GONE TO EARTH: IN SEARCH OF CHEAP INTERSEASONAL THERMAL STORAGE FOR LOW-COST ZERO ENERGY HOUSES

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ABSTRACT The paper compares the design and measured performance of the relatively conventional Autonomous House and the earth-sheltered Hockerton Housing Project, both in Nottinghamshire, England. These are both attempts by the authors at making houses for the United Kingdom climate that need no non-renewable energy inputs, but are comparable in cost with conventional houses. The conclusion is that high thermal mass combined with superinsulation is effective in giving "zero heating" performance, but it makes sense only if the house is designed for an extremely long life.

1 Introduction

This paper looks at two attempts at building houses that need no non-renewable energy inputs. It focuses in particular on the design of the Hockerton Housing Project in Nottinghamshire, England, construction of which began on site in 1995. The project was instigated by Nick Martin, a local builder, and designed by Brenda and Robert Vale. It involved the construction of a terrace of five low-cost, high-mass, earth-sheltered houses which were to be autonomously serviced; in other words, to be self-sufficient for all their servicing needs. The houses were intended to be relatively low in construction cost, and to have minimal, or even zero, running costs. They use a repetitive modular structure to simplify the construction and to make use of off-the-shelf components. Each house has a single-aspect south-facing plan to maximise the solar gain for space heating. A heat pump plus large thermal store is used for domestic hot water, with solar gain from a conservatory providing the thermal input to the heat pump. Sewage is treated in a series of reed beds and a landscaped lake. Water is collected from the whole site and stored in a reservoir formed from the spoil dug out to make the excavation for the houses, which are built on a gentle south-facing slope (facing the sun in the northern hemisphere). Electricity for the entire project will be generated by a 5 kW wind turbine on a 35 metre high tower, and additionally by the use of photovoltaic panels. The generators will be linked with the local electricity grid, allowing surplus power to be supplied to the local area. At the time of writing, planning approval for the wind turbine has not yet been granted, but the houses began to be occupied in December 1997. (see Hockerton Housing project, 1998).

2 Planning considerations: precedent

Hockerton is a village lying north of the small town of Southwell, on the busy A 617 which leads east to Newark, where the local authority, Newark and Sherwood District Council, has its offices. In the summer of 1992, the Council granted planning consent for Brenda and Robert Vale's Autonomous House in the centre of Southwell. This house, the first of its kind in the United Kingdom, uses superinsulation to eliminate the need for fossil fuel heating, makes its electricity from photovoltaic panels, with surplus being exported to the national grid, collects its total water supply from the rainwater falling on the roof, processes its own wastewater in the garden, and turns its sewage into garden compost. The Hockerton Housing Project is in many ways the complete antithesis of the Autonomous House, as Table 1 below makes clear.

Table 1 Differences between Hockerton and the Autonomous House

Hockerton	Autonomous House
rural site (agricultural land)	urban site (garden)
village edge location	town centre location
five terraced houses	single detached house
earth-sheltered construction	above ground construction
green belt	Conservation Area
single storey design	four storey design including cellar
waterborne sewage treatment	waterless sewage treatment
electricity from windpower	electricity from photovoltaics
rainwater collected from site	rainwater collected from roof

In spite of this, the relevance of the Autonomous House to the Hockerton Project is considerable. The first consideration is that it gave the Council confidence in the project. Nick Martin, the instigator of the Hockerton houses, was the builder of the Autonomous House; Brenda and Robert Vale, architects for the Hockerton Project, had designed and detailed the Autonomous House and they were living in it. The Council could see both that such a house was technically possible and that it could be built unobtrusively in an historic setting. Another similarity between the two schemes is that discussions and consultations were made with the Local Authority, both the Planning and Building Control Departments, before either project was submitted for approval. This allowed the Council's officers to become familiar with the projects, and, in both cases, to make suggestions that might improve the chances of obtaining permission for unusual schemes.

3 Similarities

The greatest visible similarity between the two projects is in the internal planning and the construction. The cellar design of the Autonomous House formed the basis of the construction for the external retaining walls of the Hockerton houses, using two skins of concrete blockwork as permanent shuttering for a reinforced concrete structural core, waterproofed by an externally applied membrane. The above ground walls of both schemes use a brick and block insulated cavity construction with the same facing brick used on both. Internal planning of both projects is based on a simple repeated bay structure spanned by precast concrete beams with block infill. This keeps all structural components to the same dimensions. This makes for low-cost construction both in terms of the ordering of materials and for simplicity of construction which saves time on site. The structural bays are then divided by non-loadbearing partitions to create the required internal spaces.

4 Mass

Notwithstanding the design similarities, it is in their thermal strategies that the two projects are most connected. The principal factors in the thermal design of the Autonomous House were the use of high levels of insulation and thermal mass. Theoretical studies suggested that a house in the United Kingdom, with low levels of solar radiation available in the winter, would need to be thermally massive to allow it to operate without conventional space heating. (for details see Vale, 1995) The need for massive construction, particularly in relation to a house which attempts to avoid the use of any conventional heating system, is supported by Lund (1993) who has said that a superinsulated house with no solar components in northern latitudes needs 100 m^3 of concrete (with a mass of 210 tonnes) to provide sufficient thermal mass to meet a zero space heating demand. Lund's paper assumes a house with an internal temperature varying on an annual basis between 17°C and 27°C.

The Autonomous House gained its thermal mass by means of making all structural elements of materials with a high thermal capacity. In practice, this meant using concrete and masonry construction, the conventional construction technique for houses in the United Kingdom. Normal construction practice was varied to the extent that the external cavity walls were built with the inner leaf of 100 mm thick dense concrete blockwork; the internal loadbearing walls were of 150 mm thick dense concrete blockwork, and all floors used precast concrete beam-and-block construction. However, no elements were made larger than was needed for structural purposes in order to provide increased mass. The total thermal mass of the house (ie. that part of the building fabric that is within the insulated envelope and able to take part in thermal exchange with the interior space of the building) is 127.2 tonnes, which represents a volume of about 69 m^3. It is probably more useful to consider the thermal storage in terms of a square metre of floor area of the heated space. In this case, the Autonomous House provides 0.22 kWh or 0.78 MJ/M^{2}K. The distribution of thermal mass is shown in in Table 2.

Table 2 Thermal mass in the Autonomous House, heated floor area 176 m^2

Element	volume	mass	thermal storage		% of total
Floors	28.1 m^3	51.5 tonnes	51.1 MJ/K	14.2 kWh/K	37%
Roof decking	8.5	5.5	15.1	4.2	11%
External walls	16.2	35.8	36.0	10.0	26%
Internal walls	16.4	34.5	35.6	9.9	26%
Total	**69.2 m^3**	**127.3 tonnes**	**137.8 MJ/K**	**38.3 kWh/K**	

At Hockerton the thermal mass strategy is increased considerably compared to the Autonomous House. The ground floor slab is 300 mm thick, twice the norm for conventional construction, but the slab is also the foundation. The internal walls are 200 mm thick, which is the thickness needed to provide the necessary 100 mm bearing for each end of the precast concrete beams that support the roof. The roof itself comprises prestressed concrete beams and concrete infill blocks, with a concrete slab laid on top to bind the assembly together. The rear wall, and the end walls of the terrace of five houses, are made in the same way as conventional masonry cavity walls, but the cavity has been made 300 mm wide, and instead of being filled with insulation, as in the Autonomous House, it is filled with reinforced concrete 300 mm thick. This provides the retaining wall function for the buried side of the house. The whole house is surrounded with 300 mm thick expanded polystyrene insulation and a tanking membrane, so all the mass is available for use as thermal mass.

Table 3 Thermal mass at Hockerton, heated floor area 114 m^2

Element	volume	mass	thermal storage		%of total
Floor	36.4 m^3	76.0 tonnes	63.6 MJ/K	17.7 kWh/K	31%
Roof decking	29.9	62.1	52.5	14.6	26%
External walls	26.4	55.1	46.5	12.9	23%
Internal walls	22.6	46.2	39.4	11.0	20%
Total	**115.3 m^3**	**239.4 tonnes**	**202.0 MJ/K**	**56.2 kWh/K**	

It can be seen that the mass is distributed more evenly in the Hockerton houses, but the elements are still appropriately sized for their constructional purposes, it is just that the construction is considerably different from the norm.

5 Thermal performance

Table 4 shows the temperatures achieved in the living room of the Autonomous House in the winter of 1995-1996.

Table 4: Winter living room temperatures in the Autonomous House 1995-1996

month	ave ext temp*	ave sunshine hours**	ave living room temp
Oct	10.7°C	87 hours	22.4°C (1995)
Nov	6.5°C	48	18.3°C (1995)
Dec	4.5°C	42	18.0°C (1995)
Jan	3.3°C	43	17.7°C (1996)
Feb	3.5°C	57	17.7°C (1996)
Mar	5.7°C	97	17.5°C (1996)

Specific heat loss for the house is 0.63 W/m^{2}K.
The site has 3344 degree days to an 18°C base (Page, 1986a)
*data from 1941-1970 (Page, 1986b); **data from 1941-1970 (Page, 1986c).

These temperatures were achieved with four (more or less) adult occupants and a consumption of about 350 kg of wood fuel in the 4.5 kW woodburning stove in the ground floor entrance hall. It can be seen that the effect of the mass of the house has been to shift the fall in internal temperature until it lags about three months out of phase with the lowest external temperature. After March the indoor temperature rose again.

If Lund's hypothesis is correct, the Hockerton houses should attain higher temperatures as a result of their greater mass. Table 5 shows this to be the case.

Table 5: Winter living room temperatures in a Hockerton house 1998-1999

month	ave living room temp	Autonomous House for comparison
Oct	21.9 (1998)	(22.4)
Nov	20.9 (1998)	(18.3)
Dec	19.2 (1998)	(18.0)
Jan	18.9 (1999)	(17.7)
Feb	19.3 (1999*)	(17.7)
Mar	n/a	(17.5)

Specific heat loss for the house is 0.99 W/m^{2}K (Michaelis et al, 1998a)
The site has 3344 degree days to an 18°C base (Page, 1986a)
Measurements from 2 Mystery Hill, Gables Drive, Hockerton.
* temperature up to and including 25 February

These very preliminary figures suggest that the greater mass is indeed performing as expected. This impression is reinforced by the fact that the lowest temperature recorded in the living room of the Autonomous House over the winter of 1995-1996 was 15.5°C, whereas at Hockerton the lowest temperature for the winter of 1998-1999 was 17.9°C on 13 January. This is in spite of the considerably lower specific heat loss rate of the Autonomous House compared with Hockerton, 0.63 W/m^{2}K as opposed to 0.99 W/m^{2}K. The temperatures at Hockerton are also more stable, with little variation from month to month compared to the

Autonomous House. It is interesting to note that the family who supplied the Hockerton temperature data reported that they were thinking of opening the bedroom windows at the end of February, as it was beginning to get too hot (in a house with no space heating system in the English winter) for comfortable sleep. (White, 1999) The comment can be made that the results from the two houses are not comparable, as they are from different years; but the figures are compared here to indicate tendencies.

6 Embodied energy considerations

Increased thermal mass seems to have improved the thermal comfort of the houses. The other question to be considered in the use of thermal mass is that of embodied energy. Does the inclusion of a very high mass make the energy balance untenable? Many figures for the embodied energy of concrete have been published, with the quoted values tending to rise over time, as shown in Table 6. (note: all values converted to MJ per tonne).

Table 6: Some quoted values for the embodied energy of concrete

Description	embodied energy	source of data
Concrete	720 MJ per tonne	(Szokolay, 1980)
Concrete 20 Mpa	1900 MJ per tonne	(Baird and Chan, 1983)
Concrete 45 Mpa	2400 MJ per tonne	(Baird and Chan, 1983)
Concrete 1:3:6	990 MJ per tonne	(BSRIA, 1994)
30 Mpa reinforced concrete	3333 MJ per tonne	(Treloar, 1996)

Taking the worst case, and using Treloar's figure of 3333 MJ for a tonne of reinforced concrete (Treloar, 1996) the concrete mass represents nearly 800 GJ, or 7 GJ/m^2. (In practice, not all of the concrete is reinforced). The insulation in each house, mostly expanded polystyrene, has a volume of about 100 m^3. Taking Treloar's value for "plastic" of 160 GJ per tonne, the insulation represents 400 GJ, half the energy of the concrete. The two materials combined have an embodied energy of 1200 GJ, or 10.5 GJ/m^2. An average house in the UK in 1991 consumed 52.1 GJ of energy for space heating (Shorrock and Brown, 1993). A house built to the 1995 Building Regulations will use 28.5 GJ of natural gas per year for space heating, or about 0.35 GJ/m^2. (DETR, 1998)

A more accurate figure is obtained by using Treloar's multiplier of 1.4 for the primary energy content of gas (Treloar, 1998), which increases the energy allocated to gas consumption to about 0.5 GJ/m^2. By removing the need for space heating in the Hockerton houses, the concrete mass and thermal insulation are together saving energy at this rate, which would have been the gas consumption for space heating if the houses had been built conventionally. The embodied energy of the concrete mass plus the insulation is equal to the space heating energy saving after 21 years. As the houses are designed to last a minimum of ten times longer than this, they are likely to show an overall saving in energy over their life.

These are preliminary estimates, and future research will make some more detailed life-cycle comparisons between the Hockerton houses and a conventional UK house. It should be pointed out that the earth-sheltered construction serves to protect the mass and insulation from the effects of weathering and ultra-violet radiation, and should assist in the achievement of a long life. The presence of the thousand year old Southwell Minster (a stone cathedral still in daily use for its original purpose, and largely unreconstructed) some 300 metres from the site of the Autonomous House provides evidence that the long-life high-mass building is a reasonable proposition in this location.

7 Costs

The Autonomous House cost £145 000 to build. This provided 176 m^2 of heated floor space, plus a conservatory (with double low emittance glazing) of 48 m^2 and a cellar of 66 m^2. The Hockerton houses cost £91 163 for a house of 114 m^2 plus a conservatory of 57 m^2. It is difficult to compare these costs with those of a conventional house, as a conventional house provides no cellar or conservatory. If the autonomous services and the conservatory at Hockerton are taken out of consideration, the houses cost £60 102. A conventional house of the same floor area would cost £53 124. (data from Michaelis et al, 1998b) The difference in cost is only £6978, or an addition of 13% on the cost of a normal house. Given that the Hockerton houses are the first of their kind, it is likely that future versions might be built for less, once the techniques become part of mainstream construction practice.

8 Conclusions

It would seem from these preliminary results, that very high mass superinsulated construction is an effective way to provide relatively low cost "zero heating" houses in the United Kingdom. The high mass makes the most of the very low solar gains in the winter. It would also appear that it is appropriate to design for a life estimated in centuries rather than decades to ensure that the additional embodied energy related to the use of mass does not exceed the operational energy savings.

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