Linford Low Energy Houses

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This paper summarises the results of tests on 8 low-energy passive solar houses at Great Linford, Milton Keynes, monitored by the Open University Energy Research Group (ERG), for Milton Keynes Development Corporation (MKDC), under contract to the Energy Technology Support Unit (ETSU), Harwell on behalf of the Department of Energy.

The views expressed are those of the contractors and do not necessarily reflect those of either ETSU or the Department of Energy.

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The full project report 'Linford Low Energy Houses' (ERG 050) is over 400 pages long and obtainable from:-

Energy Research Group,
Open University,
Walton Hall,
Milton Keynes,
MK7 6AA.

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[This report was digitised in June 2009 for the Open University's 40th Anniversary]
THE LINFORD PROJECT

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Figure S1. Location of Milton Keynes

Figure S2. The location of the Linford houses

Figure S3. Pre-design modelling produced estimates of insulation and passive solar energy savings
The Linford Project involved the design, construction and monitoring of eight low energy houses in Milton Keynes. The project started in 1976 when there was little knowledge about the detailed performance of well insulated passive solar houses. The objective was to monitor the houses in a considerable amount of detail to assess the interactive effects of high levels of insulation, passive solar and incidental heat gains and the performance of the heating system.

Milton Keynes is a new town, about 50 miles north of London (Figure S1) and is unusual in that it has several low energy housing schemes which have been promoted by its Development Corporation (MKDC). Of special note is the companion Pennyland Field Trial involving the monitoring of nearly 200 houses, many of similar design to the Linford ones. For this project the Development Corporation collaborated with the Open University's Energy Research Group, which is also based at Milton Keynes.

The first phase of these projects involved carrying out a series of design studies into the implications of low energy house design. A great deal of this work involved computer simulations to assess the effects of such things as insulation level, window area and orientation on energy consumption. The results of some of this research phase are summarised in Figure S3.

The initial investigations resulted in a clear energy brief which called for the houses to be insulated to current Danish Regulation standards and to incorporate several passive solar features. A copy of the brief was given to the developers, S & S Homes, who designed and built the eight detached four-bedroom houses on the south side of the Linford gridsquare (see figure S2).
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S4.
The Linford houses

North Facade
INTRODUCTION

The walls were insulated with 100 mm glass fibre batts, the roof with 140 mm glass fibre quilt and the perimeter of the floor slab with 25 mm of polystyrene. The houses were orientated towards the south with large areas of double glazed windows on the south side and only a minimal glass area on the north side. The main living areas were given a south aspect and thermal storage was provided by using dense concrete blocks for the internal partitions and internal leaf of the cavity walls.

To verify the theoretical predictions the houses were monitored over two years. Intensive monitoring took place during the 1981/82 and 1982/83 heating seasons. Measurements were taken in seven occupied houses and one unoccupied test house. The main funding for this work came from the Energy Technology Support Unit of the Department of Energy. Further supporting funding was provided by the Science and Engineering Research Council, Milton Keynes Development Corporation and the Open University.
Figure S5. The thermographic survey helped to identify specific areas of high heat loss such as the window lintels.
S2. Monitoring

The main monitoring activity involved recording temperatures, gas and electricity consumptions, heat flows and solar radiation in order to establish the thermal performance of the houses. In addition two other surveys were carried out during the project: a thermographic survey and a buildability study.

The thermographic survey gave an insight into the quality of the insulation and highlighted the position of cold bridges (Figure S5).

Buildability

The buildability study was undertaken during the construction by the Building Research Establishment (B.R.E.). Their researchers visited the site several times during the construction period. This was part of a wider survey of construction techniques incorporating high insulation levels.

In its report the BRE concluded that generally the insulation was easy to incorporate in the construction and did not impede the progress. A potential problem was found if the glass fibre wall batts were not installed with care.

Experience with the draughtstripping suggests that more work needs to be done to examine the timber window and door detailing, the effect of warping on door seals and the longevity of the seals.

Performance Monitoring

To establish the thermal performance of the occupied houses the following measurements were recorded:

- air temperature in all rooms
- heat delivered to the heating and hot water circuits
- gas and electricity consumption
- window openings.

These measurements were also taken in the unoccupied test house.
Figure S6. Data logging equipment in test house garage
In addition, to enable more detailed analysis, extra measurements were taken, as follows:

- loft temperatures
- heat flux in walls, floor and roof
- ventilation rate.

Each day the number of blinds or curtains covering the windows was noted.

In the garden of the test house a weather station was set up to record:

- solar radiation
- wind speed and direction
- outside temperature.

The cables from the various sensors led to a central location in the garage of the test house (Figure S6) where four dataloggers recorded the measurements onto magnetic tape. This was subsequently fed into a University main frame computer for analysis.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S7. Gas and electricity consumption for two houses show a 2:1 difference in usage.

Figure S8. Annual fuel consumption of seven Linford houses.

Figure S9. Average performance of houses with gas and electric cooking.
S3. Annual Energy Consumption

One of the most basic pieces of information to be produced is the amount of fuel used in these low energy houses.

Figure S8 shows a plot of gas and electricity consumption in two houses over the whole monitoring period. It can be seen that there was a large difference in energy consumption between these two families: the occupants of house 38 using about twice as much energy as those in house 35. The seasonal variation in gas consumption can be seen quite clearly, while the electricity usage was much more constant throughout the year.

The complete range of annual energy consumption for all the occupied houses is shown in Figure S9. Electricity consumption was around 33% of total usage. On average gas used for heating domestic hot water was 37% of the total gas consumption, while space heating gas amounted to 60% of the total gas usage.

<table>
<thead>
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<th>DELIVERED GAS FOR:</th>
<th>DELIVERED ELECTRICITY FOR:</th>
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<td>Electricity</td>
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<tr>
<td></td>
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<td>kWh</td>
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<td>3809</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>15214</td>
<td>3369</td>
</tr>
</tbody>
</table>
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S10. A wide range of preferred temperatures produces considerable variation in space heating requirement

Figure S11. Annual expenditure on fuel
The range of space heating energy consumptions is clearly dependent on the temperature at which people choose to live. Figure S10 shows the average whole house winter temperature varied between 16.2 and 20.4°C with the corresponding useful space heating rising from 3622 kWh/yr to 7962 kWh/yr. The estate average winter temperature was 18.9°C, which is quite high in relation to previous field trials.

The money spent on energy is also of interest. Figure S11 shows that the average cost of gas for space heating was only £104 per year - around £2 per week. Only two out of the seven households paid more for gas than electricity. For the majority, space heating costs barely twice that of hot water.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

13 days - 13/3/82 to 25/3/82

Intercept = $\Sigma A \cdot U$ Fabric heat loss excluding floor

Slope = $-R = \text{Solar Aperture}$

Figure S12. A typical example of the regression analysis used to estimate solar aperture and fabric heat losses.

Figure S13. The total specific heat loss was as expected but the floor and ventilation components showed a considerable discrepancy.
Measurements of temperature, space heating consumption and solar radiation were examined to determine the total heat loss of the houses. This data was manipulated using a novel application of regression analysis to estimate fabric heat losses and the response to solar radiation (Figure S12).

A considerable amount of work has been put into these regressions. The method has been developed so that it is now possible to establish the thermal characteristics of a house with measurements over typically only three weeks.

In addition to these general characteristics, detailed measurements of heat flux for the different fabric elements have allowed a breakdown of the losses into their component parts. Figure S13 shows that these individual losses were largely as expected, except for air infiltration and heat transfer through the floor.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S14. Floor heat losses twice as high as expected.

Figure S15. Infiltration rates were surprisingly low.

Figure S16. The gross heating requirement of 15,000 kWh/yr is about 10,000 kWh/yr less than house built to 1982 Building Regulations.
HEAT LOSSES

The heat loss through the floor was twice that expected (see Figure S14). This was attributed to the unusually wet ground conditions, although the figures highlight the lack of knowledge in this area and the need for further research.

In contrast to the floor losses, the infiltration rates were a third of the 1 ac/h expected. Figure S15 shows the results for the test house. Infiltration rates were, between 0.2 and 1.1 ac/h with an average around 0.5 ac/h. This was despite the fact that this house was the most 'leaky' of the eight and had an artificially high internal temperature. The average seasonal rate for all the houses was estimated as 0.3 ac/h.

These low infiltration rates, are attributed to the sheltering from the prevailing S.W. winds and a generally 'tight' standard of construction.

The effect of cold bridges is difficult to assess but the thermographs helped to reinforce the estimate that they contributed around 5% of the total house heat loss.

Figure S16 shows that the gross useful heating requirement for these houses is about 15,000 kWh/yr, compared with about 25,000 kWh/yr for the same house built to current (1982) Building Regulations.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S17.
The gross heating requirement was supplied by incidental gains, solar gains and the space heating system.

- **Incidental**: 36%
- **Solar**: 24%
- **Heating**: 38%

**Total Useful Energy Requirement**: 15,000 kWh/yr

**Roof**: 7%
**Walls**: 20%
**Windows & Doors**: 35%
**Floor**: 23%
**Infiltration**: 15%

Figure S19  Heat gains balance heat losses

Figure S18  Energy balances for the occupied houses
S5. Energy Balances

The gross heating requirement of around 15,000 kWh/yr is offset by heat inputs from the heating system, solar gains and incidental gains, (Figure S16). A series of energy balances for four occupied houses were undertaken to assess the contribution from these three sources. Useful solar and incidental gains were judged as those that did not raise the average temperature above the thermostat set point (line 2 on Figure S17).

Figure S18 shows the wide variation between the houses. For instance the absolute solar contribution varied between 2834 and 4464 kWh/yr; the percentage of the total supplied by solar gains also varied between 17 and 33%. In the 'average' Linford house incidental gains and space heating contributed 38% each (5700 kWh/yr) while solar gains made up 24% (3573 kWh/yr) of the total.

Having estimated the heat inputs it is possible to balance these against the heat losses as shown in Figure S19.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S20. Average of the incidental gains in the Linford houses

Figure S21. Incidental gains show a slight seasonal variation

Figure S22. The daily profile shows two distinct peaks in incidental gains
S6. Incidental Gains

The project produced a valuable set of data on incidental gains in the four houses.

The total gains for these large four-bedroom houses was between 4000 and 7000 kWh/yr. The winter daily average was 22 kWh/day. Figure S20 shows that 40% of this came from electrical appliances, with the rest fairly evenly distributed between hot water usage, cooking, boiler casing losses and the occupants themselves.

The plot of monthly gains (Figure S21) shows some seasonal variation due mainly to extra heat gains from the boiler casing in winter. The daily 'profiles' are useful for showing the peaks and troughs in incidental gains and electrical load (see Figure S21). In each of the houses analysed the peak occurred around 5 p.m. This is as expected, although the peak to trough ratio was higher than initially expected.
Figure S23. The effect of solar radiation on space heating and surface heat flux in the test house.
SOLAR GAINS

S7. Solar Gains

A major objective of the project was to investigate the role played by solar gains in direct gain passive solar houses.

Several carefully controlled experiments were carried out in the test house. These enabled a study to be made of the way in which solar gains were distributed around the house. The study also looked at how the solar gains were stored in the fabric, how they affected the internal temperatures and how much auxiliary heating they displaced.

The Daily Cycle

A clear insight into the daily cycle is shown in Figure S23. Immediately after sunrise on a sunny day the external temperature begins to rise rapidly. Solar radiation enters the south windows and strikes the floor. Only a small proportion of the radiation penetrates the carpet and is absorbed in the floor beneath; the remainder is dispersed in the air inside the house. This energy, together with the rapid reduction in window and ventilation heat loss due to the rising outdoor temperature, leads to a slight rise in internal temperature.

The electronic thermostats used in the test house are affected immediately by this rise in internal temperature, reducing the demand for auxiliary heating: thus solar gains are immediately displacing the back-up heating. Once this has been totally displaced, the internal temperature rises more rapidly. This causes a rapid flow to heat into storage in the walls.

Towards sunset the solar radiation drops off, the external temperature falls and the heat losses through windows and ventilation increase. During this period the internal temperature begins to fall slowly back to the set point, with space heating then being provided by a flow of stored energy back out of the walls. Once the thermostat set point is reached the heating slowly comes on again.

During the evening heat still flows out from the massive walls, saving considerably on space heating. Eventually at about dawn the walls have almost returned to equilibrium, and the cycle repeats.
Figure S24. Power traces of room heaters during dull and sunny weather show solar gains displacing auxiliary heating.

Figure S25. Solar gains clearly displace auxiliary heating in the occupied houses.
SOLAR GAINS

The test house was heated by a number of thermostatically controlled electric fan heaters. The individual outputs of these heaters have allowed the distribution of the solar gains around the house to be observed. Figure S24 shows the power outputs on a dull day and a sunny day in March. On the dull day solar gains displace space heating in the south-facing living, dining and bedroom, but the north-facing kitchen remains unaffected. On the sunny day the heating in the south-facing rooms is totally displaced by 8.30 a.m., just 2½ hours after sunrise. The kitchen lags about an hour behind and is the first room to require heating again in the evening. The southerly rooms do not require any heating until sunset. The heating comes on slowly; even at midnight it is apparent that stored solar gains are still emerging and a steady state still has not been reached.

The substitution of auxiliary heat by solar gains was clearly observed in the occupied houses as well as the test house. Gaps in the output from the boiler and rises in internal temperature as a result of solar radiation can be seen clearly in Figure S25.

Solar Aperture Regression analysis, as shown in S12, has been used to estimate the absorption of solar radiation into the house. The utilisation of solar energy is expressed as being equivalent to an unglazed, unobstructed south-facing solar aperture. This solar aperture is less than the total southerly clear glazing area of 16 m² and takes into account the transmission through the glazing and the absorption and re-reflection at the internal surfaces, including the effect of curtains.

Measurements in the test house give an equivalent solar aperture of 10 m² ± 1 m² for clear unobstructed windows and 8 m² ± 1 m² for full net curtains. Measurements in the occupied houses reinforce these estimates with solar apertures in the range 7-11 m².

A solar aperture of 10 m² is equivalent to an absolute solar contribution of between 2500 and 4500 kWh/yr, depending on the assumed length of the heating season. Results from the occupied houses were very similar.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S26. The difference between absolute and marginal solar gains

Figure S27. The steps used in assessing solar energy savings

Figure S28. The thermal mass and ventilation were effective in controlling peak internal temperature in summer
SOLAR GAINS

Marginal Solar Saving
Since to some extent all houses receive solar gains, the absolute solar contribution is not a very useful figure. Of more interest is the marginal solar energy saving (Figure S26). This compares the difference in auxiliary heating consumption between two houses with identical insulation levels but with different passive solar features.

The passive solar features which have been examined at Linford are orientation and the avoidance of overshading, concentrating the glazing on the south side and avoiding window clutter (net curtains and the like), as shown in Figure S27.

No 'normal' control houses were built, so a direct comparison, with the Linford houses was not possible, though this has been done in the companion Pennyland project. A computer simulation exercise was therefore undertaken to estimate the marginal solar savings.

For a house with unobstructed windows these savings amount to about 1400 kWh/yr of useful space heating. Of this, about one third come from correct orientation and avoiding overshading, one third is due to concentrating the glazing on the south side and the remaining third results from avoiding window clutter such as net curtains. Against this must be set a slight disbenefit of about 200 kWh/yr due to the extra thermal mass to prevent summer overheating.

Summer Overheating
Placing large areas of glazing on the south side gives a potential danger of overheating during summer. Measurements over a heatwave period in July 1983 (Figure S28) showed that this was not a great problem. The thermal mass and increased ventilation kept the peak internal temperatures below those outside.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S29. The radiator output was sufficient to give fast warm-up periods even in extreme outside conditions.

Figure S30. The boiler is always operating below 22% of absolute maximum load on a daily basis.
S8. Auxiliary Heating

Once contributions from incidental and solar gains have been taken into account the heating system has to supply the remaining house heating requirement.

The heating system was designed by the developer's sub-contractor and consists of a 17.6 kW Corvec Maxiflame boiler serving radiators in every room. Zone valves, controlled by room thermostats in the living areas and main bedrooms, separate the heated areas into upstairs and downstairs zones. Thermostatic radiator valves controlled the heat output from the radiators in other rooms, and the whole system was controlled by a single programmer.

The total radiator output was, around 7.2 kW, which was sufficient to give satisfactory warm-up rates even in the severest weather. Figure S29 shows boiler output and internal temperatures during two of the coldest days this century. The boiler is considerably oversized and could be reduced to 10 kW without affecting comfort conditions or the satisfactory supply of hot water.

Boiler efficiencies are shown in Figure S30. An annual average efficiency of around 65% was achieved. The boiler was working well below its maximum output for most of the time. With the use of a smaller cheaper boiler average efficiencies might rise by 5% saving £5 per year.

The use of room thermostats in the main south-facing room on each floor and thermostatic radiator valves in other rooms controlled the heating system well and allowed solar and incidental gains to displace auxiliary heating to full effect.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S31.
Energy saving features that were assessed for the Linford houses

Linford Reference House Shell - 1976 Building Regulation Standards

Delivered Energy kwh/yr

Savings
6037 kwh/yr useful
8059 kwh/yr delivered

Linford Reference Shell - 1982 Standards

Savings
6129 kwh/yr useful
8173 kwh/yr delivered

Figure S32. Energy savings for the Linford houses
S9. Energy Savings

While improved knowledge about the thermal performance of the houses is important, the key issue is to what extent the various measures save energy. Since there was no measured comparison, computer simulation was used to compare the performance of the Linford houses with two 'normal' house designs. One represents the houses that might have been built in place of the Linford ones in 1980. They would comply with the 1976 Building Regulation insulation standards. The other incorporates the improved insulation levels of the 1982 Regulations.

The energy savings have been split into four areas (Figure S31): savings from

(i) Insulation

(ii) Reduced infiltration

(iii) Passive solar

(iv) More efficient boiler

The Linford houses have saved an estimated 16222 kWh/yr of delivered energy over the 1976 Regulations design and 8173 kWh/yr over the 1982 design.(Figure S32)

<table>
<thead>
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<th>Measure</th>
<th>Delivered Energy Saving kWh/yr</th>
<th>Percentage of Energy Saved</th>
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<tr>
<td>Insulation</td>
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<td></td>
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<tr>
<td>'82 Regs. House</td>
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<td></td>
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<td>Insulation</td>
<td>3989</td>
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<tr>
<td>Reduced Air Infiltration</td>
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<tr>
<td>Improved Boiler Efficiency</td>
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<tr>
<td>Solar Measures &amp; Thermal Mass</td>
<td>1355</td>
<td>15</td>
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<tr>
<td>Linford as Built</td>
<td>8173</td>
<td>100</td>
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Further simple design modifications such as full underfloor insulation could save a further 2300 kWh/yr of delivered energy for little extra cost.
## SUMMARY, CONCLUSIONS & RECOMMENDATIONS

### COST-EFFECTIVENESS OF ENERGY-SAVING MEASURES

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<th>Net Cost Extra £</th>
<th>Fuel Saving £/yr</th>
<th>Payback Time yrs</th>
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<td>-9</td>
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<td>6. Wall ins. 50-100 mm</td>
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<td>18</td>
<td>152</td>
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<td>7. Floor edge ins.</td>
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<td>8</td>
<td>45</td>
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<td>5.4</td>
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<td>8. Reduced infiltration rate.</td>
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<td>31</td>
<td>18.8</td>
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<td>9. Passive solar gains + thermal mass</td>
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<td>10. Improved boiler eff.</td>
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<td>908</td>
<td>126</td>
<td>782</td>
<td>185</td>
<td>4.2</td>
</tr>
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</table>

All Costs are for March 1984.
Gas Price 33.5 p/therm.
Heating system costs are apportioned according to the reduction in house heat loss.
Whether the energy saving measures are worth implementing depends on the cost of the measure and the value of the energy saved.

The extra capital costs of each energy saving feature were estimated by Davis, Belfield and Everest, a firm of quantity surveyors, as if the houses were to be built in the spring of 1984.

For the insulation measures extra construction costs could be partially offset with savings resulting from a reduced heating system size, including a smaller and cheaper boiler.

The 'cost-effectiveness' has been assessed in terms of a flat rate payback period. The table opposite shows the payback times of the various measures, together with the overall payback times of the complete package.

Compared to the 1976 insulation standard house design, the Linford houses as built show a total fuel saving of an estimated £185/yr, with a payback time of just over four years. This is much better than the initial estimates of 10-15 years at the outset of the project, and is due to both clear performance figures and much reduced insulation costs.

Compared to the 1982 insulation standards reference house, the Linford design shows an estimated fuel saving of £93/yr, with a payback time of just under five years.
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<td>2. Roof Insulation 50 mm - 100 mm</td>
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<td>3. Wall Insulation 0 - 50 mm</td>
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<td>1982 Reference House</td>
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<td>4. Double Glazing</td>
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<td>5. More Efficient Boiler</td>
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<td>6. Infiltration Reduction</td>
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<td>7. Floor Edge Insulation</td>
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</tr>
<tr>
<td>10. Roof Insulation 100 mm - 150 mm</td>
<td>13.9</td>
</tr>
<tr>
<td>Linford as Built</td>
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COST EFFECTIVENESS
AND MARKETABILITY

Ranking the various measures, as in the table opposite, shows that they are all very cost-effective with, perhaps, the exception of the final increment of roof insulation.

The double glazing, a frameless type produced by the Sashless Window Company was particularly cost-effective. Supply and construction considerations meant that on average is was no more expensive than single glazing.

Marketability

There was no specific marketing research carried out as part of the Linford project. However, discussions with the contractor and two estate agents suggest that the market was not receptive to conservation measures at the time the houses were built, but is now becoming more interested and is prepared to pay a little more for energy saving measures. It would appear that energy saving features are worth £500-£700 in small houses and up to £2000-£3000 in larger ones. Solar measures were surprisingly high in the marketability 'ranking' of conservation measures, being below double glazing and insulation but above draughtstripping and more efficient boilers.
**OCCUPANTS' REACTIONS**

S11. **Occupant's Reaction**

Discussions with the occupants revealed that they were generally pleased with the houses and glad that they had bought them. They were delighted by the size of their fuel bills and noticed a significant reduction compared with their previous houses. All were satisfied with the heating systems and the ease with which the house could be kept warm.

Generally they enjoyed the large south-facing windows, although some were unsure of their reaction had they been overviewed from the south. While generally appreciating the concept of the cheap sashless double glazing, they expressed a strong dislike of the detailed problems of using them; the opening mechanics and cleaning in particular.

The experience of living in these houses heightened their awareness of energy use in housing and in most cases would influence their choice of subsequent houses.
SUMMARY, CONCLUSIONS & RECOMMENDATIONS

Figure S33 Insulation detailing

- 2 coats 13mm pleater
- Pleax blind
- Dual glazed windows
- Ex 225 x 25 s.w. clt-board painted
- Inner leaf of Arcon conbloc dense aggregate blockwork
- 110mm block pvc gutters on s.w. fascia board screwed to s.w. lathing mails
- Combined lintol for 100mm cavity with integral O.C.C. filled with Driltherm fibreglass wall insulation
- Dual glazed windows
- 100mm approved fibreglass cavity fill
- Combined lintol soldier airling course
- Detail B: HEAD DETAIL
- Cill DETAIL DETAIL C
- Mullion DETAIL 1:20
- Detail O

Typical section 1:100

140° loft insulation

Marley "Mendip" profile granulated roof tiles 413 x 320mm maximum gauge 338mm
36 x 25mm s.w. battens

'Briktor' reinforcement

S.W. fibre felt

113mm foil backed plasterboard

110mm block pvc gutters on s.w. fascia board screwed to s.w. lathing mails

Combined lintol for 100mm cavity with integral O.C.C. filled with Driltherm fibreglass wall insulation

Dual glazed windows

100mm approved fibreglass cavity fill

Combined lintol soldier airling course

Detail B: HEAD DETAIL

Cill DETAIL DETAIL C

Mullion DETAIL 1:20

Detail O

933 mm width of expanded polystyrene insulation to BS 3533/HG/TypeB

Cavity wall insulation 100mm glass fibre batts to be installed in accordance with manufacturers recommendations.
Conclusions and Recommendations

The package of insulation, and passive solar measures has worked well, proved very cost effective and caused no notable difficulties during the construction process. It is recommended that these measures be more widely adopted in the future.

Loft Insulation

Increasing loft insulation from 100 mm to 150 mm should be considered as being marginally cost effective. Cold bridging could be reduced if the insulation is laid both between and across the ceiling joists. At these levels of insulation it is important to design to avoid condensation in loft space. The use of the loft space for locating such things as cold water storage tanks and piped services should be given more thought. The ventilation of the roof space is important.

Wall Insulation

100 mm of fibre glass insulation in the wall cavity has been successfully incorporated into the structure. The energy savings have proved to be significant and very cost effective. The adoption of this insulation level is strongly recommended.

The installation of the glassfibre batts does require a little extra supervision and training on site.

100 mm is the limit of cavity width allowed by the present Building Regulations; beyond this the inner and outer leaves must be self-supporting. It is thus unlikely that the cost of increasing this insulation thickness would prove cost effective at present fuel prices.

Floor Insulation

The results from this and other projects have highlighted the lack of understanding of heat flow through ground floor slabs. As far as can be seen the edge insulation has worked and appears cost effective, with no installation problems. The unexpected magnitude of the ground floor heat losses suggests that insulation covering the entire floor area would be cost effective. It is strongly recommended that further research is carried out in this area.
The frameless double glazing produced by the Sashless Window Company was very cost-effective.
CONCLUSIONS AND RECOMMENDATIONS

Double Glazing

The cheap Sashless double glazing has proved exceedingly cost-effective. As a double glazing system it has performed well and has proved to be well sealed against infiltration. However, there has been a certain amount of user dissatisfaction, caused mainly by the design of the opening and sliding mechanism. These problems could be overcome by slight modifications to the design.

Passive Solar Design

Since windows are considerably more expensive per square metre than wall, larger window areas than necessary are difficult to justify, unless technological improvements can drastically alter performance. The choice of the total window area for a house is thus an aesthetic one, to produce a pleasant habitable house, rather than a question of cost-effectiveness.

Once the total glazing area for a house has been chosen, concentrating it on the south side of the house and avoiding overshadowing can save a considerable amount of energy without necessarily incurring any extra construction cost. These solar measures were well liked by the occupants and are to be highly recommended.

To obtain the maximum benefit from direct gain passive solar techniques it is important that the windows are not obstructed by net curtains or other 'window clutter'. This may be a question of the perceived privacy of the site.

The cost-effectiveness of the solar measures is potentially high. As built, though, the Linford houses incorporate a large amount of extra thermal mass, costing £155/house, which must be set against the estimated energy savings of £15.2/yr, giving a payback time of just over ten years. This thermal mass could be restricted to just the partition walls of south-facing rooms, which would cut this extra cost considerably and reduce the passive solar payback time to three years or less.

Reducing the south-facing glazing area at Linford by about 3 m² to about 35% south-facing wall area would make little difference to the energy performance, save on construction cost and reduce any potential overheating problems.

The concrete floor has not been found to contribute significantly to the thermal mass of the house.
Heating System

The central heating system has worked well maintaining good comfort conditions. Warm-up rates have been satisfactory even in the most severe weather. The output of the radiators, which are 40% larger than the nominal room heat losses, could probably be reduced slightly without affecting these warm-up rates adversely.

Lack of choice at the design stage resulted in a greatly oversized boiler. Despite this, annual efficiencies are relatively high, due to the fact that the boiler has a low thermal capacity. The boiler could be reduced in size substantially and still provide good comfort standards. This reduction in size would probably improve boiler efficiency and save on installation costs. This over-sizing would have carried a much greater penalty in operating efficiency had a high thermal capacity, cast iron boiler been used. Therefore it is recommended that low thermal capacity boilers are used and that design procedures for their selection are revised to avoid excessive oversizing.

Measured boiler standing losses suggest that there is scope for the wider application of electronic ignition.

Heating Controls

The mixture of room thermostats in the main living and bedroom and thermostatic radiator valves in other rooms has worked well; both in maintaining required comfort conditions and allowing the displacement of auxiliary heating by solar and incidental gains.

It is strongly recommended that control thermostats are placed in south-facing rooms so that the advantages of solar gains are fully realised. It is also desirable that thermostatic radiator valves are used to achieve flexible room temperature control and energy saving. It is important not to use TRVs in rooms with thermostats.
CONCLUSIONS AND RECOMMENDATIONS

Infiltration and leakage
Infiltration in the Linford houses was much lower than expected. This can be attributed to the careful attention paid to this aspect, in the design and construction of the houses in particular to draught lobbies, window and door seals, cavity insulation, cavity closers, siting and orientation and the use of a balanced flue boiler. This has shown that it is possible to achieve well sealed houses using basically traditional construction techniques. The resulting energy savings have proved to be most cost effective.

Pressure tests have been extremely useful in determining the air tightness of these houses. This very simple test can be invaluable in testing the quality of construction. It is recommended that standards for air leakage are developed and testing methods introduced for new houses.