Glasgow Houses

Phase 1 study
Post construction and early occupation

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InnovateUK project number	450055
Project author	Glasgow School of Art for Glasgow Housing Association
Report date	2013
[1]InnovateUK Evaluator	N/A

No of dwellings	Location	Type	Constructed
Four	Glasgow	Semi-detached	2010

Areas	Construction form	Space heating targets	Certification level
Not reported	2 Clay block 2 Timber frame	Not reported	Not reported

Background to evaluation

The Glasgow Houses were prototype designs using passive principles along with tried, tested, simple and low maintenance technologies to reduce heating and hot water bills for tenants. The aim was to provide a very thermally efficient exemplar houses that could be delivered on a large scale throughout the city. The design incorporated a ‘Thermoplan’ clay block or timber frame, with external insulation, highly insulated roofs, high-performance windows, thermal mass, airtight construction, sunspaces, solar thermal hot water collectors, mechanical ventilation heat recovery (MVHR), low energy lighting, and high efficiency appliances.

Design energy assessment	In-use energy assessment	Sub-system breakdown
Yes (SAP review)	Simulated only (no details)	No

The project included a series of six early-occupancy studies that used varying occupancy regimes to evaluate the performance of the houses and users perceptions of comfort and environmental quality under varying conditions. Two pressure tests were conducted. There was said to be a ‘significant’ increase in the level of air permeability over the intervening 18 month period. During the pilot study the CO_2 levels in both houses were found to be high. The system was investigated by the manufacturer and re-commissioned. Solar thermal systems were investigated. In some cases solar thermal pipework insulation was found to be sub-standard. Comparison of the MVHR systems in both houses identified differences in performance. This was likely due to issues with duct routing and failures in the (enclosed) air delivery system.

Occupant survey type	Survey sample	Structured interview
Student developed	N/A	N/A

The eccentric nature of this Phase 1 study required that specific occupant surveys were developed to deal with the short-term occupation for the four dwellings (2 plots) by the student volunteers. This was a variation to the more standard use of BUS questionnaires in BPE studies. Details are not provided.

Contents

1 Introduction and overview

In May 2009 Glasgow Housing Association (GHA) commissioned PRP Architects to develop a prototype house design that would use passive principles along with tried, tested, simple and low maintenance technologies to reduce heating and hot water bills for GHA tenants to £100 a year. The aim was to provide a very thermally efficient exemplar house that could be delivered on a large scale in housing development and regeneration projects throughout the city, and at the same time provide flexible affordable accommodation for both rent and sale.

The final design incorporated high levels of thermal efficiency using a ‘Thermoplan’ clay block with external insulation, highly insulated roof cassettes and high performance windows, thermal mass, airtight construction, sunspaces, solar thermal hot water collectors, mechanical ventilation heat recovery (MVHR), low energy lighting and high efficiency appliances. Whilst the intention was not to achieve Passivhaus standard, the performance was to get as close to this as possible within the increasingly rigid cost constraints facing the social housing sector. A series of design workshops were undertaken to refine the plans, and in summer 2010 GHA undertook to construct two pilot dwellings to examine issues of buildability, affordability and performance.

Due to uncertainties about the use of the clay block system, a decision was made to also construct two spatially identical houses using a more conventional highly insulated timber frame system which is the standard form of construction used by GHA's development partner organisation City Building LLP.

Following completion of the dwellings in September 2010 a pilot study was undertaken by the Mackintosh Environmental Architecture Research Unit (MEARU) on behalf of GHA during February of 2011 to test the feasibility of a comparative performance analysis of the dwellings. This raised a number of questions about specific elements of the design and construction, which warranted further study and now form the focus of this TSB BPE project.

The project itself undertook a standard Phase 1 analysis for both houses, alongside a series of six early occupancy studies that used varying occupancy regimes to evaluate the performance of the houses and users perceptions of comfort and environmental quality under varying conditions. These regimes were two-week periods of occupancy during which both houses were inhabited by volunteer residents who lived in the houses according to carefully designed ‘scripts’. Each ‘script’ was based on occupancy profiles derived from other monitoring projects undertaken by MEARU and on specific areas of investigation common to housing stock owned by

GHA and was designed to assess the respective performance of the dwellings under these conditions.

Figure 1. Plot 1 & 2 South and West Elevations

This study sought to quantify the as-built performance, and relative energy and environmental performance of both house types in relation to different occupancies. It has provided data about the ability of the houses to accommodate different patterns of use that are likely to be experienced in real world conditions. It has examined and tested the relative performance of the clay-block house against the timber frame and has also provided insights into the scale of variation that different regimes may produce.

It should be noted that this Final Report document has been written to provide only the most relevant information and salient findings for ease of reference. More in-depth descriptions of background, processes and findings can be found in Quarters 1 to 4 reports previously submitted to TSB for this project.

Figure 2. Plots 3 & 4 West elevation

2 About the building: design and construction audit, drawings and SAP calculation review

2.1 Design Review Process and Findings

Design & Construction Audit

As part of the design and construction review MEARU sought final Construction drawings from both PRP and GHA/ City Building. A review of these showed that while differences existed in the particular revision of some drawings, the basic information remained consistent and no significant variations in the drawing or specification information could be identified.

In extended discussions with GHA and City Building LLP it was ultimately confirmed that the dwellings were constructed exactly as presented on the final drawing issue with no variations due to strict control of construction by PRP. It would seem that the slightly unusual procurement method of this project (as a test construction) ensured that the normal variations that could be expected to arise on site were not experienced on this project and effectively what was designed *is* what was constructed. A visual inspection of the construction, as far as is practicable, supports this assertion.

In the absence of any significant constructional variations, the most relevant outcome from this part of the project relates to the effort required to try and pull the required information together. Over a relatively short period of time the natural turnover in personnel involved in the project made the information gathering a lengthy and onerous task and an experience that was repeated through various stages of the BPE project. With increasingly complex buildings being constructed this situation reinforces the importance of effective information collation, recording and storage at handover stage to aid maintenance and efficient performance of the building over its lifetime.

SAP Review

As the construction audit identified no variation between the specified and 'as-built' schemes the only variation required to update the SAP information was to replace the design elemental U-values for those identified by in-situ testing.

In accordance with the requirements of the Dwelling Characteristics Data Capture this process was undertaken using version 9.90 of the Standard Assessment Procedure. It is important to note, however, that the original SAP calculations for the project were undertaken using version 9.81 of SAP. This variation in assessment techniques would present variations in results that would not necessarily be as a result of the U-value variations alone. As such, results are presented for comparison in 3 stages; original SAP values (calculated using v9.81), original SAP data input (calculated using v9.90) and post-construction SAP values (calculated using v9.90). The results of this 3-stage process are tabulated below and allow comparison not just of the variation in SAP value due to construction anomalies but also a comparison of the impact of varied assessment methodologies.

The use of the Data Capture sheets in this process highlighted a certain inflexibility of the standard sheets in not accepting the original SAP information and this is something that should perhaps be addressed in future projects.

Plot 1 SAP Comparison;

Development Stage	SAP Version	NHER Plan Assessor Version	SAP Rating	EI Rating
Pre-construction	9.81	4.5.21	87	88
Pre-construction	9.90	5.4.0	85	88
Post-construction	9.90	5.4.0	83	86

Table 1. Plot 1 SAP value comparison

Plot 3 SAP Comparison;

Development Stage	SAP Version	NHER Plan Assessor Version	SAP Rating	EI Rating
Pre-construction	9.81	4.5.21	87	88
Pre-construction	9.90	5.4.0	85	88
Post-construction	9.90	5.4.0	84	86

Table 2. Plot 3 SAP value comparison

In the intervening period from the first production of SAP information to the more recent reassessment using v9.90 it is clear that SAP methodology has varied as identical data inputs are shown to provide varying outputs with the SAP rating of both dwellings falling from 87 to 85. As a tool SAP's value lies in being able to compare one rating with another. This comparison shows that SAP values produced historically may be skewed to have a comparatively higher reading than contemporary assessments and that the usefulness of this value should, therefore, be closely interrogated as it clearly does not represent a static benchmark.

With respect to the individual dwellings, the apparent reduction in performance between pre and post-construction values is as would be expected given the identified variation in measured fabric performance. Perhaps the most surprising aspect of this is that the Environmental Impact of both dwellings are tied at 86 yet, from u-value and whole house fabric heat-loss testing, we know the performance of Plot 3 is significantly better than that of Plot 1. This shows that the fabric performance has a limited impact on the SAP and EI rating and that other considerations, such as use of renewables, etc. may have a disproportionate importance in the SAP procedure.

Assumed and Actual Performance

From early stages of the project development it was clear that the original aspiration of the '£100 House' would not be achievable and in many ways an unrealistic target. This had been recognised during advice provided at design stages, which identified the many variables including occupancy and variable fuel prices. Overall, the design performance had the *potential* to come close to Passivhaus standard (in terms of energy use) with simulated results of around 23 kWh/m^2. This figure was highly sensitive to ventilation loads and, in particular, occupant behaviour with respect to ventilation. This figure also relied heavily on the MVHR system, without which simulated results gave annual figures of 53 kWh/m^2.

The analysis undertaken post construction using as built figures and recorded temperature profiles from the pilot study identified more realistic figures for space and water heating of £367.67 p.a. for Plot 1 and £281.25 p.a. for Plot 3. At that stage the differences between the houses were accounted for primarily by differences in U-values (0.15 for the timber frame and 0.2 for the Clay block and higher levels of window opening in Plot 1.

Even for what would be considered to be a relatively high demand scenario, especially in the NBT house (which had a lot of window opening), this is at a level where fuel poverty would not be experienced regardless of the household's economic activity, especially for a dwelling of this size and quality. Although the headline target was unlikely to be achieved in practice, the energy analysis gives predicted figures for energy use that are reasonable for a house of this size and well within what can be considered affordable. They were however some way off the predicted figures in relation to Passivhaus, (89 kWh/m^2 for Plot 1 and 67 kWh/m^2 for Plot 3).

Although the £100 figure had been a useful 'strapline' in promoting the concept of the house, the gap between SAP compliance calculations and actual consumption identifiable through predictive modelling and was borne out in the pilot study and initial analysis indicates that this remains the case. In terms of actual performance of the dwellings it is important to note that throughout the project the intermittent nature of the occupancy created limitations for gathering longitudinal data on actual consumption.

What the analysed data does identify, however, is the need for caution in working with compliance calculation (SAP) or even prediction in respect of variables of occupancy. It is key that the limitation of these tools are understood by all parties in their ability to predict and that performance expectations are thus managed. Even this simple bit of education could make the findings of BPE more palatable to varied stakeholders and improve uptake of the process.

2.2 Conclusions and key findings for this section

- Collation and effective recording of construction information (drawings, manuals, etc.) is essential prior to handover as these will be required to ensure efficient performance of the building through its lifetime.

- The usefulness of SAP as a comparative tool should acknowledge changes in the methodology over time.

- Comparative SAP results of the tested buildings highlights that significant differences in fabric performance can have a limited difference on the overall rating and that SAP may be overly skewed toward the importance of technologies and not a 'fabric first' approach.

- The timber kit dwelling performs better than its clay counterpart in terms of (regulated) energy use but both perform well by contemporary standards.

- Actual performance is significantly below performance expectations in both cases but this is largely due to the limitations of the tools (namely SAP) which caused such high expectations. It is important that the all stakeholders are aware of the limitations of such predictions and this may help to improve the uptake of the BPE process.

- The rigid process for recording SAP data for TSB is limiting for projects which were assessed using varying versions of SAP.

3 Fabric testing (methodology approach)

3.1 Testing Methods and Findings

In-situ U-value Testing

In-situ U-value measurements were undertaken in accordance with the TSB tranche 5 mandatory elements. The methodology, results and discussion of these findings are presented below.

Methodology;

The methodology used for testing and analysis is as the test procedures set out in *Hukseflux HFP01/ HFP03 manual version 1014 and TRSYS01 manual version 0810* both of which describe thermal resistance testing procedures in accordance with ISO 9869, ASTM C1046 and ASTM 1155 standards.

Refer http://www.hukseflux.com for further details.

Figure 3. U-value testing kit in-situ with co-heating equipment visible.

Results;

The table below present the results of the in-situ u-value measurements against the design values for each tested construction element (NB: all values are accurate to ± 5%)

Construction Element	**Sample Period**	**Sample Duration**	**Design U-value**	**Measured U-Value**
P1 External (N) Wall	03.04.12 @ 17.00 - 06.04.12 @ 05.00	60 hours	0.15W/m^{2}K	0.32W/m^{2}K
P1 Party Wall	03.04.12 @ 17.00 - 06.04.12 @ 09.35	64 hours 35 mins	n/a	0.42W/m^{2}K
Plot 1 DG Unit	09.04.12 @ 20.20 - 10.04.12 @ 06.20	10 hours	whole window value 1.2W/m^{2}K	1.22W/m^{2}K
P1 Roof	09.04.12 @ 20.20 - 10.04.12 @ 06.20	10 hours	0.13W/m^{2}K	0.32W/m^{2}K
P3 External (N) Wall	06.04.12 @ 10.00 - 09.04.12 @ 09.30	71 hours 30 mins	0.15W/m^{2}K	0.18W/m^{2}K
P3 Party Wall	06.04.12 @ 10.00 - 09.04.12 @ 09.30	71 hours 30 mins	n/a	0.15W/m^{2}K

Table 3. Construction elements measured U-values (test 1)

Plot 1 External (North) Wall;

The U-value of this construction element was initially calculated on a 64.5 hour duration and provided an output value of 0.33W/m^{2}K. This was significantly above the design value so further investigation was made of this result. The further analysis highlighted an anomalous external temperature reading occurring from 05.30 on 6th April. The data considered for the calculation was therefore taken from results up until 05.00 on 6th April only. When reassessed on this basis a slight improvement in U-value was identified and a final reading of 0.32W/m^{2}K was derived.

Plot 1 Party Wall;

As a party wall, theoretically mediating between two heated spaces, there is no technical requirement for this element of construction to have a U value and, as such, none was stated at design stage to provide a comparison to the measured value.

From design drawings it is know that the construction is essentially two leafs of 175mm clay block with a 30mm intermediate layer of 'insulation' (no further description on the nature of this is given). With this build up of limited thermal insulation and the temperature differential between the heated and unheated spaces the measured U-value appears reasonable.

Plot 1 Double Glazed Unit;

Initially the U-value for the double glazed unit was measured over a full 24 hour period from 9th to 10th April producing a resultant U-value of 0.66W/m^{2}K. This value appeared overly low for a high performance double glazed unit and, as such, the value was recalculated over the 10 hour overnight period from 20.20 on 9th April to 06.20 on 10th April. A value of 1.22W/m^{2}K was achieved which is more representative of the performance that could be expected from a unit of this type.

Despite being measured on a North facing elevation and out of direct solar radiation it appears that measurements made during hours of sunrise had a significant effect on the in-situ U-value. The final value appears to be reasonably robust but one which could have been further refined with an extended period of monitoring. Unfortunately due to time pressures and availability of the dwelling for experimentation, further testing of this element proved unfeasible.

Plot 1 Roof;

Owing to building orientation the roof of plot 1 is subject to solar radiation on a daily basis. As above the calculation of U-value was, therefore, based on data collected over the same period as that used for the double glazed unit. The resultant value of 0.32W/m^{2}K is significantly above the design value of 0.13W/m^{2}K.

The possible reasons for this poorer performance are as identified with Plot 1 external wall and in addition to this the limited measurement duration may have impacted on the validity of this result and this construction element may warrant further investigation.

Plot 3 External (North) Wall;

The U-value of this construction element was measured as 0.18W/m^{2}K which compares favorably with the design intent value of 0.15W/m^{2}K. The slight variation in this value could be attributed to issues with on site construction (mortar snots creating thermal bridging in the cavity for example) or due to the flux measurements being taken on or adjacent to an element of structure with lower thermal resistance than the intermediate through wall construction.

Plot 3 Party Wall;

As a party wall, theoretically mediating between two heated spaces, there is no technical requirement for this element of construction to have a U value and, as such, none was stated at design stage to provide a comparison to the measured value.

The measured value of 0.15W/m^{2}K appears reasonable given the level of party wall insulation (168mm) and the fact that this is internal and heavily sheltered.

Discussion

The values attained for Plot 1 external fabric and for the roof construction (identical between dwellings) are significantly above that suggested by the design performance specification. This could be as a result of one or a combination of the following;

Methodology not correctly applied. Test error may account for these figures although it should be noted that the test was repeated and an identical procedure was followed for the testing of the construction elements of Plot 3 where values much closer to the design intent have been identified.

Flux measured through thermal bridging element of construction. It is possible that the flux plate was placed on a joint or adjacent to cavity tie holding the cavity insulation in place. This very slight potential thermal bridge would not, however, account for such an uplift in U-value for Plot 1 but could provide an explanation for the values seen through the roof cassette (notwithstanding the fact that great care was taken to avoid elements of structure when selecting a flux plate position).

Sufficient flux not achieved. As the process was undertaken in conjunction with the Co-heating Test a constant and high temperature differential was maintained between interior and exterior ensuring that flux direction remained constant. There was, however, significant ‘noise’ around the flux measurements, which could account for the discrepancy in the design and measured values. This is evident when the flux values of Plot 1 external wall are compared to those of the Plot 1 window unit, both presented below.

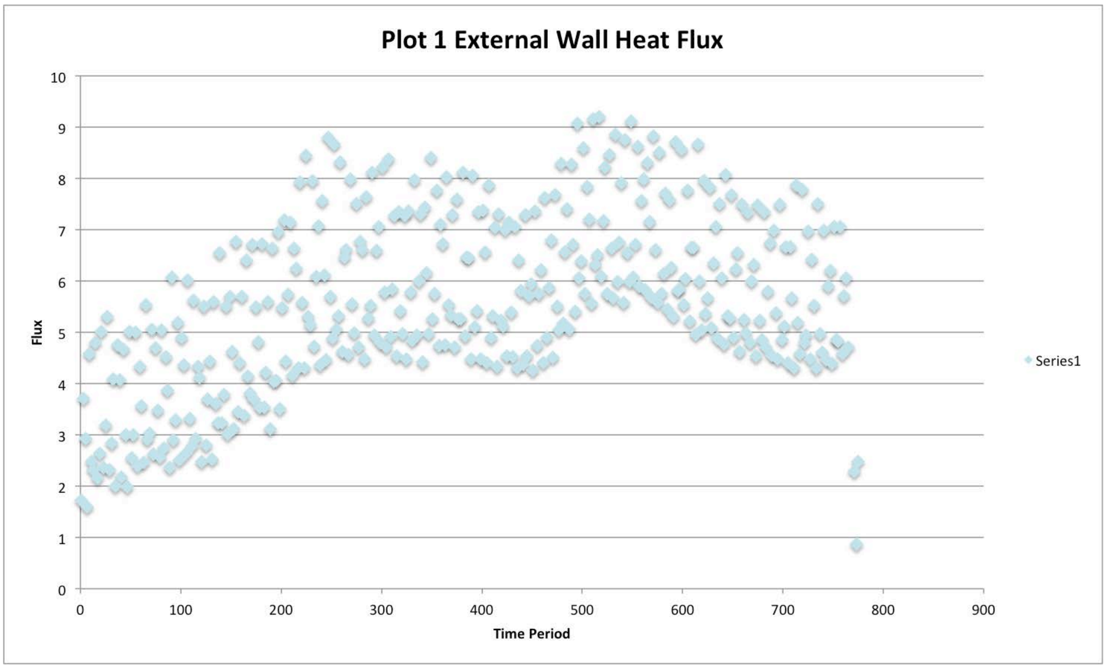

Figure 4. 'Noise' around heat flux measurements through clay block wall

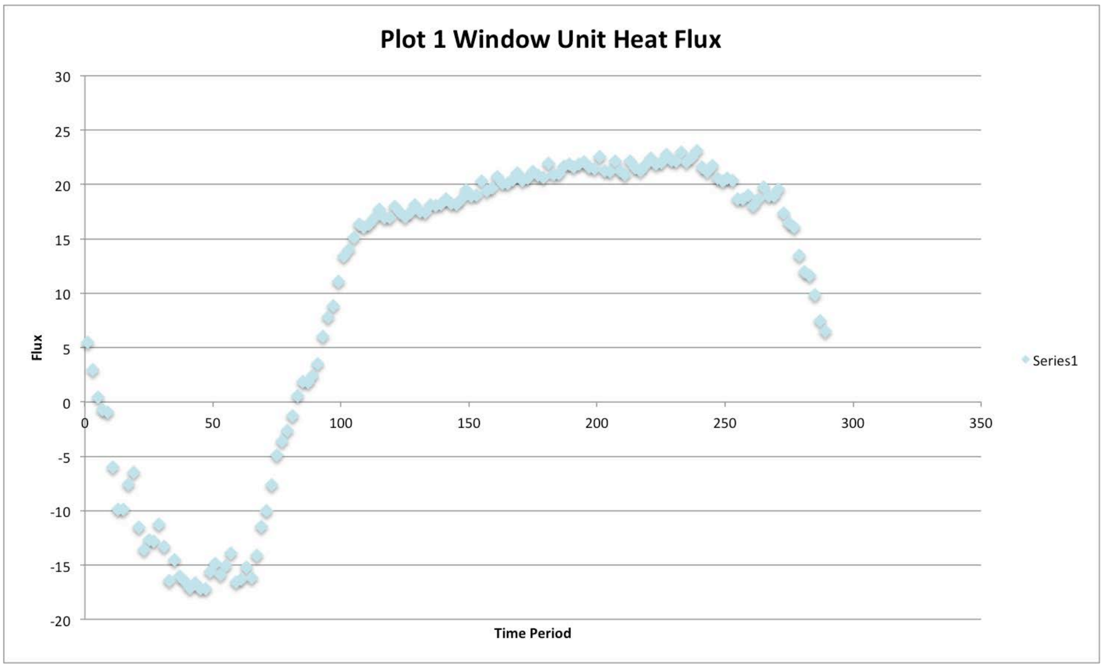

Figure 5. Graphed heat flux measurements showing a 'normal' relationship

Insufficient duration of test. Each test was undertaken for as long a duration as possible, subject to the limitations of the co-heating test, but ultimately it can be seen that the process would have benefitted from a longer span. If the process was to be repeated, over a similarly short time, then fewer construction elements would be tested but each for a longer duration.

Construction simply does not meet design intent value. This is a common issue with many construction elements arising from poor workmanship on site. In this instance it may provide the most logical explanation for the value deviation although it should be noted that the system used is one which allows little room for on site mistakes and the workmanship elsewhere on site is of a high standard.

Test 1 Conclusion;

The measured U-values for the Plot 1 party wall and window and for the external and party walls in Plot 3 represent values which are marginally poorer than those of the design intent but which are within a range that could be expected.

The values identified for Plot 1 external wall and roof construction were significantly higher than the design intent. The limited time available for testing these elements may have had a significant impact on the results as a longer duration will provide a more accurate output – particularly where a heavyweight construction is used. As such further testing of the Plot 1 external fabric was undertaken over an extended period with results presented as follows.

Methodology for the retest was as initial testing although the test period was significantly increased. In addition, thermography was used to ensure that the flux plate and thermistors were not placed on thermal bridging elements of construction - notwithstanding the fact that this should not be possible in the standard through wall construction of Plot 1.

Test 2 Result;

Construction Element	**Sample Period**	**Sample Duration**	**Design U-value**	**Original Measured U-value**	**Re-test Measured U-Value**
P1 External (N) Wall	06.11.12 @ 12.00 – 18.11.12 @ 11.50	288 hours	0.15W/m^{2}K	0.32W/m^{2}K	0.27W/m^{2}K

Table 4. Plot 1 external fabric measured U-value (test 2)

The process of retesting and allowing a longer duration of test has improved the measured U-value of the construction element but it still falls a long way short of the design intent. At this stage the value of 0.27W/m^{2}K can be confidently reported as the in-situ u-value and points towards further work perhaps being undertaken to assess why this is the case.

The retested values and the validity of the other results suggests that the higher than expected results for Plot 1 may not be entirely unfounded as shown by the results of the whole house fabric heat loss tests.

Whole House Fabric Heat Loss Testing (co-heating)

Between 30.03.11 and 10.04.11 the whole house heat loss testing was undertaken on both dwellings in accordance with the methodology specified by the TSB monitoring protocol[1].

This was in variation to the original proposal, where only one dwelling would be tested, but ultimately of greater benefit to the project as a direct comparison could then be made between the thermal efficiency of the two construction methodologies.

[1] With respect to the monitoring protocol document, the methodology calls for the internal temperature to be maintained within ±0.2°C. The thermostats used in the testing are the Honeywell T4360B model as suggested in the supporting Leeds Met procedure document. It would appear that this level of accuracy may not be achievable with this particular thermostat as technical specification state a typical temperature differential of 0.5°C.

Figure 6. Co-heating equipment installed in a first floor bedroom

Results;

On completion of the physical testing it became apparent that analysis of the co-heating test data for these dwellings was more complex than initially identified due to the requirement to calculate the performance against, essentially, 3 'external' conditions – i.e. the true external and the adjacent conditions of the unheated space of the adjoining property and the sunspace. Each of these sits outwith the insulated envelope of the property and impacts on both the results and approach to calculation.

Exploration of the appropriate calculation methodologies identified that varied approaches exist to analysis with each providing differing results. As a result the values used for direct calculation are simply the energy consumption values. These provide a suitable method for comparison as the fabric construction is the only variable between the two test dwellings (i.e. levels of solar gain are not calculated but will be identical).

	Plot 1	Plot 3
Energy Consumption	189.41kWh	155.57kWh

Table 5. Plot 1 & 3 comparative energy consumption values

This direct comparison shows that the thermal performance of the timber kit dwelling, Plot 3, is better than that of the masonry dwelling, Plot 1. This result validates the results of the in-situ U-value testing which identified the poorer performance of the masonry construction.

The conclusion of this element of testing did lead to discussion over the validity of the whole house fabric heat loss metric. While the capacity to have a single viable metric for this is attractive in terms of understanding energy efficiency the time, cost and upheaval (for residents) in achieving it has to be called in to question. Moreover the varied calculation methodologies for taking account of solar gains and adjacent temperature zones make the universal comparison of values questionable.

Thermography

Thermographic images were taken externally and internally for both dwellings on the night of 24th November 2012 in accordance with the protocols of TSB testing requirements, BRE IP 1/06 and BSRIA 39/2011.

Individual reports have been produced for each dwelling and are presented in this report as Appendix A. In each instance thermographic images of the interior are presented with supporting digital camera images to allow direct comparison. Exterior thermographic images were taken at night and, as such, identical digital images could not be taken as the FLIR camera used does not have a flash function.

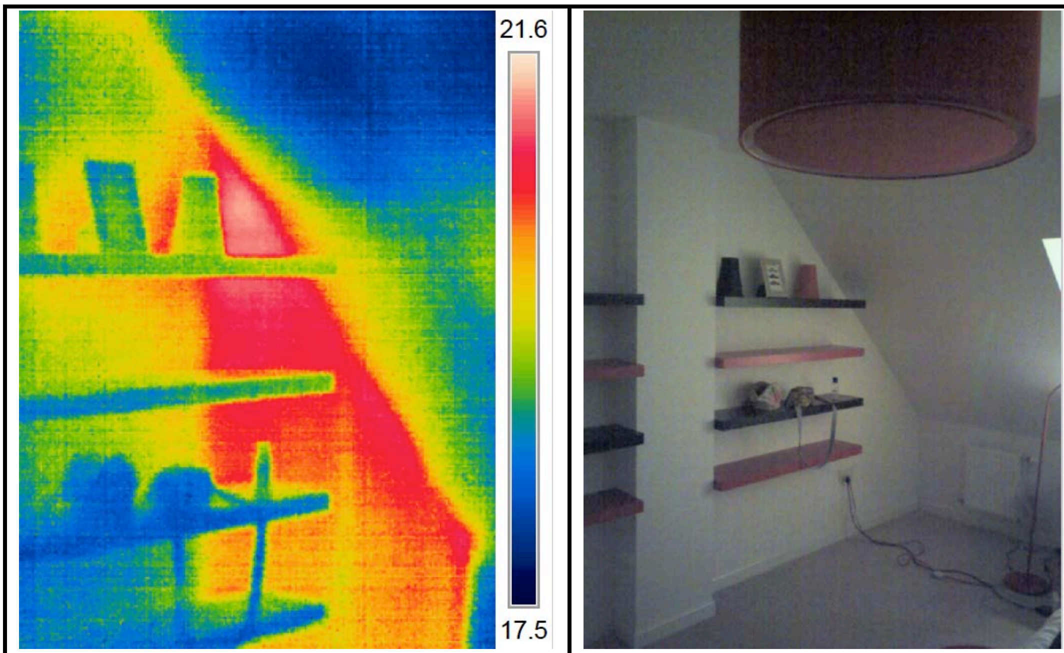

Figure 7. Example of the internal issues identified of uncontrolled heat loss in the plant space transferring into adjacent apartments as unwanted heat gains.

A full analysis is provided for each dwelling in the respective reports with the summarised key findings presented below;

- Construction fabric for both dwellings was found to be generally good quality with the only weak point identified existing at the junction between the roof cassette and wall head where the extents of insulation are limited due to the level of structure required.
- The heated draught lobby appears to represent an area of significant heat loss through it's largely glazed exterior. The inclusion of a permanent radiator in this space, as part of the heating system, allows improved comfort levels on entering the dwelling but is not energy efficient.
- Heat loss is most significant around glazed elements (junctions of frame elements and DG units) and at the head and cills of external quality doors. Although relatively significant the performance of the window units (based on area weighted temperature) was found to be good compared to the high performance fabric.
- As per the findings of the solar thermal report, unlagged pipes from the hot water cylinder were found to present significant uncontrolled heat loss to the plant space and, in the case of adjacent rooms, unwanted heat gains.

Air-tightness Testing

Pressurisation and depressurisation testing was undertaken by Elite Energy Assessors to both masonry (Plot 1) and timber kit (Plot 3) dwellings on 27.03.12 and 10.04.12.

The methodology, results and discussion of these findings are presented below and should be read in conjunction with the test reports included in this report as Appendix B.

. Plot 1, Glasgow House, Combined Air Test Report

. Plot 1, Glasgow House, Combined Air Test Report 2

. Plot 3, Glasgow House, Combined Air Test Report

. Plot 3, Glasgow House, Combined Air Test Report 2

Methodology;

Air permeability testing was undertaken on two separate occasions, straddling the period of the Whole House Heat Loss test. Testing was undertaken in accordance with the requirements of the BPE Domestic Guidance For Project Execution document and with ATTMA 2007 Technical Standards.

Results;

Test	**Test Date**	**Pressurisation** **($m^3/h/m^2$ @ 50Pa)**	**Depressurisation ($m^3/h/m^2$ @ 50Pa)**	**Mean Value** **($m^3/h/m^2$ @ 50Pa)**	**Final Mean Value**
P1 - Test 1	27.03.12	3.45	4.80	4.13	**4.03**
P1 - Test 2	10.04.12	3.28	4.59	3.93	
P3 - Test 1	27.03.12	3.17	4.93	4.05	**4.06**
P3 - Test 2	10.04.12	3.27	4.85	4.06	

Table 6. Comparative air-tightness testing results before and after co-heating

Internal Thermal Photography/ Smoke Testing;

Internal thermal photography of both dwellings identified several instances where air permeability and heat loss were significant and identifiable. These are as follows;

Both Dwellings;

Window/ wall junctions generally.

Velux type window junctions and wall ingoes (bedroom 3 and attic room).

Double door joints (to kitchen, living room, bedroom 1 and bedroom 2).

Incoming electrical service penetration in GF slab (in electric meter cupboard)

Incoming gas pipe wall penetration (WC/ utility room).

Junctions between bathroom walls and sanitary fixtures including under bath, sink outflow wall penetration and back-to-wall WC.

In addition, specific areas of air leakage were identified in Plot 1 as;

Plot 1;

Door/ wall frame between hall space and draught lobby.

Skirting boards at GF junction.

The table below presents the final air permeability values for 2012 against post construction tests which were undertaken in November 2010.

Dwelling	**Nov' 2010 Test Value ($m^3/h/m^2$ @ 50Pa)**	**Mar' / Apr' 2012 Test Value ($m^3/h/m^2$ @ 50Pa)**
Plot 1	3.02	4.03
Plot 3	3.47	4.06

Table 7. Comparative air-tightness testing results post-construction and 16 months later

A comparison of values suggests that a there has been a significant increase in the level of air permeability over the intervening 18 month period but this may not be representative of the actual situation. While it could be the case that the levels have increased due to settlement or shrinkage in the construction and movement of sealed joints, it is unclear whether the earlier test results are a result of the same test procedure and if they can, therefore, be directly compared (i.e. it is not clear from reporting if initial test were based on pressurisation, depressurisation or, in the case of the more recent tests, a mean value of both test types).

If the final, most recent values *only* are considered, both dwellings can be seen to have similar air-tightness levels of circa 4 $m^3/h/m^2$ @ 50Pa and correspond well with the design values stated in the pre-construction documents of 4 $m^3/h/m^2$ (Glasgow House Final Report, 23.10.09, PRP Architects). This would indicate that the construction has been undertaken to a high standard and as per the design intent.

The mean values for both dwellings represent a good level of air-tightness, compared to contemporary standards, and also a constructed level, which is appropriate for the use of a balanced mechanical ventilation with heat recovery system.

The measured value in Plot 1 varies significantly between the two test dates with an improved level of air-tightness identified in the second test. One explanation for this altered value could be due to thermal expansion of the construction elements during the course of the Co-heating test, where the interior of the dwellings was constantly heated to 25°C. If thermal expansion did take place then the result could be the closing, or reduction in size, of air paths between the two test dates and the subsequent reduction in air permeability.

Why this phenomena would occur only in one of the structures is not entirely clear however, particularly when the variation is apparent in the masonry dwelling which could be assumed to have the greater dimensional stability.

Thermal Mass Analysis

Testing of the comparative fabric performance in relation to extent of presence of thermal mass was undertaken in the sunspaces and adjacent apartments for both test dwellings. The results and analysis from this are presented in Section 5.1 Scenario Testing (Scenarios 4 and 5).

3.2 Conclusions and key findings for this section

- The fabric performance of Plot 1 was found to be below the design intent values and below its timber frame counterpart which achieved U-values much closer to design intent (although still slightly below stated values).
- Minimum u-value test durations noted in TSB methodology are too short to ensure confidence in validity. In this instance this required retesting which was only feasible due to the fact that the houses were not normally occupied.

- Comparison of co-heating values confirmed the results of U-value test and that Plot 3 has better fabric performance that Plot 1 (with P1 using 122% of the energy of P3 to maintain identical conditions).

- Practicality of the Co-heating test as a viable metric should be called in to question. In this instance it proved to be useful as a method of direct comparison but the cost and disruption of testing in housing under occupation seems to outweigh any benefit of having a single performance value which is not really comparable to other tests as variations exist in calculation methodology.

- Clarification from TSB required as to the appropriate methodology required for analysis of co-heating data as varied approaches exist which provide differing results.

- Thermographic images found the construction fabric for both dwellings to be generally good quality with no obvious or unexpected weak spots identified. Most heat loss was found to exist around window openings as would be expected.

- The inclusion of a radiator to the draught lobby was show in thermal imaging to represent a significant area of energy loss.

- As per the findings of the solar thermal report, unlagged pipes from the hot water cylinder were found to present significant uncontrolled heat loss and, in the case of adjacent rooms, unwanted heat gains.

- Smoke pencil tests as part of the air-permeability testing identified several areas of air leakage which could be easily remedied to improve overall air-tightness values.

- Notwithstanding this, the values achieved for both dwellings are almost exactly as the design intent, which would tend to support the previous assertions of high quality construction. In addition, the achievement of these values will support the operation of the balanced MVHR system as was intended.

4 Key findings from the design and delivery team walkthrough

4.1 Walkthrough Process and Findings

Over the course of the project a series of walkthroughs, visits and discussions were undertaken with GHA and the construction and delivery team, City Building.

On one level the unusual nature of the procurement and construction of the houses is such that is difficult to extrapolate into more normal procurement, management and maintenance processes. However, the fact that these houses were built to test certain ideas and concepts ultimately proved a very useful vehicle for the gathering and dissemination of knowledge. The houses are also subject to regular visits from the housing construction industry, including housing associations, architects, developers and residents.

Figure 8. Walkthrough of Plot 3 involving GHA, City Building and MEARU

The general consensus is that the buildings delivered offer a very high quality living environment. This is backed up by responses of test occupants in the original pilot study and subsequent testing scenarios. The build quality of both houses is clearly good, but given that these have been constructed at the Skills Academy as show houses for a new concept, this is to be expected. As noted in the construction audit, the dwellings have been delivered to the design specification, with only minor modifications (change in roof finish for example).

The overall feeling from the client body is that these houses represent a best-case scenario, particularly given the current (Housing Association Grant) funding constraints on public housing in Scotland. Subsequent developments are unlikely to replicate all the features that exist here, and the overall size is likely to be reduced in future developments.

At this stage the use of the Thermoplan blockwork is unlikely to be replicated. Monitoring and evaluation across the project only identified limited benefits (increased use of thermal mass) with the use of this system. This alone does not appear significant enough to outweigh the more significant disadvantages of cost uplift (approximately £50k per dwelling compared to timber frame), buildability and need for an imported proprietary systems.

Several discussions focussed on the rationale for the location of services. In comparison with a conventional house, which might only contain a gas boiler there is a significant amount of ‘kit’ located in the ground floor bathroom (gas boiler and controls), top floor store (thermal store, solar hot water pump and expansion vessels) and attic (MVHR). One of the issues for discussion is the relative accessibility of this. An identified concern for the client is the use of this in social housing in relation to the degree of accessibility by tenants, which could lead to equipment being interfered with or switched off. The counter argument is the need to make the equipment accessible for maintenance and repair. One possible suggestion is that all the equipment could be located in one space, freeing up space in other parts of the dwelling. The relevance of this is discussed further in relation to system testing but it is an issue which has a much wider relevance to housing design generally and clearly must be better understood by specifiers, clients and users alike.

Allied to this was the realisation during the walkthroughs that the nature of the ventilation system is not apparent to users. Because the ducting is hidden and the supply and extract grilles are identical it is difficult to determine which is which. There is also no clear path for airflow from the MVHR delivery into the bedrooms, which do not have undercuts or other vents so when the doors are closed, effectively become dead-ends. Without good occupant information it would be difficult for occupants to comprehend the system.

The sunspace is a key feature of the design and feedback is that it has amenity value over and above thermal value. This alone was seen to be unlikely to support inclusion of this relatively expensive addition to future dwellings so further work was done to assess it efficacy, in terms of energy reduction, during varied seasonal conditions. The results of this testing are presented in Section 5.1 (SC 4 results) and Appendix C – Eurosun 2012 paper.

One irony pointed out is that the sunspace in Plot 1 does not have any thermal mass (due to the external insulation system) whilst Plot 3 does. The other issue identified at walkthrough stage was the lack of any path for air movement from the sunspace into the houses, other than opening the sunspace windows. This undermines a potential benefit as a preheat ventilation space as described in Appendix C.

There was some discussion about the space below the stairs in the hall – in Plot 1 which is used as storage, in house Plot 3 it is open. The potential benefits of providing drying space were discussed, but the obvious space exists in the lower bathroom (which also contains the washing machine), but the potential of the plant spaces was also identified, which were noted to be very warm. Were these to be connected to the MVHR system and useful drying space would be provided.

4.2 Conclusions and key findings for this section

- The nature of the Glasgow House project (as test dwellings) has meant that the project has developed significantly different outcomes than could be expected from a more conventional Phase 1 project. This has, however, provided increased opportunity for testing elsewhere in the project.
- Walkthroughs and occupancy have demonstrated the overwhelmingly positive perception of the dwellings and the living standard they provide.
- Positioning, visibility and awareness of installed systems became evident as an issue, that has relevance for designers, installers and occupiers.
- Walkthroughs provided the opportunity for discussions to be held on the successful use of construction systems, the spatial arrangement and the use of passive systems.

- Perhaps most importantly the process of meeting varied stakeholders in-situ provides the opportunity for all parties to understand the decisions made through the design and construction process and allows more constructive evaluation of performance to be made. This is critical to the success of BPE in general.

5 Evaluation of guidance offered to the occupants and the physical handover process

5.1 Scenario Testing Approach and Findings

The lack of permanent residents in the Glasgow House projects means that this element of the project is somewhat eccentric to what might be expected from other Phase 1 projects. In order to simulate occupations 6 scripted scenarios were run over the duration of the BPE. In each instance student volunteers were used and with each iteration handover guidance and living ‘scripts’ were provided to the occupants. This ensured they could operate the dwellings as was required for the specified testing outcome. This methodology allowed very specific and focussed testing to be undertaken but does not provide the analysis of handover that could normally be expected.

Notwithstanding this the individual scenarios proved very successful for testing the performance of the dwellings. The methodologies employed for this and the significant findings are presented below.

General Methodology

In each instance testing was undertaken as per the detailed description of Scenario 1. Each scenario was designed to test differing aspects of performance and as such there were specific aspects being investigated, which involved variation of the living ‘scripts’ and of the constraints placed on the occupants. Descriptions of these particular nuances are provided in the description of each scenario.

Prior to undertaking the occupation periods occupants were assembled in the meeting room at the City Building Academy and given a final briefing. They were asked to complete a short consent form, and were issued with occupant diaries. They were also provided with a copy of the ‘Quick Start guide’ for these houses, but in this case this was for information only.

Occupants were given an overview of the buildings and the project. They were walked round each dwelling by the project team and the key features were identified. The programmer and TRV’s were identified for information, and the location of the MVHR unit and outlets was also pointed out. The boost control switches were identified.

During the study the houses were frequently visited by members of the research team to check on progress and deal with any queries. Issues arising out of this process included one instance where TRV’s were adjusted by an occupant, however this was noted by another occupant and rectified. In following scenarios it was found that daily visits by research team members or having a designated ‘prefect’ in the dwellings led to more strict following of occupancy guidance and more controlled outcomes.

Although this handover process was developed specifically to meet the needs of the project it was generally found to be successful and with the limited time taken to do so it illustrates not only how important good handover is but also the success that can be achieved by the hands on approach used.

Scenario 1

The first Scenario (SC1) was conducted in a two-week period between 2nd December and 16th December. There were four occupants in each house. The intention of this scenario was to provide a base case using a standard type of occupancy.

In this scenario all the equipment and appliances were checked (see Section 6) and the heating control systems were set based on a standard SAP scenario of two periods of heating, 7 – 9 in the morning and 6 – 11 in the evening. The TRV's were set at 2 on all radiators. The thermostat (located in the ground floor hall space) was set to 18^{o}C.

The occupants were recruited from the student cohort at the Mackintosh School of Architecture and were briefed about the project in a series of lead-in meetings and had a final briefing session at the Glasgow House meeting room where diaries and consent forms were issued. They were required to be in the houses overnight, but out during the day. They were asked to cook one evening meal together. There was no specific regulation of hot water use, but this was recorded in the diaries. These conditions were generally closely observed throughout the period.

Figure 9. SC1 briefing session with the 8 volunteers

Occupants were asked not to change controls or settings (with the exception of the boost switch for the mechanical ventilation in the bathrooms and kitchen), or to open windows and this was observed to a high degree. Ticksheets were provided for occupants to record certain critical activities, for example window opening, use of boost switches and some appliance use.

Monitoring included the use of Eltek GD47 temperature, CO_2 and RH sensors located in the living room, kitchen, and bedrooms, Gemini Tinytags located in the hall and bathrooms (the GD47 units require mains power), and Gemini Tinytag + located externally for external temperature and humidity. Energy consumption data was recorded from the main fiscal meters in each dwelling as no separate sub-metering was undertaken during the project.

Overall energy consumption was lower than in the pilot study, but only by a marginal amount (-2% in plot 1 and -12% in plot 3). This is a very surprising figure, given the lower demand temperatures, lower external ambient temperatures and reduced window opening. The other notable feature remained the difference in performance between the two houses in which the figure for gas equates to space and water heating

Plot 1	Elec	61.7 kWh	Gas	388.52 kWh
Plot 3	Elec	56.4 kWh	Gas	259.54 kWh

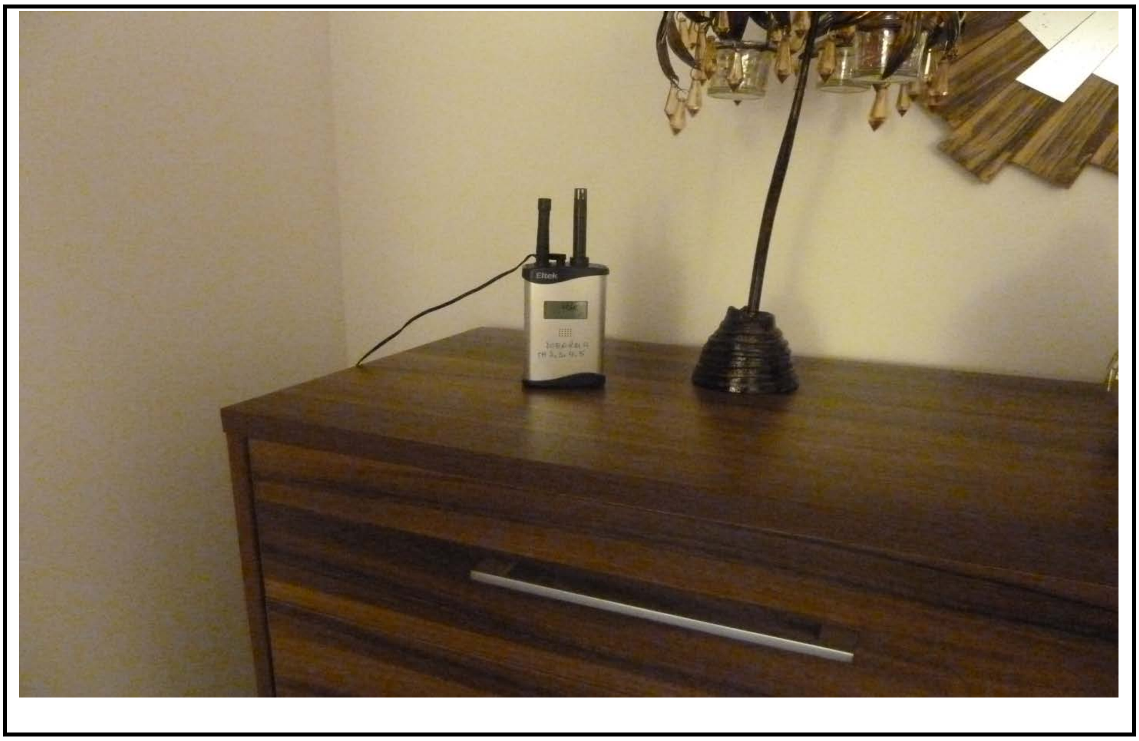

Figure 10. Eltek GD47 wireless transmitter recording CO_2, RH and temperature

In the pilot investigations, a discrepancy in energy consumption had emerged between Plot 1 and 3 (33% greater in Plot 1) and at the time this was assumed to be due to differences in fabric performance and ventilation rates, as in that study, window opening was allowed, and was found to be significantly more prevalent in Plot 1 (a total of 3248 minutes of recorded window opening in Plot 1 as opposed to just 248 minutes in Plot 3).

However in SC1 window opening was controlled much more tightly, but in spite of this Plot 1 consumption remained 33% higher. This raised a series of questions which were ultimately addressed in latter scenarios and through fabric testing.

One of these was concerned with hot water use. During the test, although the installation checks had been undertaken, some evidence of condensation was noted in the Solar Thermal system in Plot 1. The use of the STS had not thought to be making a significant contribution due to the season and the east-west orientation of the panels. However, the discrepancy raised the possibility that there may be some failure in the system, which was leading to higher hot water consumption – evidence from another project had identified hot water being circulated through the panel. This was ultimately found not to be a contributing factor in this instance but was a significant realisation which is further explained in Section 7.1 - Solar Thermal Testing.

The other possibility to be explored was whether the higher consumption rate was associated with the thermal mass – for example energy being delivered to the mass. This might be an effect based on the relatively intermittent use of the house and lower air temperatures. At this stage this was not thought to be significant, as the houses were heated outwith the scenario testing, but further investigation and analysis was undertaken and is presented in the Scenario 4 results.

With regard to the monitored environmental data the summary figures for temperature, CO_2 and RH are as follows:

GLASGOW HOUSE - TSB BUILDING PERFORMANCE EVALUATION
(Scenario 1)

Comparative Analysis of Physical Parameters (room by room)

Area	Criteria	Level	Plot 1
Living Room		Absolute Max	17.30
	Temperature (°C)	Absolute Min	9.80
		Mean	15.83
		Absolute Max	77.40
	Relative Humidity (%)	Absolute Min	41.90
		Mean	50.04
		Absolute Max	1262.00
	CO_2 Conc (ppm)	Absolute Min	375.00
		Mean	591.49
Kitchen		Absolute Max	19.30
	Temperature (°C)	Absolute Min	14.00
		Mean	16.93
		Absolute Max	79.50
	Relative Humidity (%)	Absolute Min	39.20
		Mean	48.58
		Absolute Max	1542.00
	CO_2 Conc (ppm)	Absolute Min	314.00
		Mean	605.41
Utility/ WC		Absolute Max	
	Temperature (°C)	Absolute Min	
		Mean	
		Absolute Max	
	Relative Humidity (%)	Absolute Min	
		Mean	
		Absolute Max	no value
	CO_2 Conc (ppm)	Absolute Min	no value
		Mean	no value
Bathroom		Absolute Max	
	Temperature (°C)	Absolute Min	
		Mean	
		Absolute Max	
	Relative Humidity (%)	Absolute Min	
		Mean	
		Absolute Max	no value
	CO_2 Conc (ppm)	Absolute Min	no value
		Mean	no value
Bed 1		Absolute Max	19.60
	Temperature (°C)	Absolute Min	16.60
		Mean	17.67
		Absolute Max	52.90
	Relative Humidity (%)	Absolute Min	35.30
		Mean	42.11
		Absolute Max	939.00
	CO_2 Conc (ppm)	Absolute Min	386.00
		Mean	605.53
Bed 2		Absolute Max	20.40
	Temperature (°C)	Absolute Min	15.90
		Mean	16.93
		Absolute Max	55.70
	Relative Humidity (%)	Absolute Min	37.80
		Mean	44.31
		Absolute Max	1151.00
	CO_2 Conc (ppm)	Absolute Min	393.00
		Mean	650.51
Bed 3		Absolute Max	18.50
	Temperature (°C)	Absolute Min	14.50
		Mean	16.46
		Absolute Max	56.40
	Relative Humidity (%)	Absolute Min	38.50
		Mean	44.67
		Absolute Max	1044.00
	CO_2 Conc (ppm)	Absolute Min	374.00
		Mean	543.92
Attic Room		Absolute Max	18.40
	Temperature (°C)	Absolute Min	15.70
		Mean	16.81
		Absolute Max	54.00
	Relative Humidity (%)	Absolute Min	38.00
		Mean	44.85
		Absolute Max	1300.00
	CO_2 Conc (ppm)	Absolute Min	367.00
		Mean	619.15

Area	Criteria	Level	Plot 3
Living Room		Absolute Max	20.40
	Temperature (°C)	Absolute Min	11.40
		Mean	16.78
		Absolute Max	74.50
	Relative Humidity (%)	Absolute Min	38.40
		Mean	46.33
		Absolute Max	2004.00
	CO_2 Conc (ppm)	Absolute Min	429.00
		Mean	709.54
Kitchen		Absolute Max	21.50
	Temperature (°C)	Absolute Min	14.00
		Mean	17.30
		Absolute Max	76.60
	Relative Humidity (%)	Absolute Min	36.90
		Mean	45.34
		Absolute Max	2204.00
	CO_2 Conc (ppm)	Absolute Min	425.00
		Mean	721.70
Utility/ WC		Absolute Max	22.30
	Temperature (°C)	Absolute Min	11.40
		Mean	18.22
		Absolute Max	48.30
	Relative Humidity (%)	Absolute Min	36.30
		Mean	42.98
		Absolute Max	1096.00
	CO_2 Conc (ppm)	Absolute Min	378.00
		Mean	583.13
Bathroom		Absolute Max	
	Temperature (°C)	Absolute Min	
		Mean	
		Absolute Max	
	Relative Humidity (%)	Absolute Min	
		Mean	
		Absolute Max	no value
	CO_2 Conc (ppm)	Absolute Min	no value
		Mean	no value
Bed 1		Absolute Max	18.00
	Temperature (°C)	Absolute Min	13.50
		Mean	15.95
		Absolute Max	59.20
	Relative Humidity (%)	Absolute Min	38.10
		Mean	45.91
		Absolute Max	1226.00
	CO_2 Conc (ppm)	Absolute Min	417.00
		Mean	650.15
Bed 2		Absolute Max	19.30
	Temperature (°C)	Absolute Min	15.10
		Mean	16.46
		Absolute Max	55.60
	Relative Humidity (%)	Absolute Min	36.90
		Mean	43.48
		Absolute Max	1075.00
	CO_2 Conc (ppm)	Absolute Min	460.00
		Mean	632.44
Bed 3		Absolute Max	18.20
	Temperature (°C)	Absolute Min	13.70
		Mean	15.99
		Absolute Max	61.20
	Relative Humidity (%)	Absolute Min	39.10
		Mean	47.78
		Absolute Max	1478.00
	CO_2 Conc (ppm)	Absolute Min	433.00
		Mean	683.78
Attic Room		Absolute Max	18.60
	Temperature (°C)	Absolute Min	15.20
		Mean	16.64
		Absolute Max	52.80
	Relative Humidity (%)	Absolute Min	37.70
		Mean	44.94
		Absolute Max	1055.00
	CO_2 Conc (ppm)	Absolute Min	375.00
		Mean	578.20

Table 8. Comparison of monitored physical parameters between Plots 1 & 3

CO_2 figures are an improvement on the initial pilot study and reflect the improvements made to the installation of the MVHR system (see commissioning tests). However, despite the relatively un-intensive occupancy a tendency toward peaks was still evident and the effect was worse in Plot 3. There remains a concern that the system is not providing adequate ventilation under some circumstances. Two issues for further investigation are identified – one is the specification of the system in terms of delivery rates, the other of which is the path of airflow throughout the building. It is apparent that CO_2 levels can reach high levels in bedrooms overnight. There are no pass vents in these doors and as such there is no path for air circulation to occur.

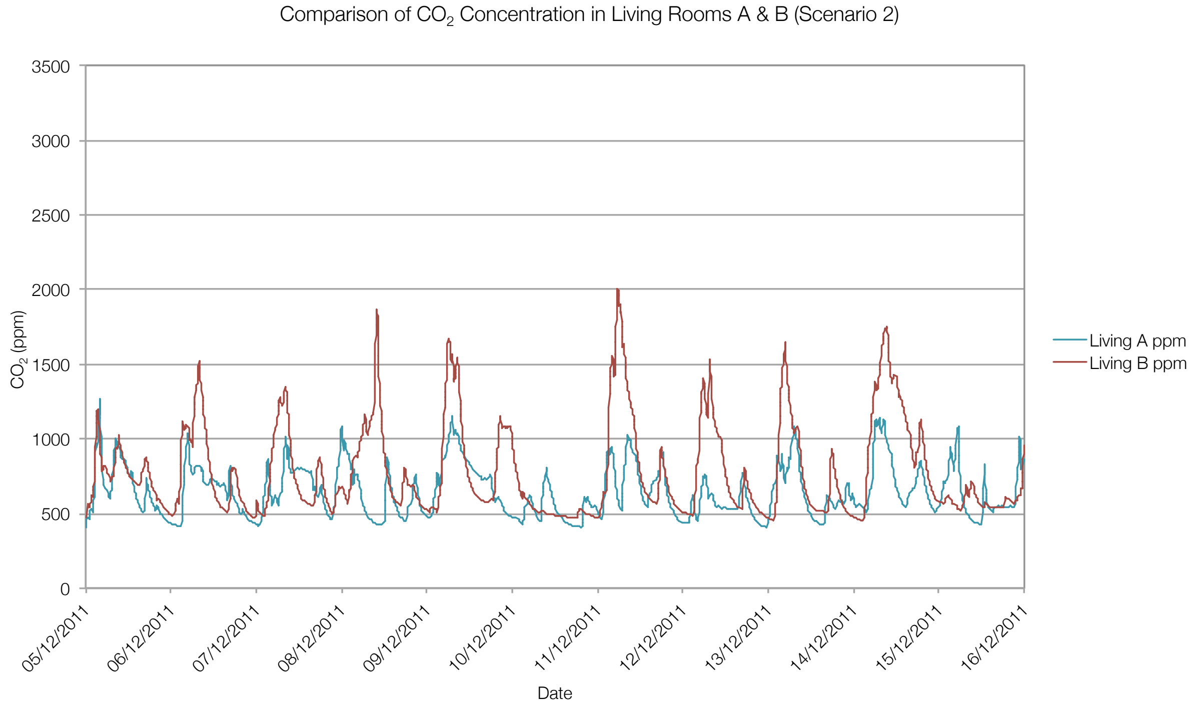

Figure 11. Markedly higher CO_2 concentrations evident in Plot 3 data

This realisation led to Scenario 2 focussing on the testing of the MVHR system in more detail, in particular looking at the energy and air quality implications of reducing or disabling the system.

Two residents from each house reported feeling cold at some point during their occupation. Despite this fact the metrics for each temperature assessment criteria indicate that the conditions were either at a mid point (or better) on a range from uncomfortable to comfortable. The only exception to this was identified by all residents in the bedrooms of Plot 3, where the temperature was felt to be too cold. This is due to the design of the occupancy scenario and not a failing of the buildings' heating systems. In the pilot study (where TRV's were set at 4) it was clear the heating system for these dwellings was actually easily capable of producing far too much heat and this had led to occupants opening windows to achieve thermal comfort. In an attempt to avoid this behaviour, this scenario was set up with the main thermostat at 18°C and TRVs set to ‘2’. In hindsight it appears that this has perhaps been too low for the residents and future scenarios addressed this by ensuring appropriate temperatures throughout the dwellings prior to occupation or by building in occupant thermal control in such a way that it did not become an additional confounding variable which could affect any future data gathering or analysis.

The pilot study had raised the issue of noise within the dwelling in Plot 1. The construction uses joist hangers for the support of the intermediate floors (instead of joists being built into the walls) and this presents a weakness in acoustic separation between the floors in the Clay houses. This may be exacerbated by the relative sound insulation between inside and out through the external fabric – lack of external (masking) noise may exacerbate internal noise.

Figure 12. Intermediate floor junction, Plot 1

Scenario 2

Scenario 2 (SC2) was conducted over a two-week period between 12th March and 26th March with 4 occupants in each house. The intention of this scenario was to test the effect on the internal environmental quality (IEQ) with varied performance levels of the MVHR system.

All methodologies, scripting, equipment, etc. were identical to the SC1 'base case' with the only adjusted variable being the alterations made to the dwellings' ventilation. In this case the MVHR systems had filters fitted with 50% card occlusions (as the MVHR test methodology) during week one and the systems then being switched off during week 2. During this second week the IEQ indicator levels were monitored at frequent intervals to ensure that occupant health was not at risk through the test process.

Figure 13. One group of student occupants following SC2.

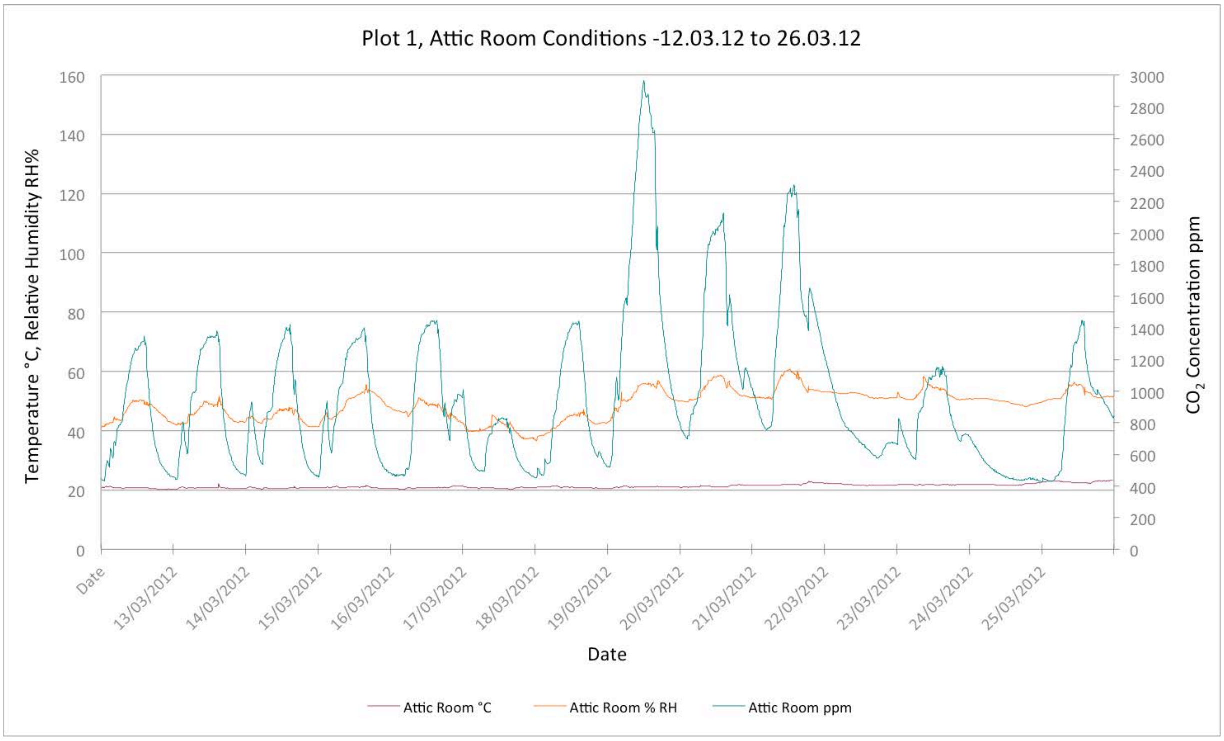

Figure 14. Increased RH and CO_2 clearly evident in week 2 with MVHR off.

Results;

The graph above illustrates the monitored physical parameters of Plot 1 attic bedroom over the full occupation period. Although this illustrates only one individual room over SC2 the profile and trends are representative of what is seen through all monitored rooms and through both houses.

During the first week of occupation the same diurnal relationship of CO_2 concentration and RH is evident through all apartments. In general the peaks in CO_2 concentration generally approach or exceed the maximum desirable level of 1000ppm (noting that the more densely occupied 2 person attic room is shown as the worst case). These relationships are comparable to those seen in the SC1 study and indicate that the impact on performance of the 50% card occlusion is limited. This, however, is not unexpected given the results of the separate MVHR testing which was undertaken in Q2 and as detailed in Section 7.1 of this report.

In week two when the system was disabled the impact on IEQ is far more pronounced. The peaks in CO_2 concentration reach levels that are indicative of very poor air quality. In addition the subsequent diurnal low levels appear to incrementally increase suggesting there is a cumulative effect of the poor ventilation and build up of pollutants. This increase in pollution levels also extends to include water vapour as RH levels are seen to incrementally increase independent of the internal temperature.

While the pattern of results of this test is not surprising the magnitude of these results is of concern. Whether an MVHR system becomes ineffective through blockage, poor maintenance or intentional disabling by occupants (a frequent problem) the issues that can arise, even over a short period, present a real risk to the quality of internal environments and, over time, to the health of residents. If the entire ventilation response of a dwelling is reliant on such a system then the understanding of these effects and means to minimise, mitigate or prevent them demands further study beyond the findings suggested by this occupancy scenario.

Scenario 3

Scenario 3 (SC3) was conducted over a seven day period between 16th April and 23rd April with 2 occupants in each house. The intention of this scenario was to test the performance of the dwellings when placed under a more intense period of occupation with residents occupying the houses for as long a period during each day as was reasonably practicable.

All methodologies, scripting, equipment, etc. were identical to the SC1 'base case' with the only adjusted variable being the duration of occupation. In previous scenarios the occupant scripts required that the dwellings were unoccupied between the hours of 8am and 6pm during the week to mimic the assumptions of Standard Assessment Procedure. In SC3 pairs of students were encouraged to maximise their periods of occupation as far as possible to emulate the living pattern of an elderly couple or those who may be infirm or unemployed. This scenario was deemed to be of particular significance to GHA as it was representative of the high proportion of tenants they support who are 'economically inactive' and who are likely to spend extended periods within their dwellings.

Figure 15. Residents of Plot 1 and 3 completing the post occupancy questionnaire in Plot 1.

Results;

The analysis of this scenario presented limited information of the effect of the constant occupation on internal environmental quality. The monitored physical parameters were found to be of limited use as the density of occupation was relatively low compared to the overall volume of the dwelling. In social housing this level of occupation in such a large dwelling is unlikely and as such the only real conclusion that could be drawn was that providing high space/ volume standards per occupant is a good thing for maintaining good IEQ as the relative impact of the occupants behaviour is minimised. Conversely, a larger volume will be more expensive to heat and therefore future designs must strike a balance between these competing criteria.

Scenario 4

The 4th of 6 scenarios was designed to assess the summer performance of the dwellings with a particular focus on the comparative thermal buffering of the varied construction methods.

This was to be achieved by assessment of the thermal performance of the sunspaces and the internal conditions of the living room and bedrooms adjacent to the sunspaces as further detailed below.

A third aspect of the scenario was intended to involve experimentation of the performance of and the impact on the sunspaces when used as a passive drying space for domestic laundering. Unfortunately due to a long wet summer this aspect of testing was not completed but is something that MEARU will test when appropriate in support of the assertions made in Appendix C.

Critically, compared to previous scenarios, this iteration was designed to be run in the absence of occupants to ensure a greater degree of control and reduce the impact of variables.

Project Methodology

The scenario was run from Monday 13th August to Monday 27th August 2012. All heating and heat producing equipment within both dwellings was switched off so that the only influence on heat gains was from passive solar sources. The mechanical ventilation with heat recovery (MVHR) system was left running for all testing to provide a fair assessment of how the houses react when operating as designed.

Monitoring equipment was installed in sunspaces (both ground and 1st floor), living rooms and bedrooms adjacent to sunspaces (further details provided below).

To provide an external base case for assessment of the interior performance, external conditions were monitored using a Vaisala WXT520 weather transmitter, Kipp and Zonen pyranometer and Eltek T-MET transmitter. Conditions were logged at 5 minute intervals using an Eltek RX250AL Squirrel data logger.

Evaluation 1

The first assessment was focused on the effect of thermal mass within sunspaces. This involved the monitoring and comparative assessment of the performance of the sunspaces in Plot 1 and Plot 3 where varied lining materials have been used; Plot 1 with a white render on rigid board insulation and Plot 3 with a dark ‘brindle’ brick. Monitoring of these spaces was undertaken using Gemini Tinytag Ultra sensors logging temperature and relative humidity at 5 minute intervals. Loggers were fixed on the interior wall at 1m altitude from both ground and first floors. Each sensor was then provided with a white paper shade to mitigate the impact of any direct solar radiation.

The test duration for this phase of the scenario was designed to be run for approximately 7 days from 13th August at 16.00 to 20th August at 12.00. Due to issues with monitoring of external conditions (refer SC4 issues below) the time period for results analysis was taken as 12.00 on 16th August to 12.00 on 20th August as this will allow comparative assessment of the space performance against known external conditions.

The analysis of the performance and thermal buffering potential of each space will review the nature and amplitude of plotted temperature profiles, particularly against periods of high solar radiation.

Evaluation 2

The second assessment focused on the effect of thermal mass within the apartments adjacent to the sunspace - namely the living room and 1st floor bedroom 2. This involved the monitoring and comparative assessment of the performance of these apartments when joined to the sunspace by the opening of the double glazed intermediate doors. This assessment was designed to test the thermal performance of the apartments where varied construction materials have been used within the construction; Plot 1 constructed from clay blocks and Plot 3 representing a lightweight timber framed structure. Monitoring of the temperature, relative humidity and carbon dioxide concentration in these spaces was undertaken using Eltek GD-47 transmitters. The result of the sampling were recorded at 5 minute intervals on an Eltek RX250AL Squirrel data logger calibrated to the same recording sequence as the Gemini loggers and weather station logger.

The test duration for this phase of the scenario was for 7 days from 20th August at 12.00 to 27th August at 12.00.

As with assessment 1 the analysis of the performance of the respective apartments was based on analysis of their temperature profiles but will also include the profiles of the sunspaces to give as full a picture as possible of the nature of heat movement and thermal storage of the various elements of built fabric.

Scenario 4 Testing Issues

The Initial installation was undertaken on 13th August but the weather station was found to be non-functional once in situ due to a software defect. Over the following 2 days attempts were made to re-configure but the station only became operational on

16th August. Weather station logging commenced from 12 noon on 16.08.12. Data from Wednesday 22nd August between 12.00 and 16.00 will be omitted from the analysis as a conference tour of the dwellings took place from 13.00 to 14.00 on that date. During the period of the tour the opening of doors and high occupancy levels rendered the controlled conditions obsolete and so the decision was made to remove this immediate section of data and to allow the dwellings a further 2 hours to stabilise before collated data was again considered valid.

On completion of the SC4 project period significant issues were identified with the monitored data. Logging from the Tinytag monitors in sunspaces was complete and unaffected but the internal monitoring from Plot 3 was found to have failed along with a significant issue with the logging of external weather conditions (a continuation of the problems identified in the Q3 report which unfortunately were not resolved). As such, the opportunity to make a direct comparison between the effect of interior thermal mass could not be undertaken with the data from this monitoring period.

Notwithstanding these issues, high quality data was successfully logged for the sunspaces which allowed analysis of their controlled thermal performance to be undertaken. Similarly the data from Plot 1 has been analysed relative to internal summer comfort conditions with the finding from both studies reported below.

Sunspace Analysis - Outcomes and Findings

The analysis is based on the data logged by the four number Tinytag Ultra loggers positioned at the ground and first floors of Plots 1 and 3 respectively. The loggers were positioned on ‘external’ walls facing approximately 12.3° north of west and at an altitude of approximately 1000mm above finished floor level. Each sensor was placed behind a white sheet of heavy paper to mimic the affects of a Stevenson Screen and to mitigate the impact of direct solar gains on recorded values

Figure 16. Illustration of TInytag logger positions and protection

		Plot 1	Plot 3
Grnd floor	Abs Max	47.9 °C	40.4 °C
	Abs Min	21.8 °C	23.4 °C
	Mean	26.1 °C	27.1 °C
	Max/ Min Range	26.1 °C	17.1 °C
1st floor	Abs Max	51.9 °C	48.5 °C
	Abs Min	22.4 °C	25.1 °C
	Mean	29.7 °C	30.6 °C
	Max/ Min Range	29.5 °C	23.4 °C

Table 9. Comparison of Plot 1 & 3 sunspace mean, max & min temperature values at 2 altitudes

Within each space the max, min and mean values for the 1st floor logger were found to be consistently above those of the adjoining ground floor space with a mean variation of around 3.5°C for each dwelling.

This result was as expected as the construction arrangement allows free air movement between the two levels and the convective effect will cause a greater concentration of heat at the higher levels. In addition the overshading of the timber first floor will go some way to reducing temperatures at ground floor and the 45° pitch glazing to the roof will significantly increase the solar gain potential of the sunspace at first floor (due to a more effective angle of incidence).

A review of the temperature trends within each space provides results which could be expected and can be explained against the design of the buffer space. One aspect which does, however, raise interest is the magnitude of the maximum temperatures in both spaces.

The sunspaces of Plots 1 and 3 were seen to achieve maximum temperatures of 51.9°C and 48.5°C respectively. Given the lack of ‘summery’ weather during this period this raises questions over what temperatures could potentially be reached in these spaces during periods of prolonged hot and sunny weather. The recorded temperatures already far exceed comfort temperatures and, although the space is designed to be used intermittently when conditions permit, the extent of these values would certainly have an impact on the temperatures of the adjacent spaces. This could lead to difficulty controlling internal temperatures during the summer months for the living room adjacent to the sunspace and particularly for the first floor bedroom, which also shares this relationship, but has no other form of window opening but through the sunspace. The efficacy of the manually operated ventilation from the sun space, provided by opening skylights, and the potential requirement for solar shading during the summer are aspects which should be further investigated with the use of this design.

If a comparative analysis is made between the two dwellings then some interesting characteristics of performance are identified. The mean temperature of Plot 3 was found to be 1.0°C and 0.9°C greater than Plot 1 at ground and first floor locations respectively. Within a summer context the slightly lower temperature of Plot 1 may be seen to be beneficial but a more in depth review of the recorded values identifies that consideration of the mean value alone does not provide a sufficiently accurate picture of performance or behaviour.

In both ground and first floor cases Plot 1 has higher absolute maximum and lower minimum values than those recorded in Plot 3. This can be simplified by reviewing the absolute temperature range existing at all 4 logger locations. These values show that the temperature swing in Plot 1 is greater than Plot 3 by some 9°C at ground floor and 6.1°C at first floor level. With all conditions remaining equal through the testing the only explanation of this degree of variation is as a result of varied lining materials used in the construction (lightweight white render and insulation for Plot 1 versus heavyweight dark brick for Plot 3). This result essentially identifies a greater temperature stability within the Plot 3 sunspace. The greater capacity of this space reduce the amplitude of heat gain and loss, through passive control of heat gain, demonstrates the impact of thermal mass and confirms the benefits of employing it in a space of this nature.

Further demonstration of the impact of thermal mass on air temperature within these spaces can be found by review of the ‘fine-grain’ 5-minute data logging.

Analysis of Temperature Profiles

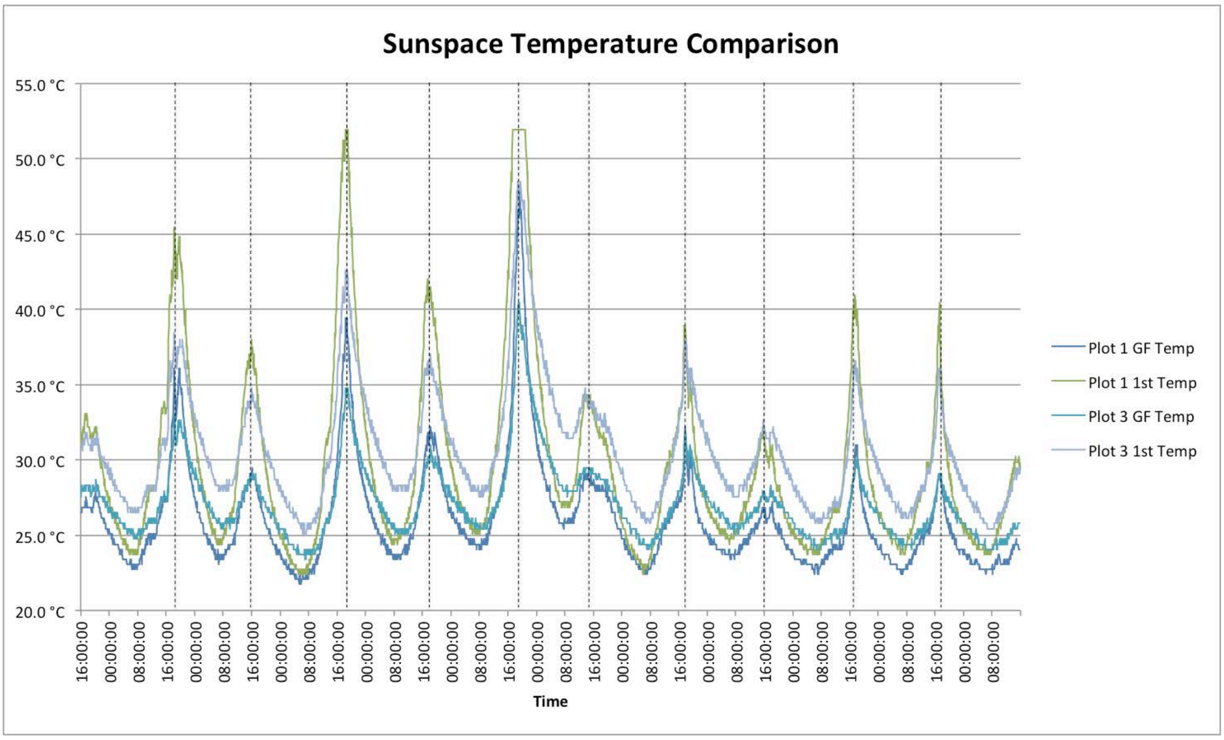

Figure 17. 4-zone monitored air temperatures for two week duration

The graph above illustrates the recorded air temperatures for all 4 zones over the full monitoring duration. The fine grain (5 minute recording intervals) of this data set against the length of duration represents a large volume of data which can be difficult to get meaningful results from. Even at this resolution, however, there are significant trends which can be identified.

Firstly a clear diurnal relationship can be seen, as would be expected, between daily high and low values. In each case the time of the daily maximum is represented by the dashed line with the value tending to correspond to a time of around 19.00 hours. External this would not represent the hottest time of the day but within the sunspace it relates directly to the time of day when the sun azimuth angle is such that the solar gains can be made by the sunspace glazing in its non-optimised orientation. Instances where the time of the maximum value varies significantly can be accounted for by cloud cover minimising solar gains prior to point of maximum potential gain.

In addition to the above, the illustration is also very useful for highlighting the rate of heat gain and loss generally by the spaces and for showing the time period where the air temperature of the space is outwith comfort norms.

A more focused view on daily profiles provides a clearer picture of the thermal performance of the varying spaces during select daily periods. In this instance the profiles illustrated are for the days with both the highest and lowest recorded daily maxima.

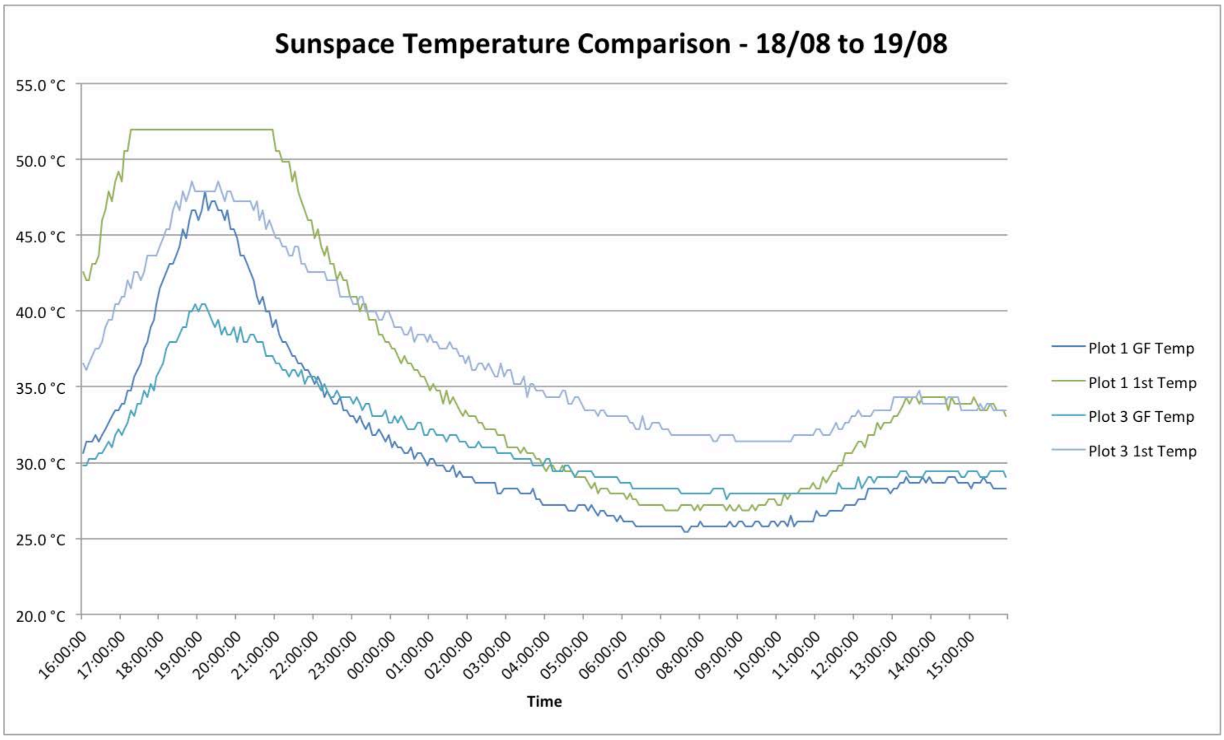

Figure 18. 4-zone sunspace air temperature daily profile (hottest day)

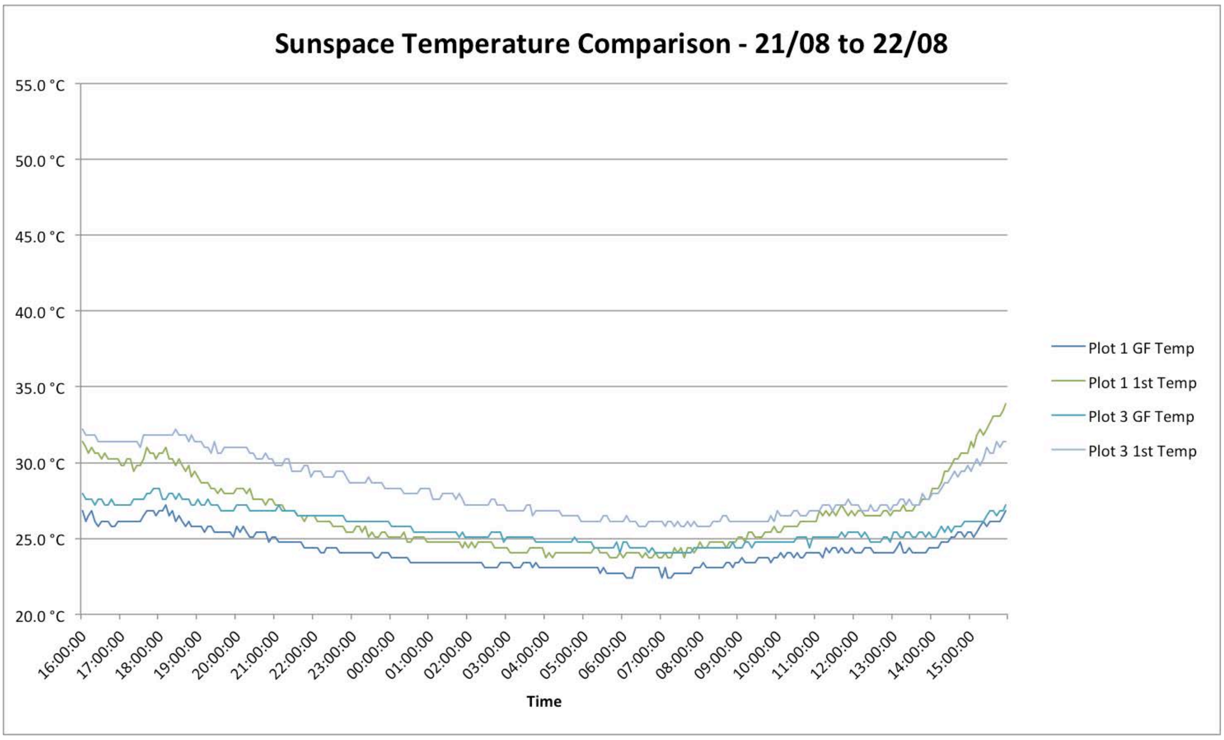

Figure 19. 4-zone sunspace air temperature daily profile (coldest day)

The uppermost graph shows the performance of all 4 monitored zones between the 18th and 19th of September - the hottest point during the test period. During the period of heating the maximum temperatures of both Plot 3 loggers can be seen to be significantly above those of the similar Plot 1 zones. From this maximum level the temperatures in all spaces are seen to decline but the rate of this decline is far more pronounced in Plot 1. The steeper gradient of decline of these profiles eventually result in even the first floor temperatures of Plot 1 being below the ground floor temperatures of Plot 3. A review of the coldest day (21st and 22nd of September) shows a similar pattern, albeit the rate of change is less due to the reduced impact of solar gain. In this instance the gradient of the plot again defines the rate of heat change and shows that Plot 3 provides much more stable thermal conditions. This can only be attributable to the additional thermal mass provided in this space.

Internal Conditions – Outcomes and Findings

Review of the data for the internal conditions within Plot 1 also revealed some interesting findings relative to the issue of thermal comfort during the summer season.

During week 1, the internal temperature of both living room and bedroom remain reasonably constant throughout both day and night. The living room temperature is around 25°C for the week and bedroom temperature is circa 27°C. As already identified the corresponding temperatures in the sunspace are very high and reach over 50°C on two days of the monitored week and around 40°C for the remainder of the week.

In week 2, again the internal temperature of the living room remains fairly constant (around but mainly below 25°C). Warmer temperatures were recorded in the 1st floor sunspace which as the bedroom temperature is 'free running' it means temperatures in excess of 30°C were recorded during early evenings on three days. Sunspace temperatures are significantly lower than in the previous week.

CIBSE summer design temperatures for free running dwellings are:

25°C - Living areas; 23°C – Bedroom areas (sleep may be impaired at temperatures above 24°C).

During the summer the risk of overheating tends to be expressed as a percentage of the annual occupied period against a benchmark temperature. In the case of a dwelling the percentage is 1% with the following temperature thresholds:

28°C - Living areas; 26°C – Bedroom areas

In week 1, the bedroom temperature does not drop below 26°C at any time during the monitoring period. But in week 2 the bedroom temperature swings more reaching a maximum temperature of 33.5°C and a minimum of 22.9°C. Lower bedroom temperatures are recorded at the latter part of week 2, but all data is lower for this period, suggesting external conditions were also cooler.

The living room temperature peaked at 26.2°C and therefore is regarded as not overheating during the two week study.

The graph below illustrates the variation on internal apartment temperatures due to sunspace (over)heating where free air movement is allowed between the volumes (week 2 when intermediate doors were opened).

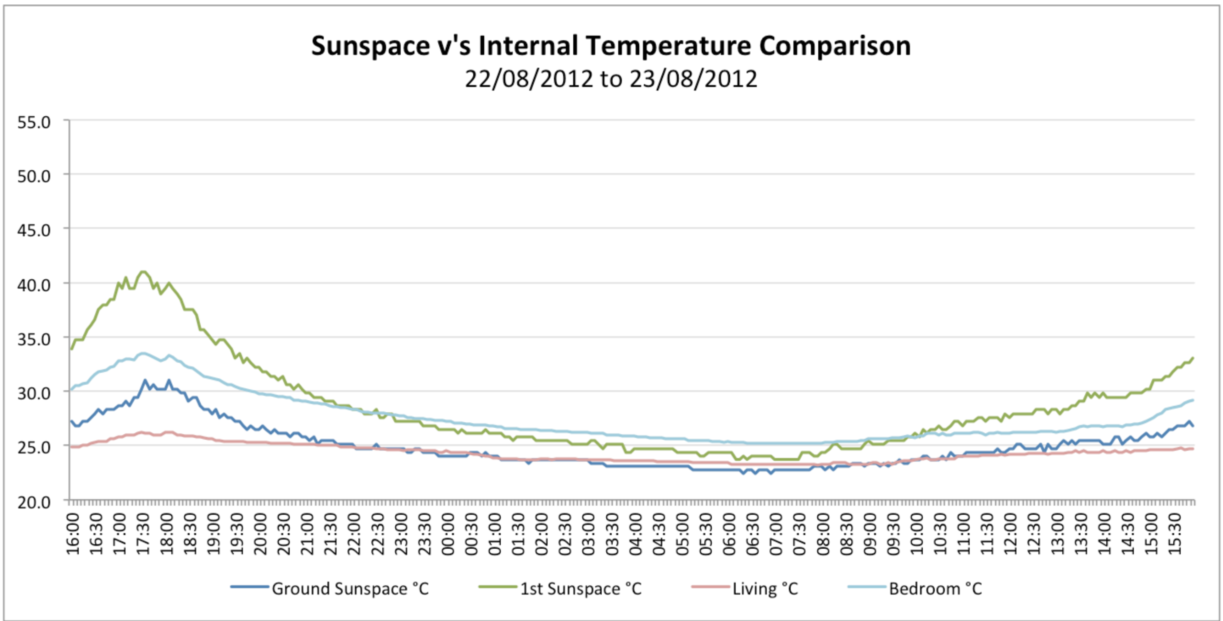

Figure 20. Living room and sunspace temperature relationships

Conclusions

From the recorded data it appears that the two monitored sunspaces perform very much as expected with the severity of thermal peaks and troughs in Plot 3 being less than those experienced in Plot 1 due to the provision of a thermally massive interior lining. With a semi-external space of this nature in the Scottish climate this characteristic of performance is key as it extends the duration that comfort temperatures can be maintained, via thermal buffering or lag, and subsequently extends the time when the ‘opportunistically occupied’ space can be used.

While considering the summer performance it can be seen that the thermal mass is of benefit as it reduces the impact of the highest and most uncomfortable temperatures that can be experienced, although as a trade off it does retain more heat during the night and therefore could make cooling less easy. This aspect of performance, although perhaps presenting an issue during parts of summer, will undoubtedly be of benefit during the much longer periods in Scotland where space heating is required. Under these conditions the proven affects of the thermal mass will be retained with only positive impacts.

During this scenario the proposed clothes drying experiment for the project didn’t take place due to poor weather and lack of sun. A review of the temperature profiles does, however, indicate that this could have been viable within the spaces during this time. Moreover, given the prevailing wet weather (the wettest summer for 100 years) it would suggest that this space could be ideally suited for this purpose as it appears to provide sufficient heat energy to aid clothes drying even at a time when external drying would be unfeasible. If used for this purpose then the impact would be improved internal environment (as significant moisture load is removed from the dwelling) and reduced energy consumption as the need to use highly energy intensive processes such as tumble drying are reduced or omitted altogether.

Scenario 5

The 5th of 6 scenarios to be undertaken as part of the Glasgow House BPE were designed to assess the effect of varied heating regimes on thermal comfort and energy use relative to the differing constructions used in Plots 1 and 3. In addition to this, the timing of the testing was such that it would provide occupation data for a 'shoulder' season as opposed to the summer and winter testing previously undertaken.

Testing was generally conducted as with earlier scenarios (1 & 2) with 4 student volunteers occupying each of the test dwellings between the dates of 8th October and 19th October 2012.

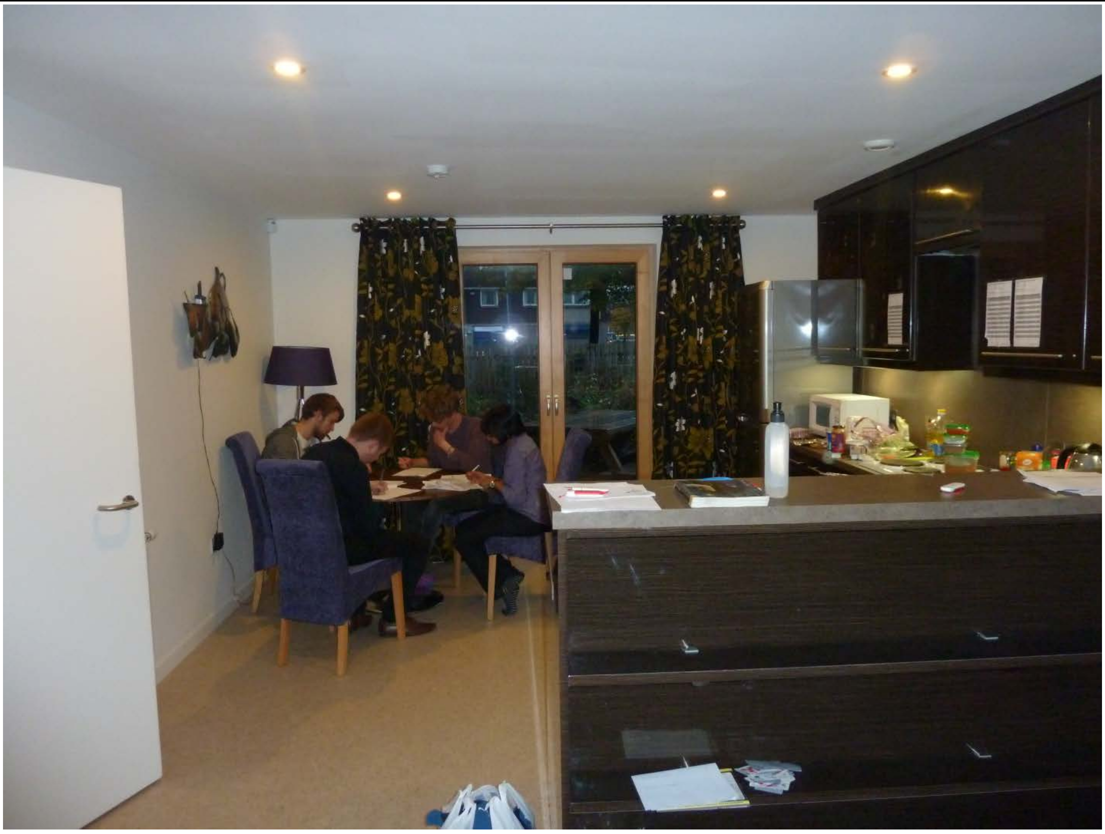

Figure 21. Residents of Plot 3 working in the communal space.

During the first week of the occupation (8th to 14th October inclusive) each dwelling was heated with two timed heat periods running from 07.00 to 09.00 and 17.00 to 23.00. The central thermostat (located in the ground floor hall) was set to 20°C and all radiator TRVs were set to '4'. On 15th October the boiler setting were changed for the remainder of the scenario and each house was provided with one long heat input between 07.00 and 23.00 with the thermostat retained at 20°C and all TRVs set to ‘2’. Throughout this period the occupants of both dwellings adhered to an occupancy script and were specifically asked not to vary any heat controls or to open windows.

Over the full testing duration the physical parameters of temperature, relative humidity and carbon dioxide concentration were again monitored in all rooms in each test dwelling. Records of daily energy use were taken by a designated student volunteer using the main fiscal meters for each dwelling and comfort levels were assessed by a process of daily comfort polls where residents were asked to define the thermal comfort and air quality.

Analysis and Findings

Scenario 5 was designed such that the impact of the varied heating regimes could be tested in terms of efficiency and comfort. As the houses were generally unoccupied during the day the move to provide a single heat input for this entire duration (week 2) may seem unusual but it was hypothesised that this approach to heating may prove beneficial in the case of the more thermally massive construction of Plot 1 – i.e. the dwelling could be heated at low level during the day with the heating being absorbed by thermal mass and then being released back to the spaced during the periods of occupation.

Assessment of the validity of this hypothesis is made below relative to the impact on energy efficiency and comfort.

Comfort

	Mean thermal comfort levels (std. dev)	
Testing Period	**Plot 1**	**Plot 3**
Week 1 (08.10.12 to 15.10.12)	4.48 (0.60)	4.61 (0.35)
Week 2 (15.10.12 to 19.10.12)	4.18 (0.48)	4.45 (0.47)

Table 10. SC5 comparison of Plot 1 & 3 mean polled comfort levels

The comfort polling process asked residents to rate the thermal comfort at 8pm each evening while in the dwelling. The ratings were based on this seven-point scale; 1) much too cold, 2) too cold, 3) comfortably cool, 4) neither too cool nor too warm, 5) comfortably warm, 6) too warm, 7) much too warm, with a value of 4 identified as the ‘neutral’ and most comfortable rating.

From the results above it can be seen that both dwellings seem to fair well in terms of thermal comfort with ratings consistently just above the optimum level. Being on the warm side of this scale is also, perhaps, a favourable result in a project which is aimed at providing warm homes and preventing fuel poverty.

From a comparative perspective, Plot 1 is closer to the optimum value under both heating regimes and makes a more significant move towards this value in week two when the single low level heating input was programmed. With such a small sample size of occupants the limitations of this approach to testing must be understood as attempts to draw conclusive statistical significance will be flawed. If, however, these limitations are understood *and* it is accepted that some form of metric is required to assess this perceptive condition then it appears that greater thermal comfort is experienced in Plot 1 under these test conditions.

Energy efficiency

The comfort values only provide one side of the story, however, and the energy implications required in achieving these must also be considered to glean a more rounded view of performance.

		Mean Daily Gas Consumption (std. dev)	
Testing Period	External Temp.	**Plot 1**	**Plot 3**
Week 1 (08.10.12 to 15.10.12)	8.6°C	38.5kWh (10.3)	26.5kWh (4.1)
Week 2 (15.10.12 to 19.10.12)	6.8°C	35.7kWh (8.2)	33.9kWh (6.1)

Table 11. SC5 comparison of Plot 1 & 3 energy consumption values

From the values presented in the table it can be seen that as the duration of the heat input is increased from week 1 to week 2 the dwellings perform largely as was hypothesised. In Plot 3 the overall energy demand rises significantly over this period as could be expected for a thermally 'light' construction – heat is being demanded during unoccupied periods and, due to the nature of the fabric, it is presumed this leads to frequent inputs from the heat system in order to maintain internal temperatures. It should also be noted that the drop in mean external temperature over this period will also lead to an increased heat demand and will account for some increase in energy consumption.

When Plot 1 is considered it can be seen that even with the fall in external temperature the overall energy demand for space and water heating actually drops between the two weeks. Moreover, when the energy demand is compared to the proportional heat demands identified during the co-heating test the relationship between heating regime and energy demand becomes more intriguing.

	Plot 1	Plot 3	P1:P3
Co-heating Test	189.41kWh	155.57kWh	1.22
Scenario 5 Week 1	38.5kWh	26.5kWh	1.45
Scenario 5 Week 2	35.7kWh	33.9kWh	1.05

Table 12. Heat regime and proportional energy demand comparison

If the co-heating test values are considered to be the base case then it can be seen that the two-heat regime is better for the timber kit dwellings than the masonry house and with the single heat input the opposite is true. In addition to this, the use of the week 2 heating regime appears to be significant enough to almost equalise the thermal performance of the plot 1 construction system which was previously found to be much weaker.

The scale and scope of this testing and analysis has obvious limitations which could have impacted on the results. For example, there is likely to be some fluctuation in hot water demand over these time periods (perhaps accounting for the relatively high level of standard deviation) though attempts were made to minimise this through the use of the occupancy scripts. Notwithstanding these limitations it would appear that the use of prolonged but lower level heat input can provide both energy and comfort benefits in thermally massive construction and that there is a clear impact on energy efficiency relative to the relationship between thermal mass and chosen heating regimes.

Testing Issues

Note, comfort levels and the impact on temperature of the varied heat regimes have had to be considered separately as there was a failure of the logging equipment during the first week. Physical data has been recorded for the thermal effect on the dwellings of varying the heat inputs but this was undertaken following the departure of the student volunteers – effectively during a ‘week 3’ of testing.

Scenario 6

The 6th and final scenario to be undertaken as part of the Glasgow House BPE was designed to take a similar approach to Scenario 5 but, this time, with the focus on the effect of varied ventilation regimes on energy efficiency and comfort.

Figure 22. All student volunteers investigating Plot 1 at the project start.

Monitoring was conducted between 19th and 30th November and followed a similar process of 'scripted' occupation by 8 student volunteers as used in previous testing scenarios. Over the duration of the project the heating systems within the houses were pre-programmed and the occupants were asked not to make variations to any settings. Occupants were given instruction on the effective use of the MVHR system and were told that this would present the sole means of ventilation over the first week (19th to 24th November) with window opening prohibited. During week 2 (25th to 30th November) the MVHR system was switched off and occupants were instructed to use window opening to affect ventilation as they required.

Over the full testing duration the physical parameters of temperature, relative humidity and carbon dioxide concentration were again monitored in all rooms in each test dwelling. Records of daily energy use were taken by a designated student volunteer using the main fiscal meters for each dwelling and comfort levels were assessed by a process of daily comfort polls where residents were asked to define the thermal comfort and air quality.

Previous testing on the Glasgow House had identified a potential energy penalty related to the use of uncontrolled occupant ventilation, compared to the use of an MVHR system, and as such this scenario endeavoured to further test this theory.

Analysis and Findings

	Mean Internal Air Quality Perception (std. dev)	
Testing Period	**Plot 1**	**Plot 3**
Week 1 (19.11.12 to 24.10.12)	4.38 (0.14)	4.75 (0.32)
Week 2 (25.10.12 to 30.10.12)	3.78 (0.22)	4.79 (0.33)

Table 13. SC6 comparison of Plot 1 & 3 mean polled IAQ levels

The use of polling to assess the perception of internal air quality (IAQ) asked residents to rate the thermal comfort at 8pm each evening while in the dwelling. The ratings were based on this seven-point scale; 1) much too fresh, 2) too fresh, 3) comfortably fresh, 4) neither too fresh nor too stuffy, 5) comfortably stuffy, 6) too stuffy, 7) much too stuffy, with a value of 4 identified as the 'neutral' and most comfortable rating.

In both dwellings and over both weeks the air quality is perceived as being generally good by the residents as values close to '4' are consistently achieved. This is also supported by the reasonably low level of standard deviation. Between the two weeks there is very little change in perception of IAQ in Plot 3 while in Plot 1 the IAQ is seen to be less stuffy during the week where the MVHR system is not used and natural ventilation was allowed.

During the same time period the measured levels of CO_2 concentration were recorded as follows;

	Mean CO_2 Concentration	
Testing Period	**Plot 1**	**Plot 3**
Week 1 (19.11.12 to 24.10.12)	822.6 ppm	939.0 ppm

Week 2 (25.10.12 to 30.10.12)	1422.2 ppm	1371.6 ppm

Table 14. SC6 comparison of Plot 1 & 3 mean CO_2 concentration levels

From the monitored data it is clear that the actual IAQ was markedly worse during the second week therefore it is worth considering why the residents would not perceive this. The first possible explanation for this is that by having the opportunity to ventilate directly to the exterior the residents feel more in control and capable of altering the environment as they require. Perhaps it is simply this level of control and the memory of their ability to create freshness that has impacted on their perception. It is also possible that the timing of the daily poll has had an influence on the results. The residents were asked to complete the poll at 8pm each evening which would not be too long after they had returned from a day out of the dwellings. At this point in time the IAQ would be significantly better than it would be at, say, 8 in the morning when the house had been densely occupied for a further half day.

It is important to note that these results do not represent a case for the use of MVHR over natural ventilation as the air quality experienced in week two is representative of a case where no background ventilator were present as would be the case with a true natural ventilation system.

The information above also presents only a limited picture by considering the mean values and not the diurnal situation which exists.

Both graphs below illustrate the physical conditions over the full monitoring period from bedroom 2 in both Plots 1 and 3. Although providing a sample from just one room of each dwelling these are generally representative of the conditions experienced through all apartments. Each clearly shows the impact on IAQ when the MVHR system was switched off on 24th November. In each instance the levels of CO_2 and RH are seen to markedly rise and, if left to continue in this cycle for a prolonged period of time, would likely present health risks to occupants.

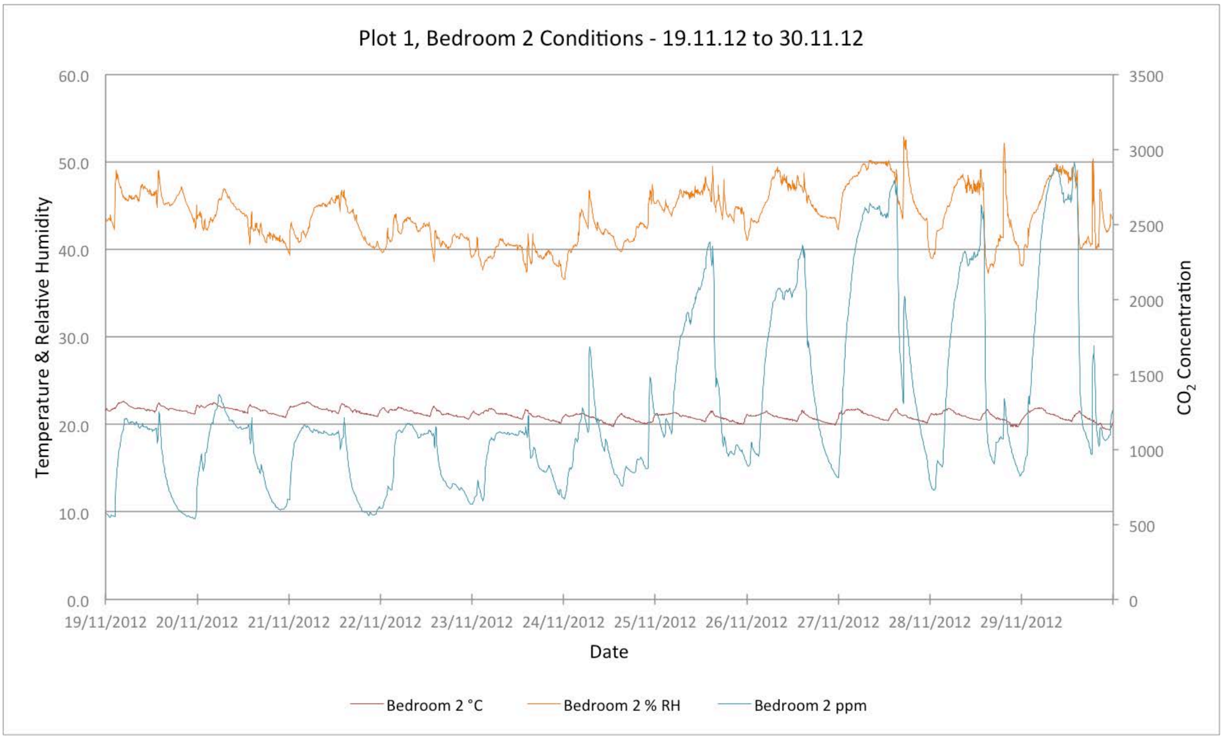

Figure 23. Extent of CO_2 peaks during periods with no MVHR (Plot 1)

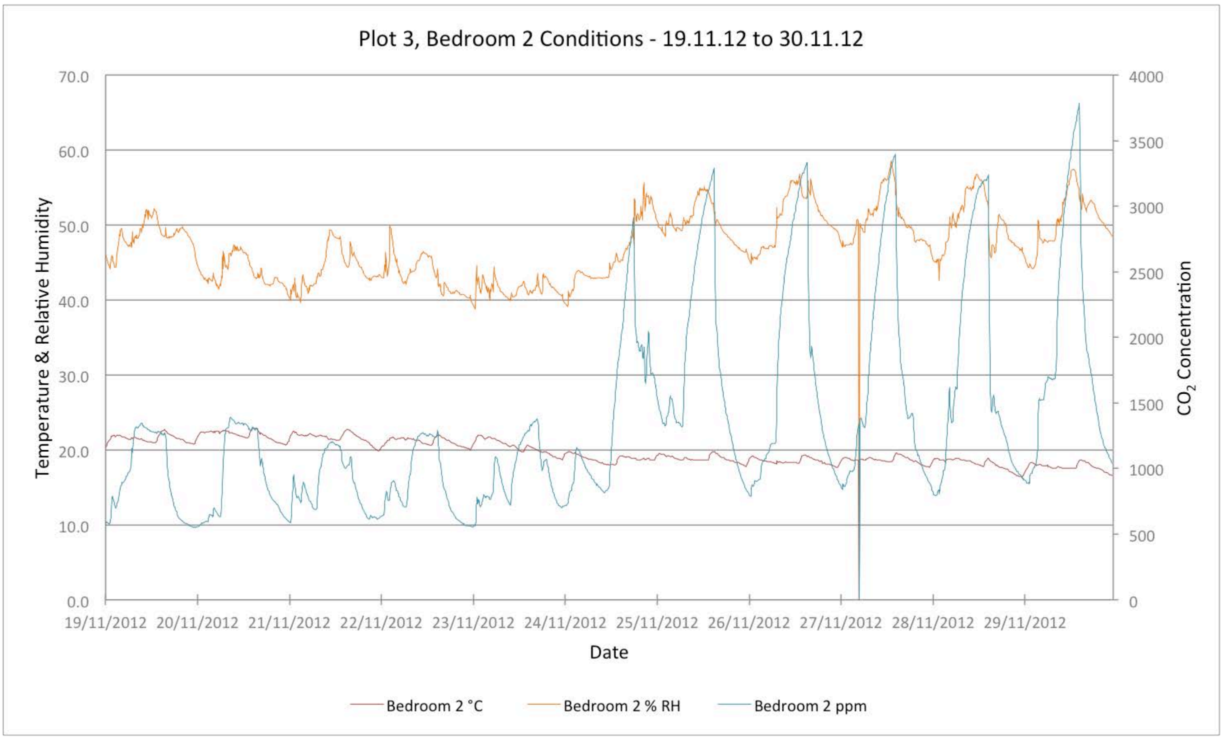

Figure 24. Extent of CO_2 peaks during periods with no MVHR (Plot 3)

Although the MVHR system was intentionally switched off in this case the impact is representative of a system, which has failed, is blocked or has been switched off by residents (frequently due to intolerance of noisy systems). This presents a clear case for concern relative to IAQ and health with two particular considerations; a) the residents were unaware that the system had been switched off as there was no visible or audible clue (evidenced by their continued completion of the 'boost' log sheets) and b) they seem to have had limited perception of the poor IAQ and increase in pollutant levels.

All of these issues are of great significance issues between the perceived quality of a space and the true measured quality is a topic which warrants further investigation beyond this study.

5.2 Conclusions and key findings for this section

- The approach taken to 'handover' the houses to the students was effective in allowing them to quickly learn how to use the systems. Although essential for ensuring control of the testing this confirms the importance of good handover procedures and suggests that some of the hands on techniques used could be applicable for effective handover to genuine residents.
- The experimental use of scripted testing scenarios proved to be a very successful method for focussed evaluation and will be used by MEARU in future projects where feasible.
- Effective heat control by the research team was found to be challenging (from the pilot study onwards) as the dwellings had a tendency to easily overheat. Sizing of heating systems and heat emitters should be carefully considered in highly thermally efficient dwellings (essentially all contemporary dwellings under new regulations).
- Scenario testing found Plot 3 to be more energy efficient in terms of regulated energy use (principally for space and water heating).
- IAQ levels were frequently found to exceed desirable maxima even when the MVHR system was operating in it's optimum range and being used as instructed by occupants.
- Lack of acoustic insulation between rooms and storeys was found to be an issue. Perception of this is possibly exacerbated by the high level of acoustic

separation from the exterior which leads to relative amplification of interior noise.

- Malfunction, blockage or override of the MVHR system was demonstrated to have the potential to create internal conditions which, over time, would impact on occupant health. Design and maintenance procedures must clearly be put in place to mitigate this.

- The impact of user behaviour on IEQ was demonstrated to be lessened where larger volumes (proportional to occupant density) were used. This is of benefit to good IEQ but must be balanced with moves to mitigate fuel poverty.

- Use of thermally massive materials in the sunspaces (Plot 3) was shown to be of benefit in mitigating the effects of high and low temperature fluctuations and increasing the time the space can be used for additional amenity.

- The use of solar shading in the sunspaces would be of benefit during summer months to protect from overheating of this and adjacent spaces.

- Even during perceived poor and wet weather the conditions achieved in the sunspaces were found to be suitable for passive drying of laundry and in this guise the value of these spaces cannot be overlooked in terms of providing relief from unwanted internal moisture gains and their latent health impacts.

- The supply of heat was shown to be significant to energy efficiency relative to construction type. A prolonged low level heat was shown to benefit Plot 1 while shorter more intense heat supply benefited Plot 3. These results were as hypothesised but the impact was greater than expected and seems to indicate that providing heat demand appropriate to construction type can have a large bearing on energy efficiency.

- Occupant were found to be less able to perceive poor air quality than had been thought and while suggestions were made over why this situation exists it suggests that systems should be put in place to identify poor IAQ and mitigate it either automatically or allow residents to deal with it manually.

- The use of fiscal metering data was found to be suitable for the purposes of this project but for future BPE projects separate sub-metering data should be considered for use where possible.

6 Occupant surveys using standardised housing questionnaire (BUS) and other occupant evaluation

6.1 Use of Project Specific Occupant Surveys and Related Findings

The eccentric nature of this Phase 1 study required that specific occupant surveys were developed to deal with the short-term occupation by the student volunteers. This was in variation to the more standard use of BUS questionnaires. A copy of a typical end of scenario questionnaire is provided as Appendix D.

Outcomes of occupant surveys were used to inform the direction of future scenarios and to provide valuable anecdotal evidence to support or confound the particular focus of the preceding monitoring period. As such, specific findings were developed from this evidence with the most significant aspects previously reported against the relevant Scenario in Section 5.1.

Beyond these specific findings the most significant outcome of the survey process, not reported elsewhere, was the overwhelmingly high regard for the houses in terms of overall comfort, layout and design. Occupants based their perceptions of the design quality relative to the experience of their own homes or term time lodgings with examples of frequently recorded comments noted below;

“Simple, functional, comfortable and ...sustainable!”

“The air quality was fine and it always felt that it was clean.”

“I think the environment was comfortable and worked well for me.”

“It was comfortable to live in, friendly environment to live in; the view through the windows was weird though”

“The Glasgow House has much more storage and better proportioned rooms. Heat retention and consistency of temperature is much better, and it definitely has a better external visual appearance. Hot water is much more efficient and comes on quicker too.”

In any BPE process it is of critical importance that successes are identified as well as failings and in this regard GHA and the other members of the delivery team can be confident that a high quality model for housing has been developed which residents found to be more than satisfactory. As a model for future social housing The Glasgow House sets a high standard to aim for.

6.2 Conclusions and key findings for this section

- The general perception of occupants was that the housing provided a very high standard of living.

7 Installation and commissioning checks of services and systems, services performance checks and evaluation

7.1 Commissioning and MVHR/ Solar Thermal Testing

The BPE Domestic Commissioning sheets are completed as far as has been reasonably practicable and are included in this document as Appendix E. Where omissions have been made it is due to the issues previously identified where information has been lost over the course of a project largely due to turnover in personnel. This natural process made the collation of this data extremely laborious on a project where it was expected the opposite would be true. This again reinforces the importance of collation of appropriate building data as identified in Section 2.1.

With respect to the Commissioning sheets themselves it is worth noting that these frequently ask for data in terms of relationships to Approved Documents which are not applicable to Scottish Building Regulations. For projects spanning the UK it would seem prudent to have documentation relevant to all regions as its omission was a factor in making the data completion so time consuming.

As well as completing the generic commissioning data for the dwellings, specific testing was also undertaken of the MVHR and solar thermal systems.

MVHR Testing

During the pilot study the CO_2 levels in both houses were found to be worryingly high and after identifying and reporting this issue the system was investigated by the manufacturer (Vent-Axia), a report on this was issued to GHA and City Building (copy provided as Appendix F) and the system was re-commissioned. In addition and as a direct result of the pilot study evaluation V-A also improved their own protocols and to ensure better design and installation standards; a real demonstration of the power of BPE on a relatively small scale project.

When testing was undertaken for the TSB project it was, therefore, on a system which had been recently and thoroughly checked and was operating at an optimum level.

The whole house MVHR system was tested on 8th March, in accordance with TSB monitoring protocol, to identify supply and extract volume flow rate for the installation. Prior to running the system testing the filters were taken out and cleaned and it was interesting to note the extent of dirt which had accumulated since the filters were cleaned prior to SC1 (some 3 months previously). In Q1 report it was hypothesised that the extent and type of 'dirt' apparent on the filters could be attributed to a recent local fire. It now appears, however, that while this may have been a contributory factor the level of blockage identified during testing is simply as a result of urban pollution. Although the hypothesised cause of the unfiltered material has varied from Q1 the note on the impact of system efficacy is, if anything, reinforced.

Figure 25. Comparison between clean and used filter with approximately 3 months of urban filtration residue.

Testing of the 2 installed systems was undertaken using TSI Airflow TA5460 with a vane anemometer and hood testing kit as shown in the image below.

Tests were undertaken for the low volume and boost flows of the system with clean filters and then latterly with a 50% area card occlusion as noted in the testing protocol. The results for both tests are also presented below.

Figure 26. Vane anemometer MVHR testing kit.

Figure 27. Clean filter and card occlusion being inserted into unit.

Plot 1 – Clean Filter

Extract Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Utility/ WC	7.23	5.49
Kitchen	9.81	6.81
Bathroom	9.3	6.3
Total	**26.34**	**18.6**

Supply Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Living Room	5.64	4.51
Bedroom 1	9.31	7.45
Bedroom 2	8.13	6.23
Bedroom 3	7.8	5.96
Attic Room	8.42	6.69
Total	**39.3**	**30.84**

Plot 1 - 50% Occlusion

Extract Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Utility/ WC	7.36	5.21
Kitchen	9.64	7.13
Bathroom	9.41	7.39
Total	**26.41**	**19.73**

Supply Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Living Room	5.65	4.44
Bedroom 1	8.84	7.11
Bedroom 2	7.96	6.1
Bedroom 3	7.53	5.97
Attic Room	8.25	6.37
Total	**38.23**	**29.99**

Plot 3 – Clean Filter

Extract Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Utility/ WC	9.23	5.64
Kitchen	12.11	8
Bathroom	8.26	5.35
Total	**29.6**	**18.99**

Supply Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Living Room	7.27	7.34
Bedroom 1	8.69	8.64
Bedroom 2	6.53	6.9
Bedroom 3	3.88	4.26
Attic Room	7.27	7.48
Total	**33.64**	**34.62**

Plot 3 - 50% Occlusion

Extract Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Utility/ WC	9.63	6
Kitchen	12.09	8.05
Bathroom	7.87	5.32
Total	**29.59**	**19.37**

Supply Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Living Room	6.52	7.29
Bedroom 1	7	7.83
Bedroom 2	6.11	6.27
Bedroom 3	4.59	4.17
Attic Room	7.8	7.33
Total	**32.02**	**32.89**

Table 15. MVHR system recorded flow rates in Plots 1 & 3 with varied occlusion levels

The results of the system testing present some interesting points of note relative to the overall performance;

1. In each of the 4 tests it appears that the system was not balanced – i.e. volume flow rate for extract and supply are not equal. Without exception the supply rate of air was greater than the extract volume by a degree ranging from 108% to 182%. While this lack of consistency and degree of variation itself warrants further investigation the impact of this situation is worth mentioning as it is creating a scenario where the dwellings are becoming positively pressurised – a practice which is increasingly open to question due to issues of interstitial condensation that are arising.

2. In the case of plot 3 both Low Volume Flow supply (background) rates are greater than the High Volume equivalents. For a balanced system this presents a situation which doesn't appear to conform to the design intent and, therefore, warrants further interrogation.

3. In the case of both dwellings the extract rate actually increased with the 50% filter occlusion while equivalent supply rates dropped marginally.

With respect to point 3 it suggests that the 50% occlusion methodology (or at least this interpretation of it) is perhaps not representative of a real life scenario or effective in replicating the impact of a blocked and dirty filter. In addition, the impact of the blockage should not assess air flow rate only but should also review the energy required to achieve these as it is possible the occlusion has a significant impact on power consumption, and therefore efficiency, but that this is not revealed by flow rates alone.

These anomalies show that even with systems as thoroughly checked as these and installed in exemplar dwellings performance is not guaranteed. Moreover, findings from the test scenarios show that even when operating as designed, good IAQ levels are not always achieved. This raises two important issues for the use of MVHR systems in domestic conditions;

1. Thorough assessment should be made of the suitability of design standards in Scotland as performance is based on theoretical and not in-situ values and is specified according to a historic standard which does not acknowledge the levels of air-tightness now being achieved.

2. If best case installations are found to be lacking in performance (as was identified by the pilot study) then what is the state of installations elsewhere and how can we be confident that such an important construction element (relative to occupants health) is being adequately dealt with.

Solar Thermal Testing

Testing of the solar thermal systems was only undertaken in Plot 3 as the panels in Plot 1 had failed since the time of commissioning. This failure was due to a depressurisation of the system at the panel although the cause of depressurisation is still unknown as a rooftop inspection has not taken place. As the system was integrated to the roof covering replacement of the failed panel would require a strip of the roof and this is not something that City Building were or are proposing to do given the finite life of these test buildings.

Before even getting into the inspection and testing of the functional system, this situation raises two important issues relative to the use of such building integrated technologies.

Firstly, the extent of 'integration' should be carefully considered at design and specification stages. The successful integration of low-carbon technologies into architectural design is a critical factor in the rate of uptake for these technologies. Successful integration could be seen as instances where the applied technology has a beneficial (or at least non-detrimental) visual impact on the architecture. In addition, and to go beyond aesthetics, successful integration can also be seen where pre-existing structural opportunities are maximised to mitigate the need for additional material, structure or cost to allow the system's application. Based on these criteria it would seem that the Glasgow House installations are successful as they present a discrete, almost imperceptible, addition to the dwellings which is reliant only on the existing roof for positioning and support. Where the success of this system is more limited, however, is in relation to the costs associated with repair if failure occurs. As is demonstrated by the current failure, the extent and cost of roof-work required to replace the panel is such that it makes it unfeasible. If these systems are to be successful over a significant time period then issues of maintenance should be thoroughly considered at design stage or the seemingly successful integration will act against the usability and efficacy of the technology.

The second aspect for consideration relates to systems, or lack of them, which can identify whether installed technologies are functioning as designed, if at all. With the case of the failure in Plot 1 it is quite conceivable that in a domestic situation, as opposed to this test environment, that the failed system could go unnoticed for months or years. This could have a significant impact on the occupants energy demand and, given the nature of this project typology, it is clear that measures should be put in place, either by automated systems or maintenance/ inspection regimes, that can assure the functionality of *all* domestic active systems.

Figure 28. External image of dwellings showing the discrete solar thermal panel installation.

In the case of Plot 3, testing of the functioning solar thermal system was undertaken by Paul Tuohy of the Strathclyde University Energy Systems Research Unit (ESRU) between 1st and 5th November 2012. A full report on this test is provided in this document as Appendix G.

- Solar thermal pipework insulation was found to be of sub-standard specification and missing in large section where it had melted away.
- Lack of insulation was seen to be likely to lead to uncontrolled overheating within the dwelling during summer months.
- Pipework for heating systems was generally found to be lacking insulation or poorly insulated leading to uncontrolled heat loss and potential for overheating.
- Cold water pipes were found to be poorly insulated creating the risk of condensation and water damage.

- Control systems for the hot water store were found to be overly simplistic and not linked to the solar energy supply rates, thus leading to energy being wasted for water heating when not required.

- Water temperature range across the depth of the thermal store was found to present potential risk of legionella growth during significant periods where of hot water draw off is made.

Image ref:		Floor:		Room:	

Figure 29. Melted and missing insulation on solar thermal pipework – plot 3.

7.2 Conclusions and key findings for this section

- The standardised commissioning sheets required to be completed for the project do not acknowledge the statutory regulations for Scotland. Requirements to complete sections relating to Approved Documents to not apply to the Glasgow House project and Scottish templates should be developed for future projects.

- Additional guidance on appropriate methodology for the 50% occlusion test of MVHR systems would seem to be useful to further assist standardisation of results and cross comparison.
- Comparison of the MVHR systems in both houses identified differences in performance despite both systems being commissioned and balanced before testing. This is likely due to issues with duct routing and failures in the air delivery system which have since been enclosed. This illustrates the importance of good design and installation of such critically important systems.
- The use of 100mm ducts as part of the air delivery system was found to be insufficient and ducts with a greater cross sectional area should be used to achieve appropriate volume flows.
- Ease of access to and frequent maintenance of filters was found to be critical for efficient system operation. The rate of filter saturation in the urban context was found to be much faster than was expected.
- Issues identified in such a well controlled system (such as failure to deliver adequate levels of fresh air) strongly point to a need to address the design requirement of building regulations and create concern for the implications of less well controlled installations elsewhere.
- Solar thermal pipework insulation was found to be of sub-standard specification and missing in large section where it had melted away.
- Lack of insulation was seen to be likely to lead to uncontrolled overheating within the dwelling during summer months.
- Pipework for heating systems was generally found to be lacking insulation or poorly insulated leading to uncontrolled heat loss and potential for overheating.
- Cold water pipes were found to be poorly insulated creating the risk of condensation and water damage.
- Control systems for the hot water store were found to be overly simplistic and not linked to the solar energy supply rates, thus leading to energy being wasted for water heating when not required. This situation could be improved through the use of better specified and integrated sub-metering of active systems.

- Water temperature range across the depth of the thermal store was found to present potential risk of legionella growth during significant periods where of hot water draw off is made.

8 Other technical issues

8.1 Additional Findings

The vast majority of issues relating to building performance are reported in the preceding sections but two additional problems were identified relating to the roof construction of Plot 1.

The original specification for this house had been for a tiled finish that would have required tiling battens on 9.5mm plywood sarking. At construction phase the finish of this roof was amended to test the use of slates produced from recycled car tyres. When the change in tiling was made, the tiling battens were omitted, with the rubber slates fixed directly to the sarking (a traditional Scottish construction detail where sarking boards are commonly used). However, it is apparent that the battens also had a role in bracing the roof cassette and their omission has led to some movement in the roof, as the sarking alone (15 – 20mm) was not stiff enough for direct nailing. Although this creates an unsightly issue it has not resulted in any water penetration or impeded performance.

Image ref:		**Floor:**		**Room:**	

Figure 30. Plot 1 roof showing recycled tyre ‘slates’ and deformation of sarking

It is not known whether the movement in the roof here was instrumental in the depressurisation and failure of the solar thermal system (see section 7.1.) but the integration of the ST panel and roof finish raised an important issue applicable to all such installations. When testing the ST systems City Building confirmed that they had a replacement panel which could be installed in Plot 1 but that this would require the roof to be stripped and was not feasible given the remaining lifespan and requirements of the building.

The use of integrated systems provides an aesthetic benefit and successful integration is a key factor in the rate of uptake and perception of active systems within architecture. If, however, this integration creates significant difficulties for maintenance, repair and replacement then it should be carefully considered when and where its use is appropriate.

8.2 Conclusions and key findings for this section

- The implications of fully integrating active systems within construction should be considered against lifespan, potential failure rate, maintenance requirements and any cost uplift which may exist in repairs (compared to stand alone systems).

9 Key messages for the client, owner and occupier

9.1 Key Outcomes from the Glasgow House

In this and the following section the 50 or so key findings from the project are summarised into a series of shorter 'messages'.

As with all BPE projects, attempts to search for improvement can lead to an imbalance in the number of negative findings. To support the movement towards energy efficient building and the BPE process itself it is, therefore, important that positive findings are also well reported.

In the case of the Glasgow House the first key outcome is to commend the Client for undertaking the project in the first place and for then undertaking a full BPE analysis in the knowledge that not all findings would be palatable in the short term but that this would lead to much wider long term improvements. More public and private Clients need to have this approach to development if BPE is to become more widespread improving the performance and efficiency of our buildings in real terms and not just on paper at design stage.

With respect to specific performance characteristics, identified through various tests, it is clear that Plot 3 is more energy efficient than Plot 1 but that both dwellings achieve high performance by contemporary standards and, as identified in the pilot study, achieve the goal of mitigating fuel poverty. This may appear to be at odds with the finding that both fall short of the targets identified in the SAP worksheets but it is important to realise that these values are designed to effectively predict actual performance and should not be deemed as such. An awareness of this is likely to give stakeholders a more realistic set of expectations from pre-construction stages and to make the findings from BPE studies more palatable.

The outcome of walkthroughs and analysis of the occupant questionnaires has shown that the perception of the dwellings and the standard of living they provide is overwhelmingly favourable. This was supported by the quality of construction which was shown through testing to be of a reasonably high standard throughout although some issues were identified with a lack of acoustic separation between rooms and storeys.

In terms of fabric thermal performance it was found that the clay block system fell below expectations and when considered against the added expense of this system its use in future projects should be questionable (noting that it was found to provide some benefits in terms of the provision of added thermal mass).

Almost all of the remainder of the project specific findings are the more negative aspects which require improvement and, interestingly, *all* are related to the use of active systems and technologies. Issues were identified in the design (including limitations of the technical standards), location, installation, commissioning and maintenance of the boiler, solar thermal and mechanical heat recovery ventilation systems. All of these are issues which are within the control of design teams, contractors and building owners and it is critical that the key findings identified in this report are used to inform these parties of the problems to be aware of at various stages of building procurement and operation.

Beyond this occupiers must then play their part as the impact they alone have can counteract all efforts to improve energy efficiency but they can only operate these systems effectively if provided with adequate information and it is here that the onus is again, at least initially, back on the owner to make the appropriate initial and continued investment in best practice handover.

9.2 Conclusions and key findings for this section

- The approach taken by GHA to undertake the Glasgow House project and the TSB BPE is to be strongly commended.
- The living standard provided by both houses was found to be very high.
- The energy efficiency of both dwellings was found to be commensurate with the aspirations of the project albeit the thermal performance of Plot 1 (masonry) was below that of Plot 3 (timber frame).
- The specification, installation, use and maintenance of active technologies was found to present the biggest obstacle to effective operation and healthy internal environments. Greater care and attention should be taken over these elements of design to ensure success as failure to do this can counteract all other efforts to achieve energy efficiency.
- Lower energy use in Plot 3, but better comfort in Plot 1
- Overall consumption estimated to be £390 - £490 per year for Plot 1 and £350 - £370 for Plot 3 for space and water heating
- In practice the difference may be less masked if better comfort as a result of thermal mass reduces excessive ventilation
- Higher than anticipated but well within affordability

A number of improvements are possible:

- The solar thermal systems made limited contribution and repairs in Plot 1 would rectify this
- Improved insulation would reduce unwanted heat loss (and internal gains) from hot water system
- Connecting the plant space to the MVHR system would redistribute heat from plant spaces and could make an effective drying space
- Heat gain from the sunspace could be used to contribute to heating and clothes drying with better ventilation opportunities. Increasing thermal mass in Plot 1 would improve its effectiveness
- Improvements in fabric performance and detailing, esp at windows and doors
- Improved controls and user interface
- In association with this better indications of diagnostics and performance of active systems, e.g. MVHR operation, need for filter changes, solar thermal performance
- Review the size of the heating system, remove radiator from the porch space and reduce radiator sizes
- Develop the ‘Quick Start’ guide to match above features

10 Wider Lessons

10.1 Next steps

This particular project offered the opportunity to test the building and methodologies with less fear of failure and this has benefitted our overall approach to BPE for use on other TSB projects but also for consultancy work. Whilst this is not applicable on the majority of built projects, it does justify the original decision to undertake a pilot study and subsequent evaluation. It is also seen to be cost effective in terms of the potential additional costs that would have been incurred had the project been undertaken on a wider scale without testing. GHA intends to use the findings from this project to aid a better understanding of performance requirements, in terms of both energy and health, and having BPE written into project briefs

The project was reported at a workshop held on the 22 April 2013, hosted by GHA at their headquarters and attended by GHA and City Building personnel, but also included architects and contractors who are working with GHA. A copy of the presentation is included in the Q4 reporting documents. This is part of an on-going dialogue between GHA and MEARU concerning the development of new housing in the city.

GHA are also in a key position to disseminate the findings and knowledge generated by the project to partner organisations, particularly housing associations in Scotland, but also contractors and manufacturers. GHA and MEARU intend to undertake much wider dissemination to practitioners, through industry events. The Glasgow House findings have been included in talks and papers given at, Eurosun September 2012 (Appendix C), Ecobuild March 2013 (Appendix H), Chartered Institute of Housing, Belfast June 2013 (Appendix I), Passive and Low Energy Architecture, Munich in September 2013 (Appendix J), and further opportunities for dissemination will be explored.

As well as implementing the findings of this project, GHA have identified the benefits and insight provided by BPE and discussions have taken place with MEARU to identify ways of undertaking BPE on the current iteration of the Glasgow House, due on site in September, but also 3 other housing projects, including a refurbishment projects with partner organisations Loretto HA and Cube HA. Currently a potential Knowledge Transfer Partnership is being scoped, to enable GHA to develop in-house capacity for BPE

Discussions are on-going with GHA and City Building to see if the current houses may be used to undertake modifications to try and improve performance. This may make a useful ‘retrofit’ project to examine the steps required to improve performance of systems and construction where possible

The project identified a fundamental need for improvement in the way that active systems are considered and implemented in projects. Whilst legislative demands are tending to lead to solutions that rely on active systems, it is apparent that their benefits are predicated on optimum performance, which may be difficult to achieve and will certainly be difficult to maintain. This information should be fed back into industry in order that improvements can be made to achieve these goals. A specific example in this case were the changes instigated by Vent-Axia in their installation and commissioning procedures. An important message for the wider industry concerned the lack of performance and diagnostic data within the active systems. There is no obvious feedback to occupants about how systems are working, or potential problems.

There is also a clear lesson about pursuit of singular targets, for example energy consumption, without considering other factors. The example highlighted in this project is the use of an MVHR system. Whilst the selection of the system is predicated on reduced ventilation heat losses, without alternative background ventilation this relatively airtight dwelling is largely reliant on the system to provide ventilation and air quality. The system therefore needs to be capable of meeting these requirements for example delivering sufficient ventilation air, which in some circumstances may not have direct energy benefits. There are also potential impacts should the system fail, be disabled (for example due to noise, concern over running costs, lack of knowledge about its purpose) or if filters become blocked. It also highlights the problems that may arise during underperformance. These are key issues throughout the industry, but particularly so for social housing providers.

The project identified several issues in relation to testing procedures. It would be difficult to undertake the co-heating test in mainstream projects, and even with collected data, outcomes are variable depending on the method of analysis. Should such a test be promoted it is thought that a more standard approach to test methodology, along with a centralised analysis may provide more comparable results. Nevertheless, in this instance the ability to make a direct comparison between the two houses was invaluable.

Consideration should be given as to whether the MVHR occlusion provides a representative test. The nature of the filter occlusion by dirt is probably not best replicated by the 50% occlusion required in the standard test.

However the project also identified that useful data can be collected during relatively short monitoring periods. Whilst not providing the comprehensive dataset that longitudinal monitoring may achieve, crucial insights can be gathered in focussed studies.

A critical message to the industry concerns the matching of design predictions with expectations of performance. Whilst tools such as SAP are important and useful tools for understanding comparative performance at design stages, their limitations are such that they cannot be used to predict performance in use. At design stages there needs to be a more realist and thorough evaluation of benefits and pitfalls of environmental strategies. At present these are significantly determined by legislative targets rather an understanding of how a dwelling may actually function. An example of this highlighted in this project is the need to consider ventilation strategies for both whole house, but also individual spaces within rooms.

This is likely to require greater resource at design and evaluation stages. The need to address energy targets, whilst at the same time meeting the environmental and social needs of occupants is a considerable challenge, and one that will be difficult to meet within current allocations for design and evaluation. This includes the need for a holistic view of energy and environmental strategies that avoids a fragmentation of approach and enables viable energy and environmental strategies to be delivered in the completed building

Although not addressed directly in this project due to the nature of the occupancy, it is also very clear that the social housing sector needs to factor in user engagement with performance, especially active systems. Where user operation is critical to performance, user understanding, user controls, handover and support, and maintenance are critical.

10.2 Conclusions and key findings for this section

- BPE is an crucial strategy in in examining the energy and environmental performance of housing for GHA
- Organisations need to develop capacity for undertaking BPE and feeding this back into specification, design procurement and construction processes

- Building Performance Evaluation has revealed significant, useful information on performance, is able to identify improvements in existing and future buildings and is a vital component is producing effective buildings in the contemporary contexts

- It helps to inform design and legislation, is able to improve (achieve) energy savings and environmental performance, health and well-being, ensures that what has been paid for is delivered, meets landlords ethical responsibility to occupants and ensures that targets and objectives are being met.

11 Appendices

List of Appendices;

A - Plot 1 & 3 Thermography Reports

B - Plot 1 & 3 Air Tightness Test Reports

C - Eurosun 2012 Paper

D - End of Scenario Questionnaire

E - BPE Domestic Commissioning Sheets

F - Vent-Axia MVHR Testing Report

G - Solar Thermal Testing Report

H - Ecobuild 2013 Presentation

I - Chartered Inst. Of Housing Presentation

J - Passive and Low Energy Architecture Paper

K - Summary of Key Findings