

The SALFORD House—Cost-Effective Integrated Design of Thermal Envelope and Mass

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ABSTRACT

The SALFORD house project was undertaken to resolve the combined problems of condensation, thermal discomfort, and high heating costs experienced in "traditional" dwellings owned by Salford City Council in northwest England, which has a temperate climate with damp, cool winters. Houses were built at an economical cost to a new low-energy design that incorporates a large thermal storage capacity contained within a highly insulated envelope. Both insulation and mass are about four times the normal, giving a long thermal time constant of days rather than hours. All internal surfaces stay warm, condensation is no longer a problem, and comfort is considerably increased. Space-heating energy use is about a third of that for equivalent houses built to current U.K. Building Regulations. The design is inherently resistant to rot, fire, noise transmission, and vandalism, is applicable to most dwellings in temperate climates, and could be adapted to an extended climatic range.

INTRODUCTION

Salford City Council owns some 40,000 tenanted dwellings. A significant number of these, of various ages and of typical, poorly insulated U.K. designs, suffered from the related problems of condensation and mold growth, principally on the inner surfaces of external walls. The steep rise in fuel costs over the past two decades has exacerbated the problem, particularly for low-income families unable to afford to heat their homes adequately. There was an urgent need for new, more suitable house designs with a much lower space-heating requirement that were also resistant to condensation and subsequent decay. The City Council approached the local university to jointly design a new low-energy dwelling that would solve the above problems.

Design Specifications

In addition to their immediate problems, the City Council was concerned with long-term economic, social, and environmental aspects and required the new house design to meet the following specifications:

1. The initial capital cost of the dwelling should be no more than that of a standard dwelling of similar size.
2. It must be built using standard construction methods and materials.
3. The houses must place no limitations on the normal living patterns of the tenants.
4. Energy consumption should be substantially lower than that of existing housing.
5. Maintenance costs should be no higher than those of existing housing.
6. The dwelling should be flexible concerning the type of fuel and heating appliances used.

BACKGROUND TO UK HOUSING

The U.K. Climate

The climate of the United Kingdom is temperate, with generally warm summers and cool, damp winters. Although moderately hot and cold spells do occur, it is unusual for them to last for more than a few days. In the northwest of England, where Salford is situated, the average number of days annually where the mean nighttime temperature stays below freezing is 16. Only once per year on average does this drop below -5°C . In summer the temperature does not often rise much above 25°C for more than a few days and to reach 30°C is exceptional. Precipitation is in the region of 1,000 mm per year falling year-round. An important feature of the climate is extended periods of dampness in winter that are conducive to mold growth on inside wall surfaces and to rot in timbers.

"Traditional" U.K. House Design

A multiplicity of regionally variant house designs has been used in the U.K. throughout time. Common features over recent decades have been tiled pitched roofs and load-bearing external walls with an outer skin of brick, a 50-mm cavity to prevent direct water penetration, and a lightweight aerated concrete block inner leaf that provides some degree of low-cost insulation. Over the past twenty years, government has, through the U.K. Building Regulations, attempted to increase, incrementally, the thermal efficiency of new designs by limiting the maximum per-

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mitted thermal transmittance. Since 1976, when the thermal regulations were first introduced, maximum U-values for external walls and roofs have been reduced from 1.0 and $0.6 \text{ Wm}^{-2}\text{K}^{-1}$, respectively, through 0.6 and $0.35 \text{ Wm}^{-2}\text{K}^{-1}$ in 1982 to the current 0.45 and $0.25 \text{ Wm}^{-2}\text{K}^{-1}$ introduced in 1990.

Internally, ground floors are often of concrete, uninsulated, and built directly on the ground, separated only by a damp-proof membrane. Upper floors are usually of timber construction, with floorboards on wooden joists. The fenestration is generally single-glazed, although double-glazing is becoming more common. There is no specific requirement for double-glazing in the 1990 Building Regulations.

UK Timber-framed Design

In the past decade, a significant proportion of new housing has been built using a timber-frame structure as the inner leaf of the external wall. This lightweight inner leaf is made of plasterboard, glass-fiber insulation, plywood board, and a damp-proof membrane. The outer leaf of the external wall is usually of brick, making the houses visually indistinguishable from a traditional design. The advantage of this method of construction is that, with no mortar and plaster involved in the inner leaf, drying-out time is virtually eliminated, which, with partial prefabrication, allows for faster construction. In addition, they may be less expensive to build and often have better thermal insulation than traditional designs. In the U.K. the use of timber for external cladding is unusual except for small decorative panels.

Heating Methods

In general in the U.K. there are two methods of space heating. One is a hydronic system using natural gas as the primary fuel or sometimes fuel oil. Hot water, produced by a boiler, is pumped around two parallel circuits. One heats the domestic hot water indirectly via a heat-exchanger in a calorifier where it is stored, and the other is a two-pipe ring to which pressed-steel panel radiators, usually located on external walls and under windows to compensate for fabric losses and cold downdrafts, are connected. The controls are simple, typically an on-off boiler programmer and a single room thermostat located in the main living room or hall. This form of heating is found in some 70% of dwellings. The second method uses "off-peak" electricity. The domestic hot water is produced using an electric immersion heater in a calorifier, and the rooms are heated independently using electric "storage" heaters. These insulated heaters, with a high thermal capacity core, are switched to be on overnight when there is a discount tariff for electricity but, because of their deliberately long thermal time constant, emit most of their heat during the daytime hours. The heaters have a manual override if required and can incorporate forced convection.

Local Authority Housing

Local authorities in the U.K. are charged with providing rental accommodations for the local populace who cannot afford to buy their own homes (legally, the involuntarily homeless). These generally include the most disadvantaged members of the community, including people who live on very limited budgets, for example, some old and single-parent families. The Housing Act implies that the Local Authority can be sued by the tenant if it does not provide housing suitable for the purpose. This can include dwellings with condensation problems or that are difficult to heat economically to acceptable levels, which can become a legal and financial burden on the authority.

THE SALFORD HOUSE

Design Philosophy

The objectives of the design were to substantially reduce heating costs and to eliminate condensation but allow flexibility in the choice of heating systems while using traditional materials and construction methods and keeping maintenance and construction costs within standard limits.

The principal heat losses in U.K. houses are via conductive transfer through the external fabric and via natural ventilation. Significant reductions in heat loss through the envelope can be achieved by increasing the insulation and in ventilation losses by improving the airtightness of the dwelling so that efficient control may be exercised.

The problem of mold growth is usually due to persistent dampness caused by condensation on the colder parts of the internal fabric or on areas with little or no air movement. It can largely be eliminated by careful, detailed design, by the avoidance of "cold bridging," by permanently increasing internal surface temperatures, and by increased ventilation—particularly by mechanical extraction of moist air from rooms such as kitchens and bathrooms. These latter two measures, if not accompanied by other changes, can result in unacceptably large increases in energy consumption.

The amount of heat energy stored in the fabric of a dwelling is determined by its temperature and its thermal capacity. The thermal capacity, coupled with the thermal transmittance, also determines the thermal time constant that governs the rate and extent to which the temperature inside a building changes with respect to varying heat input or external conditions. Well-insulated buildings of high thermal capacity are characterized by long time constants and thermal stability, whereas lightweight buildings have a fast response that, if not controlled, leads to large and rapid fluctuations of temperature. As the specific heats of most building materials are much the same, the thermal capacity of a dwelling is roughly proportional to the mass within the insulation. Thus timber-framed designs, with little mass

inside the insulation envelope, are of particularly low thermal capacity and have a fast thermal response.

The SALFORD design incorporates a very high mass within a highly insulated envelope, with reduced natural ventilation (Randell and Hoyle 1979). It is shown diagrammatically in Figure 1. The design has a low energy requirement, with a slow thermal response, which limits the large daily temperature fluctuations often associated with U.K. timber frame and, to a lesser extent, traditional designs.

Elements of the Design

Insulation A high standard of insulation, substantially above the U.K. Building Regulations, is included in the design. The lofts are insulated by 200 mm of blown fiber, giving a U-value of $0.15 \text{ W m}^{-2} \text{ K}^{-1}$. The walls are of a cavity construction, but with the cavity much wider than normal, being some 173 mm wide rather than the usual 50-100 mm and filled with high thermal resistance polyurethane granular insulation. The outer leaf is brick, and the inner leaf is dense concrete block plastered internally, leading to a U-value of $0.14 \text{ W m}^{-2} \text{ K}^{-1}$. Below the ground floor is a sealed cavity, 200 mm deep, extending to 300 mm at the perimeter, which may be filled with insulation, reducing heat transfer to the ground.

Thermal Capacity A very high thermal capacity is deliberately achieved by constructing the inner leaf of the external walls and the principal internal walls and the floors from dense concrete components. The floors are of suspended concrete beams with block infill finished with a 75 mm sand-cement screed, a total thickness of 215 mm, and the internal walls are built from 100-mm-thick dense concrete blocks. The total mass within the insulation envelope is some 40 tons for a two-bedroom house. This compares with about 10 tons for a recent traditionally built house and 2.5 tons for a U.K. timber-framed dwelling.

Fenestration The amount of glazing and the size and positioning of the windows are normal for a U.K. design. Proprietary dual-glazed sliding units with treated wooden casement frames are fitted. They are thermally efficient at an economical price. Each unit has a permanent trickle ventilation slot in the head and a drainage channel to the exterior.

Ventilation The construction method, combined with weather-stripping of the doors and windows, provides an airtightness well in excess of U.K. norms. Ventilation control is simple but effective, being achieved by a combination of the trickle vents in the windows and extract fans in the kitchen and bathroom. The extract fans can be run continuously at low speed and be linked to a heat recovery system, or they can be manually switched or controlled by a humidistat.

Heating Systems One of the main advantages of the highly insulated, high thermal capacity construction is the flexibility it provides in choice of heating system (Randell

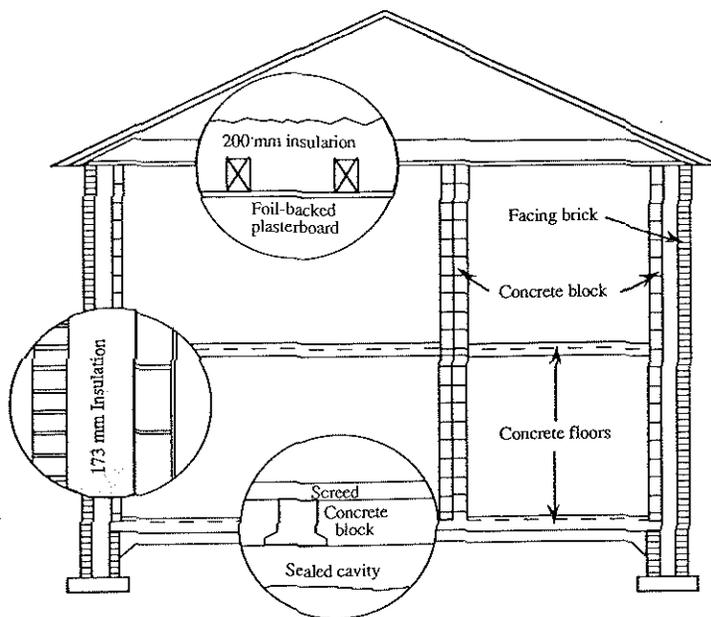


Figure 1 Section through a SALFORD house showing the high mass interior and insulated envelope.

1983). Lightweight buildings require fast-response heating systems, but heavyweight buildings can employ either fast or slow systems. The capacity of the new heavyweight design to absorb heat and to moderate fluctuations in internal temperature allows the use of either continuous low-grade heat or intermittent high-grade heating or a combination of the two. This has been demonstrated during the project by the large range of heating systems that have been used successfully to heat the dwellings, including systems as diverse as off-peak-tariff electric storage heat pumps supplying low-grade heat through embedded heating coils in the floors and by warmed air to gas convectors and individual solid-fuel room heaters. To minimize costs while giving occupants maximum control, heating in the latest houses is usually by one or two conveniently situated room-sealed gas convectors that can be thermostatically controlled or manually operated. Heat is dispersed to the rest of the house by convection and conduction.

Capital Cost Comparisons

Estimates of the capital cost of a SALFORD design house indicated that it should be closely comparable to that of a traditional house built to Salford City Council's standards. Bids for the construction of 22 houses to the new design—and also to a traditional design—were simultaneously invited. The bid ranges overlapped, but on average the bids for the new design were 7% above those for comparable traditional designs, with the lowest new design bid, which was the one accepted, 1% beneath the average bid for the traditional houses. It is thought that the difference between the two sets of bids is due to the contractors' unfamiliarity

with the design of the SALFORD house, and if there was major replication, the difference would decrease as experience was gained. The general opinion on material costs is that the overcost in extra insulation is balanced by the simpler, smaller, and less expensive heating systems that are needed.

PERFORMANCE MONITORING

Internal Conditions

The internal conditions of the dwellings were monitored over a period of 18 months as part of a government demonstration scheme (Webster 1987). Overall it was found that occupants were able to maintain adequate control of the temperature, humidity, and ventilation and expressed satisfaction with the internal environmental conditions in both cold and warm weather. Exceptional thermal stability and equable temperatures both day and night were a feature performance of the house.

Humidity Relative humidity was not continuously monitored, but regular inspection of the internal surfaces found no evidence of condensation, except on the window panes in extremely cold weather. The combination of having passive ventilators and mechanical extract in kitchens and bathrooms and being able to open the windows as desired enabled the occupants to control the internal environment adequately and economically.

Temperatures In winter the building performs as a high-capacity thermal store. The relatively high thermal conductivity of the dense concrete inner construction, enveloped by thick insulation, ensures that all the internal surfaces, including the inner surfaces of the outer walls, are at a similar and steady temperature. With warm internal walls, condensation and mold growth are no longer problems, and comfort is enhanced because of the higher overall radiant temperatures. Even in the coldest weather during the monitoring period, when external temperatures fell to -9°C , the lowest internal temperature recorded in rooms not directly heated was 14°C . In one test, with external temperatures averaging -1°C , internal temperatures dropped by just 2.5 K over 24 hours after the heating was switched off, demonstrating the performance characteristics of the massive, insulated, construction, which damps the fluctuations normally experienced due to the diurnal temperature cycle and intermittent heating.

In summer the major problem of low-energy housing of lightweight construction is daytime overheating from incidental and solar gains. The massive features of the SALFORD design obviate this problem. The insulation limits the solar gain transmitted through the walls and roof, and direct solar radiation through the fenestrated area is absorbed in the high thermal capacity of the internal structure. Cooling can be achieved simply by opening windows to increase ventilation rates.

Energy Consumptions

For a design day (20°C internal, -1°C external) the rate of heat loss of a typical three-bedroom SALFORD house is 2.25 kW. In the trials, constant comfort levels well above the U.K. norm for housing were achieved but with considerably lower energy consumptions. The average energy used to heat a two-bedroom SALFORD house was 10.6 GJ/year, some 37% of that required by a dwelling of similar size built to the current U.K. Building Regulations. Figure 2 compares the typical energy use of similarly sized dwellings built to recent U.K. Building Regulations.

Maintenance Costs

Costs-in-use for the dwellings were low. The buildings are made mostly from materials of nonorganic origin, brick, concrete, and blown fiber, and thus are inherently resistant to rot and damp. All external wood in the window frames is treated with a microporous stain and has a claimed design life of 40 years. Salford City Council is of the opinion, on presently accumulated evidence, that these dwellings should have a lower annual maintenance cost than their traditionally built dwellings.

Other Features

Features that are important to providers of mass housing for the underprivileged in society include fire, noise, and vandal resistance. The SALFORD dwellings have little timber or steel in their design and are thus more resistant to fire than traditional or timber-framed designs. Noise transmission is greatly reduced due to the massive construction, which also resists physical attack.

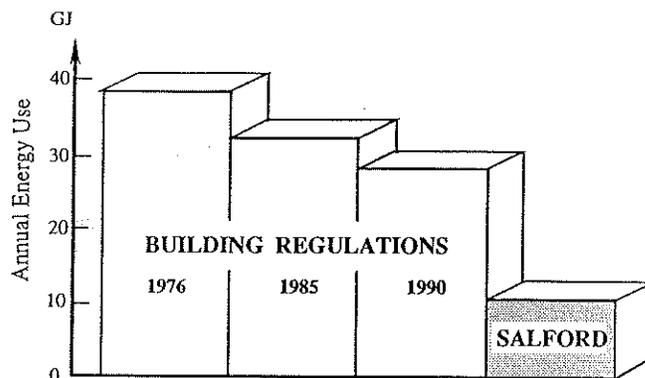


Figure 2 Average annual monitored energy use for a SALFORD house compared with calculated use for equivalent houses built to U.K. Building Regulations.

DISCUSSION

Thermal Response

Mathematical Analysis The steady-state transfer of heat by conduction to or from a dwelling can be calculated using the elemental method. This can be reduced to

$$q_c = -K_c \cdot \theta \quad (1)$$

where K_c is the total house conductance and θ is the difference between the inside and outside temperatures. The ventilation losses similarly can be expressed as

$$q_v = -K_v \cdot \theta \quad (2)$$

where K_v is the product of the ventilation air mass flow rate and its specific heat. Thus the total steady-state heat loss from a house, q , ignoring radiative components, is the sum of these two values,

$$q = q_c + q_v = -(K_c + K_v)\theta = -K\theta \quad (3)$$

where K is the total house transmittance.

In reality, the steady state is never achieved, as external temperatures vary with the diurnal and annual temperature cycles.

The basic physical relationship between heat loss and temperature change of an isothermal body over time is given by

$$q = M \cdot C \cdot d\theta/dt = W \cdot d\theta/dt. \quad (4)$$

For a well-insulated house, M would be the mass within the insulation envelope, C is the mean specific heat capacity of the building material, and their product, W , is the thermal capacity of the house.

Combining Equations 3 and 4 gives

$$d\theta/dt = -(K/W) \cdot \theta. \quad (5)$$

A finite difference between internal and external temperatures is maintained, even without space heating, due to incidental gains from the occupants, appliances, and solar radiation. This difference for traditional U.K. houses is typically 4.5 K, i.e., to maintain a design temperature of 20°C, space heating can be discontinued when the ambient external air temperature reaches 15.5°C. This temperature, T_B , is the "degree-day" base temperature used for comparisons in the U.K.

Thus, integrating Equation 5 and allowing for this factor, we have

$$T = (T_I - T_B + T_O) + (T_B - T_O) \cdot e^{-Kt/W} \quad (6)$$

where T is the internal temperature at time t after the heating system is turned off, and T_I and T_O are the initial internal and external temperatures.

The rate of heat loss can be redefined by combining Equations 4 and 6 giving

$$q = K(T_B - T_O) \cdot e^{-Kt/W} \quad (7)$$

or

$$q = K(T_B - T_O) \cdot e^{-t/t_T} \quad (8)$$

where t_T is the thermal time constant of the house, W/K. The thermal "half-life," t_H , being the time taken for a house to lose half its stored heat assuming a constant outside temperature, is related to the t_T by the equation

$$t_H = \ln 2 \cdot t_T = 0.693 t_T. \quad (9)$$

Application to U.K. House Types

The SALFORD house has distinct inner and outer structures separated by insulation and, as the density and thermal conductivity of dense concrete are both about 50 times that of the insulation, the different components of the exterior envelope can be regarded as being thermally distinct, so the equations derived are accurate enough for this construction. Effectively the heat is stored and dispersed in the concrete with only minimal losses to the outside due to the thermal resistance provided almost entirely by the insulation, which itself stores virtually no heat. The system behaves very simply, as the thermal analogue of a pure capacitance coupled through a pure resistance. In recent more typical U.K. constructions, the inner leaf of the outer wall is often of aerated block, which combines some insulation with some storage, or is timber-framed, for which the storage capacity is even less and there is no practical distinction between storage and insulation elements. In these two latter cases, the equations should be seen as being approximate at best.

Using the design parameters shown in Table 1, Figures 3 and 4 show the temperature and heat loss versus time curves for typical U.K. houses of the three types described above on a design-day in winter after the heating has been switched off. Lightweight houses store a small amount of heat and, therefore, irrespective of the insulation, heat up and cool down rapidly. In this type of dwelling, considerable energy savings can be made by intermittently operating the heating system, switching the system off, and allowing the house to cool when the house is unoccupied or at night. Even greater savings can be made in the traditional house where about four times as much heat is stored but the

TABLE 1
Thermal Parameters for
U.K. Two-Bedroom Housing Designs

	Traditional	Timber-Framed	SALFORD
Internal mass (tons)	10	2.5	40
Thermal capacity (MJ·K ⁻¹)	10	2.5	40
Design-day heat loss (kW)	8	4	2
Degree-day base (°C)	15.5	14	11.5
Total transmittance (W·K ⁻¹)	485	267	167
Thermal time constant (hours)	5.7	2.6	66
Thermal half-life (hours)	4.0	1.8	46

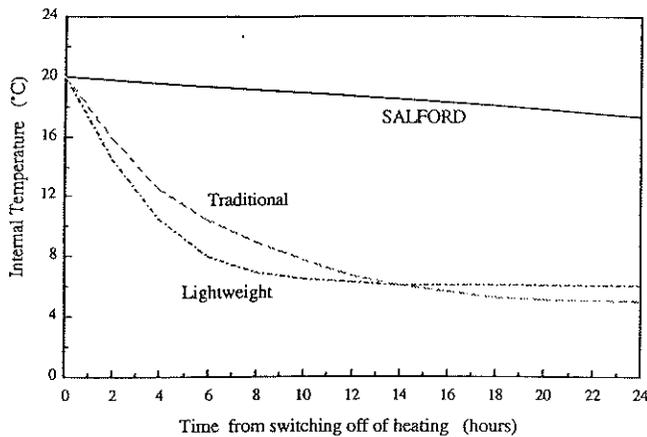


Figure 3 Calculated temperature changes in U.K. houses under winter design conditions (-1°C outside) after the heating has been switched off.

insulation is halved. It must, however, be recognized that the savings are only made because internal temperatures are allowed to fall, sometimes considerably. This will increase the risk of condensation and may be unacceptable if the house is continuously occupied—by the old or by families with young children for example. The SALFORD house in contrast maintains a steady temperature for long periods and has an almost constant but low heat loss for days irrespective of whether the heating is intermittent or continuous.

Heating Systems

Lightweight dwellings, because of their short thermal time constants, need heating systems that respond at a fast rate to rapidly re-heat the dwelling when cooling and to switch off directly when overheating. Slow-response systems, such as underfloor heating or solid-fuel heaters, would lag behind the thermal response to the diurnal cycle, resulting in large temperature swings. This means that only high-grade heating systems, such as high-temperature radiant or medium-temperature hydronic systems with direct controls, can be employed. These systems can only use primary fuel resources and are immediately vulnerable to the interruption of the fuel supply or to failure. The SALFORD house, with its much reduced heating requirement and thermally stable characteristics, can be heated not only by high-grade systems but also by a range of low-grade, or off-peak, systems, which are on the whole more sustainable or cheaper sources of heat. Even without any heating, when fuel supplies are interrupted or if the heating systems fail, reasonable temperatures are maintained for considerable periods.

The Heating Season

In the U.K. overall, the heating season traditionally lasts for about seven months, for the period that the average

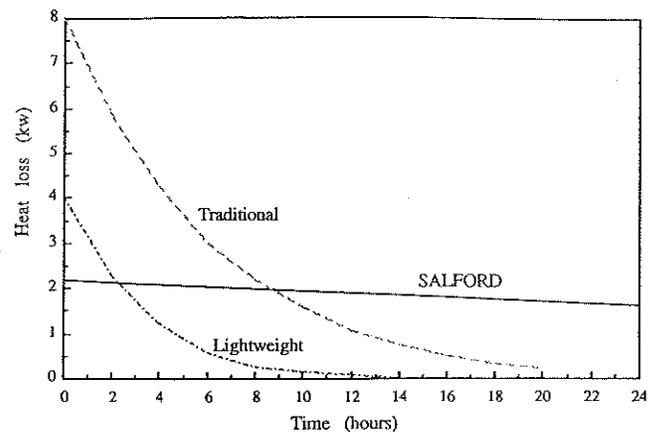


Figure 4 Calculated heat loss rates for U.K. houses under winter design conditions (-1°C outside) after the heating has been switched off.

external temperature is below the typical degree-day base of 15.5°C . Figure 5 compares the energy consumption for a SALFORD house heated by gas with that of a similarly heated house of traditional design with a 15.5°C degree-day base and a better insulated house, such as one of timber-frame construction, with a degree-day base of 14°C . Not only does the SALFORD house consume much less energy, but it has a much lower degree-day base of 11.5°C . Consequently, the length of the heating season is reduced to about four or five months. If houses to the standard of the new design are replicated in large numbers, it will have significant implications for the energy supply industries both in terms of quantity and time of delivery.

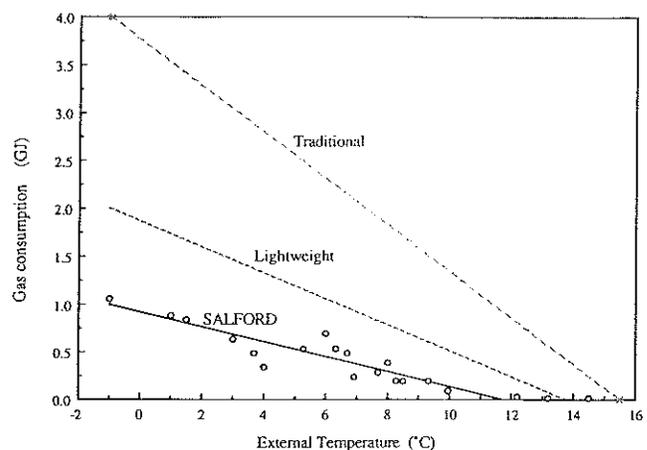


Figure 5 Monitored energy consumption in a SALFORD house vs. outside temperatures, averaged over fortnightly intervals, compared with calculated consumption for a traditional and a typical timber-frame construction.

CONCLUSIONS

The SALFORD house was designed to eliminate the problems of condensation and to substantially reduce heating costs in local authority housing. Additionally, capital and maintenance costs were to be no more than the standard for typical U.K. dwellings, traditional construction methods and materials were to be employed, and there were to be no limitations on normal occupant living patterns.

The houses built so far to the new design have achieved these aims and more. Their high thermal capacity and highly insulated envelope, together with careful design detailing, have removed condensation problems and provide stable equable internal temperatures, which is of particular benefit to continuous 24-hour occupation.

The annual energy costs are low and the dwellings may be heated in a number of different ways, either from high-grade or low-grade heat, continuously or intermittently. The dwellings are inherently resistant to rot, fire, and noise transmission.

The design is particularly suitable for low-income housing, for the accommodation of elderly people, where failure to maintain adequate temperatures in winter can have fatal consequences, and for families with young children. Room temperatures do not fall rapidly or far, even if the heating fails. The design principles are equally applicable to larger and more expensive properties, which would benefit from the low running costs and inherent security.

The house was designed for temperate climates, but the physical principles are universal and the design could be modified for a wider climatic range by adjusting the magnitude and ratio of thermal storage capacity, insulation, and ventilation rates as appropriate. To date some 200 dwellings have been built to the SALFORD design in the U.K. and, if this replication were continued, large long-term energy savings and environmental and social benefits could be achieved.

ACKNOWLEDGMENTS

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