a Partners In Innovation research project final report

Low Cost Earth Brick Construction

2 Kirk Park, Dalguise: Monitoring & Evaluation

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1. EXECUTIVE SUMMARY

This report presents the results of a two-year research programme to monitor and evaluate the performance of earth masonry in modern wall construction. The programme made a detailed study of one new building through the complete construction process, including design, procurement and occupation. It also took into consideration several other projects that used these materials.

The earth materials studied in this project, earth bricks, mortars and plasters, are generally held to have good environmental characteristics over a range of important criteria and, critically, are also believed to have wide potential for use in contemporary construction. The purpose of this research was to assess the extent to which these possible benefits could be practically realised in typical construction conditions, to highlight any significant factors affecting performance and to disseminate guidance to interested parties.

The research was carried out as part of a Partners In Innovation project, Low Cost Earth Brick Construction: Monitoring & Evaluation (ref. CC2455). The project was funded by the U.K. government’s Department of Trade and Industry and Communities Scotland, the Scottish government’s housing agency. The project was led by Arc, in association with Dundee University, Robert Gordon University, Aberdeen and the Errol Brick Company Ltd. Steering and Advisory groups, representing stakeholders across U.K. construction and experts from broad, advised and commented on the projects methodology and results.

The performance of the earth materials was assessed in the following respects:

a) **Design**: how the earth materials were designed to work with other materials and within the whole building, the use of technical data, compliance with regulations, predictability of performance.

b) **Buildability**: ease of construction, adaptability to standard labour skills, site storage, waste management, health & safety issues, robustness through construction.

c) **Durability**: shrinkage, damage from abrasion & impacts.

d) **Thermal Performance**: field monitoring of energy used in space heating and of steady state heat flows in the occupied house over one year.

e) **Moisture Performance**: field monitoring of relative humidity in a number of key locations in the occupied house over one year.

f) **Acoustic Performance**: a single field test to assess airborne sound transmission through a brick wall.

g) **Residents Response**: periodic interviews with the house occupants and their maintenance of an occupancy pattern record over one year.

The project was successful in testing the viability of earth brick construction and assessing the factors that influence its success and this report presents these results. Design and construction guidelines for earth masonry are being prepared by Arc as a separate document.

The key findings of the project are:

- **Easy to Design With.** With a basic level of guidance, the materials could be easily incorporated in the building design. Commonly used tools for the design of thermal performance, u-value and SAP calculations, were demonstrated to be poor predictors of real performance for a number of reasons, mostly unrelated to the earth materials.
• **Low Cost.** Earth brick construction is practically and economically viable in contemporary U.K. construction conditions. Specifically, it is appropriate for simple, low-cost projects that have a modest level of professional design and supervision of construction.

• **Very Low Environmental Impact.** The materials proved to be environmentally friendly. In particular they produced very little waste and had very low embodied carbon, about 14% of comparable fired brickwork and about 24% compared to lightweight blockwork.

• **Excellent Moisture Control.** Unfired clay materials have a marked ability to regulate fluctuations in moisture, which can have several important benefits. Impacts on occupant health, most importantly known asthma triggers, can be avoided by moderating internal air relative humidity. The passive control of moisture within the building fabric avoids the need for vulnerable membranes and reduces condensation risk to a level where mechanical extract in bathrooms may not be necessary.

• **Good Thermal Performance.** The thermal insulation value of the external wall construction was 30% better than predicted by the design u-value calculation, though the degree to which this could be attributed to the earth brick element could not be determined. The earth brick’s thermal mass was of benefit in moderating thermal flows, though the performance of the whole house was compromised by the lack of thermal mass in the roof.

• **Specialist Skills Needed for Plasters.** Earth brick construction is very comparable to conventional brickwork in skills, technique and rates of construction. Clay plasters can achieve a fine, attractive and durable finish, but their working qualities are significantly different to gypsum plasters, and specialist training is required to achieve good quality.

• **Defects Linked to Simple Mistakes.** There was some cracking in the brickwork related to the use of timber lintols with a high moisture content and bricks possibly getting damp in transit. Cracks and surface dusting in the plaster was the result of poor application linked to the inexperience of the plasterers.

• **Users Liked It.** The building owner/occupiers responded positively to living with earth materials. Occupancy patterns were shown to have a significant effect on the thermal performance of buildings, suggesting benefits in considering this during the design and handover of buildings.

• **Good Acoustic Insulation Depends on Detailing.** Earth brick construction can provide significant acoustic insulation but careful detailing and integration within a considered whole building design are necessary to make most benefit of these qualities.
2. THE BUILDING

The building is essentially a clay box sitting inside a timber box, resting on a concrete pad.

The walls are built on a concrete raft foundation, over which is a layer of polystyrene insulation and a concrete screed containing underfloor heating pipes, with a timber floor finish.

The external walls comprise a leadbearing timber frame of nom. 50 x 100mm softwood studs at 600mm centres, with a ‘breathing’ sheathing board and external natural larch timber rainscreen. The inner leaf of the external walls is 105mm thick earth bricks in earth mortar with a nom. 15mm two coat clay plaster finish. The bricks are set 100mm clear of the studs, giving a 200mm cavity, which is filled with cellulose recycled newspaper insulation.

The roof structure is simple softwood timber trusses, carrying timber sarking, a ‘breathing’ felt and natural slates. There is nom. 220mm cellulose insulation between the trusses and a plasterboard internal lining. Internal partitions are generally 105mm earth bricks with clay plaster both sides, except for one cross wall, which is of timber frame construction with earth brick infill between studs.

Fig. 1. View from the south

Fig. 2. View to the Kitchen

Fig. 3. Plaster Detail

Fig. 4. Construction of the External Wall
Fig. 5. Site Location.

PLAN, NTS, showing material sources
OS grid reference: 299250E 747250N.

LOCATION PLAN, 1:1250

SITE PLAN, 1:500

parking &
turning area
Fig. 6. Building Plans.

ROOF PLAN, 1:100

ATTIC FLOOR PLAN, 1:100

GROUND FLOOR PLAN, 1:100
Fig. 7. Building Sections.
Fig. 8. Building Elevations.
3. KEY FINDINGS AND CONCLUSIONS

3.1 Building Design and the Prediction of Performance

The earth materials generally fulfilled the design intentions. Their integration into the building design proved effective in the following intended respects:

- Anticipated potential difficulties from their use in the construction process were avoided.
- The walls proved robust and avoided interstitial condensation without moisture barriers.
- Internal air relative humidity was generally controlled to 40-60%, and surface condensation was inhibited.
- The thermal mass of the earth materials contributed to achieving comfort conditions.
- The mass of the earth walls contributed to acoustic insulation between internal spaces.
- An attractive internal plaster finish was achieved using unfired clay materials.

However, the intended contribution of the earth materials to the building’s air tightness and acoustic insulation was impaired by minor cracking. This was in part caused by differential movement between materials that could have been avoided by good detailing and quality control.

3.1.1 Thermal Performance.

The thermal performance of the building proved more complex than had been anticipated during the building design.

It had been intended that the thermal mass of the earth materials would, in a general and unquantified way, have a beneficial effect by moderating swings of temperature and improving comfort by surface radiation. While the thermal mass and layered construction of the external walls did prove effective in moderating heat flows through the ground floor walls, this was insufficient to compensate for the poor performance of the roof, which received a lot of solar radiation and had low thermal mass, with the result that the building occasionally overheated. This highlighted the need to consider thermal mass in a sophisticated way during the design of buildings and the benefit there would be in developing a more accurate predictive model for whole buildings under varying climatic conditions and occupancy patterns.

The u-value calculations proved a surprisingly inaccurate predictor of the thermal insulation of the external walls (9.6.8.). While there was some local variation clearly attributable to variation in the density of the cellulose insulation, the general value recorded in the building was 30% better than the design calculation and the reasons for this could not be determined (3.5.1).

The SAP calculation also proved an inaccurate predictor of the energy use of the house, which was 45% higher than predicted. This confirms that the SAP calculation should only be treated as an indicator of comparative performance between different building designs and not used as a predictive design tool. Actual energy use is significantly affected by occupancy patterns and other variable factors, which are not taken into account in SAP calculations.

3.1.2 The Relationship of Earth Materials to Other Fabric.

The interface of earth materials with other fabric was demonstrated to be the principal place where the intended performance could be compromised by defects, most commonly caused by differential movement. This was anticipated during design and generally effective detailed design meant that the defects were not serious and could be easily remedied. However, the need for careful detailing in these locations was clearly demonstrated.

3.1.3 Statutory Controls.

The earth materials, being purely internal, were not considered in the application for Planning permission.
The application for Building Warrant contained general information on the earth materials, but no unusual amount of information was required before the warrant was given. The works were inspected by the local Building Control officer, but no queries on the earth materials were reported to the Architect and there were no difficulties in obtaining the completion certificate. A similar experience was reported on two other buildings that used these materials.

3.2 The Procurement and Construction Experience

The construction of the house was funded by a combination of a Rural home Ownership Grant from Communities Scotland and mortgage from a mainstream commercial bank. Some information on the building construction was supplied to the funders, but the use of earth materials did not impede the normal process of approval. No problems relating to insurances were reported by the owners of this or the other houses studied.

The construction of the house at Dalguise was a robust test of the practicalities of building with earthen materials in conditions typical of the contemporary U.K. domestic construction industry. While the use of the materials in both constructions was essentially successful, a number of useful lessons were highlighted.

By allowing the earth construction to happen once a weathertight envelope had been established, there were no delays or defects associated with weather.

There were a few minor problems relating to transport. A forklift had to be hired to off-load the bricks, as a hy-ab could have damaged the bricks by crushing. Some bricks had to be rejected because they were damaged by rainwater during transport, and there was some indication of possible subsequent shrinkage cracking due to brick moisture content having been raised. The tonne bags of plaster also caked because of moisture ingress in transport and needed breaking up before use. Temporary covered external storage proved adequate.

The Errol Eco-Bricks and clay mortar generally performed well, being easy to use and robust. The brickwork was constructed at a rate comparable with conventional brickwork. The skills of normal bricklayers were demonstrated to be adequate with brief guidance on site of 5-10 minutes duration. The bricklayers readily adapted to the use of the materials, without any reported difficulties. The use of woodworking tools proved effective for dressing the bricks and for secondary fixings.

The plasters generally performed adequately, though there were a number of problems related to the inexperience of the contractor. The plasters achieved an attractive appearance that the occupants liked, though local dusting and cracking impaired final quality. The different working qualities of clay plasters compared to commonly used gypsum plasters were demonstrated to be significant. A plasterer needs to understand the variable drying rates and appropriate finishing techniques in order to efficiently plan the works and achieve a good quality of work. This requires a modest amount of specialist training.

There were a variety of minor defects in the earth masonry apparent after a year of habitation (5.2), taking the form of narrow cracks and dusting of the plaster surface. These were mostly the result of the lack of experience of the plasterer with clay plasters and occasionally poor quality control during construction. These could all be made good by simple plaster repairs.

Use of the earth materials generally represented low heath and safety risks, though there were a number of issues highlighted. Exposure to dust containing crystalline silica particles is recognised as giving an occupational health hazard of silicosis to people working with clay minerals in construction. The risk can be minimised by simple dust prevention and control measures. Clay plasters are heavier to work with than gypsum plasters. There was a benefit in that brickwork did not produce the continual minor hand abrasion and dryness commonly experienced when working with fired bricks, concrete blocks and cement mortar.
The need to advise other trades of the nature of any earth materials on site, to avoid problems caused by their unfamiliarity, was noted.

The level of waste produced by these materials was extremely low. It was not economic to return unused bricks to the supplier, so these were benignly disposed of by mixing them into the site soil. The lack of waste was a notable feature of the use of these materials. Aside from the ecological benefits, this had the indirect benefits of a tidier site, increased working area due to less storage of waste, and reduced cost of waste disposal.

Generally the clay brickwork costs were comparable with fired brickwork and rates of construction are also similar. The clay plaster was more expensive, both as a material and in its application.

3.3 Occupant Response

The owner/occupiers of the house at Dalguise, and the two others studied, gave a very positive reaction to the use of the earth materials in their buildings. They were sanguine about minor defects and the limitations of future changes in finishes. They were pleased with the finished appearance of the materials, which matched their expectations.

The recording and evaluation of the occupancy patterns of the building residents provided an invaluable tool for interpreting the data recorded in the remote monitoring and for developing an understanding of the overall behaviour of the building fabric. It was notable that one of the children reported headaches when she slept at a friend’s new house, but not in her own.

While the size and lifestyle of the occupants was fairly representative of contemporary family life, there were a number of individual or cultural factors that affected the way the building was used which were identified.

3.3.1 Ventilation.

The occupants were used to high levels of ventilation and spending significant periods of time out of doors. As a result, windows and doors were open for prolonged periods through the year. Though the degree of ventilation in this case may be more than is typical, it is recognised that people’s fondness for opening windows is a problem for low energy housing, especially where high degrees of air tightness and mechanical heat recovery are important to the building thermal design.

High levels of ventilation were necessary at certain times to mitigate overheating in the attic spaces and ventilation was used in the initial months to aid drying out of the plaster. However, the fondness of the occupants for fresh air exceeded these needs to an extent that significantly affected the buildings thermal and moisture performance and this was reflected in higher than predicted energy consumption. The extent to which windows and doors were open also has security implications, though these are perceived as minor in this secluded location.

For buildings to be successful, it is important that their design can cope with a variety of occupancy patterns, as these will inevitably vary over time and between individuals.

3.3.2 Occupants Previous Experience.

The occupants’ previous housing experience seems to have been of significance. Their previous house had low levels of daylight and thermal insulation, but high levels of thermal mass and was ‘very drafty’. The new house has significantly different performance characteristics.

This previous experience influenced the design brief, which included the desire to maximise southern light and have a slated roof finish, factors which contributed to overheating through passive solar gain. The clients’ previous housing experience may also have influenced the relatively simplistic design and patterns of use of the heating system, which did not have a timer control and where thermostats tended to all be at the same setting.
These findings demonstrate that a client’s previous experience of achieving comfort conditions in buildings can be significant and should be carefully considered. System controls should also be explained and a period of experimentation with settings encouraged, in liaison with the design team.

3.3.3 Adaptive Occupancy Patterns.

There was evidence of the residents adapting their occupancy patterns as they got used to living in their new house. These include modifying the way they use the heating system, proposing minor alterations to the house to add thermal mass at high level, increasing ventilation in the spaces prone to overheating and adding a veranda and possible seasonal shading to the south.

This indicates the intended flexibility of the design to alteration during use, the occupants’ increasing awareness of the performance characteristics of their building and their understanding of their ability to modify its performance through lifestyle changes and physical alterations. It suggests that new buildings would often benefit from a period of evaluation in use and subsequent fine-tuning.

Ultimately the test of a building is its ability to deliver comfort conditions, which are always, to an extent, subjective. This building has achieved a high degree of user satisfaction and the earth materials have made a significant contribution to this result. Although the exact contribution of the earth materials to moisture and thermal control has been somewhat obscured by over-ventilation, their contribution to creating comfort conditions in a number of different respects, at relatively low cost, is of significance in achieving build quality in low cost construction.

3.4 Moisture Performance.

The moisture monitoring programme produced over a million items of data on the buildings performance, with readings taken through the external walls in several locations every 15 minutes for a year. Interpretation of the results was complicated by periodic high levels of ventilation, which were not recorded in detail in the occupants log. Nonetheless an important understanding was gained about the moisture related activity of the earth materials and their role in the performance of the house as a whole.

3.4.1 Condensation.

An initial period of drying out was recorded, lasting about 2 months. During this time a modest amount of condensation was noted on the inside of windows and ventilation was increased to dissipate this. There was no surface mould found at any time. Moulds are a known health issue which can affect new housing.

No interstitial condensation was found to occur in the wall construction under any conditions, although the climatic conditions at several times of the year were favourable towards it.

3.4.2 Regulation of Atmospheric Moisture.

An ability to regulate moisture is a key quality in materials containing unfired clay and the earth walling materials demonstrated an clear ability to absorb and desorb atmospheric moisture, in line with design intentions. While the design targets were all demonstrated to have been met, the periodic high levels of ventilation and the data recording intervals make finer analysis of the data difficult. Nonetheless, it was clear that the 15mm clay plaster surface strongly regulated short-term peaks, while the brick core had a longer term moderating effect. This is in line with previous research findings (Gobel, 2000).

There was a strong short-term response recorded in the bathroom following use of the shower. Analysis of the data showed that the 15mm surface plaster coat controlled the relative humidity of the bathroom very well. The clay plaster had such a strong ability to absorb peaks of air moisture after showers, clearing the air without surface condensation, that the extract fan by comparison
had no statistically significant effect (8.5.6). This indicates that clay plaster surfaces can provide effective moisture control even in peak conditions, potentially avoiding the need for electro-mechanical air extraction, with associated savings in equipment cost, energy use and improvement of air tightness. It was not possible to quantify the short-term response in more detail due to the intervals of data collection.

Fig. 9: Decay in air moisture after showers showed no significant difference when the extract fan was turned off.

The occupants noticed an earthy smell from the clay plaster in the bathroom after showers, as the material absorbed moisture. The smell was not unpleasant, but was not expected and relates to the relatively small size of this room.

Some of the moisture absorbed into the plaster transferred into the earth brick wall cores. This long-term response of the earth brick walls to fluctuations in air moisture peaked at 2 hours after an event, but an effect continued for over 24 hours. The results indicated that peaks in air moisture resulting from, for example, showers or cooking, were absorbed readily by the clay wall materials and stored, to be released later when air moisture levels dropped. This had the effect of regulating air moisture in the whole house.

The design target of regulating internal air relative humidity levels to between 40% and 60% was generally achieved throughout the monitoring period. While there were short-term values outside this range, these were attributable to periods of very high ventilation or the use of showers. While external air relative humidity fluctuated considerably, between 24.9% and 96.1%, the mean external value was around 65%, while the mean internal value was around 45%.

Fig. 10. Air relative humidity was generally regulated to the target range of 40-60%.
The regulation of the moisture contents of building materials or of internal air, for reasons of fabric durability or occupant health, is not currently defined within U.K. technical standards. However, the regulating ability of materials containing unfired clays has clear benefits in both respects and it is recognised in guidance from CIBSE that relative humidity levels should be controlled.

The ability of a building’s fabric to self-adjust to avoid conditions where condensation will occur improves a building’s long-term durability and avoids the need for vapour control membranes, which are prone to be compromised by poor workmanship.

This significance of the regulation of internal air relative humidity to occupants’ health is considerable. The U.K. as a whole, and Scottish young people in particular, have the highest rates of asthma in the world and house dust mite allergens are known to be a major cause of asthmatic sensitisation and trigger of symptoms. Recent research recommends maintaining internal R.H. below 60% to ensure that the house dust mites critical equilibrium humidity will not be achieved. It is also recognised that designing dwellings with a high level of insulated thermal mass can help to achieve such conditions. (Howieson, 2005).

Allergy to mould spores is the major health risk associated with fungi in buildings and inhalation of mould spores can also cause toxic reactions and cancer. Relative humidity levels below 70% are thought to avoid the dangers of mould growth (CIBSE, 2004). Avoidance of high R.H. levels can also reduce the viability of bacterial disease transmission.

Low air relative humidity can also present danger of respiratory disease through drying of the throat, though the risk is considered less than that presented by dust mites and mould at high humidity levels.

3.5 Thermal Performance

The thermal monitoring programme produced a similar wealth of data on the building’s performance, with interpretation of the results again complicated by the high levels of ventilation that were known to periodically occur, but which were not specifically recorded in detail in the occupants’ log. Nonetheless a detailed understanding was gained about the performance of the earth materials and their role in the thermal response of the house as a whole.

The building has achieved a high degree of user satisfaction in terms of thermal comfort. While energy consumption was higher than predicted, it was considerably lower, approximately 25%, of the residents’ previous house and they regard the heating costs as very low.

The walls achieve a significantly better thermal insulation value than was predicted and the reasons for this are unclear. This was unexpected, has significant implications and merits further investigation.

The only significant defect was a tendency to occasionally overheat, which relates to the overall building design rather than to the performance of the earth materials. The earth materials contributed to a significant thermal mass effect in the building, which stored the benefits of passive gains and buffered against short-term climatic variations. However, the project clearly demonstrated the complexity that needs to be considered in designing and predicting the effects of thermal mass.

3.5.1 Thermal Insulation.

The monitoring demonstrated that the effective u-value of the walls was 32% better than the design calculation and the reason for this is unclear. This calculation was made using 20-day averages, which should exclude the effect of thermal mass, which was shown to end after 7 days. There are a number of possible explanations, which are outlined below, but none of which is proven by the results.
The improvement may relate to optimisation of the density of the cellulose insulation. However, the manufacturers indicate a variation of 9% in thermal conductivity depending on installation density, whereas this result is equivalent to a reduction of 33%, from 0.036 to 0.023 W/m²/K. In thickness, the improved performance is the equivalent of a 54% increase, from 200mm to 308mm. Such a scale of improved performance over design values seems unlikely.

Another possible explanation is a better than predicted performance by the earth brick and plaster. Occupants of earth buildings often report better perceived thermal performance than is predicted by steady state u-value calculations. This is usually attributed to the type of dynamic thermal mass effect that is calculated out of this result. Other explanations include a better thermal insulation related to the air contained in the earth pore structure. If the improved performance in this case was due to the earth materials, it would be the equivalent of an decrease in thermal conductivity of 42%, from 0.65 to 0.038 W/m²/K. This level of enhanced performance seems unlikely. Unfortunately, the thermal insulation value of the bricks has not been tested in isolation as this was not thought to be a significant property and the design value was estimated by relating their mass to standard conductivity data.

Whatever the explanation, the walls of the building performed significantly better than was indicated by the design calculations and significantly exceed the requirements of the contemporary building regulations.

<table>
<thead>
<tr>
<th></th>
<th>R (mK/W)</th>
<th>U-value (W/m²/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulation wall value</td>
<td>3.33</td>
<td>0.3</td>
</tr>
<tr>
<td>Wall design value</td>
<td>6.33</td>
<td>0.157</td>
</tr>
<tr>
<td>Recorded wall performance</td>
<td>9.34</td>
<td>0.107</td>
</tr>
</tbody>
</table>

Minor defects in insulation and air tightness were detected by the monitoring. In one monitored area of external wall, there was little insulation. There were also indications of high local air permeability through the sheathing, which corresponded to defects observed during construction. These defects did not significantly impair the overall thermal performance of the building and did not directly relate to the earth brick elements. However, they do demonstrate the importance of quality control during construction, even in construction designed to be simple.

3.5.2 Energy consumption.

The occupants were very satisfied with the energy consumption of the building, with annual space and water heating costs of around £300. They felt sufficient comfort to have the heating system turned off between 3rd March and 21st October, which demonstrates the beneficial effects of passive gains and thermal mass alongside good standards of insulation and air tightness. However, 45% more energy was consumed than was predicted by the design SAP calculation, 18.5 MW/h compared to 12.7 MW/h (66.5 GJ compared to 46GJ). This may have been partly caused by excessive ventilation and an unsophisticated heating system, but it also highlights the deficiencies of SAP calculations as predictive design tools.

3.5.3 Thermal Lag.

There was a very large range of variation in the thermal lag effect of the earth brick walls in relation to changes in external temperature, with an average value of around 2 hours. The response was much more regular in relation to changes in the heating system. Here 2/3 of the response had occurred by 3.7 hours, with a declining effect detected for up to seven days.
The monitoring demonstrated that there was often a 2-3 day period to local weather patterns, which, combined with the thermal lag effect of the building and the unfamiliarity of the users with the heating system, meant that the occupants often adjusted the heating system in response to weather patterns which were about to change. This lack of synchronisation meant that the heating system was being turned up at the end of a cold snap and down at the end of a warm spell. Over time the occupants understanding of the thermal behaviour of their building improved, allowing them to anticipate these changes.

The earth materials provided a degree of thermal mass, as intended, evening out temperature swings and contributing to thermal comfort. But the research also highlighted that thermal mass needs to be carefully calculated as it is essentially an unalterable passive quality in the overall thermal activity of a building. In this type of situation, it is thought that 50-100mm of thermal mass on all surfaces will give a good response for a 24 hour period (Borer & Harris, 1998. p.199).

### 3.5.4 Overheating.

The building has a tendency to overheat in summer, mainly caused by passive gain from solar radiation on the roof, which was covered in dark slates and was of lightweight construction. Indirect gains from lights and occupants were both additional factors. The relatively small quantity of earth bricks at attic level did not have sufficient thermal mass to have a mitigating effect.

Seasonal shading by, for example, deciduous trees, the use of a more reflective roof finish or the use of materials with greater thermal mass in the roof construction would be design options to remove this problem. In the short term the occupant response was to increase ventilation, which is unsatisfactory for a number of reasons, including security.

This finding demonstrates the need to consider the distribution of thermal mass throughout a building in a sophisticated manner during design, taking into consideration seasonal climate and occupancy patterns. Reliance should not be made on the simple incorporation of thermal mass in one element or material.

### 3.6 Air Tightness

The house as a whole achieved a good standard of air tightness, though this was impeded by the consequences of some poor quality control during construction. The standard achieved, 0.54 air changes/hour, was appropriate for this type of construction and use. It is within that of the proposed new part L of the Building Regulations (England and Wales). Measures that could improve performance are noted below.
The contribution of the earth brick layer to envelope air tightness was not as significant as had been anticipated. The principal pressure control layer was shown to be the sheathing and breather membrane. Poor quality control in the quality of the sheathing joints observed during construction in some places, together with the absence of folded and taped joints in the covering membrane were factors which increased permeability.

The relatively small contribution to air tightness from the unfired clay walls was traceable to leakage at junctions with windows and doors and around timber lintels. The designed draft proofing details around windows and doors were not followed during construction, with simple seals of injected silicone substituted. These were demonstrated to be ineffective.

The timber lintels used in the earth brick walling were not selected with the correct moisture content, and as a result they experienced significant shrinkage as they dried out during the monitoring period. This led to cracking in the earth brick walling above the lintels and significant potential for air movement. The minor cracking at the head of most of the earth brick walls was shown not to cause significant air leakage.

The fact that an acceptable result was achieved, despite somewhat poor quality control during construction in critical areas, indicates that the construction was tolerant of a low skilled procurement. The relatively poor result for the earth materials layer was attributable to poor quality control of interfaces with neighbouring materials. This indicates that, with better quality control, the earth materials may have the potential to achieve a significant contribution towards air tightness. In a similar manner to the acoustic tests, further tests after normal making good of defects might have achieved an enhanced, and more representative performance.

In reality, a rate of less than 0.5 air changes/hour can lead to problems of indoor air quality. This research demonstrated that, with this construction, an acceptable performance can easily be achieved, even with poor quality. With good quality control and the possibility of removing unnecessary mechanical ventilation as suggested by the moisture monitoring, a significantly enhanced performance might be achieved.

3.7 Acoustic Performance.

The tests demonstrated that the theoretical level of sound insulation provided by the relatively dense earth brick and plaster internal partitions was significantly impaired by the geometry of the building and the interface with neighbouring materials.

The layout of the building and the relatively small size of the rooms meant that there was significant flanking transmission through door openings. This is an inevitable consequence of the house design and would be less of a factor in buildings with larger rooms that had doors further apart.

There was significant flanking transmission through the mutual ceilings, which were of lightweight construction. There was discussion at design stage of the desirability of acoustic insulation in these spaces, but this was omitted on grounds of cost.

It is thought that a 4-5mm crack, typically found at the head of the earth walls, caused by drying shrinkage, also contributed to a reduction in performance. The potential for such cracking had been anticipated, as the differential movement of the earth brick elements and the structural timber frame elements was difficult to predict with complete accuracy. The strategy of making good such cracks after a year’s occupation, along with any other initial defects, is standard industry practice and would remove any significant impairment of acoustic performance.

The occupants’ perception was that there was a very good level of acoustic insulation between the rooms and that this satisfied the need highlighted in their brief. The earth brick walls therefore make a significant contribution towards achieving adequate acoustic performance in an arrangement of rooms that is demanding.
The occupants did complain of poor insulation between the attic spaces and the ground floor rooms below. This does not relate to the earth brick construction and could easily be avoided by incorporating acoustic insulation within the first floor.

The performance of the earth brick walls is fundamentally good and could be enhanced by avoiding flanking transmission. It is also good practice to repair initial shrinkage cracks which may affect acoustic performance. These measures would increase the levels of acoustic insulation towards theoretical levels.

3.8 Research Programme Methodology

The monitoring of the test house at Dalguise was carried out without any technical problems and produced a wealth of data on the performance of the building over its first year in occupation. The house overall performed well with the occupants generally very satisfied with the level of comfort the building provides.

The results give a comprehensive insight into the life of a building as its physical fabric adjusts to the patterns of life of its occupants and to the microclimate of its location. They highlight the importance of a holistic approach to design, with all elements being considered as a balanced whole. They also raise questions over the extent to which some of the potential benefits of earthen materials can be compromised by design decisions over other elements, by construction quality and by occupancy patterns.

The strength of this research was its ability to test a real life application of this technology and thus inform guidance that will have practical relevance. However this specificity also creates the weakness of not testing optimal performance or giving comparison against a comparable conventional construction. Therefore the monitoring programme, while providing the intended assessments, inevitably raises some unanswered questions and suggests subjects for further research.

3.9 Recommendations For Further Research

3.9.1 Research Areas of High Importance.

This project has highlighted opportunities for further research in a number of areas that would make important contributions to the development of the use of unfired clay materials and sustainable design more generally.


Research to provide more quantified information on the highly important ability of clay materials to absorb and desorb atmospheric moisture would enhance their use in design.

2. Design of Thermal Mass in Housing.

In the context of global warming, there would be great value in research to provide guidance on how to optimise housing response using thermal mass. This would facilitate the design of the location and quantity of thermal mass in order to maximise beneficial solar gains in the winter and minimise unwanted solar gains in the summer. The currently available information is relevant to lightweight and heavyweight buildings but is not specific enough for detailed design.


Research would be merited into clay mortars, as there seems to be a significant variation in performance between different materials. The performance demanded of clay mortars in modern thin wall construction is far greater than that required in traditional thick wall construction. This is especially relevant to flexural bond strength.

Research to provide accurate tools for the design and prediction of thermal performance would be very valuable. A large variation was clearly demonstrated in installed U-values compared to theoretical U-value and SAP calculations. These are good comparative tools but do not allow an architect, builder or homeowner to easily predict and verify what the energy performance of the building should be.

5. Ventilation.

There would be value in research into residents’ behaviour to ventilation, a major issue which has been raised elsewhere (Macintosh & Steemers, 2005, pp.17-31) relating to use of mechanical ventilation and the problem of unnecessary opening of windows identified in this project. Difference in residents’ behaviour regarding ventilation could be evaluated in two similar new houses, where one group are given pre-instructions about ventilation requirements and the other group are not. The project would test the actual value of giving guidance.

6. Thermal Insulation of Bricks.

Research to clarify the thermal insulation of the earth bricks would be useful in light of the unexpectedly good performance found in this research.

3.9.2 Research Areas of Further Interest.


It would be useful to undertake a second evaluation could be carried out after 2 or 5 years to pick up on how residents have changed their behaviour and altered their house. This would also check on the materials and the physical performance of the building. A longer life cycle evaluation would give more information and be more valuable than the short life cycle one contained in this report.

8. Biodegradability and Biodiversity.

It would be interesting to carry out research to evaluate the industrial ecology and waste implications of earth materials used in this project. This would include a detailed analysis of biodiversity in former clay pits and compare this to former stone quarries. Does clay restore more richly than stone? Also, what are actual effects of leaving the clay bricks in the Dalguise garden? Do they really improve the situation for biodiversity or make it worse?

9. Housing Typology.

It would be useful to undertake research that monitored the behaviour of people moving from one type of house to another. This could look at a number of houses and analyse where residents came from, how they behaved in their houses before and how they behaved in the new houses.


It would be interesting to evaluate the speculative explanation of the locally high U-values that for some reason there are high local moisture transfer rates. In this theory, the vapour condenses on the outside releasing latent heat. Later the water evaporates driven by external sources of energy e.g. solar gain or high ext air temperature. In other words conduction heat loss is augmented by vapour transport and phase change.
4. THE MATERIALS

4.1 Physical Properties of the Materials.

The bricks were unfired clay bricks, mass produced at a small brickworks by the Errol Brick Company, at Inchcoonans Road, Errol, Tayside. At the time of design the bricks had been subjected to extensive testing as part of the procedure for certification by the British Board of Agreement, though this had not yet been issued.

The physical properties of the materials listed below are from laboratory testing unless otherwise stated.

**Earth:**
- The base 'earth' is an alluvial clay;
- Grading: 27% clay, 54% silt, 9% sand, 10% gravel.
- Plastic Limit: 20%
- Liquid Limit: 46%
- Plasticity Index: 26%
- Linear Shrinkage: 10.7%

**Mixes:**
- The bricks are 45% 'earth', 5% sand, 50% wood shavings, by volume.
- The mortar is 1: 3: 0.25, 'earth' : sand : lignosulphate (a natural cellulose binder waste by-product from tree processing)

The bricks were supplied shrink wrapped on pallets. The mortar was supplied as dry clay powder in bags, with the cellulose additive as a liquid. These were mixed in a normal cement mixer on site, with standard building sand. The lignosulphate was added to improve bond strength. It has the added benefit of acting as a plasticiser, reducing the amount of water needed to achieve a workable mix. However, the lignosulphate sets by oxidation, meaning that the mortar, once set, cannot be re-worked. A batch of mortar would be good for about half a day. The mortar waste was intended to be returned to the factory for re-cycling into bricks, along with any brick waste.

**Masonry:**
- Brick Density: 1504 kg/m³
- Brick Compressive Strength: 6.1 N/mm²
- Mortar Compressive Strength: 1.8 N/mm²
- Masonry Compressive Strength (in accordance with BS EN 1052-1:1998)
  - Average Comp. Str.: 2.5 N/mm²
  - Characteristic Comp. St.: 2.2 N/mm²
  - Mean Elastic Modulus: 400 N/mm²
- Flexural Strength (in accordance with BS 5628-1: 1992)
  - Average Flexural Strength (parallel to bed joint): 0.281 N/mm²
  - Characteristic Flexural Strength (parallel to bed joint): 0.225 N/mm²
  - Average Flexural Strength (perpendicular to bed joint): 0.471 N/mm²
  - Characteristic Flexural Strength (perpendicular to bed joint): 0.405 N/mm²
- Initial Shear Strength (in accordance with BS EN 1052-3: 2002)
  - Average Initial Shear Strength: 0.16n/MM²
  - Characteristic Initial Shear Strength: 0.13N/mm²
  - Average Angle of Internal Friction: 38.4 deg.
  - Characteristic Angle of Internal Friction: 32.4 deg.
- Structural Fixing Test (in accordance with BS 5080-1: 1993) test carried out on M6 'Rawplug' expanding anchor bolt fixing
  - Average Ultimate Force: 1430 N
  - Standard Deviation: 125 N (10 tests)
  - Wall Ties Pull-out (in accordance with BS EN 846-5: 2000)
  - Average Tensile Capacity: 1540 N
  - Lowest Tensile Capacity (of 12 tests): 790 N
  - Thermal Conductivity (estimated): 0.65 W/mK
Specific Heat (estimated): 1 kJ/kgK
Vapour diffusion resistance coefficient (estimated): 5
Fire Resistance: (in accordance with BS 476 parts 20 & 22) on 105mm thk. brick wall, 3m. x 3m., unplastered:
Insulation: passed for 150 minutes
Integrity: passed for 150 minutes

Plasters. The proposed plasters were imported German manufactured products distributed by Natural Building Technologies Ltd., 'Claytec' undercoat and self-coloured top coat. These plasters are mixtures of natural clays, fine aggregates and plant fibres. They come dry bagged for site mixing.
Density: 1500 kg/m3
Thermal Conductivity: 0.66 W/mK
Vapour Diffusion resistance: 8

4.2 Environmental Characteristics of Materials.

The earth bricks and mortar used in the construction were supplied from a brickworks forty miles from the building site. The extraction of the clay has a beneficial effect on local biodiversity as the legacy of redundant clay pits at the factory is that they flood and develop into important wetland habitats. Several of these have been designated as Sites of Special Scientific Interest. The process of manufacture is virtually zero waste, with defective materials being returned to the start of the production cycle and re-formed into new materials.

A calculation for the building showed that the earth bricks had an embodied energy of 146 kwh/tonne and an embodied carbon of 44.6 kgCO2/tonne. Comparing the factory gate values for the earth bricks against standard data for other materials (Talbot, 1997, Borer & Harris, 1998, Benge, 2000 & others) demonstrates their relative low embodied energy:

Errol earth bricks: 123 kWh/tonne
Lightweight concrete blocks: 500 kWh/tonne
Fired common bricks: 860 kWh/tonne
Fired engineering bricks: 1120 kWh/tonne
Aerated concrete blocks: 1390 kWh/tonne

While the earth bricks are clearly lower impact than comparable materials, the values given are less dramatic than those often quoted of about 5% of the embodied energy of comparable materials. This may be because figures given elsewhere were based on handmade rather than factory produced earth bricks and it demonstrates the value of making comparisons between known properties of specific materials when making design decisions, rather than using standardised data. Having said that, it should be noted that the figures for the conventional materials given here are only an indicative guide.

The minimal level of waste associated with the construction on site was in line with predictions, though the anticipated return of waste materials to the factory did not prove economically viable, as is described in section 5.9.

4.3 Embodied Energy and Embodied Carbon Calculation.

4.3.1 Background.

The unfired clay bricks used in the Dalguise house are of particular interest in terms of the potential amount of manufacturing energy that can be saved by using them instead of highly energy intensive fired bricks.

The bricks used were manufactured at Errol Brickworks in Tayside, using a simple mechanical conveyor and continuous extrusion. The bricks are air dried in large drying chambers, in a similar manner to the air drying used for normal kiln-fired brick using a mixture of gas and electricity for
heating. They are dried for approximately two days and are then ready for use. This reduces the moisture content of the bricks to approximately 2%, and uses approximately 17% of the overall energy normally required to dry and kiln-fire bricks at the same brickworks.

The density of the bricks is 1769 kg/m³ which is somewhat lighter than normal fired bricks. This is due to the fact that 33% of the brick is composed of sawdust, from a local sawmill, while 66% is composed of the raw clay.

In order to accurately calculate the true amount of energy that a building uses, it is important to factor in the amount of energy required to manufacture and deliver all the materials to the building. Calculating this energy, the “embodied energy”, requires many factors to be taken into account, which can be highly variable. As such, embodied energy in buildings is generally considered to form 10% of the overall energy use on average, over the lifetime of a building. This figure hides huge variations however, depending on the transportation involved, the amount of energy used in the manufacturing process, the lifecycle of the actual products as it is used and the lifespan of the building.

Embodied energy has two different definitions:

1. The amount of energy required to source, process, and transport a material, product or assembly to a particular site.

2. The amount of energy required to source, process, transport, construct, service during a building lifetime, and deconstruct a material, product or assembly

Generally the UK adopts the first definition, although it can be argued that the second one is more robust because it takes into account the full life cycle of energy use in a building.

Secondary energy elements such as the amount of energy required to build the manufacturing works or the vehicles for transportation is discounted, as is the human energy required to build with the materials.

It is relatively simple to calculate the carbon dioxide emissions produced by the energy used, providing that the figures for the actual source of energy can be obtained. If these cannot be sourced, then the calculation should be based on the average emissions for the energy supplier to the area.

4.3.2 Methodology

The standard UK definition of embodied energy was followed.

The following information was required in order to ascertain the energy involved in the sourcing and manufacture of the unfired earth bricks:

- Energy used by machinery to extract all source materials: clay, filler, sand etc.
- Energy involved in material storage prior to processing
- Energy involved in processing of the different materials prior to brick manufacture
- Energy involved in transporting the different materials to the brick manufacturing base.
- Energy involved in the brick manufacturing process
- Energy involved in storing the bricks
- Energy involved in transporting the bricks to the site.

In order to obtain information on the above it was necessary to ascertain the provenance of all source material and obtain from Errol Brickworks estimates of fuel used to extract the material, transport it and store it. This involved estimates of petrol use, number of vehicle trips, electrical bills, gas bills etc.

Errol Brickworks were requested to supply fuel estimates for all the equipment, which processes the bricks and the amount of energy used for the batch of bricks on a pro-rata basis. Finally, they
were asked to provide fuel estimates for the transportation of the finished product to site on a pro-rata basis (number of trips, type of vehicle, journey length, and fuel consumption).

4.3.3 Results

The results are summarised in table 1 and 2 below. Generally the embodied energy and carbon dioxide emissions are expressed in KWh per brick (see table 1), per total bricks in construction and per total bricks including waste. Carbon emissions are calculated on the average for the supplier to the local area (see table 2.).

The numbered headings refer to the following processes:

1. Energy used by machinery to extract all source materials: clay, filler, sand etc.
2. Energy involved in material storage prior to processing
3. Energy involved in processing of the different materials prior to brick manufacture
4. Energy involved in transporting the different materials to the brick manufacturing base.
5. Energy involved in the brick manufacturing process
6. Energy involved in storing the bricks
7. Energy involved in transporting the bricks to the site by lorry.

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4.3.4 Discussion

The above figure of 146 KWh/tonne compares typically with 860 KWh/tonne for ordinary bricks (source: Borer, P, Centre for Alternative Technology, Wales) or 1,120 KWh/tonne for engineering brick. This translates as the unfired brick using nearly six times less energy than an ordinary brick (only 17% of the energy used to make a kiln fired brick), or over seven times less energy than an engineering brick. This figure is comparable to the difference between the air-drying energy component and the kiln-firing component of a kiln-fired brick. This suggests that, all other factors being equal, it is the omission of the kiln-drying component of the manufacturing process which accounts for the relatively low embodied energy of unfired clay bricks.

The figure is high compared to some figures quoted for unfired brick. This is due to the fact that although the bricks are indeed unfired, they are nevertheless dried artificially over a two day period. Traditionally, unfired bricks are simply left to dry naturally in developing countries, and this may have given rise to the common perception that unfired clay products use only a small fraction of the energy required to make a kiln-dried clay product.

Industrialised processes, which are required to deliver unfired clay products on an economic scale, will always require space-efficient drying chambers, which in turn will always require an energy input. It may be possible however to consider using waste heat from the kilns to heat these in the future. This would give a distinct advantage to having unfired and fired products manufactured side by side on the same site. Another opportunity for reducing the embodied energy of the unfired clay product is to use solar energy to pre-heat the incoming air of the drying chambers.

The exercise had provided valuable additional information on the overall environmental benefits of using unfired earth blocks for construction and could act as a benchmark for evaluating unfired earth blocks in the UK against other walling products. The legitimacy of the exercise does rely, however, on the veracity of the information obtained from manufacturers, which could not be confirmed independently.
5. DESIGN & THE PREDICTION OF PERFORMANCE

5.1 The Design of the Building.

The new house was completed in the summer of 2003 at a cost of approximately £650/m². It used mass produced earth bricks and plasters as the internal leaf of external walls and for internal partitions, combined with a structural timber frame, timber external cladding and recycled newspaper insulation.

The house is a simple rectangular plan with two single bedrooms downstairs, an open plan kitchen/dining/living area, a bath and shower room, a w.c, and two upstairs attic areas built into the roof (one above the kitchen and one above the bedrooms) which open onto the double height living area in the middle. There is a large double door, fully glazed opening from the living area to the south and windows evenly spaced around the four elevations. The attic spaces were later converted to a double bedroom and an office area. A large veranda was added to the south elevation of the house during the spring of 2004.

5.2 Design & Defects of the Earth Brick Walls.

The strategy of building simple earth brick walls, with a controlled number and size of openings and frequent intersection of walls at right angles generally proved effective. The design of the building attempted to control potential defects through the arrangement of the earth materials within the building fabric and the design of how these met other materials. In general this was successful, but the importance of detailing and specification was highlighted during monitoring, where a variety of minor defects were observed. These could all be made good by plaster repairs at the end of a defects period.

Fig.12. The inner brick lining of the external wall in construction.

The relationship of the earth brick lining to the external timber frame was a good example of a successful arrangement. The independent timber frame allowed the brick linings to be built under the protection of a weathertight envelope avoiding any delays or defects relating to weather.

The structural connection between the two layers was made with thin metal ties, which were sufficiently flexible to allow differential movement between the two materials systems. The loose insulation, which filled the cavity between the two layers, could accommodate any movement or variation in construction without loss of performance.
Fig. 13. Minor shrinkage crack at ceiling junction.

Minor cracks due to shrinkage appeared at the junction of the earth brick walls and the timber and plasterboard ceilings. These could be made good, together with other plaster defects, after a suitable period, but the use of a cornice to cover such cracks would also have been effective.

Fig. 14. Cracks caused by timber shrinkage.

More serious cracks appeared over openings caused by shrinkage of timber lintols, where the moisture content of the lintols used had been significantly higher than specified. Use of concrete lintols in situations where there is little control over construction quality, might avoid such problems.

Fig. 15. Shrinkage cracks below windows.

Shrinkage cracks appeared below several window openings, thought to be caused by moisture gain by the bricks during transport and possibly external storage. A similar vertical crack appeared in another building where the bricks were stored externally, but none were evident in a case where the bricks were stored inside.
5.3 Design for Moisture Regulation.

It was intended that the design of the clay materials would control the potential for both internal and interstitial condensation. There are no vapour control layers on this building. It was predicted by calculation at design stage that condensation would not occur within the wall, due to the layering of relative resistance to vapour diffusion (Fig. 17.). The effect of the hygroscopic qualities of the earth walls in regulating internal air humidity and surface condensation was not calculated.

In one or two places there was damage to plasterwork where furniture regularly abraded the surface. This could be avoided by use of a timber dado.

The avoidance of exposed right-angled corners generally protected plasterwork and avoided the need for timber facings or corner reinforcement beads.

In the event, it was demonstrated that no condensation occurred in the fabric of the building. The regulation of air relative humidity was also confirmed by the monitoring, with internal air r.h. generally contained between the intended limits of 40 and 60%.

The degree to which the clay plaster was able to moderate moisture in the bathroom was greater than expected. These results indicate the potential of clay materials in this respect and that adequate predictive quantitative models are not available to facilitate sophisticated design for moisture regulation.
5.4 Design for Thermal Performance.

Thermal insulation was not a significant factor in the selection of the earth materials. However it was intended that their position inside the insulation layer would lead to a thermal mass effect, absorbing passive solar gain and balancing thermal fluctuations. This was not quantified in the design stage, as only static thermal resistance calculations are required for regulatory approval. The standard SAP (thermal efficiency) calculation is shown in Fig. 18. This tool predicted that the building would perform reasonably well, but not exceptionally. The SAP calculation has limitations as a predictive design tool, being perhaps overly effected by assumed fuel usage costs, heating system and static energy calculations.

Fig. 18. The SAP Calculation.

In the event, the annual energy consumption of the building was 45% greater than predicted by the SAP calculation, 66.5GJ compared to 46GJ. This was attributed to the occupancy characteristics, in particular very high levels of natural ventilation.
5.5 Design for Acoustic Insulation.

The materials were designed to give some level of sound insulation, particularly between the bedrooms. The sound insulation of internal walls was estimated as 44 - 48 dB Rw (mean value across 100 - 3150 Hz range). In the event this value was not achieved, primarily because of flanking transmission, but the occupants were satisfied with the performance.

5.6 Design for Internal Air Quality.

Apart from the control of relative humidity, there are a range of known benefits of unfired clay materials including removal of airborne pollutants and insulation from electro-magnetic radiation. These were secondary benefits acknowledged during the design stage, but they were not quantified and did not form part of the monitoring exercises.

5.7 Design for Structural Performance.

The ability of the earth walls to carry structural loads was considered during design, but this was not utilised for ease of construction. While the earth walls are essentially non-loadbearing, they do help to brace the external timber frame.

5.8 Design for Buildability.

The materials were intended to be used by standard trades people with standard tools and equipment. Rates for building were intended to be comparable with that for fired brickwork. Waste rates were predicted to be comparable, but with brick waste returned to the manufacturer for recycling. The materials were predicted not to represent any occupational health hazards during construction, though abrasion and skin damage were anticipated to be less than with fired bricks and cement mortar. Mould was not anticipated to present a problem.

In the event, performance was generally in line with expectations, though brick waste could not be economically returned to the manufacturer and the plaster presented some difficulty for the inexperienced plasterer.

5.9 Design for Durability.

Durability was anticipated to be adequate, though less good than with harder materials. A variety of finishes were to be used, including self-finishing clay plaster, painted plaster and painted brickwork.

In the event, only the self-finishing clay plaster was used and durability was impaired by the low quality of plasterwork, caused by the inexperience of the plasterer. However, despite a persistent low level of plaster surface dusting and some impact damage to the clay plaster, the clients were happy with the materials. Screw fixings proved generally suitable for minor fixtures.

The plaster will be painted with a suitable microporous coating to reduce dusting in some areas. The clients are content to carry out occasional minor repairs to the plaster to make good abrasion damage. In the future they will consider painting some of the bedrooms with a suitable microporous paint for aesthetic variety.
6. THE CONSTRUCTION EXPERIENCE

The performance of the unfired clay materials was monitored during construction, which occurred between June and September 2003. By allowing the earth construction to happen once a weathertight envelope had been established, most problems of earth materials coming into contact with water were avoided.

6.1 The House as a Test of the Construction Process.

The construction was carried out by local, inexpensive commercial tradesmen, who had no previous experience of using earth materials and only a very brief instruction on how to use them. Site supervision was scant and quality control mechanisms were minimal. As such, the construction process was a robust test of the ability of the materials to be used in the sort of conditions that are common to low cost construction projects within the U.K.

The involvement of a range of people from the Advisory Group as well as the BBA in the monitoring of this process gave a broad base for the assessment. The study of another building built using similar materials around the same time, at Branshogle in Stirlingshire, gave the comparison of a project with higher standards of training and management control. While the use of the materials in both constructions was essentially successful, useful lessons were apparent which could inform manufacturing and construction processes.

6.2 The Bricks.

The Errol Eco-Bricks generally performed well, being easy to use and robust, though a few minor problems were noted.

The packaging and transport used for the bricks led to the creation of dust through rubbing in transport and this was a minor problem. The materials could not be off-loaded by a lorry-mounted hi-ab as this would have crushed the bricks and a forklift had to be hired.

The arrangement of holes in the bricks led to some difficulties in achieving fixings. Most unfired clay bricks on the market do not have holes and avoid these problems. The use of sawdust as a fibre in the bricks increases their vulnerability to moisture due to their expansive nature, though this did not prove to be a problem.

These comments are specific to these products and are minor issues that could be addressed by improvement to the manufacturing process.

Wood working tools proved appropriate when dressing and fixing into the bricks, for example creating curved corners to window ingoes.

Appropriate specification of moisture content and good quality control of associated timber components, for example lintols, was demonstrated to be important to avoid defects due to differential movement.

The contractor's reaction to using the materials was positive, with the lack of abrasion seen as a benefit.
6.3 The Mortar.

The Errol clay mortar generally performed well, being easy to mix and giving adequate strength. The mortar’s re-cyclability is reduced by the lignosulphate content and this may also impede the drying process, though no evidence of this was collected.

Further research would be merited into clay mortars as there seems to be a significant variation in performance between different materials. It should be noted that the performance demanded of clay mortars in this type of modern thin wall construction is far greater than that required in traditional construction which are generally much thicker. This is especially relevant to flexural bond strength.

6.4 The Plasters.

The plasters generally performed adequately, though final quality was impaired by the inexperience of the contractor.

There was some evidence of inadequate protection during transport allowing moisture to cause caking of the undercoat plaster.

The plasters achieved an attractive appearance that the occupants liked, though local dusting and cracking may lead to some walls being painted with a suitable microporous paint.

It had originally been intended that some of the plaster would be painted and some brickwork would be unplastered but painted. In the event, because of the cost effectiveness of ordering plasters in bulk, all the earth bricks received a two coat, self-finishing plaster.

Clay plasters differ significantly from the commonly used gypsum plasters in that they set by drying rather than chemical action and this takes more time. The rate of drying relates to the size of room, the type of substrate, the rate of ventilation, whether there is heating, and climatic conditions. In order to effectively plan the works a plasterer needs to understand these various factors.

The plasterer did not have such experience in this case and he became frustrated by the plasters variable rates of drying. Clear guidance should therefore be given to inexperienced contractors on this so that the works can be efficiently planned.
The self-finishing clay plasters do not lend themselves to a polished finish, which is what most plasterers are accustomed to achieving. An open pored surface facilitates air drying, which can be achieved with a wood or sponge float. Steel floats tend to produce a polished surface and, if this is over-worked, separation of the fine sand and clay binder can occur, which leads to a friable surface and dusting when the material dries. Such defects were evident in this project. Clear guidance should be given on avoiding this problem. Sample areas should be used as a standard control mechanism.

There was a minor problem with cracking linked to differential substrates, usually timber beside brick. Good practice in the use of scrim minimises this problem and guidance should include this.

6.5 Health & Safety.

All the earth materials represented low risks from a health and safety point of view. The risk of silicosis can be minimised by dust minimisation (see 3.2). The clay plasters were heavier to work than gypsum plasters.

6.6 Site Management.

There were problems with the transport of the bricks, which were taken to Stirling, offloaded, stored overnight, re-loaded and delivered to site. This involved significant extra mileage and handling and it is know that during this time there was heavy rain and the bricks were inadequately protected. This may have been the cause of some of the shrinkage problems.

Off-loading of the bricks required a forklift and this may preclude use on some sites. The materials were adequately protected by tarpaulins for temporary external storage. Prolonged storage should be internal as condensation can occur under tarpaulins. The materials were raised off the ground to prevent damage by rising damp.

6.7 Construction Skills.

The skills of normal bricklayers were demonstrated to be adequate for the construction of earth brick masonry. The different working characteristics of the bricks and mortar were adequately conveyed with brief guidance on site of 5-10 minutes duration. The bricklayers readily adapted to the use of the materials, without any reported difficulties.

The use of the plasters with a similar amount of instruction was less successful. While the skills of the plasterers were adequate in applying the materials, they did not have the experience of the variable drying rates of clay plaster required to effectively programme the works. This led to an inefficient use of time. The plasterers also tended to try an achieve a polished finish which is standard for other types of plaster but inappropriate for clay plasters and this led to minor defects, including dusting as noted in 6.4.
The plasterer did not ultimately enjoy using these materials, being frustrated by the slow drying of the plaster in small, poorly ventilated rooms, tired by the relatively heavy working qualities of the materials and dissatisfied with his efforts to achieve a suitable finish.

To achieve a more satisfactory outcome, training in clay plastering should be given to inexperienced plasterers and sample panels should be used to establish control of finishes.

6.8 Working with Other Trades.

There was some evidence of other trades people being sceptical of the working properties of the earth brickwork and this leading to difficulties on site. An example would be a heating engineer or plumber not wanting to fix equipment to an earth brick wall and asking for a secondary structure.

To avoid such problems, all trades people should be advised by the contract manager that such materials are to be used in the project and any implications for their work should be explained. Trades people without such guidance should not be on site if there is nobody available to give them guidance. Specific guidance to electricians is recommended regarding fitting of electrical boxes and conduit.

6.9 Waste Management.

Minimal waste was produced from the mortars and plasters. A small quantity of waste was produced from the bricks. There were varying quantities of unused materials, relating to the sizes of order units. While it has been thought that unused bricks and waste bricks would be returned to the manufacturer for re-use or re-cycling, this was not achieved as the cost of transport made it uneconomic. Only the excess lignosulphate mortar additive was economic to return to the manufacturer.

Other surplus earth materials were either used benignly in site landscaping or were set aside for use on other projects. The lack of waste was a notable feature of the use of these materials. Aside from the ecological benefits this had indirect benefits of a tidier site, a bigger working area, as little waste had to be stored on site, and reduced costs of waste disposal.

6.10 Cost Efficiency.

Neither of the projects studied was competitively tendered under normal contract conditions and so clear cost data is not available. However the whole construction cost of the Dalguise house of approximately £67,000 did represent 'low cost' construction.

Generally the clay brickwork costs were comparable with fired brickwork and rates of construction are also similar.

The clay plaster is more expensive as a material and in application. In recent years there has been an increasing variety of clay plasters imported into the U.K. with significant variation in cost. The development of clay plaster production within the U.K. could significantly reduce the cost of these materials. The cost of their application could be reduced by good planning and by spray application, which is common in other parts of Europe, but currently unusual in the U.K.
7. POST OCCUPANCY EVALUATION

Fionn Stevenson, MA, Dip Arch, ARB, ARIAS, University of Dundee

7.1 Aims and Objectives

A specific aim of the project was to analyse the resident’s response to the building over a period of time and relate the findings to the performance of the unfired clay bricks, using a Post Occupancy Evaluation (POE).

The objectives of the POE were to evaluate a number of physical comfort factors including:

- Heating
- Ventilation
- Lighting
- Noise
- General comfort issues

In addition, maintenance aspects were to be evaluated briefly to identify any correlations with the comfort factors.

7.2 Methodology

A number of different techniques were used to evaluate occupant responses including: physical interviews on site, telephone interviews, daily log sheets filled in by the residents and environment behaviour analysis based on the physical interviews and on site observations. The methodology was based on the author’s previous experience (Stevenson, 2002, 2004) as well as qualitative methodology by others (Watson, 2003, Leaman and Bordass, 1999, Leaman 2002).

A normative occupancy pattern was established at the first client meeting on 23rd October 2003, and a log sheet developed (see appendix 7A) with headings which correlated with factors over which the occupants had some control (opening windows, turning on the central heating, using the woodstove (see appendix 7B), using the ventilators, cooking, drying clothes etc) as well as those which they had less control over (unexpected weather patterns, visitors, unusual events).

The log sheets were collected at approximately four monthly intervals, using pre-addressed and stamped envelopes supplied by the researcher and combined with informal seasonal telephone interviews with the residents to cross check data.

The interview technique adopted was largely open ended in order to try and catch any nuances not obtained through the log sheets and interviews lasted about half an hour each time. The key physical comfort factors and maintenance aspects were covered along with any other observations that arose during the course of the interview.

Occasional site visits allowed the researcher to observe how the residents used the house as well as an independent assessment of the comfort levels.
The POE period was 12 months from November 17th 2003 to November 14th 2004 to account for all seasonal changes.

A draft POE report was prepared in early September 2004 and cross-related to the initial findings from the thermal, moisture and acoustic data obtained to that date.

7.3 Limitations of the Study

The study relied heavily on the user’s self-observations, which could not always be verified by the researcher, and the completion of the log-sheets was not always consistent. The recording on the log sheets became richer towards the end of the monitoring period, which proved to be very useful. Two out of 52 log sheets were not completed, although the missing sheets do not appear to cover a critical period. The telephone interviews relied to a large extent on the resident’s memory of the previous period, which again cannot be strictly verified.

The researchers observations of environment behaviour were strictly time-limited, providing only a snapshot analysis, and could not pick up any changes in behaviour in between the visits.

The research methods used combine qualitative analysis with quantification of the resident’s self-assessment. Although the methodology for the POE was not strictly verifiable, it provided data-rich results and a useful referent for the monitoring study. The two areas of research were cross-correlated to provide a degree of verification.

7.4 Occupancy Patterns

The residents in the house consisted of 2 adults and 2 children (one aged thirteen years and one aged ten years). The children attended School between 8.30p.m.-4p.m. during term time and were out of the house for this time period during the week. The children were more present in the house during the holiday periods and especially the six-week summer holiday period in July and August. The adults were generally out of the house from Monday to Wednesday. Weekends tended to be busy with numerous visitors both during the day and evenings. Informal social events, sometimes with up to 15 children during the day, or 8-10 adults in the evening, general took place at least once a week.

The residents stated that the main meal usually took place in the evening at about 6p.m., with soup sometimes for lunch. Resident usually showered once a day, averaging three showers a day over the year. There was no bath.

Clothes were continually drying in the house over the winter period as well as some of the summer period.

The house was empty from:
7-8th February 2004
2nd-4th April 2004
27th- May -4th June 2004-09-05

An additional adult joined the household from 23rd May 2004 for a period of approximately 6 months.

7.5 Heat

The insulation in the house was to a high standard (200mm cellulose in the walls, 120mm dense polystyrene in the floor, 220mm cellulose in the roof) combined with double glazed, low e, windows. The insulation was, unusually, placed on the outside of the thermal mass, despite the house being of timber frame construction. The 100mm width of unfired clay brickwork panelling and clay plaster together with a central stone hearth and chimney feature provided a high degree of thermal mass through out the house.
Heating for the house was provided by a centrally situated small woodstove and underfloor wet pipe central heating beneath wooden floorboards on the ground floor. The open plan nature of the house meant that the woodstove and underfloor heating also provided heating for the first floor spaces.

The woodstove was the only source of heat until the central heating was fully commissioned, some three days after the house was occupied and although, by itself, it kept the main areas warm, it did not heat the bedrooms to the required comfort level.

The residents generally kept the central heating on all the time during the winter months, with the thermostat set to 21 degrees in the living room and 19 degrees in the bedrooms in the first winter period. The residents appear to have treated the heating system in a relatively simple way, with little variation in the thermostat settings to compensate for temperature changes. Additional ventilation was used to cool the house rather than lowering the thermostat, which may have resulted in unnecessarily high heating bills, which were 45% higher (66.5 GJ for the year) than predicted for this type of house (46 GJ for the year) according to Taylor, 2004.

Given the exorbitant heating bills that the residents had been used to receiving in their previous traditional cottage, they were quite happy with the amount of energy required to run the new house and this might account for their relatively relaxed attitude to ventilation, lighting and heating which meant that the house was not running at optimum energy efficiency.

One point of interest is that the residents turned down their thermostat to 20 degrees when they switched the central heating back on in October 2004, indicating a modification of behaviour in response to the thermal performance of the house. The residents also acknowledged that they had been through a “learning curve” in terms of understanding the slow response of the building to heat input. In the first winter period they simply left the central heating on high, finding the heating regime hard to adjust, but in the second winter period they felt able to keep the central heating at a temperature slightly lower than they would have wished, but to top it up when necessary with the wood stove, which had a “huge effect” in the winter evenings. In effect the residents were unconsciously using the quick radiant response of woodstove as a way of modifying the slower thermal response of the building to the central heating changes.

The residents turned the central heating off completely on Wednesday 3rd March 2004, which is surprisingly early for a house situated half way up a hill in Perthshire at a latitude of approx 56 degrees. It was not turned on again until 9th October, seven months later, and then only briefly for a day. The central heating was finally turned on permanently on 21st October.

The woodstove was used all day with periods of 1-3 days in between for most of the winter until the middle of February 2004, at which point the period in between lengthened to 3-6 days until the beginning of March and then roughly 8 days until it was last used on 20th March 2004. It was first reused on 10th October for a few days and then intermittently for one or two evenings a week until the end of the monitoring period.

The residents felt that the quality of heat in the house was generally very even over the course of the days and seasons, with the same continual level of comfort experienced. The walls felt warm to the residents but not unpleasantly so. They did not experience the walls radiating heat and detected a noticeable difference in the air quality between their house with its central heating and friend’s houses with central heating, commenting that the air quality felt better in the house with the unfired bricks and not too dry. The average relative humidity lay between 40-60% for the whole
year, which is close to the ideal average of 50% for health and comfort (Taylor, 2004b). This may be in part due to the particular hygroscopic qualities of the clay brick, although this is difficult to prove given the complex interaction of other factors operating in the house, such as ventilation and heating.

Some degree of overheating was experienced upstairs when large numbers of people were accommodated in the house for social events, although this was not experienced downstairs. The house felt nice and dry to the residents at all times, despite the exceptionally wet weather experienced during some of the summer months.

It became apparent during one of the interviews that the residents had six 20-watt halogen spotlights in the kitchen, which were left on in the day “a lot”. This effectively provided a certain amount of background heat once the central heating and woodstove ceased to be used and may partially account for the high degree of comfort experienced despite the wet summer weather. The lighting in this area was effectively acting as a small heater. The same effect applied in the shower room, which also had three 20-watt halogen spotlights. The combined effect when all halogen lighting was on, added up to 200 watts.

It had been anticipated that the addition of the large south-facing veranda in Spring 2004 would have added considerably to the overheating effect in the summer by pre-heating the air entering the house. In fact, a solar path analysis (Fig 56 ) revealed that the main solar radiation, even in the summer, fell on the roof area of the house rather than the conservatory.

7.6 Ventilation

The ventilation to the house consisted of manually operated fans in the kitchen and shower room, combined with trickle ventilators on each window as well as all windows being openable and two openable doors on opposite elevations.

During the initial drying out period for two or three months, windows and trickle ventilators were kept open all the time to aid the drying out of the plasterwork. There was some initial condensation on the inside of the windows but this reduced as the plasterwork dried out. Windows were opened on an intermittent basis during the day only throughout the winter and spring. The trickle ventilators were generally kept open in the bedrooms but shut in the kitchen and living areas during the same period.

Once the weather became warmer, the upstairs bedroom windows were left open on a 24 hour basis during the whole summer and much of the autumn. The downstairs windows in the house
were also generally open during the day for a period once the central heating had been turned off for the summer. The front door was also open all day from late June 2004 onwards in order to avoid overheating at times.

The residents’ ventilation regime changed once the weather turned colder in October with the windows downstairs being opened on a more intermittent basis and closed at night. The upstairs bedroom window continued to remain open most nights until the end of the monitoring period.

The shower room fan was deliberately switched off for one week commencing 27th September in order to help measure the actual moisture absorption of the clay bricks more effectively. The residents reported that the bricks absorbed the shower moisture very well and dried out again after a couple of hours. There was a noticeable smell of the plaster while this was happening.

One of the residents readily acknowledged that she was “used to living in a draughty old house” and that she liked to “sleep with the bedroom windows open” not so much to reduce the heat but simply to have access to fresh air. This is a common cultural attitude in Scotland (Stevenson, 2004) and illustrates the influence of living in a traditional stone cottage on the residents’ subsequent behaviour in an entirely different house type, which demands quite different responses to ventilation and heating from the residents.

7.7 Light

The residents felt that the house was nice and airy, with reasonable daylighting levels. The researcher experienced the same comfort level with the daylighting downstairs, although the upstairs rooms had lower daylighting levels than downstairs due to the relatively smaller window areas. It was therefore a surprise to discover that the kitchen spotlights were left on for such a length of time during the day throughout the year.

7.8 Acoustics

A separate acoustic test was carried out (Charlton Smith, 2004) in addition to the POE, for airborne sound transmission between two rooms on the ground floor, effectively testing the degree of sound-reduction that the 100mm clay brickwork panel offered.

The residents themselves felt that although the sound proofing between the bedrooms and the main living area on the ground floor was very good due to the use of the brick, the upper “loft” rooms suffered from noise emanating from the kitchen/dining/living area due to the open plan nature of the house. The floors were also perceived to be less soundproof than the internal partitions.

Acoustics were generally satisfactory apart from the issues related to the open plan design. The residents intend to build an earth brick partition between the kitchen and living area as well as a partition between the upper “loft” area and the open double height space, to reduce the noise problems. The flexible plan of the house allows for this.

7.9 Comfort Issues

In general, the residents appeared to be very comfortable in their new house and were impressed by how warm it had been during cold or damp periods.
There would appear to be a degree of overheating in the summer, given that the residents felt the need to keep not only all the windows open but also the front door in order to obtain enough ventilation. The overheating was primarily in the upper level, where warm air accumulated and may have formed a "cushion" of heat despite the windows being open. Overheating was only really noticed by people sleeping or working upstairs when there were large numbers of people in the house, generating additional heat.

The residents were generally happy with the humidity levels in the house, feeling it to be "nice and toasty", despite a large amount of clothes drying continuously in the house over long periods. This may indicate that the clay plaster and unfired clay brick panels have successfully absorbed and desorbed excessive moisture in the indoor environment, giving a good degree of comfort. This again is hard to verify given the difficulty of separating out the changes due to rapid ventilation, which is much swifter and stronger, and those due to absorption/desorption.

7.10 Maintenance Issues

The residents have found the cleaning and maintenance of the house to be very straightforward.

There has been some scoring on the clay plasters due to wear and tear, but this will be filled in with a top coat at the end of the defects period.

There has been a degree of sand emanating from the plaster finishes in the bedrooms and shower room. The same problem did not occur in the living room, where an improved plastering technique was used. The problem of the loose sand on the surface of the plaster increased during the course of the monitoring and was attributed by the residents to a poor understanding of how to apply the plaster in the first place by the plasterer.

The residents noticed the smell of the plaster in shower room when there was a significant amount of moisture present, but the plaster always dried out well.

Drip marks have formed on the plaster finish by the bath and sink due to splashes and these areas are planned to be tiled in the future.

7.11 Conclusions

1. The use of daily logging sheets was not wholly successful as the residents did not complete these on time and tended to complete them retrospectively. Their accuracy cannot therefore be relied upon. The use of interviewing was more successful and revealed some surprising data.

2. The level of resident satisfaction with the performance of the house in terms of comfort appears to be high, with the exception of acoustics and a degree of overheating in the summer due to large numbers of visitors. The high degree of insulation in the house resulted in no heating being used (apart from the lighting) from the end of March 2004 until the beginning of October 2004, which is an impressive result given the high latitude.

3. The indication of overheating in the upper floors is a more surprising result, given the amount of thermal mass present in the house (solid stone chimney stack and 100mm clay brick walls with a density of 216 kg/m$^2$). Given the thickness of the clay brick walls (100mm) a thermal time lag of 4-6 hours was anticipated, which would have released stored daytime heat over the course of the evening during winter, spring and autumn. In fact, the time lag for the bricks was only 2 hours on average (Taylor, 2004). In the Summer, solar gain may well have remained relatively high until quite late in the evening given the degree of latitude, which could have resulted in heat being released during the night, making sleeping less comfortable. The solar gain was moderated by the temperature however, which was cooler for much of this particular summer.

4. Although the clay brick had a relatively high content of sawdust (30%) and voids (16%), which reduced the density of the brick by 16% compared to a normal brick, this did not significantly
affect its thermal capacity. There is no internal thermal mass to absorb the heat in the upper part of the house, which is effectively all timber frame and insulation and this may be contributing to the overheating experienced.

5. The heat rises to the upper levels in the house because the lower windows and door provide a greater ventilation area than the upper windows and the cool incoming air from the lower windows will force the hot air up through the double height space which acts as a thermal chimney. This will have added to the overheating experienced in the “loft” areas and thick insulation in the roof effectively acting as a “blanket” to keep heat in during the warm summer months.

6. The residents’ response to the overheating problem was to open the upper windows on a continuous basis. This approach was also adopted during the period that the central heating was on, indicating a large degree of over ventilation leading to unnecessary additional heating having to be provided. This is partly a cultural issue, but it is also a design issue given the build up of heat in the upper sleeping area in both the summer (due to solar radiation) and winter period (due to central heating).

7. The problems experienced with overheating in the summer will increase over the years given the predicted rise in temperatures for Scotland due to Global Warming.

8. The only maintenance issue that appeared to be of concern was the loose sand coming away from the plaster finishes in some of the rooms.

7.12 Recommendations.

1. Training of residents in energy/heat/ventilation management:
   It is important that the residents appreciate the additional heat load added by the halogen lamps in the kitchen and the inefficient use of the central heating. More use could be made of the room thermostats to help control temperatures rather than relying on additional ventilation. This is particularly important when residents are moving from old traditional stone “draughty” housing to new, highly insulated housing.

2. Increasing ventilation at the upper level of the house:
   Additional ventilation in the form of openable roof lights on the north face of the roof may help to overcome overheating at night by effectively displacing the warm air cushion which accumulates at ceiling level during the night.

3. Shading to the south elevation: The use of shading which blocks out sunshine in the summer to south facing windows may assist in controlling potential overheating. This could take the form of deciduous planting separate from the house or fixed shading devices.

4. Acoustic separation of upper “loft” areas:
   The upper “loft” areas were designed to be adapted into rooms but will require acoustic separation from the living area if noise problems are to be addressed. It is anticipated that the residents will carry this out in due course. This acoustic separation may also help overheating in the “loft” areas by preventing the cushion of warm air from the living spaces accumulating in these areas.

5. Overheating at high latitudes and in temperate climates:
   A particular thermal problem for housing in Scotland is the relatively high temperatures, which can persist until quite late in the evening in the summer months, (compared to winter) followed by a contrastingly cold night, giving a relatively high diurnal variation. An obvious solution is to combine thermal mass with greater levels of insulation. On their own, however, these measures

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1 According to Taylor, B, density of brick reduced by 16% and specific heat of brick increased by only 5%. The net effect of these two changes is admittance is reduced by only 1.4%. This is therefore a negligible change in the heat storage capabilities.
will not necessarily prevent overheating unless an adequate shading and ventilation strategy is in place.

6. **Overheating in relation to design layout:**
The provision of double height space in an open plan will require careful consideration to mitigate against the thermal chimney effect this provides leading to potential overheating in the upper areas. The positioning of thermal mass maybe critical in this respect and should be provided for at both lower and upper levels of a house. Separating the upper “loft” areas from the rest of the house with heavy partitions may help to alleviate some of the overheating.

7. **Clay plaster finishes**
The residents were clearly concerned about the continuing sand leeching out of the plaster finishes in the bedrooms, Until the construction industry is used to working with clay plasters they felt it was important that plasterers were pre-trained before commencing use of the plasters on a project.

8. **Install solar panels on SW roof**
It has been suggested by Taylor that the installation of solar panels on south facing roofs can prevent the solar energy from reaching the roof and help to keep it cool in the summer. The panels could be placed over the areas that are critical to avoid overheating. This would need further research.
Appendix 7A: Post Occupancy Log Sheet  
(CLIENT OBSERVATION)

Please fill this log sheet in on a daily basis, at the same time each day. We are interested in anything that you do that is unusual for your normal occupancy patterns. We will issue you with 52 log sheets in a folder and pre-paid envelopes. Please keep them in a safe place and forward the completed sheets to Fionn Stevenson at the end of each month for analysis. We will return copies to you. If you have any queries or problems contact: Bruce Taylor -01224-263541 (e-mail: b.taylor@rgu.ac.uk) or Fionn Stevenson 01382-345262 (e-mail: f.z.stevenson@dundee.ac.uk)

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<tr>
<th>Date</th>
<th>Week 1</th>
<th>17th Nov 2003</th>
<th>1. Occupancy Pattern Deviation – extra people or empty house</th>
<th>2. Exceptional use of Cooker (e.g. all evening/all day) or clothes drying inside</th>
<th>3. Exceptional use of Bath/Shower – extra people, or long use</th>
<th>4. Comfort level – exceptionally cold or hot (thermostat turned higher?)</th>
<th>5. Exceptional use of windows/trickl e vents – open for long periods</th>
<th>6. Daily Use of Woodstove Yes/No Approx Duration (hours)</th>
<th>7. Other unusual observations (moisture/thermal/construction related)</th>
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Additional Information Required:
Could you please forward/copy all your bills for the underfloor heating (oil costs) to Fionn Stevenson (together with log sheets) when you get them so that we can check them against the monitoring. Can you record the electronic oil level (from 1-9) at the end of each month here:
Appendix 7B: Log of Woodstove Use

The woodstove was used on the following dates

21.11.03
8.12.03
9.12.03
12.12.03
15.12.03
22.12.03
24.12.03
27.12.03
1.01.04
2.01.04
4.01.04
6.01.04
9.01.04
11.01.04
19.01.04
21.01.04
5.02.04
10.02.04
17.02.04
20.02.04
23.02.04
4.03.04
12.03.04
20.03.04  Last use of woodstove until 10.10.04

13.10.04
14.10.04
15.10.04
17.10.04
18.10.04
19.10.04
20.10.04
27.10.04
9.11.04
10.11.04
12.11.04

Central heating switched off from 3.03.04 until 9.10.04
8. MOISTURE PERFORMANCE.

by Bruce Taylor, B Sc, M Sc, C Eng., MIMechE., the Robert Gordon University, Aberdeen

8.1 Introduction

In this project there was a requirement to assess the extent to which the hygroscopic properties of the unfired clay are able to regulate the relative humidity of the air in an occupied house and whether there is any interstitial condensation risk with this type of wall construction. This report describes the monitoring of the moisture performance of the walls and the house over a period of one year.

8.2 House Construction

8.2.1 House Design

The ground floor plan of the unfired clay brick house at Dalguise is shown in Fig. 30.

The external walls comprise load bearing timber frame 50 X 100 mm studs. Frames are clad externally with breathing sheathing board (9.2 mm Panelvent), with Cladshield breather membrane. The timber rainscreen cladding is larch heartwood weatherboarding. The inner brick leaf is unfired clay brick finished with 12mm clay plaster. The cavity is filled with 200 mm cellulose insulation.

The ground floor is 150 mm thick concrete slab on the ground with 120 mm dense polystyrene insulation, 70mm concrete screed and 20 mm thick tongue and grooved flooring.

The roof is slate fixed to "Roofshield" breathing felt on 20 mm thick softwood sarking. The cavity between the sarking and the 12.5 mm plasterboard lining is 220 mm cellulose insulation.

The bathroom is equipped with a shower and not a bath. A shower can have higher moisture generation rates than a bath depending on length of shower and preferred water temperature. The bathroom extract fan is manually operated. It is not controlled by a humidistat.

8.3 Measurement procedure

8.3.1 Heat

The indoor air temperature of the chosen rooms and outdoor air temperature, the plaster surface temperature, the temperature of the air cavity in the brick, the temperature at the brick/insulation interface and the temperature at the insulation/sheathing interface were measured at 15 minute intervals. The temperature of the rear of the brick and the room air temperature define the boundary conditions for calculating heat flow and heat retention through and within the brick/plaster wall. These temperature measurements were supported by a heat flux measurement on the north west wall surface of bedroom 1.

Appendix 8A is a schedule of the instrumentation.

The location of the instrumentation is shown in Fig. 30.

8.3.2 Moisture

In a similar way to the measurement of flow and storage of heat, moisture flow and storage will be monitored by logging the indoor RH of the air in the space and outdoor RH, the RH of the cavity in the brick and the RH at the ply/insulation surface. The RH and temperature of the rear of the insulation and in the room define the boundary conditions for calculating moisture flow and moisture retention through and within the insulation/brick/plaster wall.

The bathroom is the space that will see humidities approaching saturation and hence the most likely place to see moisture absorption in the wall. Fig. 31 shows the instrumentation installed in
the bathroom. The limited area of external wall meant that the chosen location underneath the
extract fan whilst not ideal was the best that could be achieved.

The bedrooms were also instrumented because they too can have high humidities if not ventilated.

8.4 Data analysis

Logging commenced on 19th November 2003 at 13:01 hours and finished on 19th
November 2004, 13:59 hours.

Logging temperature and humidity measurements every 15 minutes is sufficiently fine for
detecting thermal lags of around 3 to 4 hours that might occur diurnally. However, the raw time
series data comprises random fluctuations on several trends of durations from 24 hours to one
year. It is necessary to separate out these trends from the raw data. It was found that a 20 day
(1,920 point) moving average revealed the long term (yearly) patterns in the humidity data (Figs 32
to 35)

The moisture content is of more significance for understanding the movement of water through the
building envelope since humidity changes due to a change in temperature as well as the addition or
removal of water vapour. The moisture content of the air at a measurement point is calculated
from the temperature and relative humidity at that point and atmospheric pressure at that time all
of which have been measured and logged. The moisture content inside the brick, typically 60 mm
from the inner wall surface, is the moisture content of the air around the temperature and humidity
probe which will be an average of the moisture content in the surrounding brick and mortar
material.

The time scales are plotted as event numbers, which correspond to the logging intervals. On the
20 day moving average the graphs begin on 9th Dec at 13:00 hours and the milestone events are
correlated with time in Table 3. Conveniently event number 10,000 is the day before the central
heating is switched off.

Table 3

<table>
<thead>
<tr>
<th>Event No</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19/11/2003</td>
<td>13:01</td>
</tr>
<tr>
<td>1920</td>
<td>9/12/03</td>
<td>13:00</td>
</tr>
<tr>
<td>5,000</td>
<td>10/1/04</td>
<td>15:31</td>
</tr>
<tr>
<td>10,000</td>
<td>2/3/04</td>
<td>21:19</td>
</tr>
<tr>
<td>15,000</td>
<td>27/4/04</td>
<td>10:30</td>
</tr>
<tr>
<td>20,000</td>
<td>18/6/04</td>
<td>16:35</td>
</tr>
<tr>
<td>25,000</td>
<td>9/8/04</td>
<td>19:32</td>
</tr>
<tr>
<td>30,000</td>
<td>30/09/04</td>
<td>23:10</td>
</tr>
<tr>
<td>34,762</td>
<td>19/11/04</td>
<td>13:59</td>
</tr>
</tbody>
</table>

8.5 Results

8.5.1 Overview of the year

The moisture performance of the clay brick walls and the house as a whole are dependent on the
occupants, their lifestyles and the weather. To provide insight into the monitoring data the
occupants kept a log of domestic events and experiences. Full details of this post occupancy
evaluation (POE) will be reported separately (Stevenson, 2004). However, significant time periods
identified from the post-occupancy log sheets are summarised in Appendix 8D.

The local weather was recorded for the whole year from basic meteorological measurements,
outdoor air temperature and humidity and atmospheric pressure. To supplement this the
significant weather events in Scotland were noted and are summarised in Appendix 8C together
with edited extracts from the BBC’s weather archive for Scotland.
This weather archive provides insight into the very significant rise in the humidity and moisture content of the outdoor temperature during the summer between 28 July (Event No 23786) and 19 August (Event No 25970) (Fig. 32.). From the BBC’s review of Scotland’s weather (BBC, 2004a) the weather for July was summarised:

“Unsettled westerly weather dominated the month with high pressure not making an appearance until the last week [25th to 31st July] bringing much fine weather. However, there were no major episodes of rain and days of frequent or heavy showers were rare.”

In contrast to relatively dry July, August was a very wet month, particularly from 9th to 13th, 15th to 19th and 26th to 27th August. Torrential rain on the 11th August (Drever, 2004) caused a landslip on A9 two miles south of Dalguise.

8.5.2 Condensation Risk

The interface between the cold side of the insulation and the Panelvent sheathing is the most likely place where interstitial condensation will occur. The maximum, minimum and average humidities from 19th Nov 2003 to 19th Nov 2004 are shown in Appendix 8B and indeed some of the highest humidities occur at the sheathing (90.75% RH for the NW in bedroom 1) but there is no evidence of condensation having occurred there or anywhere else in the wall throughout the whole year. This has been a year in which the weather was conducive to causing interstitial condensation with some very cold and some very wet periods.

8.5.3 Twenty-day Moving Averages of Relative Humidity

When the indoor air humidities are compared directly with each other (Fig. 32.) it can be seen that they all follow a similar pattern. The bathroom has the highest peak air humidity as to be expected (Appendix 8B) but when averaged over a twenty day period these sharp spikes in humidity are smoothed out. The bathroom has the highest average air humidity and the living room the lowest. The average humidity of the air in all the rooms reflects the pattern in outdoor air humidity but is about 20-30% RH lower.

Considering how the humidity profiles through the walls (Figs. 33. to 35.) they all show two general trends. The first is the increasing relative humidity as you traverse wall from inside air to the external air. The bathroom wall shows a slight deviation from this in that the humidity inside the brick is higher than bathroom air humidity. This is to be expected due to the higher moisture generation rates in the bathroom.

The second general trend is the humidities decrease through the winter into the summer and then start to rise again following the pattern in outdoor air humidity.

8.5.4 Moisture Content

The moisture content is of more significance for understanding the movement of water through the building envelope since humidity changes due to a change in temperature as well as the addition or removal of water vapour.

Fig. 36. shows the twenty day moving average living room and external air moisture content. There is a slight drying out of the living room air through the winter into the spring, which may be due to the reduction in water vapour being produced from the masonry walls. After the central heating is switched off on 3rd March (around event no 10,000) the moisture content increases slowly following the trend in the moisture content of the outdoor air. As air increases in temperature it can hold more moisture. The very wet August causes the moisture content of internal and external air both to rise sharply and subsequently to fall back.

From the 3rd May until 19th Sept inclusive it was warm enough to dry clothes outside. Therefore from event no 15600 to 28900 one source of moisture into the living room air is removed. This may explain why the living room air moisture content rises more slowly in the spring than the external air and holds up in the autumn. During the wet August clothes drying will take place indoors which would explain why the indoor air moisture content suddenly shoots up and then
down again as drier weather returns at the end of the month. If the windows are open during this wet period as is likely this will also account for why the indoor and outdoor air moisture contents closely follow each other.

The moisture content of air at the measuring point inside the brick is an average of the moisture content of the surrounding brick material. This is where evidence of water vapour storage and release is likely to be found. Fig. 37. compares the moisture content inside the bricks for the bedrooms and bathroom external walls. They start with a very similar moisture content which dries out rapidly at similar rate in all three locations through to the middle of January (just after event no 5000). Surprisingly the bathroom wall moisture content is lower than that in bedroom 1 wall. During this first phase of drying out the moisture content of the internal and external air is approximately constant.

The second phase of drying out occurs from February through to the end of April. As the wall dries out it is to be expected that the rate of evaporation of water will slow down. Fig 38. shows that during this period the moisture content inside the brick is starting to be influenced by the external air. The rise in brick internal moisture content is about six weeks later than the rise in outdoor air moisture content. However, this time shift is not replicated for other major changes in outdoor air moisture content over the remainder of the year.

8.5.5 House in Free Running Mode

A period when the family are away provides insight into on how quickly the bathroom wall responds to changes in moisture content of the air. The period from 20 May to 9 June 2004 which covered the time the family were on holiday from Thursday 27th May to Friday 3rd of June when there was only one person in the house (Appendix 7D). When the family returned on 9 June there was a lot of showering and clothes washing according to the POE log sheets.

Bathroom

The family are away on holiday between event numbers 17,880 to 18,550 and only one person is remaining in the house. This relatively quiescent period can be seen on the four hour moving average plot for the bathroom wall (Fig. 39.). The sharp spikes in bathroom air moisture content are attributed to someone showering.

Bedroom1

It is assumed that during the week the family is away that bedroom 1 is unoccupied and that the window is shut there being no reason to ventilate that room. However, before and after the holiday the normal pattern of regularly opening the window in bedroom 1 is assumed to occur. During the period when the family are away on holiday the ventilation rate is most likely to be reduced to the natural infiltration rate through the building envelope and trickle ventilators if open, this is confirmed by indoor air temperature (Fig. 41) which is quite steady. This gives an opportunity to investigate how ventilation affects the indoor air humidity and moisture content.

Fig. 42. shows bedroom 1 air humidity compared with the outdoor air humidity for 20 May to 9 June 2004. During the holiday period [AB] the indoor air relative humidity is less volatile since there are no human sources of moisture within the bedroom1 and the window will be shut for most if not all of the time. This stability in indoor RH happens whilst there are very large swings in outdoor air RH. The indoor air humidity fluctuates around 45 % RH and the outdoor air fluctuates around 65% RH. The indoor air is drier primarily because it is warmer indoors than outside (average temperature \( \approx 22 \) °C compared with \( \approx 15 \) °C outside).

When the moisture content of the indoor and outdoor air is calculated from their respective temperatures and humidities, the moisture content of the indoor air is greater than that outside (Fig 43.). This is to be expected since warmer air can hold more moisture. Also both show a generally rising trend from event 17500. At the start of the holiday the moisture content of the external air shoots up quite dramatically and then falls back but the indoor air response to this change is much more subdued suggesting that bedroom1 window is shut.
Towards the end of the holiday period the indoor air moisture content drops rapidly closely following a similar drop in outside air moisture content. Is this indicating that bedroom 1 window has been opened to air the room before the family return from holiday? There is always this uncertainty about whether changes in moisture content of the internal air are due changes in the ventilation or moisture absorption/desorption at the walls. Large and rapid changes in internal air moisture content are most likely to be due to changes in ventilation since this bulk exchange of air will have an almost immediate effect compared with absorption and desorption at the walls whose rate is governed by molecular diffusion processes, which are much slower.

In Appendix 8E calculations show that water vapour diffusion through the brick and plaster will reach steady state in times of order 14 hours and 5 minutes respectively. The reason for the faster diffusion through the plaster is that it is much thinner than the brick.

The effect of ventilating the room was examined theoretically. The relative humidity was calculated for outdoor air at temperature $T_o$ and humidity RH$_o$ assuming it was heated up to the indoor air temperature $T_i$. This is shown plotted in Fig 44 as Internal Air Calculated (Int Air Calc), along with the measured internal and outdoor air RH. As the outdoor air is warmed up to the indoor air temperature its humidity drops to a level (approximately 30 % RH) which is significantly lower than the indoor air RH.

The effect of ventilation with outside air would be to lower the moisture content and relative humidity of the air in the bedroom or if there were sources of moisture in the bedroom, such as people and walls, this water vapour would be ventilated to outside so that an equilibrium moisture content of the indoor air would be established. Both ventilation and moisture absorption/desorption from the walls contributes to the room humidity levels.

The moisture level in the bedroom air during the holiday will be an equilibrium between moisture absorption/desorption from the bedroom walls and other sources of moisture in the house. This could account for the general increase in indoor air moisture content during the holiday period, however, there is always the possibility that background ventilation is also contributing to the increase.

### 8.5.6 Bathroom Extract Fan: Effectiveness of Moisture Removal

During the week beginning Monday 27 Sept the occupants switched off the bathroom extract fan in order to see if moisture absorption by the clay bricks and plaster could be detected. The mean level of moisture levels for this week and the weeks before and after are shown in Table 4.

<table>
<thead>
<tr>
<th>Week commencing</th>
<th>20 Sept 04</th>
<th>27 Sept 04</th>
<th>4 Oct 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Air</td>
<td>8.64</td>
<td>9.39</td>
<td>8.94</td>
</tr>
<tr>
<td>Brick/Internal</td>
<td>8.77</td>
<td>8.41</td>
<td>8.24</td>
</tr>
<tr>
<td>Sheathing</td>
<td>7.90</td>
<td>7.39</td>
<td>7.07</td>
</tr>
<tr>
<td>Ext Air</td>
<td>6.16</td>
<td>7.18</td>
<td>5.86</td>
</tr>
</tbody>
</table>

The mean moisture content of the air in the bathroom does increase slightly by 0.75 g/kg (less than 9% increase). This increase is less than half of the standard deviation (Table 5) of the variation in internal air moisture content so that statistically there is no significant change in the mean moisture content of the bathroom air during these three weeks.

<table>
<thead>
<tr>
<th>Week commencing</th>
<th>20 Sept 04</th>
<th>27 Sept 04</th>
<th>4 Oct 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Air</td>
<td>1.53</td>
<td>1.73</td>
<td>1.74</td>
</tr>
<tr>
<td>Brick/Internal</td>
<td>0.37</td>
<td>0.27</td>
<td>0.57</td>
</tr>
</tbody>
</table>
The mean moisture content of the brick interior decreases slightly by 0.36 g/kg, (4% decrease). This decrease is comparable with the standard deviation (Table 5) of the variation in brick moisture content so again statistically these are so close to be regarded as not a significant change.

Fig 45 shows the fluctuations in the moisture content of the air in the bathroom after subtracting off the mean levels for each of the three weeks. The period when the fan is switched off runs from Event No 29670 to 30245. Visually the period when the fan is switched is indistinguishable from the weeks before and after. This is rather surprising since it might have been expected for the peak moisture content in the air to be markedly higher when the extract fan was off. This is suggesting that the moist air being removed by the extract fan has little effect on the moisture content of the bathroom air. It has been observed that when the extract fan is not operating and the bathroom door is open that outside air flows naturally into the bathroom via the extract fan opening. Therefore there would appear to be continual moisture migration from the bathroom to the other interior spaces as well as absorption by the clay plaster and brick. However, when someone is having a shower the bathroom door is closed which will reduce the flow of moisture laden air to the other rooms. For most of the day the bathroom door is open. This means that air flows and hence moisture flows from the bathroom to the other spaces will be significant and therefore this will be a major route for the removal of moisture from the clay bricks in the bathroom.

The occupants have observed that there has never been surface condensation on the bathroom walls following showering (Stevenson, 2004). The POE log did not mention condensation on the window so presumably if it occurred it was not sufficiently serious to attract the occupants’ attention. Therefore it is likely that the main route for moisture removal from the bathroom air is by absorption in the clay brick/plaster walls. The extract fan would appear to be unnecessary for reducing moisture levels in this bathroom.

The brick interior (54 mm below plaster finish) showed a decrease in the mean moisture content of the brick interior during the week the fan was off but as stated above this is statistically the same as the weeks before and after. Therefore if moisture absorption is taking place in the wall it is happening much closer to the surface than 54 mm.

Fig. 46. shows the fluctuations in the moisture content of the brick interior and they are markedly more stable than the weeks before and after. This is confirmed by the standard deviation, which is only 0.27 g/kg during this period.

Desorption of moisture from the clay plaster to the air would take place more rapidly than moisture diffusion into the interior of the brick which is possibly why no change in moisture content is seen there. There is quite a large area of clay plaster in the bathroom to make this surface exchange hypothesis quite plausible. If correct this means that the range of materials for the substrate of the clay plaster could be expanded beyond that of unfired clay brick. It has to be emphasised that the above picture is a hypothesis suggested by the data and requires further research.

Beginning of Heating Season

The beginning of the heating season is another time when there is likely to be some movement of moisture in and out of the wall. Fig. 47. shows the moisture profile through the NW wall in bedroom from the 1st Oct through to the 19th November. The moisture content inside the brick follows the longer term trends of the bedroom air moisture content but shows a much reduced response to the short term (approximately 24 hours) fluctuations. This is indicating that it would take longer than 24 hours for the moisture content in the brick to reach its steady state level after a step change in the air moisture content.

8.6 Conclusions
There was no evidence of condensation having occurred any where in the bathroom and bedroom external walls throughout the whole year. There was no condensation on the bathroom walls during or following showering. This lack of condensation is particularly significant as it was a year in which the weather was conducive to causing interstitial condensation with some very cold and some very wet periods.

The occupants like fresh air and the windows are open a great deal of the time through out the year. There is also ventilation induced by the use of the wood burning stove in the winter and even when not used the chimney will provide a small amount of natural ventilation as warm air is vented through it. These natural ventilation routes mean that the indoor air humidity and moisture content very quickly changes in response to changes in the outdoor air. Natural ventilation will tend to reduce the moisture content and relative humidity of the indoor air.

Large and rapid changes in internal air moisture content are most likely to be due to changes in ventilation since this bulk exchange of air will have an almost immediate effect compared with absorption and desorption at the walls whose rates are governed by molecular diffusion processes which are estimated to reach steady state in times of order of 5 min for the plaster and 14 hour for the brick.

The smaller and slower exchange of water vapour between the internal air and the clay walls is masked in the data by changes in moisture content brought about by ventilation. Nonetheless, the difference in internal relative humidity from what could be expected in conventional domestic construction under these conditions indicates a moderating influence that could be attributed to the ability of the large surface areas of unfired clays to absorb and release moisture in response to changing conditions.

The most like place to see the ability of the clay bricks to temper the air humidity is in the bathroom where there are sharp increases and decreases in air humidity and moisture content. Contrary to expectations there was little difference in the pattern of changes of moisture content in the bathroom air when the extract fan was not operating suggesting that the main route for the reduction in the spikes in humidity during showering is by absorption in the clay brick/plaster wall. The extract fan would appear to be unnecessary for reducing moisture levels in this bathroom.
## Appendix 8A: Instrumentation Schedule

### Temperature Sensors

<table>
<thead>
<tr>
<th>Room</th>
<th>Sensor Position</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bathroom</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
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</tr>
<tr>
<td>Bathroom</td>
<td>Brick/Internal</td>
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</tr>
<tr>
<td>Bathroom</td>
<td>Brick - Insulation</td>
<td>116</td>
</tr>
<tr>
<td>Bathroom</td>
<td>External Sheathing</td>
<td>307</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Surface</td>
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</tr>
<tr>
<td>Bedroom 1</td>
<td>Brick/Internal</td>
<td>60</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Brick - Insulation</td>
<td>121</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>External Sheathing</td>
<td>291</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>Brick/Internal</td>
<td>61</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>External Sheathing</td>
<td>311</td>
</tr>
<tr>
<td>Living Room</td>
<td>Internal Air</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Humidity Sensors

<table>
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<th>Room</th>
<th>Sensor Position</th>
<th>Depth (mm)</th>
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<tbody>
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<tr>
<td>Bathroom</td>
<td>Internal Air</td>
<td>-</td>
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<tr>
<td>Bathroom</td>
<td>Brick/Internal</td>
<td>54</td>
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<tr>
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<td>External Air</td>
<td>-</td>
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<td>Bedroom 1</td>
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<tr>
<td>Bedroom 1</td>
<td>Brick/Internal</td>
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</tr>
<tr>
<td>Bedroom 1</td>
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<tr>
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</tr>
<tr>
<td>Bedroom 2</td>
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</tr>
<tr>
<td>Bedroom 2</td>
<td>External Sheathing</td>
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<tr>
<td>Living Room</td>
<td>Internal Air</td>
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</table>
## Appendix 8B: Humidity statistics 19 Nov 03 to 19 Nov 04

### Bathroom

<table>
<thead>
<tr>
<th></th>
<th>Min RH (%)</th>
<th>Event No</th>
<th>Max RH (%)</th>
<th>Event No</th>
<th>Mean RH (%)</th>
<th>Stddev RH (%)</th>
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</thead>
<tbody>
<tr>
<td>Br/Int</td>
<td>30.60</td>
<td>9884</td>
<td>99.90</td>
<td>26928</td>
<td>54.41</td>
<td>8.96</td>
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<td>Sheathing</td>
<td>44.75</td>
<td>10668</td>
<td>64.85</td>
<td>5</td>
<td>52.71</td>
<td>3.71</td>
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<td></td>
<td>52.75</td>
<td>17851</td>
<td>88.75</td>
<td>4825</td>
<td>67.62</td>
<td>5.78</td>
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<td>27/05/2004 06:08</td>
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<tr>
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<td>09/03/2004 20:19</td>
<td></td>
<td></td>
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</tbody>
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### Bedroom1

<table>
<thead>
<tr>
<th></th>
<th>Min RH (%)</th>
<th>Event No</th>
<th>Max RH (%)</th>
<th>Event No</th>
<th>Mean RH (%)</th>
<th>Stddev RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br/Int</td>
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<td>67.55</td>
<td>25067</td>
<td>52.66</td>
<td>5.35</td>
</tr>
<tr>
<td>Sheathing</td>
<td>53.05</td>
<td>20082</td>
<td>73.75</td>
<td>10</td>
<td>59.08</td>
<td>4.09</td>
</tr>
<tr>
<td></td>
<td>56.15</td>
<td>17687</td>
<td>90.75</td>
<td>939</td>
<td>69.77</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>29/11/2003 07:31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10/08/2004 12:07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19/11/2003 13:05</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Bedroom2

<table>
<thead>
<tr>
<th></th>
<th>Min RH (%)</th>
<th>Event No</th>
<th>Max RH (%)</th>
<th>Event No</th>
<th>Mean RH (%)</th>
<th>Stddev RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br/Int</td>
<td>33.80</td>
<td>9857</td>
<td>76.35</td>
<td>25073</td>
<td>52.37</td>
<td>5.35</td>
</tr>
<tr>
<td>Sheathing</td>
<td>47.80</td>
<td>12916</td>
<td>69.95</td>
<td>8</td>
<td>55.05</td>
<td>4.17</td>
</tr>
<tr>
<td></td>
<td>53.35</td>
<td>23603</td>
<td>84.75</td>
<td>11956</td>
<td>67.06</td>
<td>5.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26/07/2004 05:51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>05/04/2004 17:10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Living Room

<table>
<thead>
<tr>
<th></th>
<th>Min RH (%)</th>
<th>Event No</th>
<th>Max RH (%)</th>
<th>Event No</th>
<th>Mean RH (%)</th>
<th>Stddev RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int Air</td>
<td>27.65</td>
<td>9879</td>
<td>70.90</td>
<td>25352</td>
<td>48.56</td>
<td>5.77</td>
</tr>
<tr>
<td>Ext Air</td>
<td>24.90</td>
<td>17495</td>
<td>96.10</td>
<td>3296</td>
<td>75.35</td>
<td>11.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>23/05/2004 13:08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>01/03/2004 15:04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|          |            |          | 23/12/2003 21:24 |          |             |               |
|          |            |          | 13/08/2004 11:22 |          |             |               |
Appendix 8C: Significant Weather Events in Scotland – Nov 03 to Nov 04

<table>
<thead>
<tr>
<th>Period</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 2003</td>
<td>An exceptionally warm month for UK and Scotland in particular</td>
</tr>
<tr>
<td>Christmas 03 to 1 Jan 04</td>
<td>Cold snap, snow in Aberdeen</td>
</tr>
<tr>
<td>Tues 27 – Sat 31 Jan 04</td>
<td>Snow in Aberdeen. It will have layen longer at Dalguise</td>
</tr>
<tr>
<td>Sun 22 Feb – Thurs 4th March</td>
<td>Snow in Aberdeen</td>
</tr>
<tr>
<td>Sun 25 – Mon 26 April 04</td>
<td>Hot period</td>
</tr>
<tr>
<td>Monday 9th – Sat 14th Aug 04</td>
<td>Very heavy rain</td>
</tr>
<tr>
<td>Friday 19th – Sat 20th Nov 04</td>
<td>Snow in Aberdeen</td>
</tr>
</tbody>
</table>

BBC’s review of Scotland’s weather
15th to 22nd June
“A spell of northerly winds with cool and showery weather lasted from the 15th to the 22nd [June] there were only a few showers and the temperature fell to 2 ºC at Dalmally and Tulloch Bridge.”

BBC, 2004b summarised the weather for July:
“Unsettled westerly weather dominated the month with high pressure not making an appearance until the last week [25th to 31st] bringing much fine weather. However, there were no major episodes of rain and days of frequent or heavy showers were rare.”

In contrast to relatively dry July, August was a very wet month. Torrential rain on the 11th August (Drever, 2004) caused a landslip on A9 two miles south of Dalguise. BBC, 2004c describes the weather around this period:
“On the 9th fronts associated with a deep depression to the southwest of Ireland reached the southwest of Scotland and became slow moving. Much rain fell over the southern half of Scotland during the next 4 days .......................The depression eventually cleared away to the east on the 13th and a ridge of high pressure developed to give fine weather for a couple of days.”

15th to 19th August
Low pressure in the Atlantic extended its influence over Scotland on the 15th and unsettled weather with much cloud and some outbreaks of rain returned. A deep depression developed and moved northeast across the north of England on the 18th, pushing an active front and its associated band of rain north across Scotland. The rain was heaviest in places exposed to the east and 50mm was recorded at Loch Tay, close to the site of a landslide in Glen Ogle.

20th to 22nd
The depression was followed by cool northerly winds on the 20th and a broad ridge of high pressure on the 21st and 22nd. This gave plenty of sunny weather with the temperature at Tulloch Bridge falling to -1°C.

23rd to 31st
Unsettled and changeable conditions returned between the 23rd and 30th as two depressions passed close to Scotland, the first to the south and the second to the north. There was much rain overnight on 26th/27th with 50mm measured at Sloy. The month ended with a ridge of high pressure giving a sunny day on the 31st with the temperature falling to 0°C at Tulloch Bridge.”
### Appendix 8D: Significant Domestic Events

<table>
<thead>
<tr>
<th>Period</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon 8th Dec 03</td>
<td>Wood burning stove starting to be used extensively</td>
</tr>
<tr>
<td>Mon 22nd Dec 03</td>
<td>Start of School holidays</td>
</tr>
<tr>
<td>Mon 22nd Dec 03 to Sun 4th Jan 04</td>
<td>Lots of extra people in the house</td>
</tr>
<tr>
<td>Mon 5th Jan 04</td>
<td>Schools go back</td>
</tr>
<tr>
<td>Wed 3rd March 04</td>
<td>Central heating switched off</td>
</tr>
<tr>
<td>Sat 20th March 04</td>
<td>Last use of wood burning stove for winter season</td>
</tr>
<tr>
<td>Fri 2nd April 04 to Sun 4th April 04</td>
<td>House empty</td>
</tr>
<tr>
<td>Tue 6th April 04 to Sun 11th April 04</td>
<td>School holidays, all at home</td>
</tr>
<tr>
<td>Mon 19th April 04</td>
<td>Schools go back</td>
</tr>
<tr>
<td>Fri 30th April 04 to Mon 3rd May 04</td>
<td>School holidays</td>
</tr>
<tr>
<td>Mon 3rd May 04</td>
<td>Starting to dry clothes outside</td>
</tr>
<tr>
<td>Thu 27th May 04 to Fri 3rd June 04</td>
<td>Family on holiday, only one person in house</td>
</tr>
<tr>
<td>Sun 23rd May</td>
<td>Additional adult joins household for 6 months</td>
</tr>
<tr>
<td>Fri 3rd June 04</td>
<td>Lots of showers and washing</td>
</tr>
<tr>
<td>Mon 7th June 04</td>
<td>Extra adult in house for next months</td>
</tr>
<tr>
<td>Wed 28th June 04</td>
<td>Start of School holidays</td>
</tr>
<tr>
<td>Mon 26th July 04</td>
<td>All out all day</td>
</tr>
<tr>
<td>Tues 27th July 04</td>
<td>All out all day</td>
</tr>
<tr>
<td>Tue 8th to Wed 9th Aug 04</td>
<td>Mother and children away</td>
</tr>
<tr>
<td>Tue 17th Aug 04</td>
<td>Children back to school</td>
</tr>
<tr>
<td>Tue 17th to Thu 18th Aug 04</td>
<td>House empty and lights off all day</td>
</tr>
<tr>
<td>Mon 30th Aug 04</td>
<td>Weather starting to get colder. One upstairs window closed during day and open slightly at night. Other windows always open. Children’s bedrooms (bedrooms 1 and 3) open all day if out. House still warm though</td>
</tr>
<tr>
<td>Mon 6th Sept 04</td>
<td>Noticing now if house feels cold, shut the windows and house really quickly warms up again even if no sun,</td>
</tr>
<tr>
<td>Mon 20th Sept 04</td>
<td>Starting to dry clothes inside</td>
</tr>
<tr>
<td>Mon 27th Sept 04</td>
<td>Bathroom extract fan switched off for one week</td>
</tr>
<tr>
<td>Mon 4th Oct 04 to Sun 17th Oct 04</td>
<td>School holidays</td>
</tr>
<tr>
<td>Sat 9th Oct 04</td>
<td>Central heating on (except bedroom2)</td>
</tr>
<tr>
<td>Sun 10th Oct 04</td>
<td>Central heating off at 11 am (too hot)</td>
</tr>
<tr>
<td>Sun 10th Oct 04</td>
<td>Wood burning stove lit at 7 pm</td>
</tr>
<tr>
<td>Wed 11th Oct 04</td>
<td>Wood burning stove used in evening on regular basis</td>
</tr>
<tr>
<td>Mon 18th Oct 04</td>
<td>Schools go back</td>
</tr>
<tr>
<td>Thu 21st Oct 04</td>
<td>Central heating on in all rooms (All room thermostats set at 20 ºC)</td>
</tr>
<tr>
<td>Mon 25th Oct 04</td>
<td>All room thermostats turned down to 15 ºC</td>
</tr>
<tr>
<td>Mon 1st Nov 04 to Sat 6th Nov 04</td>
<td>Bedroom 1 thermostat turned down to 10 ºC</td>
</tr>
<tr>
<td>Sat 6th Nov 04</td>
<td>All room thermostats turned up to 20 ºC</td>
</tr>
</tbody>
</table>
Appendix 8E: Estimate of vapour diffusion times for clay brick and plaster

The water vapour resistances \( R \) of unfired clay brick and clay plaster are 75 MNs/(gm) and 40 MNs/(gm) (Morton 2002)

The water vapour diffusivity \( D_w \) (m\(^2\)/s) is given by (Hall & Hoff, 2002)

\[
D_w = D_v \frac{R T}{M}
\]

where

- Vapour permeability \( D_v = 1/R \)
- \( R \) is universal gas constant of 8.314 J/(K mol)
- \( M \) is the molar mass of water of 0.018015 kg/mol

The water vapour diffusivity \( D_w \) of clay brick and plaster are \( 1.8 \times 10^{-6} \) m\(^2\)/s and \( 3.4 \times 10^{-6} \) m\(^2\)/s at 20 ºC.

Steady state diffusion (linear concentration gradient through a material) is established for time \( t \) very much greater than \( L^2/D_w \) (Cussler, 1984)

For the brick (0.1m thick) \( L^2/D_w \) evaluates to 1.4 h

For the plaster (0.01m thick) \( L^2/D_w \) evaluates to 30 s

The times for the steady state to be established will be an order of magnitude bigger ie 14 h and 5 min respectively for brick and plaster.
Fig. 30. Ground Floor Plan Dalguise
Table 1: Living Room Temperature and Humidity Data

<table>
<thead>
<tr>
<th>Time (Event No)</th>
<th>Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
</tr>
<tr>
<td>10000</td>
<td>60</td>
</tr>
<tr>
<td>15000</td>
<td>70</td>
</tr>
<tr>
<td>20000</td>
<td>80</td>
</tr>
<tr>
<td>25000</td>
<td>90</td>
</tr>
<tr>
<td>30000</td>
<td>40</td>
</tr>
<tr>
<td>35000</td>
<td>50</td>
</tr>
</tbody>
</table>

Fig. 31. Instrumentation in Bathroom

Fig. 32. Internal Air Humidities Compared
Fig. 33. Bathroom Humidity - 20 day moving average

Fig. 34. Bedroom 1 Humidity - 20 day moving average
Fig. 35. Bedroom 2 Humidity · 20 day moving average
Fig. 36. Living room moisture content

Fig. 37. Moisture content at brick interior
Brick & Ext Air (19 Nov 03 to 19 Nov 04)
20 day moving av

Moisture Content (g/kg)

Time (Event No)

Bathroom
Bedroom 1
Bedroom 2
Ext Air

Fig. 38. Influence of external air moisture content on brick interior

Bathroom (20 May to 9 Jun 04)
4 hour moving average

Moisture content (g/kg dry air)

Time (Event No)

Int Air
Brick/Intl
Ext Air

Fig. 39. Bathroom moisture content - 4 hour moving average
Bedroom 1 (1 Oct to 19 Nov 04)
4 hour moving average

Fig. 40. Bedroom 1 Moisture Content - 4 hour moving average

Bedroom 1 (20 May 04 - 9 Jun 04)
(4 hour moving av)

Fig. 41. Bedroom 1 Temperatures - 4 hour moving average
Fig. 42. Bedroom 1 relative humidity during holiday period AB

Fig. 43. Bedroom 1 air moisture content during holiday period AB
Fig. 44. Bedroom 1 influence of outdoor on internal humidity

Fig. 45. Fluctuation in moisture content of bathroom air
Fig. 46. Fluctuation in moisture content of brick interior

Fig. 47. Bedroom 1 Moisture Content - 4 hour moving average
9.0 THERMAL PERFORMANCE

Bruce Taylor, B Sc, M SC, C Eng., MIMechE., the Robert Gordon University, Aberdeen

9.1 Introduction

In this project there was a requirement to assess the thermal insulation and thermal capacity effects of unfired clay brick walls in an occupied house. This report describes the monitoring of the thermal performance of the walls and the house over a period of one year.

This work is timely as the proposed changes to Part L in England and Wales (ODPM, 2004, Section 2, p15)) require that “provisions should be made to limit excessive solar gains [in houses] during the summer”. The provisions include, amongst the usual solar control considerations, using thermal capacity coupled with night ventilation. Thermal mass as a measure to reduce overheating in summer can have the advantage over solar control methods that daylighting and views need not be sacrificed.

More specific guidance has recently come from CIBSE (2005) which, in order to counter projected rising outdoor temperatures of between 3.6 and 6.9 ºC above 1961-1990 averages in London by the later part of this century, the use of high thermal mass in living areas as a means of reducing peak temperatures is advocated.

9.2 House Construction

9.2.1 House Design

The ground floor plan of the unfired clay brick house at Dalguise is shown in Fig. 48.

The external walls comprise load bearing timber frame 50 X 100 mm studs. Frames are clad externally with breathing sheathing board (9.2 mm Panelvent), with Cladshield breather membrane. The timber rainscreen cladding is larch heartwood weatherboarding. The inner brick leaf is unfired clay brick finished with 12mm clay plaster. The cavity is filled with 200 mm cellulose insulation.

The ground floor is 150 mm thick concrete slab on the ground with 120 mm dense polystyrene insulation, 70mm concrete screed and 20 mm thick tongue and grooved flooring.

Roof is slate fixed to “Roofshield” breathing felt on 20 mm thick softwood sarking. The cavity between the sarking and the 12.5 mm plasterboard lining is 220 mm cellulose insulation.

The proportion of glazing in the walls is modest as the overall percent glazing is: 16%, of wall area or 21%, of ground floor area (Appendix 9A)

9.2.2 Clay and Envelope Properties.

As the heat storage and the time shift between heat input and temperature rise with a wall is crucially dependent on the physical properties of the surface layers to a depth of up to 100 mm it is important to record the physical properties assumed in theoretical calculations so that results from the monitoring exercise are compared with theoretical expectations.

From Appendix 9B it can be seen that clay plaster provides over 2.5 times as much physical mass as plasterboard (8 kg/m²). When the clay brick is also included (216 kg/m²) it can be seen that the inner leaf has 27 times the physical mass as conventional plasterboard lining in timber frame construction.

9.3 Heating System

The heating system is underfloor hot water system supplied from oil fire combi-boiler. The hot water pipes are laid on top of the 12mm floor insulation. There is very little heat lost to the ground or stored in the concrete slab. The timber floor should heat up quite quickly. The controls
for the heating system are very basic consisting of a thermostat in each of the downstairs bedrooms and in the living area. There is no time control of the boiler operation.

Domestic hot water for shower as well as sinks is supplied from this boiler. Space heating is supplemented by a wood-burning stove, which is installed in thermally heavy weight chimney breast.

9.4 Measurement Procedure

9.4.1 Heat

The indoor air temperature of the chosen rooms and outdoor air temperature, the plaster surface temperature, the temperature of the air cavity in the brick, the temperature at the brick/insulation interface and the temperature at the insulation/sheathing interface were measured at 15 minute intervals. The temperature of the rear of the brick and the room air temperature define the boundary conditions for calculating heat flow and heat retention through and within the brick/plaster wall. These temperature measurements were supported by a heat flux measurement on the north wall surface of bedroom 1.

Appendix 9C is a schedule of the instrumentation. The location of the instrumentation is also indicated in Fig. 48. The Instrumentation panel in bedroom 1 is shown in Fig. 49.

9.4.2 Moisture

In a similar way to the measurement of flow and storage of heat, moisture flow and storage will be monitored by logging the indoor RH of the air in the space and outdoor RH, the RH of the cavity in the brick and the RH at the ply/insulation surface. The RH and temperature of the rear of the insulation and in the room define the boundary conditions for calculating moisture flow and moisture retention through and within the insulation/brick/plaster wall.

9.5 Data Analysis

Logging commenced on 19th November 2003 at 13:01 hours and finished on 19th November 2004, 13:59 hours.

Logging temperature and humidity measurements every 15 minutes is sufficiently fine for detecting thermal lags of around 3 to 4 hours that might occur on diurnally. However, the raw time series data comprises random fluctuations on several trends of durations from 24 hours to one year. It is necessary to separate out these trends from the raw data. It was found that a 20 day (1,920 point) moving average revealed the long term (yearly) patterns in the temperature data (Figs. 50. to 53.).

The time scales are plotted as event numbers, which correspond to the logging intervals. On the 20 day moving average the graphs begin on 9th Dec at 13:00 hours and the milestone events are correlated with time in Table 6. Conveniently event number 10,000 is the day before the central heating is switched off.

<table>
<thead>
<tr>
<th>Event No</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19/11/2003</td>
<td>13:01</td>
</tr>
<tr>
<td>1920</td>
<td>9/12/03</td>
<td>13:00</td>
</tr>
<tr>
<td>5,000</td>
<td>10/1/04</td>
<td>15:31</td>
</tr>
<tr>
<td>10,000</td>
<td>2/3/04</td>
<td>21:19</td>
</tr>
<tr>
<td>15,000</td>
<td>27/4/04</td>
<td>10:30</td>
</tr>
<tr>
<td>20,000</td>
<td>18/6/04</td>
<td>16:35</td>
</tr>
<tr>
<td>25,000</td>
<td>9/8/04</td>
<td>19:32</td>
</tr>
<tr>
<td>30,000</td>
<td>30/09/04</td>
<td>23:10</td>
</tr>
</tbody>
</table>
When the indoor air temperatures are compared directly with each other (Fig. 54.) it can be seen that outside the heating season the living room air temperature is a good proxy for the other spaces with the exception of bedroom 2 and good indicator for the performance of the whole house. Bedroom 2 was used as a study up until about April May time when it reverted to use as a bedroom for an additional adult. One reason why bedroom 2 was cooler than bedroom 1 during the summer was possibly the occupant preferred the windows to be open more frequently and for longer. There is insufficient detail in the POE log to confirm this.

9.6 Results

9.6.1 Overview of the Year

The performance of the clay brick walls and the house as a whole are dependent on the occupants, their lifestyles and the weather. To provide insight into the monitoring data the occupants kept a log of domestic events and experiences. Full details of this post occupancy evaluation (POE) will be reported separately (Stevenson, 2004). However, significant time periods identified from the post-occupancy log sheets are summarised in Appendix 9F.

The local weather was recorded for the whole year from basic meteorological measurements, outdoor air temperature and humidity and atmospheric pressure. To supplement this, the significant weather events in Scotland were noted and are summarised in Appendix 9E. This data was supplemented by the BBC’s weather archive for Scotland, edited highlights of which are also included in Appendix 9E. This weather archive provides insight into the very significant dip in the outdoor temperature during the summer (Figs.50. to 53.).

The maximum, minimum and average temperatures from 19th Nov 03 to 19th Nov 04 are shown in Appendix 9D. On the face of it the house would appear to overheat during the summer: the living room rising to maximum temperature of 26.8 ºC. However, the durations of the high temperatures during the summer are short as can be seen from Table 7.

<table>
<thead>
<tr>
<th>Reference Temp (ºC)</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of year reference temp is exceeded (%)</td>
<td>46.5</td>
<td>20.3</td>
<td>5.7</td>
<td>0.8</td>
<td>0.03</td>
</tr>
</tbody>
</table>

It should be noted that it has been a relatively cool summer and in a more normal summer these higher temperatures would occur for longer periods.

9.6.2 Twenty-day Moving Averages

Figs. 53. and 55. show that the living room air temperature, a good representative temperature for the whole house given its location, reaches a minimum of 20.4 ºC just before the central heating is switched off (Point A) on 3rd March just at the beginning of a cold snap (Fig. 53.). The living room air temp begins long upward trend on 17 April (event no 14, 073) (Point E) over 6 weeks after the central heating is switched off on 3rd March. The living room temperature rises to a maximum of 23.7 ºC by the middle of August (Point H). During the same period the outdoor temperature rose from 3.2ºC to 18.0 ºC (A to D). The unsmoothed differences between internal and external air temperatures without the heating system running varied between 19ºC in the spring and 0ºC in the summer with a mean temperature difference of around 9ºC.

The instantaneous peak living room temperature of 26.8 ºC occurred on 14th June whilst the instantaneous minimum was 14.2 ºC on 2nd March (Appendix 9D). There is a cold spell during the summer between 17th June (point B) and 8th July (Point C). These warm and cold periods during the summer provide an opportunity to study the thermal responsiveness of the house. This is discussed in section 6.5.
The house did overheat slightly. The extent of overheating was mitigated by the high levels of ventilation preferred by the occupants and by the relatively cool summer. The maximum temperatures are limited by ventilation and thermal mass but it is not possible to conclude anything about the relative proportions of these two methods of cooling.

From the solar chart for Dalguise (Fig. 56.) it can be seen solar gains in the afternoon will start to significantly increase from the last week in February onwards. In particular two critical points occur at 2 and 4pm (points a and b respectively) solar time in the afternoon. At point a the sun is clear of the hills (altitude greater than 20) after the 21 Feb and clear of point b after the 25 March. After the 25 March the SW facing walls and roof have unobstructed exposure to the sun. As the year progresses the solar exposure of the SW walls will decrease in comparison to that received by the SW roof.

Fig. 53. indicates that the house is gaining heat from outside just after the central heating is switched off. The indoor living room temperature in the summer might have peaked at a lower temperature if the central heating was switched off sometime in February rather than on 3rd March.

The temperature profiles through the bathroom and bedroom walls (Figs. 50. to 52.) show similar trends. There is marked difference between the temperature profiles through bedroom 1 wall and the bathroom and bedroom 2 wall. Fig. 51. is showing a large temperature difference between the internal air and the sheathing temperature. The large difference between the internal air and the wall surface temperature may be due to the temperature sensor for bedroom 2 being covered by a plywood panel for aesthetic reasons (Fig. 49.). There is a comparatively small temperature difference across the cellulose insulation, which may indicate a local deficiency in the insulation. The heat flux sensor and infra-red thermography confirmed this to be the case.

9.6.3 End of heating season

The fine detail of the living room and outdoor air temperatures around the time that the central heating is switched off are shown in the 4-hour moving average graphs (Fig. 57.). The timing of the central heating being switched off coincided with a few days of very cold nights and relatively warm days (ie period of large diurnal temperature swings). These two factors produced the lowest temperatures seen in the living room momentarily dropping almost to 15 ºC. Otherwise the indoor temperature remains relatively constant at temperature just exceeding 20 ºC. The outdoor temperature as well showing the expected diurnal pattern rises in temperature in two steps. For the purposes of analysing heat storage effects in the clay brick walls this is too complex a time varying sequence of too short a duration to draw any meaningful conclusions from. A more promising data sequence occurred later in the spring when the house came closest to free running mode.

9.6.4 House in free running mode

A period when the family are away provides insight into on how quickly the building responds to changing weather conditions alone. The period from 20 May to 9 June 2004 which covered the time the family were on holiday from Thursday 27th May to Friday 3rd of June when there was only one person in the house (Appendix 9F). This is the closest that the building gets to a passive condition. The central heating was switched off on Wed 3 March and the wood-burning stove was not used at all after Saturday 20th March. For this shorter 10 day period a 4 hour moving average was used which would reveal any daily temperature cycles occurring (Figs. 58. to 61.).

The family are away on holiday between event numbers 17,880 to 18,550 and only one person is remaining in the house. Fig. 61, for the living room shows that during this period there were two deviations from the normal diurnal cycle of external temperature that will influence the living room air temperature. It is not possible to separate out the two effects of a variation in external temperature and change in heat loads due to the house occupancy being reduced from 4 to 1.
Analyses of the obvious diurnal cycle in external air temperature over the period 20 May to 9 June confirms a strong 24 hour period (Fig. 62.). A similar analysis for the living room air temperature (Fig. 63.) shows only an approximation to a 24 hour cycle with a number of quite longer periods from 25 to 28 hours.

Comparing the time differences between maxima and minima on the living room air temperature and the exterior temperature indicate that on average the indoor living room temp lags the outdoor temperature by 2 hours. However, the time lags (phase differences) are not normally distributed and are very widely spread, ranging from -4.25 hours to +10.25 hours. This indicates a more complex response than the thermal time constant of 3.6 hours for the walls in response to sudden changes in operation of the central heating system.

The indoor and outdoor temperatures are not as strongly phase locked together as Fig. 61. might suggest.

On top of these cycles there is an upward trend in both the external and internal temperatures.

The bathroom (Fig. 58.) and bedroom 2 (Fig. 60.) show similar diurnal patterns to the living room. An interesting feature is that the sheathing temperature momentarily exceeds the indoor air temperature for these spaces. This will be due to solar and ground radiation on the thermally lightweight cladding causing the sheathing to heat up quickly. This would have the very beneficial effect of drying out any residual interstitial condensation in the sheathing and insulation. These effects are not observed in bedroom 1 (Fig. 59.) where the exterior walls face north west and north east and the north east wall is more strongly shaded by trees.

Bedroom 1 shows a sharp drop in temperature in the morning of 23 May down to 15.9 ºC with corresponding sharp drops in the interior wall temperatures. This may be due to the bedroom window being opened. Shortly before this the external air temperature drops to a minimum of 6.1 ºC. The rapid fall and subsequent rise in internal brick temperatures in response to a sharp downward spike in air temperature is surprising and is suggesting there is not as much thermal buffering from the clay bricks as one might expect.

9.6.5 Cold Snap in Summer

This weather archive provides insight into the very significant dip in the outdoor temperature during the summer (Figs. 50. to 53.). The 24 hour moving average plot for 28 May to 30 July Fig. 54. shows more clearly that mean outdoor temperature plunged 10 ºC from 19.4 ºC on 15 June (event No 19,670) to 9.4 ºC on 19 June (event no 20,109). The mean temperature did not rise significantly above 15 ºC until 13 July (event no 22,423). From the BBC’s review of Scotland’s weather (BBC, 2004a) it can be seen that this corresponded to “a spell of northerly winds with cool and showery weather”

During this cold period the living room temperature fell only 3ºC from 24.9 ºC on 15 June to 21.8 ºC on 17 June. It then held to a temperature of around 22 ºC whilst the outdoor temperature continued to fall. This is a little surprising and would suggest that the wood-burning stove was used. However, the occupant’s log does not record that the stove was used during this period. The living room temperature fell a further 2.4 ºC on 23 June to 20.4 ºC by 25 June. The outdoor air temperature did not get above 15 ºC until 13 July (event 2423).

BBC, 2004b summarised the weather for July

"Unsettled westerly weather dominated the month with high pressure not making an appearance until the last week [25th to 31st] bringing much fine weather. However, there were no major episodes of rain and days of frequent or heavy showers were rare."

In contrast to relatively dry July, August was a very wet month, particularly from 9th to 13th, 15th to 19th and 26th to 27th August. Torrential rain on the 11th August (Drever, 2004) caused a landslip on A9 two miles south of Dalguise.
9.6.6 Beginning of heating season

The POE data sheets are more detailed in the autumn when the central heating was switched on and the occupants were more adventurous in their operation of the central heating system. For these reasons the responsiveness of the walls and the house for the period 1 Oct to 19 Nov 04 were studied in greater detail than comparable period in the spring around the 3rd March when the heating was switched off and are reported here.

Fig. 65. shows the 24 hour moving average indoor air temperatures for bedrooms 1 and 2 and the living room for the period 1 Oct to 19 Nov 2004. For this analysis the bathroom was ignored because its temperature is not controlled by its own individual room thermostat. The outdoor temperature is shown for comparison.

The significant points A to I correspond to the events listed in Table 8 below.

Putting together the POE reports and temperature data the scenario can be postulated. Sometime on Saturday 9th October 2004 the central heating was switched on because outside it had turned decidedly chilly. However, the combination of central heating and rapidly rising outdoor temperatures meant that by the Sunday morning (at most 24 hours later) it was too hot indoors so the central heating was switched off. For almost the next fortnight although there was a further sharp dip in temperature the wood burning stove was sufficient to keep the house comfortable. Just after a few cold days the central heating was switched on again on 21st October again coinciding with a rise in outdoor temperature. This meant that by the 25th October the thermostats all had to be turned down from 20 °C to 15 °C. The living room and bedroom 2 responded quite quickly to the central heating coming on but bedroom 2 took a bit longer (windows open?).

From the solar chart (fig. 56.) one can see that from the 16th October onward (Point a) there are no solar gains after 2pm. Further more from the 14th September onward (Point b) there are no solar gains after 4pm.

<table>
<thead>
<tr>
<th>Point</th>
<th>Event No</th>
<th>Date &amp; Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30857</td>
<td>9/10, 21:26</td>
<td>Central heating on (except bedroom 2)</td>
</tr>
<tr>
<td>B</td>
<td>30910</td>
<td>10/10, 10:41</td>
<td>Living Room temp 20.0 °C and rising. Central heating off</td>
</tr>
<tr>
<td>C</td>
<td>31040</td>
<td>11/10,19:11</td>
<td>Living Room temp peaks at 24.34 °C and rising. Wood burning stove used on a regular basis</td>
</tr>
<tr>
<td>D</td>
<td>32000</td>
<td>21/10, 19:27</td>
<td>Central heating on (all rooms set to 20 °C)</td>
</tr>
<tr>
<td>E</td>
<td>32373</td>
<td>25/10, 16:42</td>
<td>All room thermostats turned down to 15 °C</td>
</tr>
<tr>
<td>F</td>
<td>33003</td>
<td>1/11, 6:13</td>
<td>Ext air temperature is 10 °C and falling. Some time later bedroom 1 thermostat set to 10 °C</td>
</tr>
<tr>
<td>G</td>
<td>33472</td>
<td>6/11, 3:28</td>
<td>Ext air temperature is 10 °C and rising. Some time later all room thermostats set to 20 °C</td>
</tr>
<tr>
<td>H</td>
<td>33562</td>
<td>7/11, 1:58</td>
<td>Bedroom 1 temp = 20.13 °C (local min)</td>
</tr>
<tr>
<td>I</td>
<td>33691</td>
<td>8/11, 10:13</td>
<td>Bedroom 1 temp = 23.16 °C (local max)</td>
</tr>
</tbody>
</table>

Turning down the thermostats on 25th Oct also coincided with a fall in outdoor temperature. The living room and bedroom 1 temperatures fall at a similar rate. It would appear to take about 2.5 days for the house to respond to this change in thermostat setting. However, definite conclusions are precluded because the outdoor temperature also fell rapidly during this period.

The temperature plot for bedroom 1 throws doubt as to whether it was the thermostat in this bedroom that was turned down. Even bedroom 2 looks questionable.

When the central heating is turned up to 20 °C in all spaces they respond quickly (about 18 hours) but again this coincided with a rise in outdoor air temperature. The rising outdoor temperature
means that the temperature difference across the walls is decreasing and hence the conduction heat losses are decreasing. Therefore adding heat into the space will cause it to heat up quicker.

A tentative conclusion would be that the house takes about 2 to 3 days to fully respond to the central heating coming on or a major change in the thermostat settings. However, the air temperatures do start to change very soon after the central heating controls are changed. There appears to be a conflict with the finding in section 3.5.3 that “on average the indoor living room temp lags the outdoor temperature by 2 hours”. Appendix 9F summarises the differences between the two situations to gain insight into a possible explanation. The first thing to point out is the difference in meaning between the two times. In the free-running mode the graphs are displaying a time shift (phase difference) and the heating mode the graphs are displaying a response time i.e. the time taken for the air temperature to reach 90% of its steady state value. Here in lies a problem, the system never gets any where near the steady state before other influences (e.g. mean outdoor temperature falling or rising for several days) cause the system to speed up or slow down its response.

The time delay or lag of 2 to 3 days refers to how long it appears from the graphs that the living room air temperature to fully respond to the occupant making a step change in the operation of the central heating system. The date but not the time is known when changes to the heating system are made. I have tended to assume the evening but they could be the morning. There is thus an uncertainty of 12 hours in when the change is initiated. The heating control system will introduce a number of delays plus there will time for the boiler to heat water and the water to flow through the pipes and eventually be emitted into the space as mixture of radiant and convective heat. Radiant heat will be apparent more quickly to the occupant however, it is air temperature that is being measured.

This is a much more complex situation than in the free-running mode where the outdoor air temperature is directly influencing the indoor air temperature via ventilation and solar radiation through the windows and doors are heating up internal surfaces directly. This could explain why there is very short time delay between the indoor air temperature responding to changes in the outdoor air temperature.

To summarise, the time delays refer to the whole house and everything in it, including the masonry walls. However, in the free-running mode the system is smaller and simpler than the central heating start-up case and comes closer to giving an indication of the response time of the masonry wall.

It is noteworthy that the temperature scales on the thermostats grossly overstate the temperature by up to 5 ºC. Thus a cool temperature setting of 15 ºC will actually achieve a very temperature of over 20 ºC. This would seem to provide a psychological barrier to people turning the thermostat down.

One can construct the following hypothetical model of how people interact with their heating systems. People will switch their heating system on for the winter if there is a cold period lasting two or more days. However, in the UK, especially in the autumn that is typically all that a cold spell would last so they switch the central heating on just as a warm spell of weather arrives. A similar thing happens during an exceptional warm spell in the autumn and the occupants switch the central heating off or turn the thermostats down just as the weather is about to turn colder.

9.6.7 Thermal Response for Clay brick wall

It was noted that the unsmoothed temperature and heat flux data for Bedroom 1 for the period 24 - 26 October (Fig. 66.) may provide a more objective method of determining the thermal response of the clay brick wall. The heat flux sensor data which gives confirmation that the temperature rise seen in the bedroom in both the air and the brick is due primarily to a change in state of the heating rather than some other factor like a drop in outside temperature.
The thermal time constant is defined mathematically as the time required for the output of a system (temperature in this case) to reach 63.2% of its final value after a step change at the input (a sharp reduction in wall heat flux in this case).

An almost ideal temperature profile to analyse, that comes very close to the step changes in input that drive an exponential rise in output in a system with capacity (in this case thermal capacity), occurs between event numbers 32340 to 32390 (Fig. 66.) when the indoor air temperature falls (23.45 ºC to 21.8 ºC) and then rises to 22.85 ºC. The start of the temperature decay coincides with a sharp drop in heat flux and the start of the temperature rise coincides with a sharp increase in heat flux.

Fitting an exponential curve to the initial part of the data to estimate the time constant at the interior of the brick gives Fig. 67. An assumed initial temperature of 20.2 ºC gives a time constant of 3.6h that gives a better fit to the data than an assumed final temperature of 20.0 ºC, which gives a time constant of 4.6 h (Fig. 69.). Visual comparison between Figs. 69. and 70. clearly shows that an assumed final temp of 20. 2 ºC gives a better fit to the unsmoothed data and so the best estimate of the time constant for temperature changes inside the brick in response to a step change in heat flux at the surface is 3.6h.

A 1% change in assumed final temperature gives a 28% change in thermal time constant. This is an inherent characteristic with inverse analysis methods in that the desired results are very sensitive to small changes in the inputs.

9.6.8 Wall U-values

The 20 day moving average heat flows as measured by the heat flux sensor (red circle in Fig. 49) through the Northwest wall in bedroom 1 decrease during the summer as the mean temperature difference across the wall decreases (Fig. 71.). Averaged over a 20 day period the heat flow is always outwards through the wall. Dividing the average heat flow by the average temperature difference gives the 20 day average thermal transmittance (U-value) at that point in the wall (Fig. 72.) Averaged over the whole year the mean U-value is 0.5717 W/m²/K with a standard error in the mean of only 0.0002 W/m²/K.

The mean U-value of 0.57 W/m²/K is almost four times greater than design value of 0.157 W/m²/K. It needs to be stressed that this measured U-value is only for one point in the wall and is by no means representative of all the walls. The very high value provides further evidence that the temperature profiles through the bedroom 1 wall are correct and that there is a local deficiency in the thermal insulation at this point. Infra-red thermography confirmed that the measurements in bedroom 1 are at the lower edge of a cold area extending up to the ceiling and that in the other rooms where measuring temperature profiles through the walls there are no deficiencies in the insulation.

Since the standard error in the mean U-value is only 0.0002 W/m²/K the wide variation in U-value throughout the year from a minimum of 0.44 W/m²/K to a maximum of 0.65 W/m²/K is significant. The changes in U-value are probably due to changes in thermal conductivity of the greatest thermal resistance in the wall i.e. the insulation. Changes of thermal conductivity in the cellulose insulation may arise due to lower moisture content, which would explain why U-value improves over the summer, and air flow in the insulation.

To verify that the above measured value for the Bedroom 1 wall is unrepresentative, an estimate of the U-value for the bathroom wall based on the standard value used for the internal surface resistance of wall, $R_{si} = 0.123$ m²K/W and the formula

$$U = \frac{1}{R_{si}} \frac{(T_{ai} - T_s)}{(T_{ai} - T_{wi})}$$

was made where
$T$ is the indoor air temperature
$T'$ is the wall surface temperature
$T''$ is the outdoor air temperature

Fig 73 shows the results of such a calculation using 20-day average temperatures. The mean U-
value for the bathroom wall is 0.1069 W/m\(^2\)K with a probable error of 0.0001 W/m\(^2\)K. As with the
bedroom 1 U-value, the wide variation in bathroom U-value throughout the year from a minimum of
0.05W/m\(^2\)K to a maximum of 0.18 W/m\(^2\)K is statistically significant. The mean U-value of 0.107
W/m\(^2\)K is 30 % less than design value of 0.157 W/m\(^2\)K (Morton, 2002). The most probable source
of this difference is the cellulose insulation rather than the brick since the brick constitutes about
only 7% of the total thermal resistance of the wall.

It is not possible to say with certainty which characteristics of the insulation lead to this low U-value
but given the high value in bedroom1 appears to be due to lack of insulation then the low value in
the bathroom may be due to a fortuitously optimum packing density of the fibres. Due to the
nature of the dry-blown installation process for cellulose insulation the U-values achieved in a
building can vary significantly over the building envelope and differ markedly either up or down
from the design value. This has major implications for the energy actually used for space heating
(see section 9.2 above).

9.7 Comparison with Theoretical Expectations

9.7.1 Performance of Walls

The results from the monitoring exercise are compared with theoretical expectations based on the
known construction of the internal and external walls and best estimates of the properties of the
unfired clay bricks and clay plaster. It is useful also to compare both the measured and expected
performance of the unfired clay brick walls with comparable conventional equivalent materials.
Appendix 9B summarises the physical properties of the relevant materials and Appendix 9H lists
the calculated steady state and transient heat transfer characteristics (U-value, admittance and
decrement factor) based on these physical properties. The method used to calculate these is
described by Davies 1994 and it is equivalent to the method outlined in CIBSE 1999. Therefore,
Appendix 9F is a useful supplement to Tables 3.54 to Tables 3.60 of CIBSE 1999.

The transient heat transfer characteristics are conventionally calculated assuming a 24 hour
(sinusoidal) periodic cycle. Since there are in reality longer periodic cycles also driving heat flows
and temperature changes, for example the 7 day cycle of five working days followed by the
weekend and the seasonal cycle (365 days), the transient heat transfer characteristics were
calculated for these longer cycles. These results are also included in Appendix 9H. The
admittance of the exterior and interior clay walls is still of a significant magnitude for the 7 day
cycle but is almost irrelevant for season fluctuations. Thus while the most significant effect of
thermal mass occurs over 3.6 hours, the effect carries on for up to 7 days.

Heat transfer through the exterior walls from the outside for periods of 7 days and longer may be
calculated using the steady state transmittance. In other words for heat flowing into the building
from outside the thermal storage effect of the unfired inner clay leaf is negligible for periods
longer than 7 days. The surface factors of the exterior and interior clay walls tends to unity for
periods greater than 7 days meaning that a heat flow with a period of 7 days or longer is not
absorbed by the wall but appears immediately at the room index temperature. Heat flows with
periods longer than 24 hours will have much smaller amplitudes than the 24 hour fluctuation and
are generally ignored in the design of buildings incorporating thermal mass.

9.7.2 Energy Performance of House

The energy required for space and water heating over the 12 month period has been estimated
from the quantities of oil delivered to the house. The energy used for space and water heating for
12 months from 19 Nov is 66.5 GJ. This is 45% greater than the SAP estimate of 46 GJ (Appendix
9H).
The reasons why energy consumption for space and water heating would appear to be high are U-values in certain locations of the envelope are higher than design values energy consumption in a house is very strongly affected by the occupants and their lifestyles.

It is for these two reasons of construction quality and occupant behaviour that SAP calculations should not be used as a predictor of energy consumption. The SAP method is intended for comparing the design of one house with another and as a design tool is useful.

SAP estimates the energy for domestic hot water at 10.9 GJ/year, which amounts to 36% of the total energy consumption. This is to be expected in a well insulated house. Upper and lower estimates of hot water usage based on number of occupants rather than floor area as SAP does (Appendix 9G) of 12.5 GJ/year and 7.1 GJ/year bracket the SAP estimate. As with space heating energy for DHW is going to vary markedly between similar sized households depending on lifestyle.

Conventional wisdom is that underfloor heating should be left on all the time during the heating season and hence no time controller was installed. However, maintaining a constant temperature during the day when everybody is out and during the night when everybody is in bed seems to be wasteful of energy especially when windows are left open.

9.8 Conclusions

The thermal mass almost has helped moderate the indoor temperatures in the house. Comparatively high temperatures were experienced during the summer of the first year of occupation (max of 26.8 ºC) but these occurred for extremely short periods and so the overheating is not judged to be serious. The building was on average 9 ºC warmer than the outside temperature from spring through to autumn and during very warm periods the temperature difference would become zero. An internal temperature in excess of 23 ºC occurred for only about 5% of the summer (or 20% of the whole year).

However this overheating relates to the design of the roof and indirect gains, rather than to the wall construction. The overheating, while not particularly onerous, was kept low due to the relatively cool summer and the excessive use of ventilation as well as any thermal mass contributions. The modest amount of glazing helped while the lack of thermal mass at high level did not. The roof, given its large area and orientation to the afternoon sun, is probably the major internal heat gain in the summer. The glazed veranda erected in the spring of 2004 may also have contributed to the internal gains. The areas that experience the greatest overheating are the double height space and attic spaces. In the design of the building these attic spaces were intended as storage rather than as bedrooms. The occupants intend to put windows into the roof and this will improve ventilation and improve opportunities for night cooling which are lacking in the building at the moment.

The walls do store and release heat. For a step change in heat flow (caused, for example, by a sharp change in the building heating system) into the inner surface of the external wall the thermal time constant (time to reach 63.2% of the final temperature change) is 3.6 h.

In free-running mode (that is, when the heating system is turned off) the indoor living air room temperature lags the outdoor air temperature by very approximately 2 hours on average. However, the time lags (phase differences) are not normally distributed and are very widely spread, ranging from -4.25 hours to +10.25 hours.

There is no evidence, experimental or theoretical, for significant heat storage and release beyond 7 days.

At the one spot where the heat flux was measured there is a deficiency of insulation and so the measured average U-value over the year of 0.57 W/m²/K is not typical of exterior walls. An indirect method of estimating the U-value based on wall surface temperature estimates the annual average U-value for the bathroom wall as 0.107 W/m²/K, which is 30% less than the design value of 0.157
W/m²/K. The explanation of the large differences in the measured U-values at two spots in the building envelope most likely lies in the insulation since this comprises 88% of the thermal resistance compared with only 7% for the brick. These measurements may be indicative of the differences that can be achieved in the packing density of the dry-blown loose fibres under site installation conditions.

The energy used for space and water heating for 12 months from 19 Nov at 66.5 GJ is 45% greater than the SAP estimate of 46 GJ. The SAP estimate of the energy for domestic hot water at 10.9 GJ/year (36% of the total energy consumption) lies between upper and lower estimates of 12.5 GJ/year and 7.1 GJ/year based on the number of occupants rather than floor area as SAP does. As with space heating, energy for DHW will vary markedly between similar sized households depending on lifestyle. Quality of build and occupant behaviour can vary so widely that SAP calculations should not be used as a predictor of energy consumption. They are useful for their intended purpose of comparing one design with another and for comparison with a notional benchmark.

The reasons why energy consumption for space and water heating would appear to be high are:

1) U-values in certain locations of the envelope are markedly higher than design values
2) energy consumption in a house is very strongly affected by the occupants and their lifestyles.

9.9 References


Appendix 9A: Areas of Glazing

<table>
<thead>
<tr>
<th>WINDOWS</th>
<th>% of wall</th>
<th>( \text{m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORTH EAST</td>
<td>W9, W10, W11, W12, W13</td>
<td>5.61</td>
</tr>
<tr>
<td>NORTH WEST</td>
<td>W14</td>
<td>1.23</td>
</tr>
<tr>
<td>SOUTH WEST</td>
<td>W1, W2, W3, W4, W5</td>
<td>7.86</td>
</tr>
<tr>
<td>SOUTH EAST</td>
<td>W7, W6, W8</td>
<td>3.69</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>18.39 ( \text{m}^2 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DOORS</th>
<th>% of wall</th>
<th>( \text{m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOUTH WEST</td>
<td>D1</td>
<td>4.2</td>
</tr>
<tr>
<td>NORTH EAST</td>
<td>D2</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Overall percent glazing, 18%, of wall area or 23%, of ground floor area

Technical Standards section J3.3 Elemental method allows a maximum of 25% of total floor area (Scottish Executive 2001).
### Appendix 9B: Physical Properties of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity (W/m.K)</th>
<th>Specific Heat (kJ/kg.K)</th>
<th>Vapour resistivity (MN.s/g.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay brick</td>
<td>1850</td>
<td>0.24</td>
<td>920</td>
<td>75</td>
</tr>
<tr>
<td>Clay plaster</td>
<td>1370</td>
<td>0.66</td>
<td>800</td>
<td>40</td>
</tr>
<tr>
<td>Cellulose insulation</td>
<td>50</td>
<td>0.038</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td>Panelvent</td>
<td>740</td>
<td>0.08</td>
<td>2800</td>
<td></td>
</tr>
<tr>
<td>Timber Cladding</td>
<td>500</td>
<td>0.14</td>
<td>1760</td>
<td></td>
</tr>
</tbody>
</table>

- Density of clay plaster: $1370$ kg/m³
- Thickness of plaster: $0.015$ m
- Surface density of plaster: $20.6$ kg/m²

- Density of clay brick: $1850$ kg/m³
- Thickness of brick: $0.105$ m
- Surface density of brick: $195$ kg/m²

- Surface density of plaster + brick: $216$ kg/m²

Duplex Wall board, 12.5mm has surface density of $8$ kg/m²

## Appendix 9C: Instrumentation Schedule

### Temperature Sensors

<table>
<thead>
<tr>
<th>Room</th>
<th>Sensor Position</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td>External Air</td>
<td>-</td>
</tr>
<tr>
<td>Bathroom</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>0</td>
</tr>
<tr>
<td>Bathroom</td>
<td>Brick/Internal</td>
<td>54</td>
</tr>
<tr>
<td>Bathroom</td>
<td>Brick - Insulation</td>
<td>116</td>
</tr>
<tr>
<td>Bathroom</td>
<td>External Sheathing</td>
<td>307</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Surface</td>
<td>0</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Brick/Internal</td>
<td>60</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Brick - Insulation</td>
<td>121</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>External Sheathing</td>
<td>291</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>Brick/Internal</td>
<td>61</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>External Sheathing</td>
<td>311</td>
</tr>
<tr>
<td>Living Room</td>
<td>Internal Air</td>
<td>-</td>
</tr>
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</table>

### Humidity Sensors

<table>
<thead>
<tr>
<th>Room</th>
<th>Sensor Position</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathroom</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bathroom</td>
<td>Brick/Internal</td>
<td>54</td>
</tr>
<tr>
<td>Bathroom</td>
<td>External Sheathing</td>
<td>307</td>
</tr>
<tr>
<td>Bathroom</td>
<td>External Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>Brick/Internal</td>
<td>60</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>External Sheathing</td>
<td>291</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>Internal Air</td>
<td>-</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>Brick/Internal</td>
<td>61</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>External Sheathing</td>
<td>311</td>
</tr>
<tr>
<td>Living Room</td>
<td>Internal Air</td>
<td>-</td>
</tr>
</tbody>
</table>
### Bathroom Temperature

<table>
<thead>
<tr>
<th></th>
<th>Int Air</th>
<th>Surface</th>
<th>Brick/Intl</th>
<th>Brick/Ins</th>
<th>Sheathing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>16.05</td>
<td>17</td>
<td>16.7</td>
<td>16.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Event No</td>
<td>9958</td>
<td>9885</td>
<td>9885</td>
<td>3975</td>
<td>3972</td>
</tr>
<tr>
<td>Max</td>
<td>30.4</td>
<td>26.85</td>
<td>26.275</td>
<td>25.75</td>
<td>28.3</td>
</tr>
<tr>
<td>Event No</td>
<td>26927</td>
<td>22422</td>
<td>24233</td>
<td>24237</td>
<td>24231</td>
</tr>
<tr>
<td>Mean</td>
<td>21.9</td>
<td>21.7</td>
<td>21.4</td>
<td>21.1</td>
<td>14.8</td>
</tr>
<tr>
<td>Stddev</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.6</td>
<td>3.9</td>
</tr>
</tbody>
</table>

### Bedroom1 Temperature °C

<table>
<thead>
<tr>
<th></th>
<th>Int Air</th>
<th>Surface</th>
<th>Brick/Intl</th>
<th>Brick/Ins</th>
<th>Sheathing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>15.25</td>
<td>15.35</td>
<td>14.975</td>
<td>10.65</td>
<td>6.8</td>
</tr>
<tr>
<td>Event No</td>
<td>17475</td>
<td>9885</td>
<td>9884</td>
<td>3964</td>
<td>3964</td>
</tr>
<tr>
<td>Max</td>
<td>26.075</td>
<td>24.35</td>
<td>24</td>
<td>23.3</td>
<td>22.7</td>
</tr>
<tr>
<td>Event No</td>
<td>25496</td>
<td>25398</td>
<td>24071</td>
<td>24037</td>
<td>24036</td>
</tr>
<tr>
<td>Mean</td>
<td>21.4</td>
<td>20.0</td>
<td>19.6</td>
<td>17.5</td>
<td>15.6</td>
</tr>
<tr>
<td>Stddev</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td>2.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Bedroom2 Temperature °C

<table>
<thead>
<tr>
<th></th>
<th>Int Air</th>
<th>Brick/Intl</th>
<th>Sheathing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>15.9</td>
<td>15.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Event No</td>
<td>30843</td>
<td>30842</td>
<td>3972</td>
</tr>
<tr>
<td>Max</td>
<td>25.775</td>
<td>24.35</td>
<td>27.2</td>
</tr>
<tr>
<td>Event No</td>
<td>24228</td>
<td>24256</td>
<td>19624</td>
</tr>
<tr>
<td>Mean</td>
<td>20.3</td>
<td>19.5</td>
<td>13.9</td>
</tr>
<tr>
<td>Stddev</td>
<td>1.4</td>
<td>1.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

### Living Room

<table>
<thead>
<tr>
<th></th>
<th>Ext Air</th>
<th>Ext Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>14.2</td>
<td>-5.05</td>
</tr>
<tr>
<td>Event No</td>
<td>9976</td>
<td>3921</td>
</tr>
<tr>
<td>Max</td>
<td>26.775</td>
<td>24.9</td>
</tr>
<tr>
<td>Event No</td>
<td>19623</td>
<td>25363</td>
</tr>
<tr>
<td>Mean</td>
<td>21.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Stddev</td>
<td>1.4</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Appendix 9E: Significant Weather Events in Scotland – Nov 03 to Nov 04

<table>
<thead>
<tr>
<th>Period</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 2003</td>
<td>An exceptionally warm month for UK and Scotland in particular</td>
</tr>
<tr>
<td>Christmas 03 to 1 Jan 04</td>
<td>Cold snap, snow in Aberdeen</td>
</tr>
<tr>
<td>Tues 27 – Sat 31 Jan 04</td>
<td>Snow in Aberdeen. It will have laid longer at Dalguise</td>
</tr>
<tr>
<td>Sun 22 Feb – Thurs 4th</td>
<td>Snow in Aberdeen</td>
</tr>
<tr>
<td>March 04</td>
<td></td>
</tr>
<tr>
<td>Sun 25 – Mon 26 April 04</td>
<td>Hot period</td>
</tr>
<tr>
<td>Monday 9th – Sat 14th Aug</td>
<td>Very heavy rain</td>
</tr>
<tr>
<td>04</td>
<td></td>
</tr>
<tr>
<td>Friday 19th – Sat 20th Nov 04</td>
<td>Snow in Aberdeen</td>
</tr>
</tbody>
</table>

BBC’s review of Scotland’s weather
15th to 22nd June
“A spell of northerly winds with cool and showery weather lasted from the 15th to the 22nd [June] there were only a few showers and the temperature fell to 2 ºC at Dalmally and Tulloch Bridge.”

BBC, 2004b summarised the weather for July:
“Unsettled westerly weather dominated the month with high pressure not making an appearance until the last week [25th to 31st ] bringing much fine weather. However, there were no major episodes of rain and days of frequent or heavy showers were rare.”
In contrast to relatively dry July, August was a very wet month. Torrential rain on the 11th August (Drever, 2004) caused a landslip on A9 two miles south of Dalguise. BBC, 2004c describes the weather around this period:
“On the 9th fronts associated with a deep depression to the southwest of Ireland reached the southwest of Scotland and became slow moving. Much rain fell over the southern half of Scotland during the next 4 days .......................The depression eventually cleared away to the east on the 13th and a ridge of high pressure developed to give fine weather for a couple of days.”

15th to 19th August
Low pressure in the Atlantic extended its influence over Scotland on the 15th and unsettled weather with much cloud and some outbreaks of rain returned. A deep depression developed and moved northeast across the north of England on the 18th, pushing an active front and its associated band of rain north across Scotland.

The rain was heaviest in places exposed to the east and 50mm was recorded at Loch Tay, close to the site of a landslide in Glen Ogle.

20th to 22nd
The depression was followed by cool northerly winds on the 20th and a broad ridge of high pressure on the 21st and 22nd. This gave plenty of sunny weather with the temperature at Tulloch Bridge falling to -1°C.

23rd to 31st
Unsettled and changeable conditions returned between the 23rd and 30th as two depressions passed close to Scotland, the first to the south and the second to the north. There was much rain overnight on 26th/27th with 50mm measured at Sloy.

The month ended with a ridge of high pressure giving a sunny day on the 31st with the temperature falling to 0°C at Tulloch Bridge.”
## Appendix 9F: Significant Domestic Events

<table>
<thead>
<tr>
<th>Period</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon 8&lt;sup&gt;th&lt;/sup&gt; Dec 03</td>
<td>Wood burning stove starting to be used extensively</td>
</tr>
<tr>
<td>Mon 22&lt;sup&gt;nd&lt;/sup&gt; Dec 03</td>
<td>Start of School holidays</td>
</tr>
<tr>
<td>Mon 22&lt;sup&gt;nd&lt;/sup&gt; Dec 03 to Sun 4&lt;sup&gt;th&lt;/sup&gt; Jan 04</td>
<td>Lots of extra people in the house</td>
</tr>
<tr>
<td>Mon 5&lt;sup&gt;th&lt;/sup&gt; Jan 04</td>
<td>Schools go back</td>
</tr>
<tr>
<td>Wed 3&lt;sup&gt;rd&lt;/sup&gt; March 04</td>
<td>Central heating switched off</td>
</tr>
<tr>
<td>Sat 20&lt;sup&gt;th&lt;/sup&gt; March 04</td>
<td>Last use of wood burning stove for winter season</td>
</tr>
<tr>
<td>Fri 2&lt;sup&gt;nd&lt;/sup&gt; April 04 to Sun 4&lt;sup&gt;th&lt;/sup&gt; April 04</td>
<td>House empty</td>
</tr>
<tr>
<td>Tue 6&lt;sup&gt;th&lt;/sup&gt; April 04 to Sun 11&lt;sup&gt;th&lt;/sup&gt; April 04</td>
<td>School holidays, all at home</td>
</tr>
<tr>
<td>Mon 19&lt;sup&gt;th&lt;/sup&gt; April 04</td>
<td>Schools go back</td>
</tr>
<tr>
<td>Fri 30&lt;sup&gt;th&lt;/sup&gt; April 04 to Mon 3&lt;sup&gt;rd&lt;/sup&gt; May 04</td>
<td>School holidays</td>
</tr>
<tr>
<td>Mon 3&lt;sup&gt;rd&lt;/sup&gt; May 04</td>
<td>Starting to dry clothes outside</td>
</tr>
<tr>
<td>Sun 23&lt;sup&gt;rd&lt;/sup&gt; May</td>
<td>Additional adult joins household for 6 months</td>
</tr>
<tr>
<td>Thu 27&lt;sup&gt;th&lt;/sup&gt; May 04 to Fri 3&lt;sup&gt;rd&lt;/sup&gt; June 04</td>
<td>Family on holiday, only one person in house</td>
</tr>
<tr>
<td>Fri 3&lt;sup&gt;rd&lt;/sup&gt; June 04</td>
<td>Lots of showers and washing</td>
</tr>
<tr>
<td>Mon 7&lt;sup&gt;th&lt;/sup&gt; June 04</td>
<td>Extra adult in house for next months</td>
</tr>
<tr>
<td>Wed 28&lt;sup&gt;th&lt;/sup&gt; June 04</td>
<td>Start of School holidays</td>
</tr>
<tr>
<td>Mon 26&lt;sup&gt;th&lt;/sup&gt; July 04</td>
<td>All out all day</td>
</tr>
<tr>
<td>Tues 27&lt;sup&gt;th&lt;/sup&gt; July 04</td>
<td>All out all day</td>
</tr>
<tr>
<td>Tue 8&lt;sup&gt;th&lt;/sup&gt; to Wed 9&lt;sup&gt;th&lt;/sup&gt; Aug 04</td>
<td>Mother and children away</td>
</tr>
<tr>
<td>Tue 17&lt;sup&gt;th&lt;/sup&gt; Aug 04</td>
<td>Children back to school</td>
</tr>
<tr>
<td>Tue 17&lt;sup&gt;th&lt;/sup&gt; to Thu 18&lt;sup&gt;th&lt;/sup&gt; Aug 04</td>
<td>House empty and lights off all day</td>
</tr>
<tr>
<td>Mon 30&lt;sup&gt;th&lt;/sup&gt; Aug 04</td>
<td>Weather starting to get colder. One upstairs window closed during day and open slightly at night. Other windows always open. Children’s bedrooms (bedrooms 1 and 3) open all day if out. House still warm though</td>
</tr>
<tr>
<td>Mon 6&lt;sup&gt;th&lt;/sup&gt; Sept 04</td>
<td>Noticing now if house feels cold, shut the windows and house really quickly warms up again even if no sun,</td>
</tr>
<tr>
<td>Mon 20&lt;sup&gt;th&lt;/sup&gt; Sept 04</td>
<td>Starting to dry clothes inside</td>
</tr>
<tr>
<td>Mon 27&lt;sup&gt;th&lt;/sup&gt; Sept 04</td>
<td>Bathroom extract fan switched off for one week</td>
</tr>
<tr>
<td>Mon 4&lt;sup&gt;th&lt;/sup&gt; Oct 04 to Sun 17&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>School holidays</td>
</tr>
<tr>
<td>Sat 9&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>Central heating on (except bedroom2)</td>
</tr>
<tr>
<td>Sun 10&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>Central heating off at 11 am (too hot)</td>
</tr>
<tr>
<td>Sun 10&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>Wood burning stove lit at 7 pm</td>
</tr>
<tr>
<td>Wed 11&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>Wood burning stove used in evening on regular basis</td>
</tr>
<tr>
<td>Mon 18&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>Schools go back</td>
</tr>
<tr>
<td>Thu 21&lt;sup&gt;st&lt;/sup&gt; Oct 04</td>
<td>Central heating on in all rooms (All room thermostats set at 20 °C)</td>
</tr>
<tr>
<td>Mon 25&lt;sup&gt;th&lt;/sup&gt; Oct 04</td>
<td>All room thermostats turned down to 15 °C</td>
</tr>
<tr>
<td>Mon 1&lt;sup&gt;st&lt;/sup&gt; Nov 04 to Sat 6&lt;sup&gt;th&lt;/sup&gt; Nov 04</td>
<td>Bedroom 1 thermostat turned down to 10 °C</td>
</tr>
<tr>
<td>Sat 6&lt;sup&gt;th&lt;/sup&gt; Nov 04</td>
<td>All room thermostats turned up to 20 °C</td>
</tr>
</tbody>
</table>
Appendix 9G: Thermal Response Time

<table>
<thead>
<tr>
<th>2hrs</th>
<th>2 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>On average the indoor living room temp lags the outdoor temperature by 2 hours</td>
<td>House takes about 2 to 3 days to fully respond to the central heating coming on or a major change in the thermostat settings</td>
</tr>
<tr>
<td>Can rephrase as: On average the indoor living room temp leads the outdoor temperature by 22 hours</td>
<td>Time is a phase difference Time is a response time (0 to 90%)</td>
</tr>
<tr>
<td>Time is a phase difference</td>
<td>Time is a response time (0 to 90%)</td>
</tr>
<tr>
<td>Free-running</td>
<td>Central heating</td>
</tr>
<tr>
<td>only one occupant</td>
<td>family at home</td>
</tr>
<tr>
<td>Steady almost sinusoidal fluctuation in outdoor temp (the main driver for indoor temp change) with period of 24 hours</td>
<td>Large changes in outdoor temp, plus step changes in heat inputs. Beginning of heating season</td>
</tr>
<tr>
<td>4-hour moving average (reveals diurnal fluctuations)</td>
<td>24-hour moving average (diurnal fluctuations smoothed out)</td>
</tr>
<tr>
<td>Outdoor temp and solar gains the main drivers for indoor temp change.</td>
<td>Outdoor temperature, sporadic heat input from boiler and wood burning stove, occupant activities are determining the indoor temp change</td>
</tr>
<tr>
<td>More windows open for longer</td>
<td>Fewer windows open for shorter periods</td>
</tr>
<tr>
<td>Section 6.4</td>
<td>Section 6.6</td>
</tr>
</tbody>
</table>
Appendix 9H: Thermal Properties of Clay wall Construction

<table>
<thead>
<tr>
<th>Construction</th>
<th>Transmittance U (W/m²K)</th>
<th>Admittance Y (W/m²K)</th>
<th>Decrement factor h</th>
<th>Surface factor h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay brick wall</td>
<td>0.157</td>
<td>3.82</td>
<td>1.82</td>
<td>0.15  -2.28</td>
</tr>
<tr>
<td>Plasterboard (high density), 12mm, wall</td>
<td>0.169</td>
<td>1.08</td>
<td>4.51</td>
<td>0.66  5.33</td>
</tr>
<tr>
<td>Brick inner leaf, gypsum plaster</td>
<td>0.163</td>
<td>4.42</td>
<td>2.07</td>
<td>0.31  0.58</td>
</tr>
<tr>
<td>Gable wall, plasterboard, normal density, 15mm</td>
<td>0.167</td>
<td>0.99</td>
<td>4.37</td>
<td>0.65  5.19</td>
</tr>
<tr>
<td>Roof</td>
<td>0.174</td>
<td>1.00</td>
<td>4.43</td>
<td>0.78  6.63</td>
</tr>
<tr>
<td>Floor</td>
<td>0.196</td>
<td>2.45</td>
<td>1.59</td>
<td>0.00  0.00</td>
</tr>
<tr>
<td>Clay brick Interior wall</td>
<td>1.383</td>
<td>4.25</td>
<td>2.43</td>
<td>N/A  N/A</td>
</tr>
<tr>
<td>Ceiling 19mm timber flooring on 100mm joists, 12mm plasterboard ceiling</td>
<td>1.880</td>
<td>1.89</td>
<td>0.80</td>
<td>N/A  N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Construction</th>
<th>Period hours</th>
<th>Admittance Y (W/m²K)</th>
<th>Decrement factor h</th>
<th>Surface factor h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay brick wall</td>
<td>24</td>
<td>3.82</td>
<td>1.82</td>
<td>0.15  -2.28</td>
</tr>
<tr>
<td></td>
<td>168 (7 days)</td>
<td>1.71</td>
<td>27.4</td>
<td>0.86  60.3</td>
</tr>
<tr>
<td></td>
<td>8760 (365 days)</td>
<td>0.162</td>
<td>310</td>
<td>1.00  4355</td>
</tr>
<tr>
<td>Clay brick Interior wall</td>
<td>24</td>
<td>4.25</td>
<td>2.43</td>
<td>N/A  N/A</td>
</tr>
<tr>
<td></td>
<td>168 (7 days)</td>
<td>1.07</td>
<td>36.5</td>
<td>N/A  N/A</td>
</tr>
<tr>
<td></td>
<td>8760 (365 days)</td>
<td>0.02</td>
<td>2184</td>
<td>N/A  N/A</td>
</tr>
</tbody>
</table>
Appendix 9I: SAP Calculation

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sap rating</td>
<td>138</td>
</tr>
<tr>
<td>Total floor area (m²)</td>
<td>185.18</td>
</tr>
<tr>
<td>House volume (m³)</td>
<td>366.6564</td>
</tr>
<tr>
<td>Glazing / Floor Area</td>
<td>18%</td>
</tr>
<tr>
<td>Effective air change rate</td>
<td>0.640</td>
</tr>
<tr>
<td>Specific Heat Loss (W/K)</td>
<td>205.93</td>
</tr>
<tr>
<td>Heat loss parameter (W/m²K)</td>
<td>1.11</td>
</tr>
<tr>
<td>Energy required for water heating (GJ/year)</td>
<td>16.53</td>
</tr>
<tr>
<td>Solar Gains (W)</td>
<td>349</td>
</tr>
<tr>
<td>Useful gains (W)</td>
<td>1363</td>
</tr>
<tr>
<td>Mean internal temperature (°C)</td>
<td>20.02</td>
</tr>
<tr>
<td>Degree Days</td>
<td>1650</td>
</tr>
<tr>
<td>Space heating requirement (GJ/year)</td>
<td>29.350</td>
</tr>
<tr>
<td>Hot water / total heating (%)</td>
<td>36%</td>
</tr>
</tbody>
</table>
Fig. 48. Ground Floor Plan Dalguise
Fig. 49. Instrumentation in Bedroom 1
Fig. 50. Bathroom Temperatures - 20 day moving average

Fig. 51. Bedroom 1 Temperatures – 20 day moving average
Fig. 52. Bedroom 2 Temperatures - 20 day moving average

Fig. 53. Living area Temperature - 20 day moving average
Fig. 54. Indoor Air Temperatures compared

Fig. 55. Extent of Overheating during summer
Fig. 56. Solar Chart for Dalguise Site
Living Room Temp (21 Feb 04 - 22 Mar 04)
4 hour moving av

Fig. 57. End of Heating Season - 4 hour moving average

Bathroom (20 May 04 - 9 Jun 04)
(4 hour moving av)

Fig. 58. Bathroom Temperatures - 4 hour moving average
Fig. 59. Bedroom 1 Temperatures - 4 hour moving average

Fig. 60. Bedroom 2 Temperatures - 4 hour moving average
Livingroom (20 May 04 - 9 Jun 04)
(4 hour moving av)

![Graph showing temperature variations over time.]

**Fig. 61. Living room Temperatures - 4 hour moving average**

External Temp Periods
(20 May to 9 Jun 04)

![Bar chart showing frequency of external temperature periods.]

**Fig. 62. Periodic Analysis of External Air Temp**
Fig. 63. Periodic Analysis of Living Room Air Temp

Fig. 64. Cold snap around midsummer
Fig. 65. Start of Heating Season

Bedroom 1 (19 Nov 03 to 19 Nov 04)
20 day moving average

Fig. 66. Heat flow through wall and temperature difference across it
Fig. 67. Average U-value

Fig. 68. Start of Heating Season – Temperature and Heat Flux
Fig. 69. Decay of Temperature inside Brick: Time constant = 3.6h

Fig. 70. Decay of Temperature inside Brick: Time constant = 4.6h
Fig. 71: Heat flow through wall and temperature difference across it

Fig. 72. U-value for Bedroom1
FIG. 73. U-VALUE FOR BATHROOM
10. MEASUREMENT OF AIR PERMEABILITY.

by Bruce Taylor, B Sc, M SC, C Eng., MI MechE, Carla Ruiz Soliva & Christopher Ross
the Robert Gordon University, Aberdeen

10.1 Introduction

The purpose of the test is to characterize the air permeability of the building envelope of the unfired clay brick house at Dalguise to gain insight into whether this form of internal leaf construction is more or less leaky than conventional plasterboard lining and to determine the infiltration rate for the purpose of heat loss calculations. Identification of major air leaks was undertaken.

The fan pressurisation method in accordance with BS EN 13829 (British Standards Institution 2001) was used.

The measurements were carried out on Wednesday 23 June 2004. Test conditions were ideal on the day: small temperature difference between indoor and outdoor air temperature and wind speed was estimated at Force 1 on the Beaufort scale. This is well within the maximum recommended limit of Force 3 for conducting these measurements.

10.2 House Construction

The ground floor plan of the unfired clay brick house at Dalguise is shown in Fig. 74.

The external walls comprise load bearing timber frame 50 X 100 mm studs. Frames are clad externally with breathing sheathing board (9.2 mm Panelvent), with Cladshield breather membrane. The timber rainscreen cladding is larch heartwood weatherboarding. The inner brick leaf is unfired clay brick finished with clay plaster. The cavity is filled with 200 mm cellulose insulation.

The ground floor is 150 mm thick concrete slab on the ground with 120 mm dense polystyrene insulation, 70mm concrete screed and 20 mm thick tongue and grooved flooring.

Roof is slate fixed to “Roofshield” breathing felt on 20 mm thick softwood sarking. The cavity between the sarking and the 12.5 mm plasterboard lining is 220 mm cellulose insulation.

10.3 Measurement Procedure

In outline, a blower door (Fig 75.) was installed in the rear door of the house and the depressurization of the house was measured as function of air flow rate extracted from the house via the fan. The following tests were carried out

1) Pressure test house of house in use to determine the infiltration rate for heat loss calculations
2) Pressure test with vents, flues, trickle vents all sealed to determine infiltration through building envelope.

A survey was conducted to locate major air leaks.

10.4 Results

The key results are summarised here and the detailed measurements and results of calculations are included in Appendix 10A.

<table>
<thead>
<tr>
<th>Building Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal volume of house</td>
<td>366.9 m3</td>
</tr>
<tr>
<td>Envelope area for air leakage</td>
<td>221.66 m²</td>
</tr>
<tr>
<td>Ground Floor area of house</td>
<td>92.59 m²</td>
</tr>
</tbody>
</table>

These were measured from AutoCad drawings prepared from the following Tom Morton Associates construction issue drawings of the house at Dalguise:
10.4.1 House in Use

In this condition all external doors and windows are shut and trickle ventilators are closed. All internal doors are open, except door to the larder.

Air infiltration at 50 Pa depressurisation 10.7 ach
Air infiltration at atmospheric pressure 0.54 ach
Envelope air permeability at 50 Pa 17.76 m³/(hr.m²)
Specific air permeability at 50 Pa 42.53 m³/(hr.m²)

An air infiltration rate, n, of 0.54 ach is calculated from the following empirical relationship (British Standards Institution, 1999):

\[ n = \frac{n_{50}}{20} \]

where \( n_{50} \) is the air change rate measured at 50 Pa

This level of air infiltration is acceptable for domestic construction. It is a reasonable compromise between minimising ventilation heat loss whilst maintaining a reasonable level of ventilation for control of moisture and indoor air quality. An infiltration rate of much less than 0.5 ach could lead to potential problems associated with poor indoor air quality. The air change rate of 0.54 ach for the house in use is the appropriate variable to use in SAP or energy simulation calculations.

10.4.2 Building Envelope

For this test the kitchen and bathroom extract fans were sealed off as were the flues from the oil fired boiler and the wood burning stove. In this condition air infiltration is only through the building envelope.

Air infiltration at 50 Pa depressurisation 10.4 ach
Air infiltration at atmospheric pressure 0.52 ach
Envelope air permeability at 50 Pa 17.3 m³/(hr.m²)
Specific air permeability at 50 Pa 41.3 m³/(hr.m²)

Sealing up major penetrations of the envelope such as wood burning stove flue (100 mm diameter) and extract fans reduces the air infiltration rate only slightly this is because although these openings have large apparent openings they also have a large frictional pressure losses associated with them which will restrict the flow.

The envelope air permeability 17.3 m³/(hr.m²) is an indicator of the air tightness of the form of construction used at Dalguise. The floor construction is impermeable to air so the air permeable parts of the envelope are the walls and the roof.

Specific air permeability that is based on the ground floor area rather than exposed envelope area, is useful for estimating the anticipated air infiltration in buildings of similar design and construction but of a different size.

The flow rate through the Dalguise building envelope at any given pressure may be calculated from the following equation

\[ Q = 184.7 \ P^{0.77} \]
where

\[ Q \text{ is the infiltration into the house through the envelope (m}^3/\text{h)} \]
\[ P \text{ is the depressurisation (Pa).} \]

This equation was derived from measurements over the range of depressurisations 12.5 Pa to 50 Pa and so should be used with caution outside this range. This equation for the building characteristic is shown on the graph in Appendix 9A with the measured data for comparison.

Air is leaking into the building through visible gaps and cracks and also through microscopic pores. The air leakage pathways will range in scale from micrometers (millionths of a meter) to millimetres. The sum total of the area of these air flow path ways at a depressurisation of 50 Pa may be envisaged as flowing though one circular duct of diameter 490 mm. This corresponds to an equivalent leakage area (ELA) of 188,000 mm$^2$.

### 10.4.3 Location of the Leaks

A test was made to see if there was any particular room or rooms that might be contributing to the air leakage. By opening, in turn, each of the doors to the bathroom and bedrooms 1, 2, and 3 (drwg no RF/2 revision F) and feeling with the back of the hand the air flow through slightly opened door one can get a qualitative indication of where major leaks are. There was not a great deal of difference between these four rooms but in order of increasing air tightness they were ranked bathroom, bedroom 1, bedroom 3, bedroom 2.

This technique also eliminated the possibility of major air leaks from the external wall behind the floor mounted kitchen units.

The location of air leaks and their ranking on a scale of 1 (slight), 2 (moderate), 3 (lot) is shown in Figs. 76. to 86. Whilst feeling with the hand for air leaks might seem crude it has the advantage over smoke in that one is directly feeling the cooling effect of a draught which is a direct indication of how important an air leak is from the point of view of human comfort.

The main air leaks tend to come from around gaps in the construction (eg between top of window frame and timber lintels) rather than cracks in the walls that have opened due to settlement and/or drying out. These wall cracks (e.g. running vertically underneath windows and at wall to ceiling junctions) whilst visually intrusive are not, individually contributing significantly to the air infiltration.

The most significant (air flow = 3 on scale) areas where air is leaking into the building are

- **Dining area, west window, gap between window frame and timber lintel** (fig. 76.)
- **Living Area, west patio doors, Gap at top of lintel on right and left hand sides** (fig. 77.)
- **Bedroom 1, wall/ceiling joint above window** (fig. 80.)
- **East Entrance, wall/ceiling joint above door** (fig. 82.)
- **East Entrance, gap above door lintel on RHS** (fig. 82.)
- **Utility room, gap between lintel and window frame** (fig. 83.)
- **Studio, upstairs, corners of chimney where goes through ceiling** (fig. 85.)

Whilst the air leakage around the upstairs south window frame is slight it is note worthy that the identical window in the north wall is virtually air tight. At this upper level the wall construction is conventional timber frame with plasterboard lining. Also in the upstairs north bedroom there was a slight air flow between the clay brick partition wall and the plasterboard ceiling where there are visible gaps.

The above are the areas where attention should be focussed if there is a desire to improve the air tightness of the building. The visually intrusive cracks may be filled in primarily for aesthetic reasons although they will also improve the air tightness.
10.4.4 Location of the Air Barrier in Wall

The primary air barrier or pressure boundary in the wall is likely to be the Panelvent sheathing with Cladshield breather membrane. To check this out the pressure was measured inside the bathroom external wall at the interface between the insulation and the Panelvent whilst the building was depressurised. At 44 Pa depressurisation approximately 70% (31 Pa) of the pressure drop between outside and inside occurred between the timber cladding and the cold side of the insulation. The remaining 30% pressure drop (12 Pa) occurred across the insulation and the clay brick plaster wall. The test was repeated at 22 Pa and only about 20% (4 Pa) of the pressure drop occurred across the insulation and the clay brick plaster wall. Cellulose insulation has a quite a high air permeability (Taylor and Imbabi 2000) and almost certainly orders of magnitude greater than the clay brick. This means the cellulose insulation makes a negligible contribution to pressure drop in the wall.

These tests confirm that the main pressure boundary in the Dalguise house wall is the Panelvent sheathing with Cladshield breather membrane.

10.4.5 Building Regulations

Proposals for Amending Part L of the Building Regulations (England and Wales) and Implementing the Energy Performance Buildings Directive is out for consultation (ODPM, 2004). An initial reading of this indicates that the government is setting a worst acceptable building envelope air permeability of 10 m$^3$/(m$^2$.h). The relevant area for calculating this is the entire building envelope including in the case of the Dalguise house the impermeable concrete floor.

On this basis the Dalguise house has an envelope air permeability of 9.6 m$^3$/(m$^2$.h) (Appendix 10A) which would comply with the proposed changes to Part L.

10.4.6 Discussion

The cracks in the unfired clay brick inner leaf are not contributing as much to the air infiltration as much as one might expect due to
- air infiltration is being controlled by the other layers in the construction
- gaps at joints between window and door frames, solid timber lintels are wider than the cracks in the brickwork

The main gaps seem to be associated with the solid timber lintels (lintel to window and door frame and lintel to wall). These gaps are often visible only by careful inspection since they are out of the line of sight of the casual visitor.

The pressure control layers in the construction are:

Walls - Panelvent sheathing with Cladshield breather membrane.
Roof – sarking with Roofshield Cladshield breather membrane.

Cellulose insulation has a much higher air permeability than panel vent. Using data from (Taylor and Imbabi 2000) the air permeance of 200mm of dry blown cellulose insulation is estimated at 2.2 m$^3$/(m$^2$.hPa). This is almost one thousand times greater than the permeance of 0.002 m$^3$/(m$^2$.hPa) (Wilson, 2004). The Cladshield although much thinner (0.5 mm) than the Panelvent its air permeance is probably of the same magnitude as the Panelvent if not lower. The external wooden cladding is of excellent craftsmanship so air will flow into the ventilated cavity mainly through the design openings at the top and bottom of the ventilated cavity. The cladding will contribute to the air tightness of the building particularly under windy conditions, however, the main pressure barrier has been found to be the Panelvent sheathing and the Cladshield breather membrane.

By similar considerations the main pressure barrier in the roof is judged to be the sarking and the Roofshield breather membrane.

10.5 Conclusion
The air change rate of 0.54 ach for the house in use is the appropriate variable to use in SAP or
energy simulation calculations.

Unfired clay brick inner leaf construction whilst prone to settling or shrinkage cracking does not
contribute significantly to the air infiltration into the building since the primary pressure boundary
is the Panelvent sheathing and the Cladshield breather membrane.

The Dalguise house has an envelope (including the concrete floor) air permeability of 9.6 m$^3$ / (m$^2$.h) which would comply with the proposed building envelope air permeability of 10 m$^3$ / (m$^2$.h) for Part L of the Building Regulations (England and Wales).

Prudent design practice would be to ensure that the pressure boundary or pressure control layer is
entirely located on the cold side of the insulation

1. Attention is paid to choice of materials for the sheathing and breather membrane to get the
balance between the requirements for high vapour permeability and low air permeability.

2. The builder needs to ensure that the sheathing and breather membranes are installed
correctly and that any gaps and penetrations are sealed before external cladding is fixed.

10.6 References

Transmission heat loss coefficient - Calculation method, London: BSI

Determination of air permeability of buildings – Fan pressurization method, London: BSI

ODPM, 2004, Proposals for amending Part L of the Building Regulations and Implementing the

Transactions, 106, Part 1,

Wilson, M., 2004, Director, Panel agency, Kent, Private communication.
Appendix 10A: Air Permeability Measurements & Results

Building Unfired Clay brick house, Dalguise

<table>
<thead>
<tr>
<th>Date</th>
<th>23-Jun-04</th>
</tr>
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Building Data

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<th>Value</th>
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<tbody>
<tr>
<td>Internal volume of house</td>
<td>366.9 m³</td>
</tr>
<tr>
<td>Envelope area for air leakage</td>
<td>281.92 m²</td>
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<tr>
<td>Ground Floor area of house</td>
<td>92.59 m²</td>
</tr>
<tr>
<td>Windows &amp; doors</td>
<td>24.89 m²</td>
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House as lived in

<table>
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<tr>
<th>Parameter</th>
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<tr>
<td>Barometric Pressure</td>
<td>987.95 mbar</td>
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<tr>
<td>Indoor Air Temp</td>
<td>18.5 °C</td>
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<tr>
<td>Outdoor Air Temp</td>
<td>13.2 °C</td>
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</table>

Air extracted from house

<table>
<thead>
<tr>
<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td>Flow rate at 50 Pa</td>
<td>4000 m³/hr</td>
</tr>
<tr>
<td>Mass flow rate at 50 Pa</td>
<td>4676 kg/hr</td>
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Air flow into house

<table>
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<tr>
<td>Flow rate at 50 Pa</td>
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<tr>
<td>Air infiltration at 50 Pa</td>
<td>10.7 ach</td>
</tr>
<tr>
<td>Air infiltration at atmos pressure</td>
<td>0.54 ach</td>
</tr>
<tr>
<td>Envelope air permeability at 50 Pa</td>
<td>13.97 m³/(hr.m²)</td>
</tr>
<tr>
<td>Specific air permeability at 50 Pa</td>
<td>42.53 m³/(hr.m²)</td>
</tr>
<tr>
<td>Envelope (inc floor, windows, doors) air permeability at 50 Pa</td>
<td>9.9 m³/(hr.m²)</td>
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</table>

House with vents sealed up

<table>
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<td>Barometric Pressure</td>
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</tr>
<tr>
<td>Indoor Air Temp</td>
<td>21.1 °C</td>
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<tr>
<td>Outdoor Air Temp</td>
<td>13.2 °C</td>
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Air extracted from house

<table>
<thead>
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<td>Flow rate at 50 Pa</td>
<td>3930 m³/hr</td>
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<td>Mass flow rate at 50 Pa</td>
<td>4544 kg/hr</td>
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Air flow into house

<table>
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<td>Flow rate at 50 Pa</td>
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<td>Air infiltration at 50 Pa</td>
<td>10.4 ach</td>
</tr>
<tr>
<td>Air infiltration at atmos pressure</td>
<td>0.52 ach</td>
</tr>
<tr>
<td>Envelope air permeability at 50 Pa</td>
<td>13.58 m³/(hr.m²)</td>
</tr>
<tr>
<td>Specific air permeability at 50 Pa</td>
<td>41.34 m³/(hr.m²)</td>
</tr>
<tr>
<td>Envelope (inc floor) air permeability at 50 Pa</td>
<td>9.6 m³/(hr.m²)</td>
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Envelope flow characteristics

<table>
<thead>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barometric Pressure</td>
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</tr>
<tr>
<td>Pressure (Pa)</td>
<td>Out Flow (m³/hr)</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>50</td>
<td>3900</td>
</tr>
<tr>
<td>45</td>
<td>3500</td>
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<td>40</td>
<td>3350</td>
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<td>26</td>
<td>2160</td>
</tr>
<tr>
<td>23</td>
<td>2000</td>
</tr>
<tr>
<td>21</td>
<td>1900</td>
</tr>
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<td>18</td>
<td>1700</td>
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<td>16</td>
<td>1600</td>
</tr>
<tr>
<td>15</td>
<td>1500</td>
</tr>
<tr>
<td>12.5</td>
<td>1400</td>
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</table>

Equivalent Leakage area

<table>
<thead>
<tr>
<th>Outdoor temp</th>
<th>16</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor humidity</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>Standard Atmospheric pressure</td>
<td>101.325</td>
<td>kPa</td>
</tr>
<tr>
<td>Air specific volume</td>
<td>0.8262</td>
<td>m³/kg dry air</td>
</tr>
<tr>
<td>Depressurisation</td>
<td>50 Pa</td>
<td>ELA (mm²) 187582.68 equivalent hole dia 488.8 mm</td>
</tr>
</tbody>
</table>
Solid line shows flow characteristic of building envelope

\[ Q = 184.7 \ P^{0.77} \]
Fig. 74. Ground Floor Plan Dalguise
Fig. 75. Blower Door Installed

Fig. 76. Air Leakage Kitchen/ Dining Room
Fig. 77. Air Leakage Bathroom

Fig. 78. Air Leakage Bedroom 2
Fig. 79. Air Leakage Bedroom 1

Fig. 80. Air Leakage Bedroom 3
Fig. 81. Air Leakage Living Room

Fig. 82. Air Leakage Utility Room
Fig. 83. Air Leakage Upstairs Gallery

Fig. 84. Air Leakage Upstairs Studio
Fig. 85. Air Leakage Upstairs Bedroom
11. RESISTANCE TO THE TRANSMISSION OF SOUND.
Nick Charlton Smith, BArch MPhil MIOA FRIAS RIBA MaPS,
the Charlton Smith Partnership

11.1 Introduction.

The agreed test requirements for the project were to measure the sound insulation of an internal partition consisting of a single leaf of earth brick plastered to each side. The test regime has been based upon the current requirements for sound insulation between dwellings even though the partition involved is internal to one dwelling. There are currently no standards of sound insulation for internal partitions within Scottish dwellings and there are no intentions of early revision of the building standards, in Scotland. There are no Building Standards requirements and test methods relating to internal-external control of sound either in Scotland or in England and Wales Regulations. Accordingly such testing was not implemented.

11.2 Methodology.

Tests to measure the performance of an internal wall of the research study house were carried out on the 2nd December 2003 in accordance with the requirements of Part H of the Technical Standards - The Building Standards (Scotland) Regulations 1990 and in accordance with BS EN ISO 140-4: 1998). The equipment was calibrated in accordance with good practice and the standards and all equipment calibrated and certified traceable to measurement standards at the UK National Physical Laboratory. The rating assessments were carried out in accordance with BS EN ISO 717/1-1997).

Tests were carried out using a Norsonics Building Acoustics Analyser Type Nor-823A Building Acoustics dual channel Analyser, Type 811 Loudspeaker and two measuring microphones, testing levels simultaneously in the source and receiving rooms with tests carried out at one third octave band intervals using filtered continuous spectrum. The Analyser was also used to test the Reverberation Times for each receiving room and to calculate the average transmitted, received and difference levels and resultant $D_{nT,sw}$ levels, taking into account the reference value and actual values of reverberation.

The equipment was set up within the north-east facing bedrooms (1 and 3) with source and source microphone in Bedroom 1 and receiving microphone and computer in Bedroom 3.

11.3 Results.

Generated noise levels were measured in third octaves across the range 100 Hz to 3150Hz. The source loudspeaker was placed to give a diffuse distribution of sound. Microphones and source were moved between measurements and four measurements were carried out for each test pair. The receiving room reverberant conditions were measured to enable normalised transmission losses to be computed. The resultant data is as shown in table 9 below:

<table>
<thead>
<tr>
<th>Third Octave Centre Frequency (Hz)</th>
<th>Level across partition (dB)</th>
<th>Difference</th>
<th>Normalised value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>29.8</td>
<td>278</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>26.6</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>25.0</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>24.9</td>
<td>22</td>
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</tr>
<tr>
<td>250</td>
<td>24.6</td>
<td>23</td>
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</tr>
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<td>315</td>
<td>26.2</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>25.2</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>
Overall calculated value of $D_{n,Tw}^\text{w}$: 27  
Sum of differences: 30

The tested wall consisted of 105mm earth bricks with 13 to 20mm clay plaster. A significant crack between wall and ceiling was noted. This varied in width but was typically some 4 to 5mm wide. It was considered that this crack would contribute significantly to reduced sound insulation of the partition. Gaps below doors to both rooms were lightly plugged with paper towelling to reduce flanking transfer.

11.4 Test values and predicted performance.

Test values are well below those predicted using the mass law. The test conditions were by no means ideal for measuring sound insulation as there is considerable flanking of sound transmission both via ceilings and via doors through the corridor.

It is also noted that the crack along the top of the partition constitutes some 0.02% of the area of the partition. If this crack is open from one side to the other then the commensurate reduction in insulation of the partition (based upon the predicted performance of 44 to 48dB) would be some 18dB. This reduction would give an $R_w$ value of some 29dB i.e. some 26 to 30dB (the weighted value would be of the order of 3 to 5dB higher). This value range includes the mean value of the measured insulation and the measured value of $D_{n,Tw}^\text{w}$.

Accordingly we would anticipate that tests carried out with reduced flanking and cracks fully filled would give insulation values in the predicted range of 44 to 48 dB $R_w$.

It is concluded that testing would be more appropriate once the building has reached moisture equilibrium and all cracks have been fully sealed up. A further set of tests would be useful and advantage would be gained from comparisons with laboratory tests of a rendered (internal and external) panel of earth brickwork.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>$D_{n,Tw}^\text{w}$</th>
<th>$R_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>24.5</td>
<td>20</td>
</tr>
<tr>
<td>600</td>
<td>28.4</td>
<td>23</td>
</tr>
<tr>
<td>800</td>
<td>32.6</td>
<td>28</td>
</tr>
<tr>
<td>1k</td>
<td>35.6</td>
<td>33</td>
</tr>
<tr>
<td>1.25k</td>
<td>42.2</td>
<td>39</td>
</tr>
<tr>
<td>1.6k</td>
<td>34.5</td>
<td>33</td>
</tr>
<tr>
<td>2.0k</td>
<td>28.8</td>
<td>25</td>
</tr>
<tr>
<td>2.5k</td>
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<td>28</td>
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<tr>
<td>Mean Value</td>
<td>29.3</td>
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</tr>
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</table>

Table 9: Sound Insulation - Computed results
12. REFERENCES


Howieson, S., 2005, Housing & Asthma, Spon Press


