded by the Danish Ministry of Energy.

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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 9. The later tests were performed in one house at a time, using a radioactive tracer, Kr-85. These results are also shown in Figure 9.

Measurements of Air Leakage by Pressurization and Depressurization.

In all six houses depressurization measurements were made - in four houses, additional pressurization tests were carried out. The normal operating conditions of the houses result in a slight depressurization. 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. The results are shown in Figure 10. House C is represented by two leakage curves for reasons discussed later. In the same Figure the air change rate at a differential pressure of 50 Pa is listed. D*, E* and F* represent measurements in three houses with external shutters - in these measurements the shutters have been closed, but the windows behind them opened.

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 both 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 10 the curve C2 shows the air leakage values when the porch doors and a leaking loft hatch had been sealed with tape. In B, all windows and doors open inward, and the results illustrate that the weather stripping, though good, is the weak point in this connection. The results D*, E* and F*

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