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The Pennyland and Linford low energy housing projects

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SYNOPSIS
This paper is a summary of the results of two complementary low energy housing projects that have been monitored by the Open University Energy Research Group. Over the past nine years these have involved the design, monitoring and evaluation of nearly two hundred new houses.

The results have clearly shown the benefits of simple energy saving measures. The large-scale Pennyland field trial has demonstrated a halving of gas heating energy consumption, worth about £115/yr per house at 1984 prices for an estimated extra construction cost of £440, giving an overall payback time of under five years. A social survey showed that the measures were also well liked by the occupants.

The companion eight-house Linford project has allowed detailed study of the various measures involved:

Insulation to Danish BR77 standards,
Use of low thermal capacity gas boilers,
Airtight construction,
Direct gain passive solar design.

Detailed costings of the projects have also given a full breakdown of their relative cost-effectiveness.

INTRODUCTION

Milton Keynes is a new town of currently about 200 000 inhabitants, about 80 kilometres north of London. Initial construction work started in the early 1970s. This also coincided with the start of the Open University sited in the south of Milton Keynes.

The weather in Milton Keynes is typical of the central UK, with about 2200°C-degree-days to a base 15.5°C. Normally winters are dull and wet with only a little snow (though the winter of 1981/82 did contain some thoroughly arctic conditions). Summers are mild with peak temperatures rarely reaching 30°C.

Following the oil crisis of 1973, the large house construction programme in Milton Keynes seemed a golden opportunity to test out energy saving measures, especially since at the time 30% of UK energy consumption was used in heating houses. In 1975, a special liaison group was formed between the Open University and Milton Keynes Development Corporation (MKDC) to promote a number of schemes. At the time, one was already under way, the Bradville solar house fitted with 36 m² active solar panels [1]. Monitoring and analysis showed that although the solar system did save large amounts of energy, the same performance could be achieved at a fraction of the cost using energy conservation and simple passive solar design [2].

In 1977, after extensive discussions with architects and some computer modelling, a

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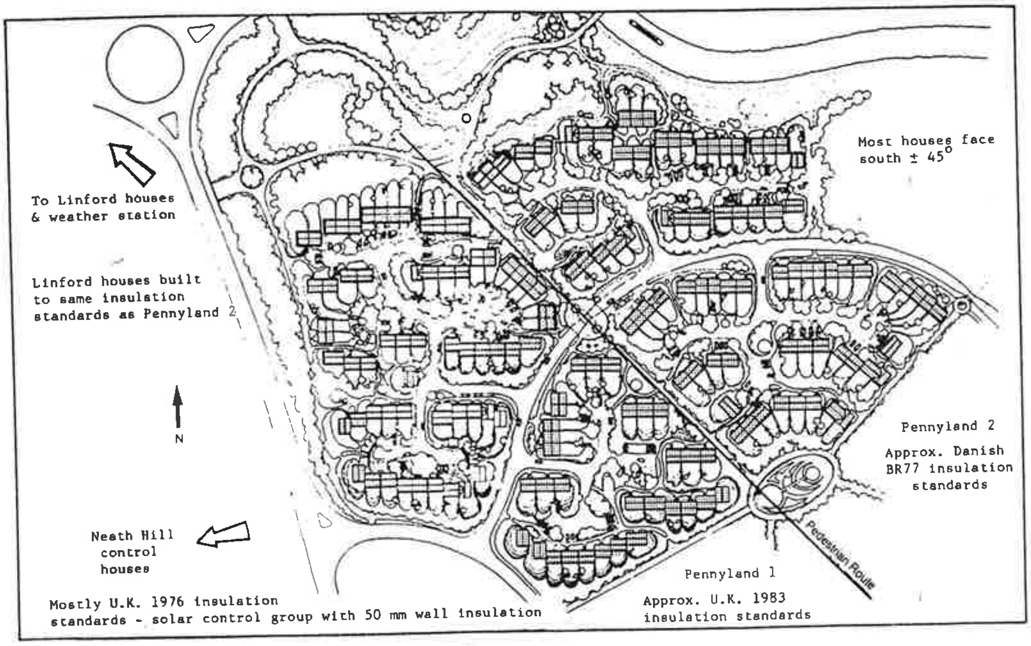

Figure 1
Pennyland estate layout avoids overshading.

design brief for the basic experimental houses was reached:

- Roof insulation approx 150 mm thickness.
- Wall insulation 100 mm thickness.
- Double glazing.
- 25 mm thick edge insulation to ground floor slab.
- Draught-stripping.
- Houses to face south within 45°.
- Houses must not be overshaded by others to the south.
- Windows concentrated as far as possible on the south side.
- Dense concrete internal construction to store solar gains.
- High efficiency low thermal capacity gas boilers.
- Efficient heating controls.

This basic list was then used for two housing schemes, the large scale Pennyland estate consisting of 177 terrace houses and the Linford scheme of eight larger detached houses.

Perhaps to readers in Scandinavia and Canada it will seem rather quaint that it should be necessary to test out insulation levels as poor as this, since these levels were made mandatory in 1979 in Denmark as standard BR77. However, insulation was only introduced into the UK housing regulations at all in 1975, only a few years before the beginning of these projects.

Given the practical problems of construction and experimental design, as well as considerations of house selling price, the projects soon multiplied into a bewildering array of house types and experimental comparisons. The Pennyland scheme was intended both to test out passive solar design for the UK Department of Energy (DEn) and also insulation levels for the Department of Environment (DoE). The Linford scheme has been primarily a passive solar one. In the event, most of the analysis work has been funded by the Science and Engineering Research Council (SERC).

The experimental considerations can basically be broken down into an insulation experiment and a solar one, with excursions into boiler efficiency and air infiltration. Readers who find this paper a little confusing should bear in mind that it is a digest of 1000 pages of project reports [3, 4, 5].

THE INSULATION EXPERIMENT

The Pennyland study followed on from the DoE's *Better Insulated House Programme* field trials. Due to cash limitations only a half of the estate (which we will call Pennyland 2) could be insulated up to the full standard, the remainder (Pennyland 1) being insulated approximately at a level which was to become the UK 1983 Building Regulation standards, i.e.:

- Roof insulation 80 mm (1983 standards 100 mm).
- Wall insulation 50 mm.
- Single glazing.
- No floor edge insulation.

The neighbouring estate in Neath Hill in particular acted as a control group, being built to the UK 1976 insulation standards:

- Roof insulation 50 mm.
- Unfilled cavity walls.
- Single glazing.
- No floor edge insulation.

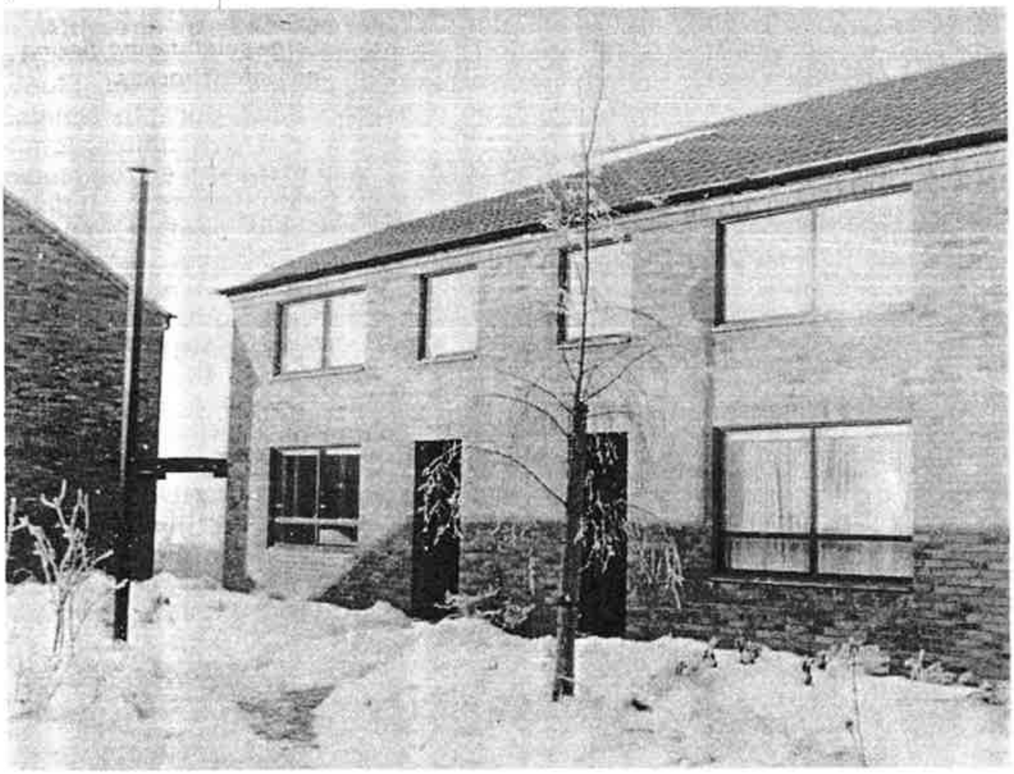

Figure 2
Shadow of roofline on a Pennyland house at 1400h on a January day.

THE SOLAR EXPERIMENT

Within the Pennyland estate, two different house shapes were used, a normal deep plan "dual aspect" type, with about two thirds of the glazing on the south side of the house, and a shallow plan "single aspect" type with more glazing on the south side. The Pennyland houses were laid out to avoid overshading and to face approximately south (see Figures 1 and 2). A "non-solar" control group was created on the Neath Hill estate of randomly oriented overshaded houses. They were given retrofit foam cavity wall insulation in an effort to bring them up to the Pennyland area 1 insulation standards. The fact that this group differed vastly in energy consumption from the Pennyland houses turned out to be one of the most interesting features of the whole project.

Finally, the Linford houses were of an identical single aspect design, with the full insulation level. They were similar in design to the Pennyland 2 single aspect houses, though with more floor area (110 m² instead of 90 m²), a larger amount of south-facing glazing and a small north-facing glazing area (see Figures 3 and 4).

CONSTRUCTION

Building work started on the Pennyland site in 1980. The houses were built by a large building contractor using a poured concrete technique. The inner skin was made of dense concrete cast in-situ, with fibreglass insulation batts (50 mm or 100 mm according to insulation level) outside, and finally a brick outer skin built up afterwards. The inner skin was sufficiently dense to act as a vapour barrier.

The Linford houses, built by a smaller local firm, followed using more conventional construction techniques. 100 mm fibreglass insulation batts were fitted between a dense concrete blockwork wall inner leaf and a brick outer skin.

Both schemes used the same type of double glazing using unframed sheets of 5 mm thick glass sliding in plastic tracks and surrounded by thick wooden frames. Roof insulation consisted of conventional rolls of fibreglass, 80 mm thickness for Pennyland 1 and 140 mm for Pennyland 2 and Linford. 25 mm thickness of edge insulation was built into the floor slabs of the Linford and Pennyland 2 houses.

The construction process was inspected by the Building Research Establishment who concluded that the extra insulation did not pose any extra building difficulties. The first Pennyland houses were completed in early 1981 and performance monitoring was started in October 1981. The Linford houses were not all completed until late 1981 and they were mainly monitored over the winter of 1982/83.

MONITORING

Pennyland. It was realized at the outset that previous British field trials had not produced clear answers on energy savings primarily

Figure 3
Large south-facing glazing on Linford houses.

because of the variability of energy use due to occupant behaviour. Spreads in annual energy consumptions of 3 to 1 or more are common in identical houses simply because different people have different life styles. To test whether house design saves energy it is necessary to compare large numbers of experimental and control houses, averaging out occupancy effects. Also the houses must all be built in the same place. Small micro-climate differences from even quite close sites can blur the final results. The large house construction programme in Milton Keynes thus provided a unequalled experimental opportunity.

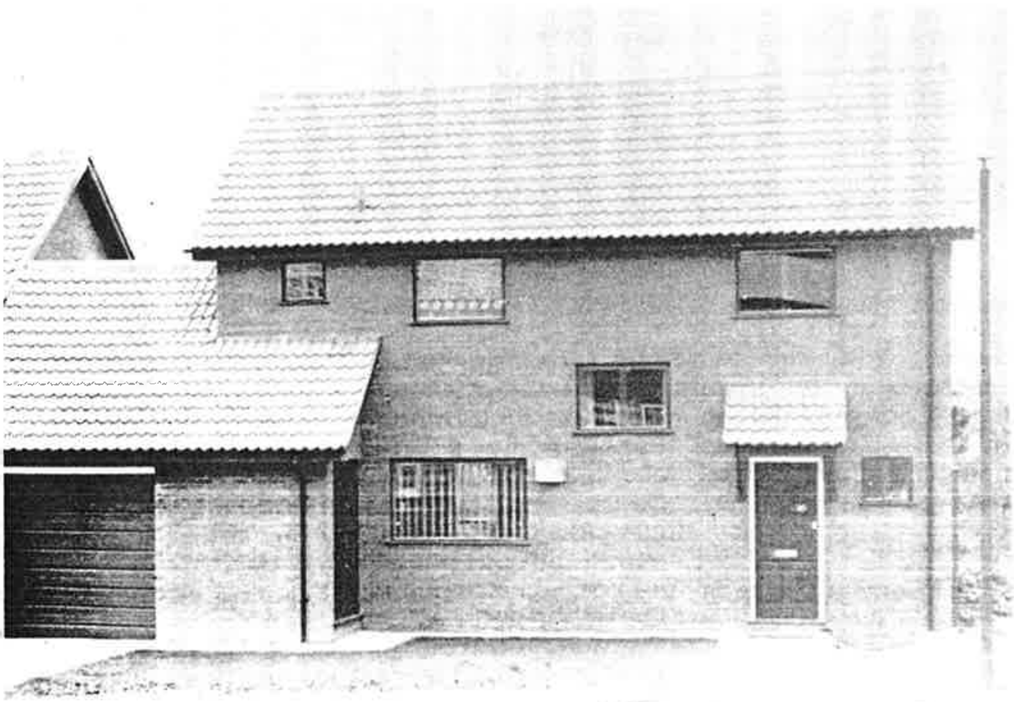

Figure 4
North facade of a Linford house.

Although it seemed that comparisons of experimental groups of 15–30 houses each would be sufficient to distinguish insulation savings of 2000–3000 kWh/yr, it was clear that simple comparisons of annual fuel consumption would not be adequate to quantify the likely solar savings, then estimated to be about 500–1000 kWh/yr. Instead the approach was to try to correlate weekly space heating energy consumption, measured with a heat meter in the central heating system, with whole house inside-outside temperature difference, measured with a special house temperature meter, and with incident solar radiation, as measured at the Linford weather station. The more "solar" the house design, the more incident solar radiation should affect the weekly space heating consumption.

Temperatures in 60 Pennyland houses and 19 Neath Hill houses were measured using a specially developed "Differential Temperature Integrator" designed and built at the Open University. This device sampled three internal temperatures, living room, kitchen and a bedroom, and also the external air temperature. It then subtracted the external temperature from each of the internal temperatures and clocked up three cumulative "degree-day" totals, one for each zone. These could be read, along with the space heating and gas and electricity meters on readouts located in the external meter cupboards of each house. This "low-tech" method of data gathering worked quite well, even if it did require a long-suffering and weatherproof meter reader.

Weather data was measured at a station in the garden of one of the nearby Linford houses. Working back from recorded external air temperatures allowed Pennyland weekly average internal temperatures to be calculated for more routine assessments.

In addition to space heating consumption, water heating energy consumption was

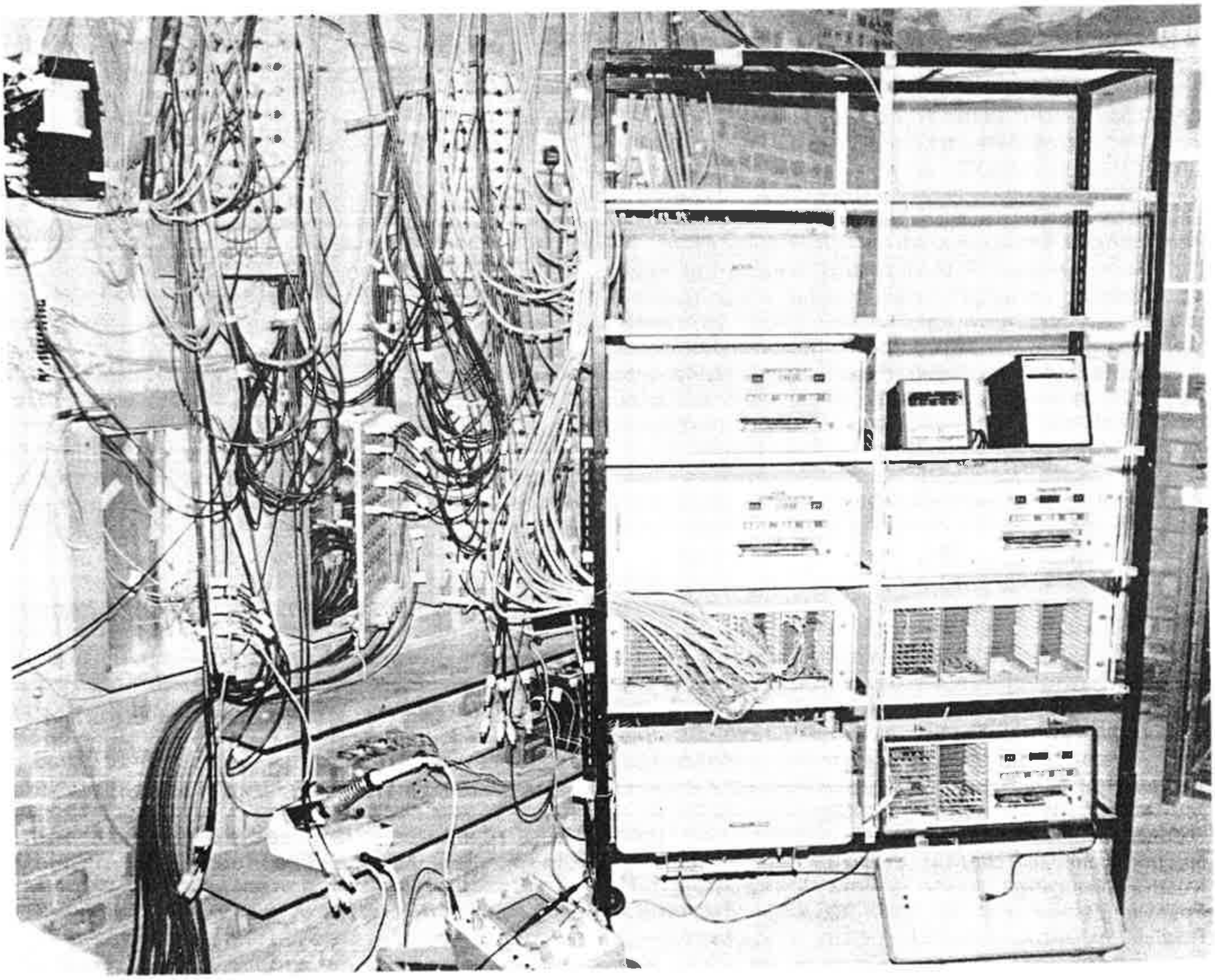

Figure 5 Data-logging equipment in the Linford test house garage.

measured in some of the Pennyland and Neath Hill houses. This, when taken with measurements of gas input to the boiler allowed boiler efficiencies to be worked out.

In order to complete the house energy balance pictures, cooking gas was also measured on a weekly basis in a large number of houses.

As well as physical measurements a social survey of residents' attitudes was carried out by MKDC and compared with results from other estates.

Linford. Seven of the Linford houses were occupied and the eighth used as a test house for controlled experiments. The monitoring level was much more intensive. Temperatures were measured in every room. Space and water heating, cooking gas, boiler gas and electricity were all measured on a 15-minute timescale. Micro-switches were installed on all windows to monitor window opening. In the test house, heat flux sensors were installed in the roof, walls and floor.

Data was recorded on five dataloggers in the test house garage (Figure 5). The magnetic tape cartridges were taken to be read into a computer at the university every week. The project generated 40 megabytes of data and the creation of a computer database system and "cleaning" the data (sorting out the 40 kilobytes of sensor, recording and human errors) were major tasks.

The main aim of the Linford monitoring was to quantify energy flows within the house. However, it also provided very valuable descriptive information about how the houses and their heating systems were used. Generally while the Pennyland experiment has *demonstrated* energy savings, the Linford houses have *explained* them.

The test house was used for detailed experiments in solar absorption. The house was heated by five thermostatically controlled electric fan heaters and carefully maintained at a constant internal temperature. This made the substitution of solar gains for electric heating clearly visible (see Figure 6). A large amount of work went into developing a statistical method for quantifying solar gains by correlating daily total heating consumptions with daily incident solar radiation.

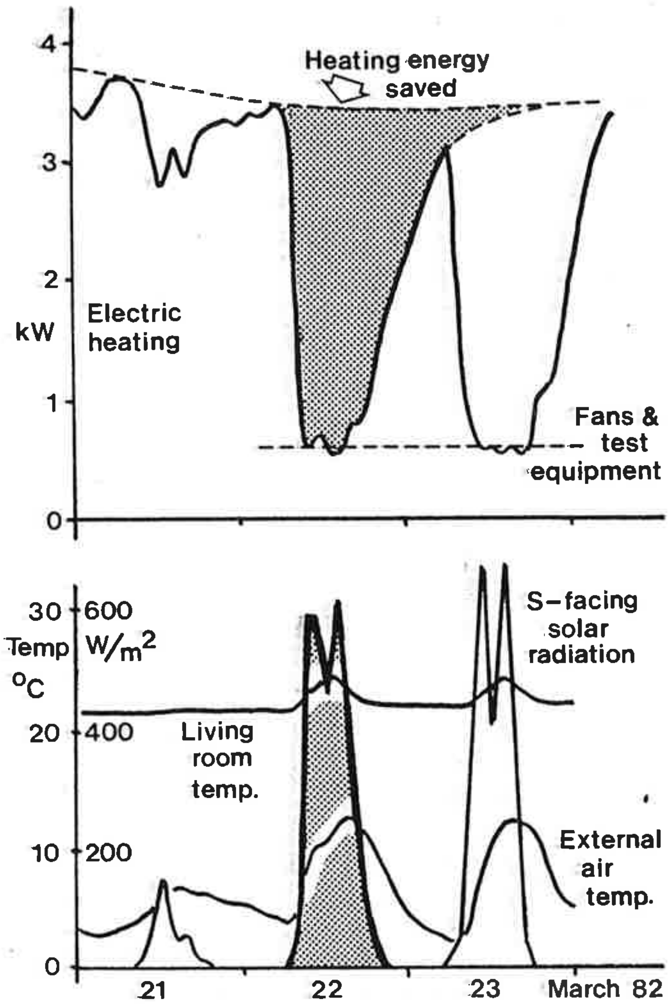

Figure 6 Carefully controlled heating in the test house made solar gains clearly visible.

The test house also contained an air infiltration rig capable of automatically recording the whole house air change rate for long periods of time.

Table 1
A comparison of gas and electricity consumption. (October 1981–September 1982)

	No. of houses	DELIVERED ENERGY Gas kWh/yr	Gas £/yr*	Electricity kWh/yr	Electricity £/yr
MK 4-estate sample (75/76 data)	150	22172	253	2416	121
Neath Hill uninsulated	18	23400	267	Not measured	
Neath Hill insulated	14	22480	256	3086	154
Pennyland 1	33	14010	160	2856	143
Pennyland 2	15	11530	131	2598	148

* Spring 1984 prices.

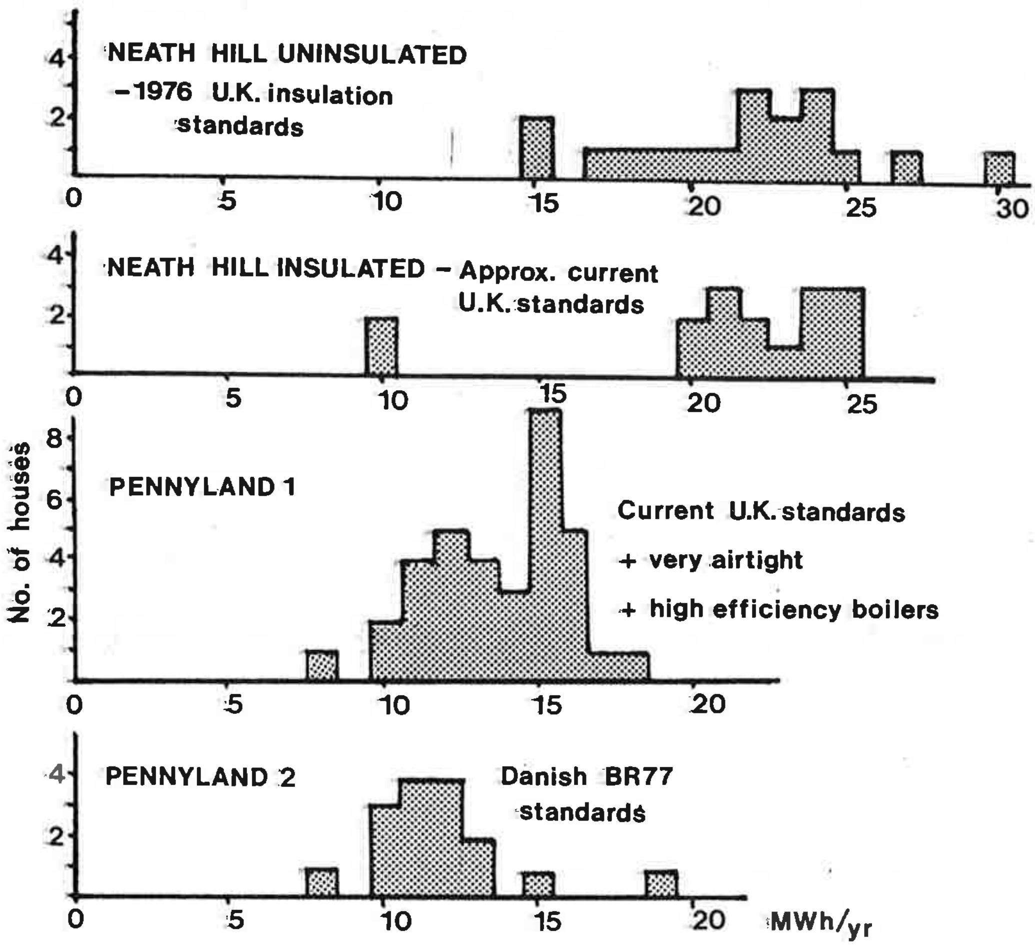

Figure 7
Histograms of annual gas consumption of the four main insulation groups (October 1981–September 1982).

RESULTS

Pennyland Comparisons. The clearest demonstration of energy savings is shown in Figure 7, illustrating the spread of annual gas consumptions for similar sized houses in the four main Pennyland and Neath Hill insulation groups. The averages are also given in Table 1.

This clearly shows a halving of annual gas consumption, bringing heating costs below those for electricity for lighting and appliances (the differences in electricity consumption are not statistically significant). Although the graph also illustrates problem of different occupancy patterns, there are obviously enough houses to produce convincing answers.

Data from the houses with detailed monitoring equipment has been analysed to correct for minor differences in internal temperature, number of occupants and within-group differences in heat loss (some houses are centre-terrace, others end-of-terrace) in order to bring out the energy differences between different house designs. This had allowed some apportioning of the savings to the different measures involved.

In addition to calculating energy savings by direct comparison of house groups, the design computer model (a cut-down version of the American NBSLD response factor model) was updated, mainly from detailed test data from the Linford project. It allowed a very detailed disaggregation of the energy savings, step by step, and together with detailed costings, payback times for each one. It also served as a useful "go-between" for the various sets of experimental data.

Occupant Satisfaction. The internal temperatures in all the houses measured, Neath Hill, Pennyland and Linford were high, averaging 17–20°C over the winter. These are amongst the highest recorded in UK post-war field trials.

The social survey showed good satisfaction. 81% of the Pennyland residents said that they could keep their house warm enough, compared to only 51% in a wider Milton Keynes survey. This was all the more encouraging since the winter of 1981/82 prior to the social survey contained some of the coldest weather in Britain this century, with a minimum temperature of −17°C measured at Linford. More important only

3% of Pennyland residents said they could not *afford* to keep their house warm enough, compared to 28% in a wider Milton Keynes survey.

LINFORD AND PENNYLAND DETAILED RESULTS

Insulation. The energy comparisons of the two halves of the Pennyland estate suggest that adopting the Danish BR77 insulation standards will save each year between 5 and 6.8 GJ (1400 and 1900 kWh) of useful space heating energy for a typical 3-bedroom house. Computed estimates were slightly higher.

Spot measurements on wall and roof heat losses were carried out in the Linford test house, indicating a wall U-value of about 0.3 W/m²K and a roof U-value of about 0.2 W/m²K, as expected. The roof insulation could have been installed better and future houses should really have two layers of loft insulation, one between the joists and another at right angles over the top covering them. The total heat loss of the test house was also measured and was found to be as expected with one important exception, that of the floor heat loss. This was also borne out by thorough inspection with an infra-red camera.

Floor Heat Loss. Heat flow measurements in the floor of the Linford test house showed losses about double that expected. The floor slab was provided with 25 mm thickness of edge insulation tucked in under the slab and extending 1 m in from the perimeter. Infra-red camera observation showed large heat flows out from the building around the foundations. These were also visible on some of the Pennyland houses. There did not appear to be any particular fault with the insulation, rather there simply wasn't enough of it to cope with conduction through the damp clay soil. Research into the subject of floor heat loss showed up a thorough lack of information. There appeared to be only one other set of actual measured data, and design information rested firmly on computer modelling carried out in 1950! There is a serious need for further research in this area and given the project results, it is probably wise to insulate completely under a building with at least 50 mm thickness.

Boiler Efficiency and Controls. One of the surprises of the Pennyland experiment was just how much effect improved gas boiler efficiency could make. The Pennyland Area 1 houses used 50% less gas than their insulated counterparts in the Neath Hill estate, despite almost identical insulation standards.

The Neath Hill houses had been equipped with a conventional gas boiler with a heavy cast-iron heat exchanger. The Pennyland houses used a Chaffoteaux low thermal capacity boiler with a lightweight heat exchanger and a balanced flue construction. The Linford houses had a similar, but larger model. Analysis showed that the heavyweight type had almost twice the "standing losses" (pilot flame and some cycling losses) of the lightweight type.

The fuel bill savings due to the improved boiler efficiency at Pennyland amount to about £35/yr per house, and for no extra capital cost. The Pennyland boilers had maximum efficiencies of around 83%, although average seasonal efficiencies were below 70%. Maximum efficiencies for the Neath Hill type were only about 73%. Even these boilers should now be considered obsolete, as new designs of condensing gas boilers are being introduced, with peak efficiencies that could reach 95%.

The wet radiator heating systems seemed popular, over 80% of Pennyland residents being more satisfied than with the heating system in their previous home. No instructions were issued on the heating controls, but 70% said that they used their time clock, and only 13% said they didn't understand it. The elderly in particular needed instruction in its use.

Some houses were fitted with warm air heating systems. These were not as popular and although they weren't monitored in detail, the occupants didn't feel they were making energy savings.

Airtightness. Airtight construction of houses is a mixed blessing. On the one hand it cuts heat losses, reduces internal draughts and increases comfort. On the other, low air change rates mean increased condensation and mould growth.

The Linford and Pennyland houses turned out to be surprisingly airtight. Fan pressurization tests were carried out by British Gas and actual air infiltration rate measurements were made over long periods in the Linford test house.

The Linford houses showed air leakages of 50 Pa pressure of about 8 air changes/h and sample Pennyland ones only 6 air changes/h. The Neath Hill control houses were closer to 14 air changes/h, probably a fairly typical figure for current UK houses. These figures correspond to seasonal average air change rates of around 0.3 air changes/h for Pennyland, 0.4 air changes/h for Linford and 0.7 air changes/h for Neath Hill.

Since the Linford houses used fairly standard construction techniques, the low air change rates are probably due to good attention to building detail and draught-stripping. The Pennyland houses had the additional benefit of a poured concrete bunker construction, leaving few gaps in the walls for air to leak through.

The low air change rates may have also produced increased comfort. Despite the high internal temperatures measured in the Neath Hill houses, only 40% of occupants felt that they could keep their houses warm enough compared to 81% in Pennyland.

The reverse side of the coin was also shown up in the social survey. Inhabitants of both the Pennyland and Neath Hill control houses were asked whether they had condensation or mould growth. Equal percentages in each estate (about two-thirds) said they had condensation, but a half of the Pennyland residents said they had some mould growth, as opposed to only 15% in Neath Hill. The mould was where it might be expected, in bathrooms and toilets, and only occurred in the midwinter period.

The Linford houses had micro-switches fitted to the windows allowing some assessment of when they were opened. Curiously, the windows needed open to stop condensation (kitchen, WCs and bathroom) were precisely the ones that weren't opened. Obviously future house designs must be both well sealed and contain purpose-built ventilation to these rooms.

The extensive measurements of air infiltration rates in the Linford test house tied up well with a theoretical model and suggested that modest energy savings could be made by aligning terraces SW–NE rather than broadside on to the prevailing south-westerly winds.

Direct Gain Passive Solar Design. No area of these projects has received more study than the quantification of the passive solar contribution and its separation from insulation savings. All houses are to a certain extent heated by *absolute* solar gain. What we are really concerned with is the *marginal* passive solar gain – how much less heating energy a solar house uses than a non solar one. Given the rather small proportion of the final total savings attributable to these *marginal* passive solar gains, the amount of attention paid to them may seem a little curious.

In the UK, passive solar design is seen, like active solar, as "alternative energy generation". It is the province of the Department of Energy along with wind and wave power. Insulation, however is "energy conservation" and is largely the responsibility of the Department of Environment. The large energy savings shown in these projects and their detailed breakdown has largely occurred as a by-product of the detailed quantification of solar gains funded by the Department of Energy.

In the Pennyland field trial strenuous efforts were made to disaggregate the effects of insulation and passive solar design by comparing fuel bills of the various solar and insulation house variants and by correlating weekly fuel consumptions with solar radiation and temperature to assess which houses absorbed most solar radiation.

In the Linford test house controlled experiments were carried out to assess the amount of solar radiation absorbed under different conditions, varying degrees of window obstruction and with and without insulation over the concrete floor slab.

Absolute passive solar gains are not easy to work out. They are essentially a *negative* quantity, heating energy that has *not* been used. They can only be accurately worked out when *all* the other heat flows in the house have been measured. This requires a lot of measurement. In the Linford test house it required near continuous measurement of air infiltration rates and considerable infiltration modelling to fill in the gaps when the measuring rig wasn't working.

A correlation technique was developed to measure the response to solar radiation of the house in terms of a south-facing "solar aperture". Using a daily average energy balance equation ("days" being taken from dawn to dawn):

$$Q = (\Sigma U.A + C_v).\Delta T + F - R.S$$

where Q = Daily total electric space heating
$\Sigma U.A$ = House total fabric heat loss (excluding floor)
C_v = Air infiltration rate
ΔT = House inside-outside temperature difference
F = Floor heat loss
R = Solar Aperture or "Recuperation factor"
S = Daily total solar radiation on south-facing vertical surface.

This can be rearranged:

$$(Q - F)/\Delta T - C_v = \Sigma U.A - R.S/\Delta T$$

It can then be drawn as a graph whose y-intercept is the house fabric heat loss and slope is the solar aperture (Figure 8). Different

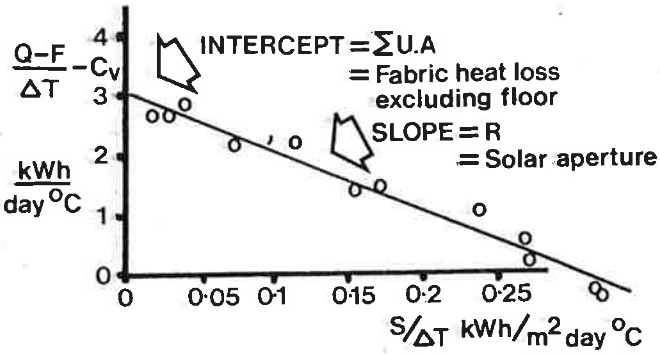

Figure 8 House thermal calibration plot (Linford test house data).

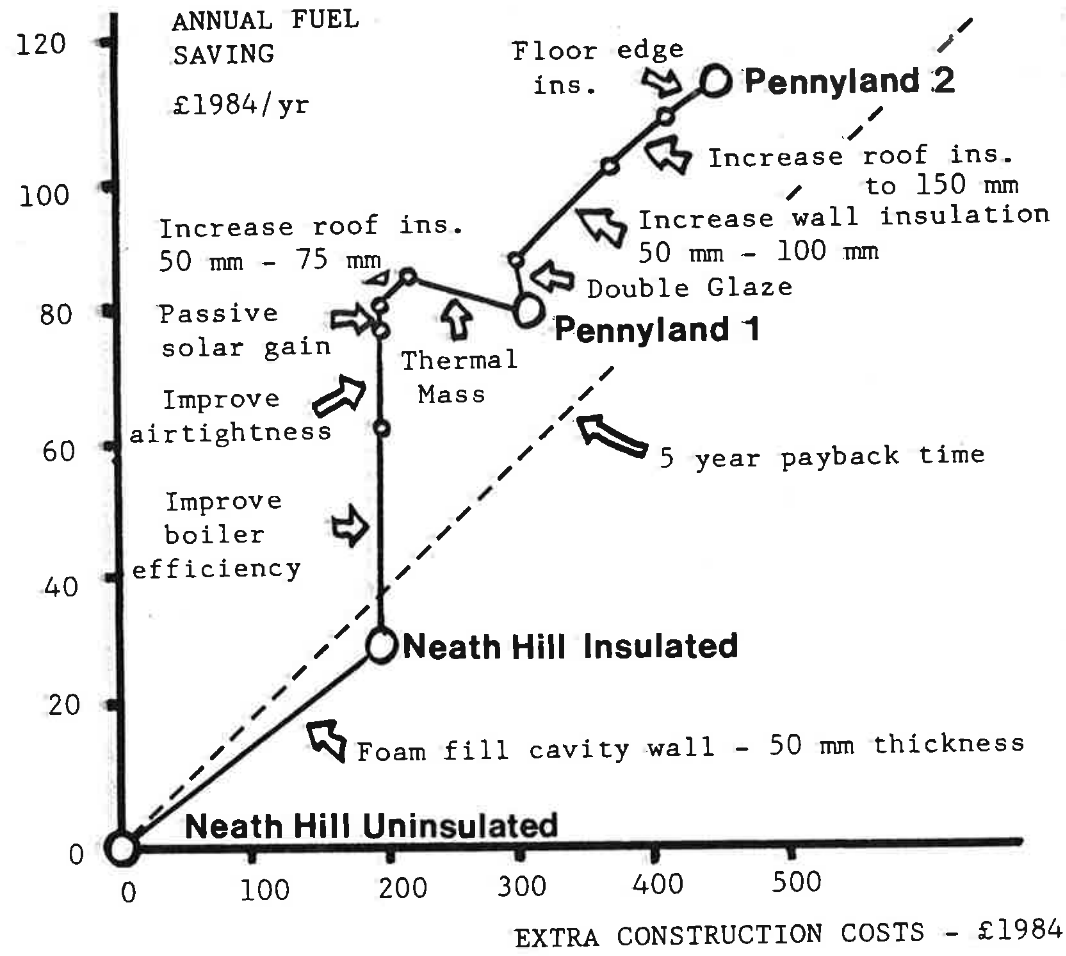

Figure 9
Post-project computed energy savings breakdown.

variations on this theme were used for the Linford and Pennyland occupied houses.

Generally, the mechanics of direct gain passive solar heating have been a bit disappointing. The solar absorption of the Linford test houses with clear windows was about 25% less than initially expected. The full reasons for this are not yet clear, but test cell measurements suggest that 10% of the discrepancy is due to the relatively light painted interiors of most houses.

Curiously, one of the tenets of passive design that the floor slab is important in storing solar heat, appeared to be untrue. Very little of the incident solar radiation on the floor actually penetrated into the concrete. Most was simply turned into hot air at the surface.

Another finding has been that the main mechanism of direct gain solar heating is by instantaneous substitution of solar heat for the auxiliary heating system. Some energy is stored in the house interior and carried over to the evening, but little is carried into the next day. This means that a passive solar house must have a highly responsive heating system.

More important to passive solar performance have been questions of privacy. Large south-facing windows may give unimpeded access for the sun, but they also give unimpeded access to the prying eyes of the neighbours. The occupants respond with barriers of curtains. In the Linford houses, which were not overlooked from the south, about a half of the south-facing windows were not obstructed. On the Pennyland estate, virtually all south-facing windows had some kind of obstruction, mostly white net curtains, but many with half-drawn blinds, shutters and curtains.

The Linford test house experiments showed that white net curtains reduced the solar absorption of the windows by about 20%, without providing any detectable insulation effect.

The most important information on passive solar design has come from the detailed costings of the houses. One vital fact is that windows (especially double glazed ones) are very expensive, at least £100/m². This makes them at least £60/m² more expensive than insulated wall. Given that a south-facing window has a very similar winter energy balance to insulated wall, this extra cost is difficult to justify. There seems no real cost-effective reason for incorporating larger windows than necessary in a building. The choice of window size is largely aesthetic.

The extra thermal mass of a text-book passive solar design can also be expensive. The dense concrete blockwork used in the Linford houses was 50p/m² more expensive than normal lightweight blockwork, not to buy, but because the builders charged more to erect it. Dense blockwork should not be used in the inner leaves of external walls since its higher thermal conductivity increases heat losses. Indeed, given the modest glazing areas on the Pennyland houses, the thermal mass appeared unnecessary. Measured peak summer temperatures in the best insulated and most solar Pennyland houses were only 1°C higher than in the Neath Hill houses built with conventional lightweight concrete interiors.

Finally, when building terraces of houses, such as at Pennyland, shallow, wide houses capable of having most of the glazing on the south side have more external surface area (and heat loss) than narrow-fronted deep-plan houses. Consequently they are more expensive to build. There is little hope that the calculated passive solar energy savings can overcome these extra costs.

The best that can be said for direct gain passive solar design is that avoiding overshading, facing houses south (within about 45°) and concentrating normal amounts of glazing on the south side can save modest amounts of useful energy (around 1.1 MJ/year (300 kWh/year) for the small Pennyland houses, and around 3.6 MJ/year (1000 kWh/year) for the larger Linford ones). Excessive glazing areas simply increase construction costs, create privacy problems and promote summer overheating, requiring expensive extra thermal mass. Solar houses are, not surprisingly, warmer than non-solar ones on sunny days. Whether this can be deemed "useful" or not is a matter for debate. If this extra temperature were 100% useful and had to be paid for with conventional heating, it would raise the estimated passive solar savings by about 50%.

Popularity. It must be said that the passive solar features were popular. When Pennyland residents were asked what features they liked most about their houses, the seven top items were related to the appearance and layout of the houses and the low fuel bills. The concern with appearance is no doubt influenced by the proximity of other estates suffering the full ravages of "modern" architecture, to which

Table 2
Post-project computed energy savings.

	Delivered Energy Saving kWh/yr	£/yr	Net Extra Cost £	Payback Time years
NEATH HILL UNINSULATED				
50 mm wall insulation	2642	30.1	198	6.6
NEATH HILL INSULATED				
Improved boiler	2862	32.6	0	0
Reduced ventilation rate	1319	15.0	0	0
Passive solar gains*	283	3.2	0	0
Roof insulation 50 mm–75 mm	485	5.5	20	3.6
Thermal mass	−695	−6.1	93	Inf.
PENNYLAND 1				
Double glazing	729	8.3	−13	0
Insulation				
Wall 50 mm–100 mm	1351	15.4	68	4.4
Roof 75 mm–150 mm	661	7.5	40	5.3
Floor	348	4.0	34	8.5
PENNYLAND 2				
OVERALL				
Neath Hill uninsulated to PENNYLAND 2	10016	114.2	440	3.9
PENNYLAND 1 to 2	3120	35.2	129	3.7

* Solar gains due to avoiding overshading, correct orientation, and concentrating two-thirds of glazing on south side of a deep plan house.

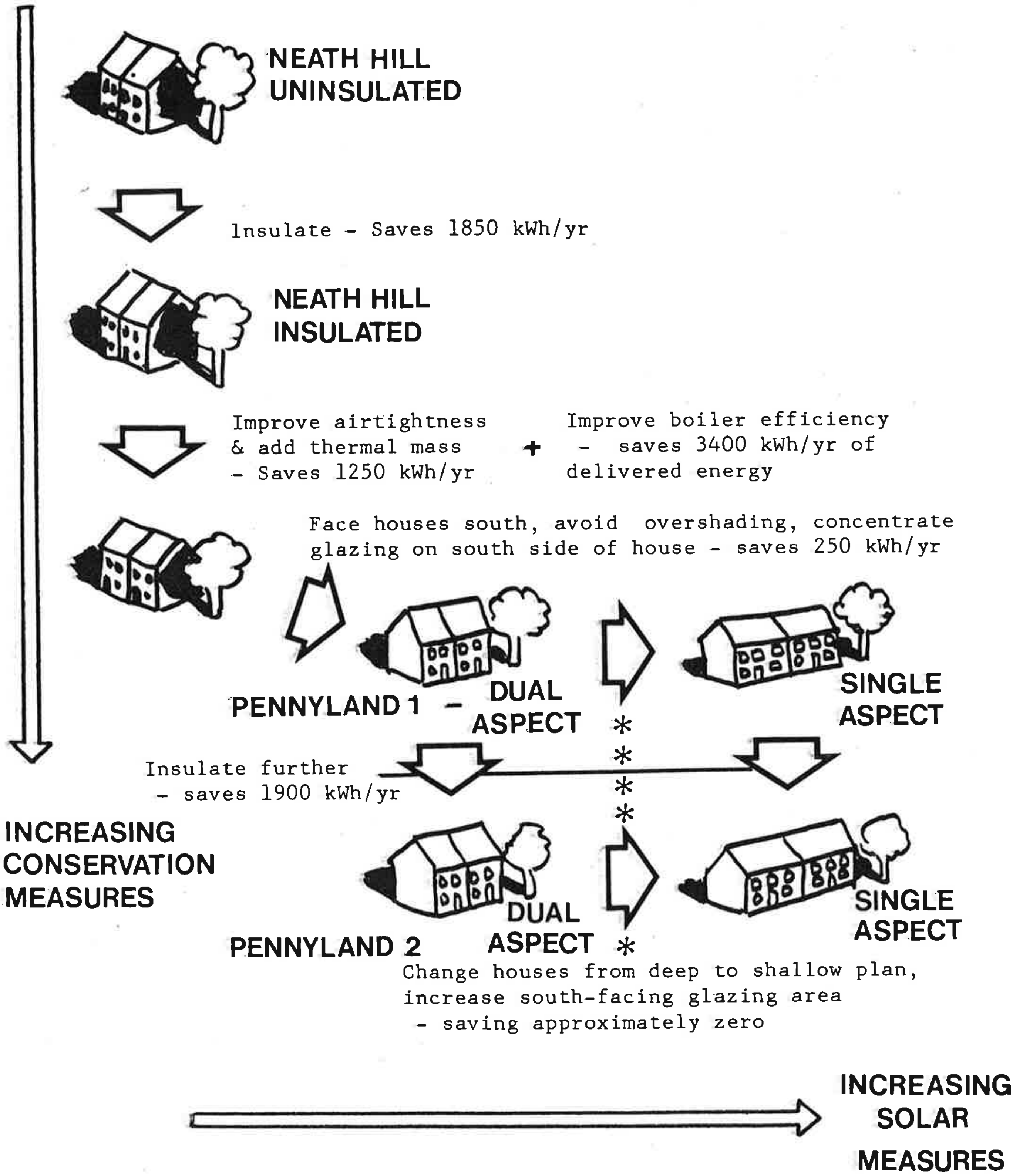

Figure 10 Summary of useful energy savings from measurements (*may differ slightly from computed results in Table 2*).

Neath Hill and Pennyland are clearly "post-modern" light relief. The least popular features were security from burglary (also related to window design and privacy) and car parking (related to estate layout).

The gardens on the south side are ideal for passive solar expansion and to date the occupants of two Pennyland houses have added conservatories and another, a very large glazed patio door.

COST-EFFECTIVENESS

Another important study was the detailed costing of the various measures. This was done at the end of the project as if the houses were to be built using normal construction methods (i.e., as Linford). The results were very encouraging, with insulation costs being much smaller than originally estimated. Figure 9 shows a plot of post-project computed energy savings against extra construction cost (net of savings due to a smaller heating system) for a Pennyland type 3-bedroom deep plan end-of-terrace house. The steeper the slope, the more cost-effective. The individual payback times are also given in Table 2 below.

Some features have zero payback time. The high efficiency boilers save energy without extra capital cost. The frameless double glazing was estimated to be no more expensive than normal single glazing. Since it allowed some reductions in heating system size it actually *reduced* total capital costs.

With the exception of the extra thermal mass, all the measures are cost-effective. It seems likely that a further increase in wall insulation to 150 mm thickness would also be cost-effective.

CONCLUSIONS AND FUTURE PROJECTS

These two projects have shown that low energy houses can be built in the UK cheaply and without problems. Just as the previous "Better Insulated House Programme" led to the improved Building Regulation insulation standards of 1983, it is to be hoped that the Pennyland 2/Linford levels will be made mandatory in the near future (1987 seems to be the favourite date).

The projects have also shown that fabric U-values alone do not make a low-energy house. What is needed is a full "integrated low energy house design" approach that attempts to minimize the heating cost to the consumer. This requires taking heating system efficiency and fuel type, airtightness and passive solar features all into account (see Figure 10).

This approach has been applied in the new Milton Keynes Energy Park project. Here developers have been invited to submit house designs, which must first pass a computer appraisal to make sure that they are at least as good as the Pennyland and Linford houses. There is still plenty of scope to cut the fuel bills further, with thicker insulation, higher efficiency heating such as off-peak electric heat pumps, or combined heat and power generation.

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