GHA

MACKINTOSH ENVIRONMENTAL ARCHITECTURE RESEARCH UNIT
THE GLASGOW SCHOOL OF ART

GLASGOW HOUSE
Performance Evaluation
Final Report – May 2011

Preface

This report has been produced by the Mackintosh Environmental Architecture Research Unit (MEARU) on behalf of Glasgow Housing Association (GHA) and, in broadest terms, analyses the simulated and in use performance of two prototype houses constructed for GHA by City Building (Glasgow) LLP at, Norfolk Street, Glasgow.

The authors acknowledge the assistance given throughout the project by GHA, City Building and in particular by the 8 student test subjects who made the 'in use' analysis possible.

Contents

1.0 Executive Summary

The following summary should be read in conjunction with the original Scope of Service, Appendix 1.

1.1. Simulated Performance

1.1.1 Three differing scenarios were simulated for both houses using a 'hybrid' methodology that allowed for contributions made by the sun spaces and which was verified against previously measured precedents.

1.1.2 These scenarios identified that in terms of energy consumption the performance of the timber frame (TF) construction could closely match that of the clay block masonry (NBT).

1.1.3 A limitation of the simulation was the ability to identify individual daily profiles of temperature. Any benefits of thermal mass would not be easily identifiable without further dynamic simulation, but thermal mass is likely to be beneficial in respect of thermal comfort, especially in warm and sunny weather.

1.1.4 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.

1.1.5 This figure was highly sensitive to the ventilation loads and, in particular, occupant behaviour with respect to ventilation.

1.1.6 The simulations highlighted the potential benefits of using the sun spaces for Solar Ventilation Preheat (SVP) and the resultant reduction in heat load demand if incorporated (by passive means) into future designs.

Recommendations

a) Whilst simulation has value in terms of comparison between different designs, caution should be exercised when using simulation tools to predict actual performance, as construction and occupancy factors will lead to significant differences between predicted and actual performance. Further development should not rely on SAP calculations as estimates of actual performance.

1.2 As Built Performance

1.2.1 A test occupancy was undertaken using volunteers to occupy the houses using identical regimes over the two week period. The houses were occupied overnight, heating on between 7 – 9 hrs and 15 – 23 hrs. TRV's were set to 4 in the first week, but this was found to result in uncomfortably high temperatures, so were set to 2 in the second week. Whilst care was taken to ensure as close an occupancy as possible, some differences occurred, principally in the amount of window opening, with large amounts of opening events in House A, Week 1.

1.2.2 The as-built energy consumption was found to be 2.86 and 1.79 times greater respectively, than predicted for the NBT and TF dwellings. Although these results seem high compared to the simulation, they are well within the performance standards of an energy efficient dwelling of this size in relation to contemporary technical standards. The following aspects were identified as those which could have affected the difference between predicted and actual performance results and difference between the actual dwellings:

a) Underestimation of ventilation rates
b) U-values higher than predicted
c) Overestimation of incidental gains
d) Water heating consumption underestimated and/or boiler efficiency overestimated.
e) Calculation methodology too blunt relative to dynamic reality

1.2.3 Of these, ventilation appears to be a key factor and this is supported by the monitored difference between the two houses, in which more window opening occurred in House A.

1.2.4 The large amount of window opening was driven mainly by high temperatures in the first part of the study leading to greater ventilation losses and higher gas consumption. The fact that comfort temperatures were exceeded in cold weather with TRVs set at 4, and easily achieved with the TRVs set at 2, indicates that the heating provision is oversized and therefore the heating controls are likely to cause energy wastage.

1.2.5 Higher than predicted U-values, and particularly heat loss through the windows (refer 1.3 below) may also have had a significant impact and may warrant further study.

1.2.6 However, in economic terms, the performance in the NBT dwelling was found to have a weekly energy cost of just £7.07 for space and water heating (£367.67 p.a.) and in the Timber Frame these were £5.41 a week (£281.25 p.a.). Even for what would be considered to be a relatively high demand scenario, especially in the NBT house, 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.

1.2.7 The MVHR system performed well in terms of heat recovery from extracted air from kitchens and bathrooms, but was not able to deliver reasonable volumes of fresh air to internal spaces and this led to poor air quality.

1.2.8 Users had difficultly with the ventilation boost controls which did not clearly identify that they were operating, which could lead to them not being used, or left on for long periods.

1.2.9 The short monitoring period could not clearly highlight the benefit of thermal mass in House A compared with House B. Average air temperatures in House A, were slightly lower, suggesting improved radiant temperatures, but this is not otherwise evidenced. This will in part be due to the winter period, but may also be due to lack of sufficiently exposed thermal mass.

Recommendations

b) The nature of the heating system and especially the controls should be further examined. Options may include a reduced heat output through a smaller boiler and/or smaller radiators, or alternative heating provision – e.g. individual feature heaters in living spaces, or provision of heating through the ventilation system.

c) The specification and placement of controls should be given close attention, with consideration given to more understandable and accessible programmers and room thermostats, better design of MVHR boost switches

d) Further investigation is required with respect to the effectiveness of MVHR systems in achieving good internal air quality. The capacity of the system should be sufficient to provide good air quality for high occupancy and under peak conditions. Improved sensor activation, for example temperature, humidity and air quality may be advantageous. Partial MVHR to bedrooms with SVP to living rooms is another option.

e) The potential to include some heating element in a larger MVHR system would reduce the need for space heating by radiators.

f) The MVHR system should be located to ensure easy maintenance of elements such as filters. The layout of the system should also be designed to ensure good distribution of air supply and extract, and avoid to long duct runs and changing in direction.

g) Grouping of plant elements together may provide a more effective use of space and assist maintenance.

h) Provision of more effective thermal mass should be explored. The preferred position would be at intermediate floors, which would have acoustic as well as thermal benefits, in particular avoidance of solar overheating.

i) These items could be examined through modifications to the existing Glasgow House.

1.3 Thermographic Analysis

1.3.1 No significant cold spots were identified on internal or external fabric at corners or construction junctions. This indicates a considered approach to the construction detailing but more importantly a high quality of on site construction an execution of the design details

1.3.2 Thermographic images indicate relatively high heat loss through the top half of window frames. This appears to be due to both a convective effect through the frame air spaces and the use of a metallic glazing spacer.

1.3.3 Relatively high heat loss was visible from the heated porch.

Recommendations

j) Future specification of windows should address potential bridging and convection losses through improved seals.

k) The porch space should not be heated, but should act as a buffer.

l) Specification of elements such as thermal blinds or shutters may improve window performance.

1.4 Sun Spaces

1.4.1 As the study was undertaken in winter no significant solar gain effects were monitored during this study, but potential benefits of the sun spaces for useful heat gain and passive recovery via SVP were identified in the simulation and are beneficial.

1.4.2 There was some evidence of ventilation into the sunspaces during high temperatures. Although overheating should be avoided, this tactic did provide some thermal relief without corresponding external heat loss.

1.4.3 Beyond the quantifiable benefits of these spaces their worth, in terms of increased amenity and potential for dealing with domestic laundry drying practice, sunspaces should be carefully considered and included in future design proposals.

Recommendations

m) We would recommend the inclusion of sunspaces in future design proposals. As well as the quantifiable energy benefits of these spaces, they add amenity, utility value and increased equity.

n) Improvements in performance could include increased thermal mass in the sunspaces (there is little mass in the clay house due to the external insulation), and an improved strategy for solar ventilation preheat, which will allow an easy path for warm air to be transferred to the house. This might potentially be used in conjunction with a reduced MVHR system supply to the bedrooms while SVP deals with the main living space – see recommendation d) above.

1.5 External Liaison

1.5.1 The study has been conducted using methodologies consistent with external Post Occupancy Studies, which will allow comparison with other similar work. An application to the Technology Strategy Board Building Performance Evaluation programme for further investigations has been submitted.

1.6 Qualitative Analysis (in addition to Scope of Service)

1.6.1 In overall design terms the houses were rated very highly by the occupants.

1.6.2 Acoustic performance, particularly from floor to floor was identified by occupants as a problem, but was not measured as part of this study. Whilst this may be slightly perceptual in the sense that the fabric performance reduces external noise, noise transmission was clearly an issue and may have been exacerbated in House A by the nature of joist hanger connections at wall/floor junctions and possible flanking transmission through the block voids.

1.6.3 Detailed examination of effects of laundry were not examined, but work emerging from another on-going study has identified the environmental effect of domestic laundry practices on environmental performance and energy use

Recommendations

o) Improved acoustic separation through the use of thermal mass between floors, and better sealing at floor edges

p) The relative effects of occupancy highlights the impact that occupants can have on the performance of energy efficient dwellings and so there is a need to effectively educate occupants (tenants) on the use of building systems and energy efficient best practice.

q) Provide a dedicated clothes-drying space within the dwelling to reduce moisture production at source and improve amenity.

2.0 Evaluation of Energy Use Based on Simulated Scenarios

2.1 Aims

To evaluate space heating loads of respective NBT Thermoplan block and timber-frame houses (coded NBT or Dwelling A and TF or Dwelling B respectively hereafter) using three scenarios. In terms of the key variable, ventilation, these are as follows: 1) with mechanical ventilation heat recovery (MVHR) systems, assuming the given efficiency of 91% is realistic when multiplied by an in-use factor of 0.85 for as-built insulated ducts) with a controlled natural ventilation system (e.g. passive stack), but without a ‘solar ventilation preheat’ (SVP) contribution; 3) as 2), but with SVP from the west-facing, double-height sunspaces.

In order to support the analytical methodology for the three scenarios above, monitored data for 18 homes over two September-May years is used, with three different demographic categories a) households with infants under 10; other households with adults below pension age; pensioner households; respectively in a 18%, 35% and 47% proportion. Not only is the mean whole-house monitored temperature for these dwellings closely matched to those predicted for theoretical demand settings for the Glasgow House, but also the mean monitored temperatures in the 18 west-facing sunspaces are used in the Glasgow House evaluation (see methodology in section 2 below).

Hence, the aim is to provide predictions, robustly supported by monitored data with regard to differing household make-up, in relation to three differing theoretical ventilation regimes adopted for the Glasgow House; and, based on the same monitored data, providing a realistic expectation for the thermal contribution of the west-facing conservatories of the Glasgow House.

2.2 Methodology

Preamble for all scenarios

The methodology used is a modified form of BREDEM, the ‘ancestor’ of NHER, SAP, RDSAP etc. This splits the heated accommodation into two zones - 1: ‘living-kitchen’ and 2: ‘rest of house’ - and also makes allowance for the solar-enhanced buffer effect and the SVP effect of the unheated conservatory; noting in the latter case that SVP is a misnomer in that it also includes a passive form of heat recovery in overcast and nocturnal periods. The methodology also uses Glasgow solar data and Glasgow degree-days, with appropriate adjustment for self-shading in the former case; and splits the predictions into 3-month chunks for autumn (September-November), winter (December to February) and spring (March to May), using complete calendar months rather than starting from the autumnal equinox (solar transmission and degree-day data available for complete calendar months).

Scenario 1: with MVHR as built

A Calculate fabric heat loss for NBT and TF houses, with U-values checked against information on drawings (provided to MEARU by GHA) and/or additional information (e.g. specification of insulation used below solid floors). Note that there are several different conditions, and hence U-values, for losses via the roof, and walls are also split between general areas and lintels, with further linear thermal bridges - y-value (mean conductivity in W/mK) multiplied by length in metres to give loss in W/K - calculated according to a specific condition (i.e. default value not used). It should also be noted in this regard, that due to the presence of the unheated conservatories, it is necessary to calculate U-values (and total thermal resistances) through components between heated zones and the conservatory, as well as between heated zones and outside via the conservatory. The former is required when calculating heat gains from the conservatory to the heated interior (S1:H below), and the latter is required in order to calculate the 'heat loss parameter' (HLP), in turn used to estimate mean zone temperatures (S1:C below).

B Estimate mean rates of ventilation for each zone, based on knowledge of construction (infiltration rate), and monitoring experience of seasonal window-opening tendencies (greatest in spring relative to outside temperature); and hence the proportion of total ventilation demand that will be subject to MVHR - using given efficiency of 91% multiplied by an 'in use' factor of 0.85 for insulated ducting to give 77.35% (i.e. energy required for 22.65% of MVHR portion). Each of the three seasons will therefore have a different rate of ventilation to be multiplied by the heated volume of each zone and a standard coefficient to give the ventilation loss in W/K; and, given that MVHR implies a fine-tuning capability for ventilation, rates for zone 1 are assumed to be somewhat higher than those for zone 2. Note that although drawings provided to MEARU indicate slight dimensional differences between the NBT and TRF dwellings, the NHER Data Input Sheets show identical floor areas. Therefore, for the sake of simplicity, volumes for zones 1 and 2 calculated for the NBT dwelling are also used for that of the TF, and hence respective ventilation losses used for each scenario are uniform.

C Estimate HLP for each house type, each of the three seasons, and for the MVHR rated as S1:B above. Use respective HLP values to calculate indoor air temperatures in each zone for each season, extrapolating from tables in BREDEM handbook, 1985, and assuming the following demand schedules: NBT - 21^{o}C demand in living room, whole house heated all-day (16 hours) for mixed response heating system (to recognise role of heavy NBT construction even though heat emission is from radiators); TF - as for NBT except use responsive heating system to recognize radiators in conjunction with light timber construction. Check the values obtained for each house type and each season for suitable 'fit' relative to 2-year mean Sep-May average data for 18 monitored dwellings with west-facing sunspaces, and that estimated temperatures provide an adequate degree of thermal comfort.

D Calculate the mean average conservatory temperature from 2-year monitored data for 18 dwellings (due west-facing vertically glazed sunspaces) in each of the three seasons. Note that apart from internal temperatures and solar gain, the key variables for the conservatory are the frequency and extent to which the occupants open outer windows and dividing windows/doors. One may calculate temperatures in unheated buffer spaces (Porteous, 1990) and use a spreadsheet method to do this (Kondratenko and Porteous, 2005), this method is still reliant on assumptions with respect to ventilation rates between the conservatory and outside, as well as between the conservatory and inside. Since 18 different households over two heating years takes account of differing habits with respect to opening inner and outer windows (Porteous and Ho, 1997) and tilted glass compensates for north of west orientation, it was considered more robust to make use of these measured means, provided there is a reasonable fit between internal temperatures derived for NBT and TF and the equivalent monitored means for the same set of dwellings.

E Estimate incidental gains and solar gains for each zone in each of the three seasons - incidental gains appropriate to size of dwelling, modern tendencies with regard to appliances (e.g. 5 persons, large TV, 4 other computers/TVs) and appropriate allocation between zones; solar gains for respective orientations/tilts from Climate in the United Kingdom (Page and

Lebens, 1986) allowing for significant shading and multiple layers of glass in the case of transmission to heated rooms via the conservatory.

F Calculate the gain/loss ratio (Watts divided by W/K = K) for each of the three seasons for each zone in each house type; and subtract from respective internal temperature values (S1:C) to give corresponding internal base temperatures (temperatures for which additional heating may be required). Note that if base temperatures, Tb, are negative values, there will be no space heating load for that zone; and internal temperatures will rise above the estimated values. However, in this regard, they would need to exceed around 26-28^{o}C in order to necessitate cooling action - shading or opening windows.

G Interpolate degree-day values for respective positive internal base temperatures from Climate in the United Kingdom (Page and Lebens, 1986) for each of the zones in each house type, for each of the three seasons.

H Deduct respective 2-year mean autumn, winter and spring conservatory temperatures, Tc, from corresponding internal base temperatures, Tb, multiply by fabric heat loss between heated zone and conservatory (W/K) and then by number of days in each 3-month set and 0.024 to give heat gain to interior (assuming a negative Tb –Tc difference) for each 3-month period (kWh).

I Multiply degree-day values (for zones with a positive Tb value) by total fabric and ventilation loss direct to outside (i.e. excluding heat exchange between heated zone and conservatory), and by 0.024 to give gross space heating load for each 3-month season (kWh); and then deduct any solar gain from the conservatory (S1:H) to give net space heating load. The total value from September to May for both zones is then divided by internal floor area (123.15 m^2 as given on NHER Final Design Data Input sheet) to express the total space heating load per square meter (kWh/m^2). This may then be compared to benchmark values such as 15 kWh/m^2 for PassivHaus.

Scenario 2: no MVHR, no SVP* allowance (*Solar Ventilation Preheat)

A As S1:A above.

B As S1:B above, except that the entire ventilation component is deemed natural - i.e. directly between heated zones and outside, with no heat recovery or SVP included (implying conservatory functions as a buffer only). Given that natural ventilation denies the controllability of MVHR, a uniform rate is now assumed for both zones, based on the assumed demand rates for each of the three seasons used in S1:B

C As S1:C above, except that there are no MVHR variants.

D As S1:D above..

E As S1:E above.

F As S1:F above, noting that negative Tb values are now less likely due to the larger ventilation component. Note also that if the numerator in the gain/loss ratio remains constant (same as S3:F), but the denominator increases by equal increments, the ratio is not linear - i.e. increasingly smaller ratios will have an ever more significant effect in terms of raised internal base temperatures, and hence raised space heating loads.

G As S1:G above

H As S1:H above.

I As S1:I above.

Scenario 3: no MVHR but allow for SVP (Solar Ventilation Preheat)

A As S1:A above.

B As S2:B above, except entire ventilation component deemed natural or passively controlled, but with a SVP component - e.g. passive stack to promote SVP from conservatory into heated spaces. Pragmatic 'what if?' assumptions are made for the proportion of SVP based on a range deemed from the maximum possible, 50%, to a more achievable level of 25%. As SVP's combination of passive heat recovery and solar contribution precludes reasonable advance knowledge of efficiency, as with MVHR, the ventilation component of heat loss (W/K) for each of the three seasons will be split. Firstly 50% or 75% of it is added to fabric loss and used relative to outside temperature (ambient) to determine HLP and base temperature. This means that the calculation of base temperature is predicated on a lower overall rate of ventilation. However, secondly, the corresponding 50% or 25% is computed relative to mean conservatory temperatures, and the heat gain or loss worked out - i.e. deduct respective autumn, winter and spring conservatory temperatures, Tc, from corresponding internal base temperatures, Tb, multiply by ventilation component (W/K) between heated zone and conservatory and then by number of days in each 3-month set and 0.024 to give gain to interior (assuming a negative Tb –Tc difference) for each 3-month period (kWh).

C As S1:C above, except that there are no MVHR variants.

D As S1:D above..

E As S1:E above.

F As S2:F above, noting that negative Tb values may occur as S1:F due to the ventilation component reducing relative to that in S2:F. Note also that if the numerator in the gain/loss ratio remains constant (same as S1:F), but the denominator increases by equal increments, the ratio is not linear - i.e. increasingly smaller ratios will have an ever more significant effect in terms of raised internal base temperatures, and hence raised space heating loads.

G As S1:G above

H As S1:H above.

I As S1:I above.

2.3 Results

2.4 Scenario 1, NBT with MVHR as built

2.4.1 Fabric heat loss

Z1	component	area (m^2)	U-value (W/m^2K)	Loss (W/K)
	East wall	5.58	0.15 (checked)	0.837
	Lintel	0.22	0.17	0.075
	Window	3.33	1.29	4.296
	Cold bridge	length (m)	y-value (W/mK)	Loss (W/K)
	Window reveals	5.915	0.09	0.532
	Party wall	2.39	0.09	0.215
Sub-total East façade (also for west façade to conservatory)				5.955
	component	area (m^2)	U-value (W/m^2K)	Loss (W/K)
	floor	20.232	0.13 (checked)	3.93
	west wall/outside	9.13	0.38 mean via c'y	3.48
Sub-total: fabric loss for HLP - items (1+2+3) = item (4) 13.365				

Note: ventilation loss sub-totals for Sep-Nov, Dec-Feb and March-May to be added to item (4) to give total z1 specific heat loss for HLP (see 2.4.3 below)

Z2	component	area (m^2)	U-value (W/m^2K)	Loss (W/K)
	Ext'l wall	66.63	0.15 (checked)	9.5445
	Lintels	3.95	0.17	0.6715
	Roof constr'n 'a'	23.77	0.27	6.418
	Roof constr'n 'b'	30.2445	0.232	7.017
	Roof constr'n 'c'	14.285	0.237	3.3856
	Floor over porch	2.7025	0.15	0.4054
	Floor to ground	18.2125	0.13 (checked)	2.368
	Ext'l window 1	3.496	1.27	4.44
	Ext'l window 2	1.088	1.21	1.3163
	Ext'l window 3	3.326	1.29	4.2905
	Ext'l window 4	5.1747	1.26	6.5201
	Vert'l Velux	0.805	1.30	1.0465
	Roof Velux S.Br	0.9775	1.30	1.2708
	Roof Velux D.Br	2.25	1.30	2.925
	Composite	11.925	0.323 mean via c'y	3.8518
	Cold bridge	length (m)	y-value (W/mK)	Loss (W/K)
	Window reveals etc	33.27	0.09	2.994
Sub-total: total fabric loss for HLP				58.465

Z2 from heated spaces to conservatory - separate sub-set

component	area (m^2)	U-value (W/m^2K)	Loss (W/K)
Bedroom walls	8.13345	0.15	1.22
Bedroom lintels	0.44	0.17	0.075
Window	3.33	1.29	4.296
Cold bridge	length (m)	y-value (W/mK)	Loss (W/K)
Window reveals	5.915	0.09	0.532
Party wall corner	2.39	0.09	0.215
Sub-total: total fabric loss for z2 to conservatory			6.338

2.4.2 Ventilation heat loss

Target values assumed based on various monitoring studies (e.g. Porteous, Kondratenko and Sharpe, 2004; Porteous and Menon, 2006), with a slight fall from autumn to winter and a marked increase during spring. Consequent schedules for autumn, winter and spring, and for assumed efficiencies for MVHR of 91% (NHER Data Input provided by GHA) and 80% follow:

Sep-Nov 1.25 ac/h, comprising 0.15 infiltration, 0.2 user, 0.9 MVHR
If MVHR is 77.35% efficient, this gives a mean rate of 0.55 ac/h
This rate is assumed to correspond approx. to 0.59 ac/h z1 and 0.54 ac/h z2
Ventilation loss (W/K): Sep-Nov = 13.97 z1, 35.23 z2.

Dec-Feb 1.05 ac/h, comprising 0.15 infiltration + user, 0.9 MVHR
If MVHR is 77.35% efficient, this gives a mean rate of 0.35 ac/h
This rate is assumed to correspond approx. to 0.39 ac/h z1 and 0.34 ac/h z2
Ventilation loss (W/K): Dec-Feb = 9.23 z1, 22.18 z2.

Mar-May 1.65 ac/h, comprising 0.15 infiltration, 0.6 user, 0.9 MVHR
If MVHR is 77.35% efficient, this gives a mean rate of 0.95 ac/h
This rate is assumed to correspond approx. to 0.99 ac/h z1 and 0.94 ac/h z2
Ventilation loss (W/K): Mar-May = 23.44 z1, 61.32 z2.

2.4.3 Heat loss totals, Heat Loss Parameters (HLPs), internal temperatures

Having estimated the ventilation loss for the two zones in each of the three seasons, these can now be added to the fabric heat loss from 2.4.1:

Zone 1: Sep-Nov: 13.97 + 13.365 (4) = 27.33 W/K
Zone 2: Sep-Nov: 35.23 + 58.465 (5) = 93.69 W/K

Zone 1: Dec-Feb: 9.23 + 13.365 (4) = 22.60 W/K
Zone 2: Dec-Feb: 22.18 + 58.465 (5) = 80.64 W/K

Zone 1: Mar-May: 23.44 + 13.365 (4) = 36.81 W/K
Zone 2: Mar-May: 61.32 + 58.465 (5) = 119.79 W/K

Per S1:C above respective Heat Loss Parameters (HLPs) for each of the three seasons are found by dividing zone 1 and 2 heat loss values from above table by respective floor areas; mean whole-house HLPs are then based on respective zone volumes for added accuracy (given the Z 2 ceiling coombs). Whole-house HLPs then determine the mean internal temperature in each zone for each season for the demand schedule specified in S1:C;

Sep-Nov temp. z1 20.55°C; z2 19.31°C; mean z1&2 19.64°C
Dec-Feb temp. z1 20.57°C; z2 19.36°C; mean z1&2 19.68°C
Mar-May temp. z1 20.51°C; z2 19.19°C; mean z1&2 19.54°C

NB: the 91% MVHR gives a whole-house Sep-May mean of 19.62°C
These means align closely with the 2-year, 18-flat precedent of 19.63°C

2.4.4 Conservatory temperatures from 18-dwelling, west-facing precedent

Sep-Nov 15.23°C; Dec-Feb 12.34°C; Mar-May 16.17°C

2.4.5 Incidental and solar gains for Glasgow House

z1: Sep-Nov 625 W; Dec-Feb 571 W; Mar-May 742 W
z2: Sep-Nov 667 W; Dec-Feb 614 W; Mar-May 1,096 W

2.4.6 Internal base temperatures, Tb, from gain to loss ratios

For z 1, all Tb values are negative or close to zero due to favourable gain/loss ratio; therefore, the degree-days space heating load may be disregarded.
For, z 2, there are positive Tb values a follows:

Sep-Nov temp. z2 19.31°C - 667/93.69 =	12.19°C
Dec-Feb temp. z2 19.36°C - 614/80.64 =	11.75°C
Mar-May temp. z2 19.19°C - 1096/119.79=	10.04°C

2.4.7 Degree-day values for zone 2

Sep-Nov degree-days =	343
Dec-Feb degree-days =	735
Mar-May degree-days =	307

2.4.8 Useful heat gain (kWh) from conservatory to z2 (from 2.3.4 and 2.3.6)

Sep-Nov 6.338 W/K x (12.19-15.23) x 91 x 0.024 = - 42
Dec-Feb 6.338 W/K x (11.75-12.34) x 90 x 0.024 = - 8
Mar-May 6.338 W/K x (10.04-16.17) x 92 x 0.024 = - 86

Sep-May useful heat gain total from conservatory = -136 kWh

Note: we now have all the information required to calculate the space heating load. In this scenario, due to low Tb values in z1, the calculation is for z2 only.

2.4.9 Space heating loads (kWh and kWh/m^2); note: z2 = z1 +2 as z1 = 0

Sep-Nov 89.855 W/K x 343 x 0.024 =	+ 740
Dec-Feb 76.805 W/K x 735 x 0.024 =	+1,355
Mar-May 115.945 W/K x 307 x 0.024 =	+ 854

91% MVHR: Sep-May net heat demand = 2,949 -136 = 2,813 kWh

Divided by total floor area of 123.15 m^2:
Sep-May heat demand = 22.84 or **23 kWh/m^2** rounded up

2.5 Scenario 2, NBT with no MVHR and no SVP allowance

2.5.1 Fabric heat loss

Same as 2.4.1

2.5.2 Ventilation heat loss

Target values as 2.4.2 above, except no heat recovery coefficient:

Sep-Nov 1.25 ac/h, comprising 0.15 infiltration and 1.1 user.
Ventilation loss (W/K): Sep-Nov = 29.60 z1, 81.54 z2.
Dec-Feb 1.05 ac/h, comprising 0.15 infiltration and 0.9 user.
Ventilation loss (W/K): Dec-Feb = 24.86 z1, 68.50 z2.
Mar-May 1.65 ac/h, comprising 0.15 infiltration and 1.5 user.
Ventilation loss (W/K): Mar-May = 39.07 z1, 107.64 z2.

2.5.3 Heat loss totals, Heat Loss Parameters (HLPs), internal temperatures

Having estimated the ventilation loss for the two zones in each of the three seasons, these can now be added to the fabric heat loss from 2.4.1/2.5.1:

Zone 1 Sep-Nov: 29.60 + 13.365 (4) = 42.965 W/K
Zone 2 Sep-Nov: 81.54 + 58.465 (5) = 140.005 W/K

Zone 1 Dec-Feb: 24.86 + 13.365 (4) = 38.225 W/K
Zone 2 Dec-Feb: 68.50 + 58.465 (5) = 126.965 W/K

Zone 1 Mar-May: 39.07 + 13.365 (4) = 52.435 W/K
Zone 2 Mar-May: 107.64 + 58.465 (5) = 166.105 W/K

Per S1:C above respective Heat Loss Parameters (HLPs) for each of the three seasons are found by adding respective heat loss pairs from the above table and dividing by the floor area. Whole-house HLPs then determine the mean internal temperature in each zone for each season for the demand schedule specified in S1:C;

Sep-Nov temp. z1 20.48°C; z2 19.10°C; z1+2 19.47°C
Dec-Feb temp. z1 20.50°C; z2 19.16°C; z1+2 19.52°C
Mar-May temp. z1 20.43°C; z2 18.99°C; z1+2 19.37°C

NB: the above gives a whole-house Sep-May mean of 19.45°C
This mean aligns reasonably with the 2-year, 18-flat precedent of 19.63°C

2.5.4 Conservatory temperatures from 18-dwelling, west-facing precedent

Sep-Nov 15.23 °C; Dec-Feb 12.34°C; Mar-May 16.17 °C (i.e. same as 2.4.4)

2.5.5 Incidental and solar gains for Glasgow House - same as 2.4.5

z1: Sep-Nov 625 W; Dec-Feb 571 W; Mar-May 742 W
z2: Sep-Nov 667 W; Dec-Feb 614 W; Mar-May 1,096 W

2.5.6 Internal base temperatures, Tb, from gain to loss ratios

Sep-Nov z1 Tb = 20.48°C - 625/42.965 =	5.93°C
Dec-Feb z1 Tb = 20.50°C - 571/38.225 =	5.56°C
Mar-May z1 Tb = 20.43°C - 742/52.435 =	6.28°C
Sep-Nov z2 Tb = 19.10°C - 667/140.005 =	14.34°C
Dec-Feb z2 Tb = 19.16°C - 614/126.965 =	14.32°C
Mar-May z2 Tb = 18.99°C - 1,096/166.105 =	12.39°C

2.4.7 Degree-day values for zones 1 and 2

z1 Sep-Nov degree-days =	80 (79.74)
z1 Dec-Feb degree-days =	254 (254.02)
z1 Mar-May degree-days =	118 (117.62)
z2 Sep-Nov degree-days =	499 (499.23)
z2 Dec-Feb degree-days =	966 (965.96)
z2 Mar-May degree-days =	482 (481.93)

2.5.8 Useful heat gain (kWh) from conservatory (from 2.5.4 and 2.5.6)

NB: as TB values are positive in z1 and z2, there will be gains to both:

z1 Sep-Nov 5.955 W/K x (5.93-15.23) x 91 x 0.024 = -121.0
z1 Dec-Feb 5.955 W/K x (5.56-12.34) x 90 x 0.024 = - 87.00
z1 Mar-May 5.955 W/K x (6.28-16.17) x 92 x 0.024 = -130.00

z2 Sep-Nov 6.338 W/K x (14.34-15.23) x 91 x 0.024 = - 12.0
z2 Dec-Feb 6.338 W/K x (14.32-12.34) x 90 x 0.024 = + 27.0
z2 Mar-May 6.338 W/K x (12.39-16.17) x 92 x 0.024 = - 53.0

Note: we now have all the information required to calculate the space heating load (ignoring the positive value for z2 in the Dec-Feb tranche).

2.5.9 Space heating loads (kWh and kWh/m^2) for z1 + 2

z1 Sep-Nov 39.485 W/K x 80 x 0.024 = + 76 - 121 = <0
z1 Dec-Feb 34.745 W/K x 254 x 0.024 = + 212 - 87 = 125
z1 Mar-May 48.955 W/K x 118 x 0.024 = + 139 - 130 = 9
Sub-total z1 **134 kWh**

z2 Sep-Nov 136.165 W/K x 499 x 0.024 = + 1631 - 12 = 1,619
z2 Dec-Feb 123.125 W/K x 966 x 0.024 = + 2854 - 00 = 2,854
z2 Mar-May 162.265 W/K x 482 x 0.024 = + 1921 - 53 = 1,868
Sub-total z2 **6,341 kWh**

z1 + 2 Sep-May heat demand = 6,341 +134 = **6,475 kWh**

Divided by total floor area of 123.15 m^2:
Non-MVHR: Sep-May heat demand = 52.58 or **53 kWh/m^2** rounded up

Note: this represents an increase of **30 kWh/m^2** or 130% cf. the MVHR

2.6 Scenario 3, NBT with no MVHR but with SVP allowance

2.6.1 Fabric heat loss

Same as 2.4.1 and 2.5.1

2.6.2 Ventilation heat loss

Target values as 2.5.2 above, but now there will be some SVP gain similar to the buffer gains in 2.5.8 above. Thus if we assume sub-scenario a) with 50% of natural ventilation coming via the conservatory the ventilation load direct to the outside will be as follows:
Ventilation loss 50% SVP (W/K): Sep-Nov = 14.80 z1, 40.77 z2.
Ventilation loss 50% SVP (W/K): Dec-Feb = 12.43 z1, 34.25 z2.
Ventilation loss 50% SVP (W/K): Mar-May = 19.54 z1, 53.82 z2.

Ventilation loss 25% SVP (W/K): Sep-Nov = 22.20 z1, 61.16 z2.
Ventilation loss 25% SVP (W/K): Dec-Feb = 18.65 z1, 51.38 z2.
Ventilation loss 25% SVP (W/K): Mar-May = 29.30 z1, 80.73 z2.

2.6.3 Heat loss totals, Heat Loss Parameters (HLPs), internal temperatures

Having estimated the ventilation loss to outside for both zones in each of the three seasons, these can now be added to the fabric heat loss as before:

Zone 1 50% SVP	Sep-Nov:	14.80 + 13.365 (4) =	28.165 W/K
Zone 1 25% SVP	Sep-Nov:	22.20 + 13.365 (4) =	35.565 W/K
Zone 2 50% SVP	Sep-Nov:	40.77 + 58.465 (5) =	99.235 W/K
Zone 2 25% SVP	Sep-Nov:	61.16 + 58.465 (5) =	119.625 W/K
Zone 1 50% SVP	Dec-Feb:	12.43 + 13.365 (4) =	25.795 W/K
Zone 1 25% SVP	Dec-Feb:	18.65 + 13.365 (4) =	32.015 W/K
Zone 2 50% SVP	Dec-Feb:	34.25 + 58.465 (5) =	92.715 W/K
Zone 2 25% SVP	Dec-Feb:	51.38 + 58.465 (5) =	109.845 W/K
Zone 1 50% SVP	Mar-May:	19.54 + 13.365 (4) =	32.905 W/K
Zone 1 25% SVP	Mar-May:	29.30 + 13.365 (4) =	42.665 W/K
Zone 2 50% SVP	Mar-May:	53.82 + 58.465 (5) =	112.285 W/K
Zone 2 25% SVP	Mar-May:	80.73 + 58.465 (5) =	139.195 W/K

Per S1:C and S2:C above, whole-house HLPs - then determine the mean internal temperature in each zone for each season for the demand schedule specified in S1:C;

Sep-Nov temp. 50% SVP z1 20.54°C; z2 19.28°C; z1+2 19.62°C
Sep-Nov temp. 25% SVP z1 20.51°C; z2 19.20°C; z1+2 19.55°C
Dec-Feb temp. 50% SVP z1 20.86°C; z2 19.32°C; z1+2 19.73°C
Dec-Feb temp. 25% SVP z1 20.53°C; z2 19.24°C; z1+2 19.58°C
Mar-May temp. 50% SVP z1 20.52°C; z2 19.23°C; z1+2 19.72°C
Mar-May temp. 25% SVP z1 20.48°C; z2 19.11°C; z1+2 19.47°C

NB: 50% SVP gives a whole-house Sep-May mean of 19.69°C
25% SVP gives a whole-house Sep-May mean of 19.53°C
This mean aligns well with the 2-year, 18-flat precedent of 19.63°C

2.6.4 Conservatory temperatures from 18-dwelling, west-facing precedent

Sep-Nov 15.23°C; Dec-Feb 12.34°C; Mar-May 16.17°C (i.e. same as 2.4.4)

2.6.5 Incidental and solar gains for Glasgow House - same as 2.4.5

z1: Sep-Nov 625 W; Dec-Feb 571 W; Mar-May 742 W
z2: Sep-Nov 667 W; Dec-Feb 614 W; Mar-May 1,096 W

2.6.6 Internal base temperatures, Tb, from gain to loss ratios

50% SVP Sep-Nov z1 Tb = 20.54°C - 625/28.165 =	-1.30°C
50% SVP Dec-Feb z1 Tb = 20.56°C - 571/25.795 =	-1.58°C
50% SVP Mar-May z1 Tb = 20.52°C - 742/32.905 =	-1.98°C
50% SVP Sep-Nov z2 Tb = 19.28°C - 667/99.235 =	+12.56°C
50% SVP Dec-Feb z2 Tb = 19.32°C - 614/92.715 =	+12.70°C
50% SVP Mar-May z2 Tb =19.23°C - 1,096/112.285 =	+ 9.47°C
25% SVP Sep-Nov z1 Tb = 20.51°C - 625/35.565 =	+2.94°C
25% SVP Dec-Feb z1 Tb = 20.53°C - 571/32.015 =	+2.69°C
25% SVP Mar-May z1 Tb = 20.48°C - 742/42.665 =	+3.09°C

25% SVP Sep-Nov z2 Tb = 19.20°C - 667/119.625 = +13.62°C
25% SVP Dec-Feb z2 Tb = 19.24°C - 614/109.845 = +13.65°C
25% SVP Mar-May z2 Tb = 19.11°C - 1,096/139.195 = +11.24°C

2.6.7 Degree-day values for zones 1 and 2

For z1 at 50% SVP, since all Tb values are negative, there is no heating load. For z1 at 25% SVP, an estimated load of 146 kWh is more than offset by heat gains relative to Tb from the conservatory; thus there is no heating load.

50% SVP Sep-Nov z2 degree-days = 370 (369.48)
50% SVP Dec-Feb z2 degree-days = 820 (820.00)
50% SVP Mar-May z2 degree-days = 274 (273.53)

25% SVP Sep-Nov z2 degree-days = 444 (444.21)
25% SVP Dec-Feb z2 degree-days = 906 (905.50)
25% SVP Mar-May z2 degree-days = 393 (392.56)

2.6.8 Useful heat gain (kWh) from conservatory (from 2.6.4 and 2.6.6)

z2 50% Sep-Nov 6.338 W/K x (12.56-15.23) x 91 x 0.024 = - 37.0
z2 50% Dec-Feb 6.338 W/K x (12.70-12.34) x 90 x 0.024 = + 5.00 (ignore)
z2 50% Mar-May 6.338 W/K x (9.47-16.17) x 92 x 0.024 = - 94.00

z2 25% Sep-Nov 6.338 W/K x (13.62-15.23) x 91 x 0.024 = - 22.3
z2 25% Dec-Feb 6.338 W/K x (13.65-12.34) x 90 x 0.024 = + 18.00 (ignore)
z2 25% Mar-May 6.338 W/K x (11.24-16.17) x 92 x 0.024 = - 69.00

Note: we now have all the information required to calculate the space heating load.

2.6.9 Space heating loads (kWh and kWh/m^2); note: z2 = z1 +2 as z1 = 0

The first step is to calculate heating loads less buffer gains from conservatory:
z2 50% Sep-Nov 87.395 W/K x 370 x 0.024 = + 847 - 37 = 810
z2 50% Dec-Feb 88.825 W/K x 820 x 0.024 = +1749 - 0 = 1,749
z2 50% Mar-May 108.42 W/K x 274 x 0.024 = + 713 - 94 = 619
Sub-total z2 (effectively z1 + z2) 50% SVP **3,178 kWh**

z2 25% Sep-Nov 115.785 W/K x 444 x 0.024 = + 1234 - 22 = 1,212
z2 25% Dec-Feb 106.005 W/K x 906 x 0.024 = + 2305 - 0 = 2,305
z2 25% Mar-May 135.355 W/K x 393 x 0.024 = + 1277 - 69 = 1,208
Sub-total z2 **4,725 kWh**

The next step is to calculate the SVP gain/loss for 2
z2 50% Sep-Nov 40.77 x (12.56 - 15.23) x 91 x 0.024 = -238
z2 50% Dec-Feb 34.25 x (12.70 - 12.34) x 90 x 0.024 = + 27
z2 50% Mar-May 53.82 x (9.47 - 16.17) x 92 x 0.024 = -796
Sub-total z2 (effectively z1 + z2) 94-(95+96+97) **2,171 kWh**

z2 25% Sep-Nov 20.39 x (13.62 - 15.23) x 91 x 0.024 = - 72
z2 25% Dec-Feb 17.125 x (13.65 - 12.34) x 90 x 0.024 = + 49
z2 25% Mar-May 26.91 x (11.24 - 16.17) x 92 x 0.024 = -293
Sub-total z2 (effectively z1 + z2) 94-(95+96+97) **4,409 kWh**

Divided by total floor area of 123.15 m^2:
50% SVP: Sep-May heat demand = 17.63 or **18 kWh/m^2** rounded up
25% SVP: Sep-May heat demand = 35.80 or **36 kWh/m^2** rounded up

Note: The value for 50% SVP is **5 kWh/m^2** lower than for MVHR, but 50% SVP is probably unrealistic in practical terms. However, 25% SVP should be attainable, provided suitable air pathways from conservatory to z2 are provided; and hence the estimate of **36 kWh/m^2** is considered realistic.

2.7 Scenario 1, TF with MVHR as built

2.7.1 Fabric heat loss: the only change from the NBT Block construction is that the estimated U-value for walls (from drawings provided) is slightly higher at 0.2 W/m^2K, and lintols at 0.376 W/m^2K - see modified values for W/K:

Z1	W/K
Sub-total East façade (also west façade to cons'y)	6.324
Sub-total: fabric loss for HLP	13.975

Z2	W/K
Sub-total: total fabric loss for HLP	62.800
Sub-total: total fabric loss for z2 to conservatory	6.338

2.7.2 Ventilation loss - all as 2.4.2 (91% eff't x 0.85 MVHR as for NBT)

2.7.3 Heat loss totals, Heat Loss Parameters (HLPs), internal temperatures

Having estimated the ventilation loss for the two zones in each of the three seasons, these can now be added to the fabric heat loss from 2.7.1:

Zone 1: Sep-Nov: 13.97 + 13.975 = 27.945 W/K
Zone 2: Sep-Nov: 35.23 + 62.80 = 98.030 W/K

Zone 1: Dec-Feb: 9.23 + 13.975 = 23.205 W/K
Zone 2: Dec-Feb: 22.18 + 62.80 = 84.980 W/K

Zone 1: Mar-May: 23.44+ 13.975 = 37.415 W/K
Zone 2: Mar-May: 61.32 + 62.80 = 124.120 W/K

Whole-house HLPs then determine the mean internal temperature in each zone for each season for the demand schedule specified in 2.3.1:

Sep-Nov temp. z1 20.24°C; z2 19.00°C; mean z1&2 19.33°C
Dec-Feb temp. z1 20.30°C; z2 19.08°C; mean z1&2 19.40°C
Mar-May temp. z1 20.14°C; z2 18.81°C; mean z1&2 19.16°C

NB: the 91% MVHR gives a whole-house Sep-May mean of 19.30°C
This mean aligns reasonably with the 2-year, 18-flat precedent of 19.63°C, but note the slight reductions in temperature compared with NBT above.

2.7.4 Conservatory temperatures from 18-dwelling, west-facing precedent

Sep-Nov 15.23°C; Dec-Feb 12.34°C; Mar-May 16.17°C

2.7.5 Incidental and solar gains for Glasgow House

z1: Sep-Nov 625 W; Dec-Feb 571 W; Mar-May 742 W
z2: Sep-Nov 667 W; Dec-Feb 614 W; Mar-May 1,096 W

2.7.6 Internal base temperatures, Tb, from gain to loss ratios

For z 1, all Tb values are negative or close to zero due to favourable gain/loss ratio; therefore, degree-days and space heating load are disregarded.
For, z 2, there are positive Tb values a follows:

Sep-Nov temp. z2 19.00°C - 667/98.03 =	12.20°C
Dec-Feb temp. z2 19.08°C - 614/84.98 =	11.85°C
Mar-May temp. z2 18.81°C - 1096/124.12 =	9.98°C

2.7.7 Degree-day values for zone 2

Sep-Nov degree-days =	344
Dec-Feb degree-days =	744
Mar-May degree-days =	303

2.7.8 Useful heat gain (kWh) from conservatory to z2 (from 2.7.4 and 2.7.6)

Sep-Nov 6.838 W/K x (12.20-15.23) x 91 x 0.024 = - 45.0
Dec-Feb 6.838 W/K x (11.85-12.34) x 90 x 0.024 = - 7.0
Mar-May 6.838 W/K x (9.98-16.17) x 92 x 0.024 = - 93.0

Sep-May useful heat total = -145 kWh

2.7.9 Space heating loads (kWh and kWh/m^2); note: z2 = z1 +2 as z1 = 0

Sep-Nov 93.85 W/K x 344 x 0.024 =	+ 775
Dec-Feb 80.80 W/K x 744 x 0.024 =	+1,443
Mar-May 119.94 W/K x 303 x 0.024 =	+ 872

Sep-May net heat demand = 3,090 -145 = 2,945 kWh

Divided by total floor area of 123.15 m^2:
Sep-May heat demand = 23.90 or **24 kWh/m^2** rounded up

Note: there is a minor difference in this estimate compared with the NBT; but it should be noted that U-values for TF wall panels are calculated in accordance with drawings provided, whereas it is now understood that Kingspan foam insulating slabs have been used in the as-built construction.

2.8 Scenario 2, TF with no MVHR and no SVP allowance

2.8.1 Fabric heat loss

Same as 2.7.1

2.8.2 Ventilation heat loss

Target values as 2.5.2 above:
Sep-Nov 1.25 ac/h, comprising 0.15 infiltration and 1.1 user.
Ventilation loss (W/K): Sep-Nov = 29.60 z1, 81.54 z2.
Dec-Feb 1.05 ac/h, comprising 0.15 infiltration and 0.9 user.
Ventilation loss (W/K): Dec-Feb = 24.86 z1, 68.50 z2.
Mar-May 1.65 ac/h, comprising 0.15 infiltration and 1.5 user.
Ventilation loss (W/K): Mar-May = 39.07 z1, 107.64 z2.

2.8.3 Heat loss totals, Heat Loss Parameters (HLPs), internal temperatures

Having estimated the ventilation loss for the two zones in each of the three seasons, these can now be added to the fabric heat loss from 2.7.1/2.8.1:

Zone 1 Sep-Nov: 29.60 + 13.975 (4) = 43.575 W/K
Zone 2 Sep-Nov: 81.54 + 62.800 (5) = 144.340 W/K

Zone 1 Dec-Feb: 24.86 + 13.975 (4) = 38.835 W/K
Zone 2 Dec-Feb: 68.50 + 62.800 (5) = 131.300 W/K

Zone 1 Mar-May: 39.07 + 13.975 (4) = 53.045 W/K
Zone 2 Mar-May: 107.64 + 62.800 (5) = 170.440 W/K

Whole-house HLPs then determine the mean internal temperature in each zone for each season for the demand schedule specified in S1:C;

Sep-Nov temp. z1 20.07°C; z2 18.69°C; z1+2 19.06°C
Dec-Feb temp. z1 20.12°C; z2 18.77°C; z1+2 19.13°C
Mar-May temp. z1 19.97°C; z2 18.51°C; z1+2 18.90°C

NB: the above gives a whole-house Sep-May mean of 19.03°C
This mean aligns reasonably with the 2-year, 18-flat precedent of 19.63°C, although the difference of 0.6K indicates that conservatory temperatures adopted from the same precedent may be on the optimistic side for TF.

2.8.4 Conservatory temperatures from 18-dwelling, west-facing precedent

Sep-Nov 15.23°C; Dec-Feb 12.34°C; Mar-May 16.17°C (i.e. same as 2.4.4)

2.8.5 Incidental and solar gains for TF Glasgow House - same as 2.4.5

z1: Sep-Nov 625 W; Dec-Feb 571 W; Mar-May 742 W
z2: Sep-Nov 667 W; Dec-Feb 614 W; Mar-May 1,096 W

2.8.6 Internal base temperatures, Tb, from gain to loss ratios

Sep-Nov z1 Tb = 20.07°C - 625/43.575 = 5.73°C
Dec-Feb z1 Tb = 20.12°C - 571/38.855 = 5.42°C
Mar-May z1 Tb = 19.97°C - 742/53.045 = 5.98°C

Sep-Nov z2 Tb = 18.69°C - 667/144.340 = 14.07°C
Dec-Feb z2 Tb = 18.77°C - 614/131.300 = 14.09°C
Mar-May z2 Tb = 18.51°C - 1,096/170.440 = 12.08°C

2.8.7 Degree-day values for zones 1 and 2

z1 Sep-Nov degree-days = 76 (76.14)
z1 Dec-Feb degree-days = 246 (246.39)
z1 Mar-May degree-days = 106 (105.47)

z2 Sep-Nov degree-days = 477 (476.81)
z2 Dec-Feb degree-days = 945 (945.15)
z2 Mar-May degree-days = 455 (454.56)

2.8.8 Useful heat gain (kWh) from conservatory (from 2.8.4 and 2.8.6)

NB: as TB values are positive in z1 and z2, there will be gains to both:

z1 Sep-Nov 6.324 W/K x (5.73-15.23) x 91 x 0.024 = -131.0
z1 Dec-Feb 6.324 W/K x (5.42-12.34) x 90 x 0.024 = - 95.0
z1 Mar-May 6.324 W/K x (5.98-16.17) x 92 x 0.024 = -142.0

z2 Sep-Nov 6.838 W/K x (14.07-15.23) x 91 x 0.024 = - 17.0
z2 Dec-Feb 6.838 W/K x (14.09-12.34) x 90 x 0.024 = + 26.0
z2 Mar-May 6.838 W/K x (12.08-16.17) x 92 x 0.024 = - 62.0

We now have all the information required to calculate the space heating load.

2.8.9 Space heating loads (kWh and kWh/m^2) for z1 + 2

z1 Sep-Nov 39.854 W/K x 76 x 0.024 = + 76 - 131 = <0
z1 Dec-Feb 35.114 W/K x 246 x 0.024 = + 212 - 95 = 125
z1 Mar-May 49.324 W/K x 106 x 0.024 = + 126 - 142 = <0
Sub-total z1 **125 kWh**

z2 Sep-Nov 140.16 W/K x 477 x 0.024 = + 1605 - 17 = 1,588
z2 Dec-Feb 127.12 W/K x 945 x 0.024 = + 2883 - 00 = 2,883
z2 Mar-May 166.26 W/K x 455 x 0.024 = + 1816 - 62 = 1,754
Sub-total z2 **6,225 kWh**

z1 + 2 Sep-May heat demand = 6,225 +125 = **6,350 kWh**

Divided by total floor area of 123.15 m^2:
Non-MVHR: Sep-May heat demand = 51.56 or **52 kWh/m^2** rounded up

Note: close correspondence with equivalent NBT value, although comfort levels are slightly lower, and values used for the conservatory may be on the optimistic side.

Hence it is deemed unnecessary to repeat the calculations for the equivalent TF SVP model - sections 2.6 and 2.7 demonstrate adequate consistency.

2.9 Conclusions

2.9.1 The methodology is steady-state in the same way as SAP or NHER, and thus reliant on the fact that dwellings operate over 24-hour cycles, and that energy moving into storage will move out again during repeated cyclical operation. Since it uses monthly averages, totals broken down into 3-month seasonal bites are thought to be reasonably reliable. The methodology adopted with regard to conservatories adds further weight to the analysis. Even though there are minor differences - sectional design, glazing specification and orientation (the Glasgow House facing some 14 degrees north of due west) - the influential variables are window opening habits and indoor temperatures (close match found between predicted Glasgow House temperatures and 18-house mean of measured precedent). The validity of the use of two zones and measured and derived long-term data for Glasgow is also supported by monitoring evidence.

2.9.2 However, even though the methodology as a whole is superior to SAP or NHER, it cannot show individual daily profiles of temperature, and hence effectively hides the value of the additional thermal capacity in the case of the NBT house. In reality this difference could lead to the TF house having higher than anticipated heating loads. Consider a situation where the lack of capacity leads to solar overheating. Action taken to remedy such a situation is routinely to open a window, rather than adjust heating controls. Such action could intermittently nullify the efficacy of the MVHR. The NBT house would be less likely to overheat in the first place, and then, if a window were open for a period, it would have a relatively small impact on stored energy. The only way to accurately predict the consequences of such actions, comparing a light building with a heavy one is to run sophisticated dynamic simulations - e.g. using ESP-r, developed at Strathclyde University.

2.9.3 Nevertheless, the methodology adopted clearly shows that for a given heat demand schedule, it is theoretically possible for the TF construction to match that of the NBT, albeit TF has slightly lower levels of achieved comfort. Temperatures are less than one degree lower than the equivalent values for the monitored dwellings whose mean sunspace data were used for the conservatories for both NBT and TF Glasgow Houses. This means that the reductions attributed to the conservatory in the case of the TF house may be slightly optimistic, but this is not considered significant.

2.9.4 The results also show that the MVHR system, taken together with the specification adopted for bounding elements as well as the thermal value of the conservatories, does enable a performance that comes fairly close to the PassivHaus standard of 15 kWh/m^2. A difference of 8-9 kWh/m^2 may look significant expressed as a percentage (increase of over 50%), but in absolute terms it is not so marked, as evidenced by the predicted values for natural ventilation with no SVP, or with one quarter of the supply by SVP via the conservatory. However the estimated Glasgow House MVHR value of 23-24 kWh/m^2 is reliant on the efficacy of the theoretical (laboratory) 91% efficiency multiplied by a broad-brush coefficient of 0.85, itself based on assumptions regarding effectiveness of insulation around ducting. On the other hand, the complete loss of the heat recovery takes predictions up by approximately 30 kWh/m^2 to over 50 kWh/m^2; thereby giving an indication of sensitivity to ventilation loads once the fabric of a dwelling has become energy efficient.

2.9.5 The scenario with a viable SVP strategy (controlled ventilation from the conservatory to heated rooms, say by passive stack) indicates a theoretical possibility of more than matching the MVHR (if half of all fresh air can be introduced via the buffer), with a load as low as 18 kWh/m^2. Perhaps more realistically, by dropping SVP's share to one quarter, the estimated heating load comes to 36 kWh/m^2. In any event, the thermal performance of such spaces may compromised by too much opening of either inner windows or outer windows by users, as well as heated zone temperatures being set too high. Advice would be helpful in this regard, especially as there are no handles on the outside of the French windows to the conservatory. If these doors are left wide open during hours of darkness or in overcast cold weather, not only will the buffering effect be negated, but also the area and volume to be heated will be significantly enlarged.

Postscript: On a cautionary note, despite the use of long-term data from 18 dwellings in support of this analysis, there is frequently a significant gap between prediction and reality, as well as the range of influence attributable to individual lifestyles/actions by occupants (Sharpe and Porteous, 2001).

On a more positive note, recent work in Glasgow (Fung, 2008) found that flats, originally built with 100% glazed screens to the outer wall of living rooms and later refurbished with balconies converted to conservatories in front of these screens, had the best air quality of a much larger and representative set of house types, as well as very good well-being indicators. These findings bode well for the essential character of the Glasgow House generated by the double-height conservatory with its generous double-glazing.

3.0 Evaluation of Energy Performance Based on ‘In Use’ Scenario

3.1 Comparison of Simulated and In Use Energy Efficiencies

3.1.1 Aims

This section of the report uses the methodology from the scenarios in section 2 and refines this data to simulate the energy performance for the last two weeks in February. These simulated values are then compared to the monitored performance to give a comparative analysis between the theoretical and actual performance values.

Tables summarising key measured environmental variables

		House A (NBT)				House B (TF)		
Living		CO_2	Temp	RH		CO_2	Temp	RH
	Mean	598	19.8	51.2		1019	21.3	43.4
	Max	1909	24.3	79.4		3301	24.9	52.8
	Min	347	16.4	40.4		557	19.0	34.8
Example:		1909	21.0	59.1		3301	24.5	49.6
kPa for ex.	1.46				1.50			
Kitchen	Mean	977	20.7	49.2		1233	22.0	41.8
	Max	2552	25.3	76.0		3565	25.7	62.8
	Min	572	17.8	39.4		693	19.2	33.5
Example:		2552	22.5	56.6		3565	23.6	54.5
kPa for ex.	1.50				1.56			
Bedroom1	Mean	1013	20.6	40.5		946	20.2	41.8
	Max	1536	23.3	51.3		1718	22.5	53.2
	Min	713	17.3	32.3		585	17.5	32.9
Example:		1536	20.2	39.0		1718	20.7	46.7
kPa for ex.	0.92				1.13			
Bedroom2	Mean	992	20.1	47.4		782	20.3	41.2
	Max	2007	22.9	59.3		2006	22.7	54.6
	Min	497	17.1	38.1		445	17.9	32.5
Example:		1777	20.9	59.3		801	20.3	54.6
kPa for ex.	1.45				1.30			
Attic Bedrm	Mean	749	20.0	44.5		895	19.8	44.0
	Max	1176	22.2	57.6		1907	21.6	67.5
	Min	478	16.8	32.6		713	16.7	36.4
S. Bedroom	Mean	770	19.1	40.8		1123	19.1	45.7
	Max	1316	22.0	53.2		2097	21.9	67.5
	Min	681	16.6	31.1		713	16.7	36.4
Sunspace	Mean		11.6	81.4			10.6	69.8
	Max		22.1	95.7			20.5	80.3
	Min		6.4	54.7			7.2	53.5
Ambient[1]	Mean		5.5	86.5			5.5	81.0
	Max		13.7	98.9			13.7	92.7
	Min		- 1.7	44.5			- 1.7	44.4\

[1] Note: RH values ‘from atmosphere\ (i.e. entering heat exchanger) used as ambient values

3.1.2 NBT In-use Energy Consumption

Space heating loads (kWh and kWh/m^2); note: z2 = z1 +2 as z1 = 0

14-28 Feb 76.805 W/K x 84 x 0.024 = + 155 kWh

Divided by total floor area of 123.15 m^2:
14-28 Feb heat demand = 1.26 kWh/m^2
Divided by boiler efficiency of 90.1% = [2]**1.39 kWh/m^2**

The above may be compared with quasi-measured data as follows:

Total 58.847 m^3 x 40.0385 (calorific value) x 1.02264 (correction factor) divided by 3.6 = 669.3 kWh.
Deduct 181 kWh for water heating (7.1 kWh/day divided by 0.55 efficiency x 14 days); giving net space heating estimate = 488.3 kWh or **3.97 kWh/m^2**

In other words, the quasi-measured consumption is [2]2.86 times greater than the predicted consumption.

3.1.3 TF In-use Energy Consumption

Space heating loads (kWh and kWh/m^2); note: z2 = z1 +2 as z1 = 0

14-28 Feb 80.8 W/K x 83.16 x 0.024 = + 161.3 kWh

Divided by total floor area of 123.15 m^2:
14-28 Feb heat demand = 1.31 kWh/m^2
Divided by boiler efficiency of 90.1% = [2]**1.45 kWh/m^2**

The above may be compared with quasi-measured data as follows:

Total 43.979 m^3 x 40.0385 (calorific value) x 1.02264 (correction factor) divided by 3.6 = 500.2 kWh.
Deduct 181 kWh for water heating (7.1 kWh/day divided by 0.55 efficiency x 14 days); giving net space heating estimate = 319.2 kWh or **2.6 kWh/m^2**

In other words, the quasi-measured consumption is [2]1.79 times greater than the predicted consumption.

Comparing 3.1.2 with 3.1.3, we may note that the mean temperature in House B (TF) in zone 2 is less than that of House A (NBT): 19.7 cf. 20.21°C. On the other hand, although irrelevant in the theoretical prediction, the mean zone 1 (living-kitchen) temperatures differ in reverse: 21.65 cf. 20.25°C.

3.1.4 Analysis of Results

There are five possible reasons to explain the gap between prediction and monitored results:

a) Underestimate of ventilation rates
b) U-values higher than predicted
c) Overestimate of incidental gains
d) Water heating consumption underestimated and/or boiler efficiency overestimated.
e) Calculation methodology too blunt relative to dynamic reality.

---

[2] Figures amended from March 2011 report to take account of boiler efficiency

The explanation may involve a combination of all five, but it is likely that ventilation is a key culprit, partly in an effort by the occupants to perceptually achieve comfort, and partly due to lower in-use efficiency of the MVHR than predicted.

Window opening could explain the bulk of the difference between House A and House B, since the occupants of the former opened windows quite liberally, especially during the first week when the thermostat was at level 4 compared with 2 in the second week. For example, the bedroom occupied by the couple kept their bedroom window open overnight (approx. 8 hours) for three days in the first week, and the occupant of the attic bedroom for one night. The living room window was also opened relatively frequently.

By contrast those in House B rarely opened windows in either the first or second week. The contrasting window regimes did not result in House A having significantly better air quality in bedrooms compared with House B, but differences were evident in the respective Living-kitchens, with house B exceeding 3,000 ppm CO_2 with the regular occupancy up to the last evening, and exceeding 3,500 ppm on the last evening when six occupants were present for some hours.

Beyond these specific events the most striking statistic relevant to occupant affected building ventilation, which may present an explanation for the differing performance, is that during the occupancy period there were a total of 3248 minutes of recorded window opening in Dwelling A as opposed to just 248 minutes in Dwelling B.

The maxima for CO_2 were above the 1,000 ppm threshold in all rooms and in both house types, with House B (TF) having significantly higher values than House A (NBT). Disregarding ancillary accommodation and respective living-kitchens, since House B ‘s population increased above the 4 student occupants on the last day, the mean maximum values for all bedrooms was 1,489 ppm for House A (NBT) and 1,912 ppm for House B (TF), the latter value 28% higher than that of the former. This is consistent with the fact that House A ventilated more frequently than House B, since occupancy regimes were closely matched; and this then helps to explain why House A had greater energy consumption for space heating than House B.

Theoretical U-values are generally found to be over-optimistic compared with built reality. In this instance the thermal imaging indicates specific weakness around the window frames (ref section 4.3 for further detail), and the windy weather experienced during the February fortnight would also have raised the U-values of the glazing itself above theoretical values (i.e. caused greater heat loss).

The student cohort may have occupied the dwellings less intensively than some families, especially if young children or unemployment were involved – thus reducing metabolic incidental gains. However, in this regard the occupants in House B seemed to socialise together more in the Living-kitchen and consequently had poorer air quality in that space, as well as higher temperatures. The possibility of underestimating water heating consumption could also be due to occupants’ behaviour, but it might on the other hand be due to overestimating the efficiency of the system.

Finally, although the theoretical prediction indicated that there should be no heating load for zone 1 (living-kitchen), it is unlikely that the radiators in these spaces remained off. In this regard, it may be noted that the TRV setting was lowered to 2 during the second half of the monitoring period due to complaints of over-heating. In turn, this influenced the tendency to open windows in Dwelling A.

3.2 Comparison of Annual Energy Costs for NBT and TF Dwellings

3.2.1 Aims

This section of the report will take the measured energy consumption over the observational period and extrapolate this across a year (based on the BREDEM calculations from report section 2.0) to provide a figure for thermal and electrical energy consumptions over a year. These figures will then be converted to a monetary value to provide a more tangible outcome and provide a real world understanding of the energy consumption of the two Glasgow Houses.

3.2.2 Methodology

Section 2.0 of this report identifies the predicted space heating demands of the respective NBT and TF dwellings per m^2. Subsequently Section 3.1 quantifies an 'in use' m^2 space heating demand based on the measured energy consumption over the duration of the project minus an estimated value for water heating.

With respect to each dwelling the ratio of these predicted and qausi-measured figures will be used to create a coefficient which can be multiplied against the predicted figures over the full heating season (September to May). This will ensure that measured data can be appropriately applied over the spread of environmental and seasonal conditions experienced during the heating season and as factored into the original BREDEM calculation methodology.

3.2.3 Measured Energy Consumption of Dwellings

Over Two Week Period:

Dwelling A:

Electricity	-	82.4 kWh
Gas	-	58.847 m^3
	=	669.3 kWh*

Dwelling B:

Electricity	-	80.5 kWh
Gas	-	43.979 m^3
	=	500.2 kWh*

*m^3 to kWh based on utility provider methodology and correction values for conversion.

3.2.4 Results - Dwelling A: NBT with MVHR as built

Ratio of predicted scenario to quasi-measured data

= Quasi-measured data (3.1.2) divided by Predicted (3.1.2)
= 3.97 kWh/m^2 divided by 1.39 kWh/m^2 = **2.86**

Annual space heating load
Predicted space heating load x coefficient
= 2,813 kWh x 2.86 = **8,045.18 kWh**

Annual water heating load
Using the estimated daily load and assumed efficiency from 3.1.2, an annual water heating load is derived by multiplying the daily load by 365 and subtracting the annual energy produced by the solar water heaters (based on a Scottish annual mean of 425 kWh/m^2)

= 365 x (7.1kWh/day divided by 0.55) – (425 x 4) = **3,011.81 kWh**

Total gas consumption
Space heating load + water heating load
= 8,045.18 + 3,011.81 kWh = **11,057 kWh**

Annual electrical load
Measured load over monitoring period divided by no. of days x 365
= 82.4 kWh divided by 14 x 365 = 2,148.28 or = **2,148 kWh**

Annual Energy Demand

Gas - 11,057 kWh
Elec - 2,148 kWh

Annual Energy Cost
Gas consumption x price (p/kWh) + 365 x standing charge (p/day)
= (11,057 x 2.966) + (365 x 6.08)
= £327.95 + £22.19
= £350.14 (exc. VAT)
= £367.67 (inc. VAT @ 5%)

This corresponds to a weekly heating and hot water cost of **£7.07**

Electricity consumption x price (p/kWh) + 365 x standing charge (p/day)
= (2,148 x 11.293) + (365 x 8.66)
= £242.57 + £31.61
= £274.18 (exc. VAT)
= £287.89 (inc. VAT @ 5%)

This corresponds to a weekly electricity cost of **£5.54**

Total energy cost = gas + electricity
= **£655.56** (based on Scottish Power 'Capped for Free' utility package)

This corresponds to a weekly energy cost of **£12.61**

3.2.5 Results - Dwelling B: TF with MVHR as built

Ratio of predicted scenario to quasi measured data
= Quasi-measured data (3.1.3) divided by Predicted (3.1.3)
= 2.59 kWh/m^2 divided by 1.45 kWh/m^2 = **1.79**

Annual space heating load
Predicted space heating load x coefficient
= 2,945 kWh x 1.79 = **5,271.55 kWh**

Annual water heating load
Using the estimated daily load and assumed efficiency from 3.1.3, an annual water heating load is derived by multiplying the daily load by 365 and subtracting the annual energy produced by the solar water heaters (based on a Scottish annual mean of 425 kWh/m^2)

= 365 x (7.1kWh/day divided by 0.55) – (425 x 4) = **3,011.81 kWh**

Annual gas consumption
Space heating load + water heating load
= 5,271.55 + 3,011.81 kWh = **8,283 kWh**

Annual electrical load
Measured load over monitoring period divided by no. of days x 365
= 80.5kWh divided by 14 x 365 = 2,098.75 or = **2,099 kWh**

Annual Energy Demand

Gas - 8,283 kWh
Elec - 2,099 kWh

Annual Energy Cost
Gas consumption x price (p/kWh) + 365 x standing charge (p/day)
= (8,283 x 2.966) + (365 x 6.08)
= £245.67 + £22.19
= £267.86 (exc. VAT)
= £281.25 (inc. VAT @ 5%)

This corresponds to a weekly heating and hot water cost of **£5.41**

Electricity consumption x price (p/kWh) + 365 x standing charge (p/day)
= (2,099 x 11.293) + (365 x 8.66)
= £237.04 + £31.61
= £268.65 (exc. VAT)
= £282.08 (inc. VAT @ 5%)

This corresponds to a weekly electricity cost of **£5.42**

Total energy cost = (gas + electricity)
= **£563.33** (based on Scottish Power ‘Capped for Free’ utility package)

This corresponds to a weekly energy cost of **£10.83**

3.2.6 Conclusions

Factors previously identified relative to the increased energy consumption (compared to the predicted) remain pertinent to the energy costs above. For instance, the extent of ventilation of Dwelling A will have had a significant impact on the space heating required for the dwelling and will have contributed to it's apparently poorer performance than its timber framed counterpart. Respective boiler efficiencies may also be relevant.

With respect to electrical consumption it is important to note that the project participants brought limited luggage and personal effects with them to the houses and that in a real life scenario these family houses could easily have a greater density of electrical appliances and therefore a greater electrical demand.

Notwithstanding the above, and whilst acknowledging that the weekly energy costs exceed those identified at the outset of the Glasgow House project, it seems unfeasible that a 7 person house would have a disposable income of less than £126.10 per week. To this end the measured data would seem to point to the dwellings making a significant contribution to mitigating the effects of fuel poverty.

3.3 Performance of MVHR System

3.3.1 Aims

In order to asses the in use thermal and electrical efficiency of the installed Mechanical Ventilation Heat Recovery (MVHR) system, as opposed to the lab efficiencies stated in SAP appendix Q, the following experimental data was gathered from each house;

1. Temperature readings at all inlets and outlets
2. Electrical power use of the ventilation units.
3. Air flow rates at all inlets and outlets

3.3.2 Methodology

In each instance the methodology for data gathering was as follows;

1. Gemini Tinytag Ultra data loggers (fig. 01) were inserted into the system ductwork adjacent to the inlet and outlet spigots. These small loggers were used to minimise any additional air flow turbulence within the duct and any associated impact this may have on the power draw of the fan. The loggers were sited approximately 30 cm away from inlets and outlets to achieve a balance between achieving a temperature reading which accurately reflects the temperatures experienced across the unit but which, again, does not adversely affect the turbulence and airflow at the spigot. Temperature readings were taken at five minute intervals over the full duration of the study.
2. The power supply for each unit was adapted from a 13 amp fused spur to a standard 3 pin plug arrangement. A Grant Instruments Kilowatt Hour Transmitter (fig. 02) was used as an intermediate between the unit and the mains electrical supply to log the energy use of the unit. Readings were taken at five minute intervals over 4 days between 24^{th} and 28^{th} Feb and recorded on the Eltek Squirrel Data Logger (fig. 03)
3. A TSI Airflow (TA460-X) digital anenometer (fig. 04) was used to record the supply and extract air velocities. In each instance the probe was carefully inserted into the centre of the duct adjacent to the room valve and rotated until the highest reading was achieved. Due to the sensitivity of the meter great care was taken in ensuring that the highest reading possible was recorded as it was assumed that this would represent the 'true' airflow where the level recorded was not impinged by the sensor's protective housing.


Fig.01


Fig. 02


Fig. 03


Fig.04

3.3.3 Data Analysis

For calculation of the efficiency of the MVHR system all relevant values were taken as a mean for the period of 13.00, 24.02.11 to 12.55, 28.04.11 to ensure that an appropriate range of operating conditions were covered and that an accurate picture of 'in use' performance could be gleaned.

3.3.4 Temperature Readings

	Dwelling A	Dwelling B
From atmosphere (°C)	9.3	9.7°
Temp differential (°C):	10.9	8.5
To dwelling (°C)	20.2	18.2
From dwelling (°C)	21.8	22.1
Temp differential (°C):	8.9	8.3
To atmosphere (°C)	12.9	13.8

3.3.5 Electrical Energy Use

	Dwelling A	Dwelling B
Total energy draw (kWh)	4.013	1.845
Mean energy draw (KWh/d)	1.003	0.461
Mean power (W)	41	19

3.3.6 Air Flow Rate

At the end of the experimental period spot readings were taken at all supply and extract room valves within each dwelling for both 'normal' and 'boost' ventilation rates.

The mean values for each household taking into account 'normal' airflow only were as follows;

Supply & Extract	Dwelling A	Dwelling B
Mean air velocity (m/s)	1.375	1.353
Mean air flow (l/s)	10.80	10.62
Mean air flow (m^3/h)	38.88	38.24

The mean values for each household taking into account the boost setting were identified as follows;

Supply & Extract	Dwelling A	Dwelling B
Mean air velocity (m/s)	1.853	1.441
Mean air flow (l/s)	14.55	11.32
Mean air flow (m^3/h)	52.38	40.74

Looking at the results it can be seen that while the two systems perform to a relatively similar standard under the normal airflow or 'trickle' setting there is a marked variation in performance when the boost setting is in use.
For calculation of the thermal efficiency the normal (or trickle) airflow figure will be used.

If air flow values are considered against the volumes of the houses it can be seen that in the best case (Dwelling A) the air flow allows for 0.18 air changes per hour (ac/h) and in the worst case (Dwelling B) this performance would only equate to 0.14 ac/h. With such low level rates of air change questions should be raised on the effectiveness of the system particularly when this is considered against a minimum air supply rate of 8 l/s per person which corresponds to 1,000 ppm CO_2 concentration.

While the overall ventilation rate is relatively poor, there are individual examples where the measured flow rate adequately meets the desired air change rate. For example, bathroom B set to 'boost' achieves 26.39 l/s or 95 m^3/h in a space with a volume of 11.2 m^3. This corresponds to a good air change rate of 8.4 ac/h when compared to the recommendations of the Scottish Building Regulations Technical Standards of a minimum of 3 ac/h.

The measured data has provided significant evidence to show that, in terms of providing sufficient fresh air the system is struggling to perform effectively.

Where the system does appear to perform effectively is in the extraction from wet rooms and from discussion with the manufacturer it appears that this is the primary design concern of this particular system. Effective as it is in this role it does not, however, lend itself to an overall high quality of internal air.

3.3.7 Efficiency:

Passivhaus standard dwellings achieve certification based on their in use performance rather than pre-construction, theoretical values. While the Glasgow House project has not been designed to meet this particular standard its analytical techniques are of greater relevance to the 'in use' testing of a ventilation system than those employed by SAP (appendix Q) when assessing efficiency. As such the following formula, referenced from Passivhaus Institute has been employed to calculate the in use thermal and electrical efficiency of the installed MVHR systems in both dwellings.

Thermal Efficiency:

$$\eta_{HR} = \frac{\delta_{FD} - \delta_{TA} + P_{EL} / (VC)}{\delta_{FD} - \delta_{FA}} \quad (\%)$$

Where

η_{HR} = thermal efficiency (%)
δ_{FD} = air temperature from dwelling (°C)
δ_{TA} = air temperature to atmosphere (°C)
δ_{FA} = air temperature from atmosphere (°C)
P_{EL} = electric power used by the unit (W)
V = ventilation air flow rate (m³/h)
c = heat capacity of air (0.33 Wh/m³K)

Electrical Efficiency:

$$\eta_{EL} = P_{EL} / V \quad (\text{Wh/m}^3)$$

Where

η_{EL} = electrical efficiency (Wh/m³)

Based on the above and the measured performance values for the respective MVHR systems their efficiencies can be calculated as;

Dwelling A:

$$\eta_{HR} = \frac{(21.8 - 12.9 + (41 / (38.88 * 0.33))}{(21.8 - 9.3)}$$

η_{HR} = 96.7%

η_{EL} = 41 / 38.88

η_{EL} = 1.054 Wh/m³

Dwelling B

$$\eta_{HR} = \frac{(22.1 - 13.8 + (19 / (38.24 * 0.33))}{(22.1 - 9.7)}$$

η_{HR} = 79.1%

η_{EL} = 19 / 38.24

η_{EL} = 0.49 Wh/m³

3.3.8 Conclusion

A cursory review of the measured efficiencies of the MVHR systems in dwellings A and B shows that they have high thermal efficiencies of 96.7% and 79.1% respectively. While appearing to perform to a very high standard in the case of A and good in the case of B, it is important to not only consider the theoretical thermal efficiency but also the system *effectiveness*.

The high levels of CO_2 concentration identified during the project, and discussed earlier in this report, indicate that the system is not effective at delivering fresh air in the volume required for the potential occupancy when compared to recognised norms for internal air quality. This is clearly shown through both dwellings on Graph 01 (ref. appendix A) where peaks in CO_2 concentration for the 2 week monitoring period are plotted against Pettenkoffer's maximum value of 1000 ppm for good air quality; which, as stated above, corresponds with 8 l/s per person present in a room.

This limitation is further supported when the measured flow rates for the system are considered (ref. appendix B). In the worst case the scenario (Dwelling B Living room) the system delivered air at a rate of 6.36 l/s to the main communal room in a dwelling which could feasibly have 7 residents. This results in a delivery rate of just 0.91 l/s per person – a rate which is over 8 times less than the recommended minimum of 8 l/s per person or 1000 ppm CO_2 concentration.

Consideration of the low air speed within the system would seem to provide an explanation of the high thermal efficiencies as the slower the air moves through the recuperator, the more time there is for effective heat transfer to take place. This is supported by sample calculations where all measured factors are retained but a new higher ventilation air flow rate is substituted into the equation. As the ventilation air flow rate increases towards a suitable rate the thermal efficiency drops to a level more in keeping with what would be expected and what was assumed in the simulated scenarios.

To increase the delivery effectiveness of this system, or any such future installations, there should be greater consideration given to the air supply rate even if this is apparently to the detriment of the thermal efficiency.

In terms of electrical efficiency if the systems are compared to the minimum standards for Passivhaus rated systems (required to have an electrical efficiency <0.45 Wh/m^3) it can be seen that the unit in Dwelling A falls far short of achieving this standard while that in Dwelling B is relatively close to achieving this standard. At this point it should be noted, however, that the recorded energy consumption in Dwelling B is only around 25% of what the manufacturer would expect and so this figure must be discounted until further analysis of the system can be undertaken by Vent-Axia to identify why the electrical draw is so low.

While the electrical efficiency of the unit in Dwelling A appears low compared to Passivhaus standard it is important to remember that the capital cost of a unit/ system which provides this level of efficiency is far greater than that used in the Glasgow House. Unless full Passivhaus standard is to be sought then the benefit of this improved efficiency could be outweighed by the increased costs to a level which negates any benefits. For tangibility it may help to understand that running the unit in Dwelling A only requires the same energy input as a 40 W incandescent light bulb.

4.0 Evaluation of Performance Through Thermographic Imaging

4.1 Aims

Thermographic imaging was used to compare the performance of the two construction types and to identify any particular problem areas with respect to energy efficiency of the external envelope.

4.2 Methodology

A FLIR ThermaCAM B360 thermal imaging camera was used to record interior and exterior images of the external envelope of both Dwelling A and B.
Images were taken over the nights of 17th and 28th February, starting at 00.00 hours with clear conditions and ambient temperatures of below 0°C.
Both dwellings were occupied as per the project regime and heated to approximately 21°C at the time of recording.
Resultant images were collated and analysed for significant instances of fabric heat loss relative to the colour associated temperature spectrum presented on each image.

Note; the calibration of the temperature spectrum is specific to each image as the temperatures are represented from coldest (black/dark blue) to hottest (red/white). In some instances spot temperature readings have been taken and these are identified on each relevant image.

4.3 Results and Analysis

4.3.1 Walls

Fig. 05 and 06 illustrate the relatively even wall temperatures across the external skin of the dwellings. The limited variations at corners, cills and floor zones indicate the successful design and construction critical details where thermal bridging could normally be expected.
It is interesting to note the difference in wall temperature, circa 2°C, between A and B which is either due to the increased thermal mass of the brick outer skin to B or that this dwelling is actually more effective in its heat retention capacity.

Fig. 05

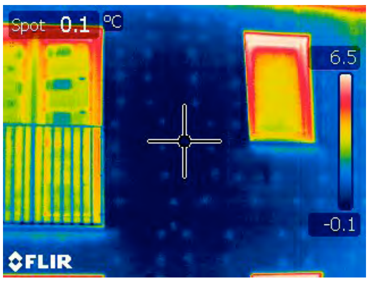


Fig. 06

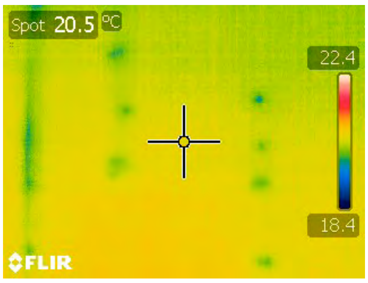


Fig. 07

Fig. 07 shows cooler spots on Dwelling B's interior wall lining caused by mechanical fixings. It could normally be expected that some thermal bridging of the timber kit would be evident internally but in this instance it appears the use of insulated plasterboard has proved effective in reducing this.

4.3.2 Roof

Fig. 08 identifies an isolated instance of heat loss at the junction of party wall and roof in Dwelling B. This either represents the sole identified instance of a defect in workmanship or is as a result of some heat convection in the party wall, acoustic separation airspace. If this is the result of the latter then the design of this particular junction may warrant further investigation.

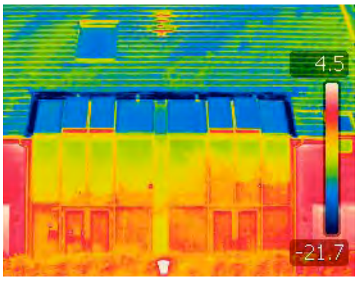


Fig.08

4.3.3 Windows

Review of several exterior images highlighted an apparent issue with thermal leakage through the upper aluminium part of the window frame (ref fig. 09 and 10). Internally, fig. 11, there was further evidence that the frame and perimeter of the glazing were suffering significant heat loss. The relatively cool temperature of the jambs suggests that the issue is largely with the glazing unit itself. Review of PRP construction details and specification seems to confirm that this may be the case.

With future proposals the use of a plastic glazing spacer rather than metal and review of the aluminium facing detail may reduce the heat loss through this construction element and improve the overall efficiency of the dwellings.

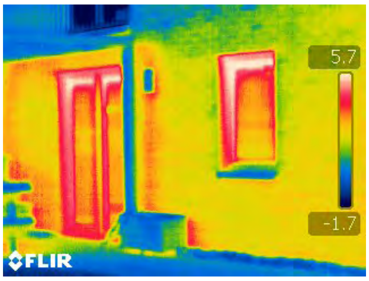


Fig. 09

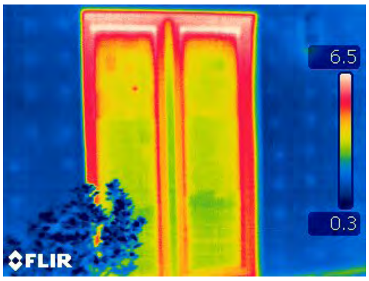


Fig. 10

Fig. 11

4.3.4 Porch

Fig. 12 identifies significant heat loss from the recessed glazed porch. It would seem that this is due to the large area of glazing, with a relatively high U-value compared to the external wall, and the use of a radiator within the glazed porch. Omission of the radiator in this location, by considering it simply as a buffer thermal space, as well as downsizing elsewhere or substituting for other methods of heat emission (ref section 3.1.4) would lead to improved energy efficiency in future construction projects.

Fig.12

5.0 Evaluation of Sun Spaces

5.1 Sun Space Benefits

The theoretical benefits of the sun buffer space are identified in section 2.0 of this report. During the monitoring period this space performed largely as anticipated in terms of its capacity to provide heat and buffer the associated 'internal' windows. Without further testing it can, therefore, be reasonably assumed that the simulated scenarios (i.e. suggestion of 25% air supplied by the conservatory) will affect heating load as predicted, providing a suitable means of control is provided – see conclusion below.

5.2 Energy Use

As the simulated scenarios identify, if the conservatory space was used in conjunction with a passive stack system then it would be able to contribute to the space heating load and reduce the reliance on fossil fuels. Because no air is presently drawn actively or passively from this space its contribution to reducing heat demand may appear limited. From a purely economic viewpoint it may therefore seem that the addition of these sun spaces does not represent a good return. This, however, would represent a limited view of the value that such a space can contribute to the dwelling. The payback period for this alone may not make it a feasible addition to the design but it should be considered in a holistic and not purely energy-saving sense.

5.3 Added Value

In terms of amenity, the quality of such spaces can be invaluable. In a 'for sale' market this would be financially quantifiable but in the social rented sector the added amenity alone makes the system worth considering.

5.4 Functionality

All of the occupants identified a need to dry internally during the project but no specific space was provided to facilitate this. Sun buffer spaces, with some additional evolution of the design, may present a viable position for a semi- internal drying space and effectively lend themselves to reducing the burden placed on the internal environment from domestic laundering and drying – a process which can have a significant impact on the quality of internal environments.

5.5 Conclusion

While section 2.8.5 notes that poor use of this space could result in an increase in the building's heated envelope and an increase in energy use, in the tested scenario, where the occupants were not allowed to vary the heating controls, the buffer space was actually instrumental in conserving energy. Of the 3,284 minutes that windows were opened in Dwelling A, 2,481 of these were open onto the sun space (normally when occupants had gone to bed) and as such the heat loss from the dwelling was significantly less than it would have been had the windows been directly open to the exterior.

In its current design form the sun space provides key benefits to the dwelling overall but these could be enhanced. Designing in a form of user controlled ventilation panel between the sun space and the internal space would allow a greater degree of flexibility, improve ventilation potential and also reduce dwelling heat load. Furthermore, a space that positively encourages the introduction of house plants will enhance the quality of air provided – e.g. better ion balance, removal of VOCs, detoxification of formaldehyde, etc.

6.0 Qualitative Analysis

6.1 Aims

The project aimed to place quantitative values for the qualitative aspects of design and the occupant's experience of their habitation.

6.2 Methodology

At the end of the monitoring period the residents completed a short questionnaire querying their perception of qualitative aspects of and within the dwellings. Numeric values were assigned to each of these responses and the results collated. The collation of these subjective responses provides a viable metric for the given field of questioning.

A compiled table of responses is presented in Appendix C. The main points of note are discussed below.

6.3 Results

6.3.1 Thermal

The results from week 1 in Dwelling A, along with anecdotal evidence, show that it was uncomfortable during this period and that, principally, this was due to it being too hot. Graph 02 (Appendix D) shows the mean temperatures through both houses over this period of occupation and confirms the validity of the resident's perception. As previously noted this resulted in the occupant response of window opening and ultimately energy being wasted.

This tendency and causal relationship to energy wastage is further highlighted by Graph 03 (Appendix E) which shows the heating profiles of both living rooms over a 24 hour period on 16th February. The most significant trend illustrated by this graph is that of the two timed heating periods starting at 08.00 and 18.00 hours respectively. In each instance the room temperature rises to an uncomfortable level and requires occupant intervention and heat loss to drop it back to a level of stability. The problem with this is clearly highlighted when this heat profile is compared to that of an identical time period on 26th February (Graph 04, Appendix F) when the radiator TRVs had been reduced from a setting of 4 to 2. Under these conditions the dwellings exhibit a greater degree of thermal stability and improved comfort levels as exhibited by the removal of the need to manually ventilate the space and expel heat to the atmosphere (such behaviour would appear as sharp and significant drops in temperature).

In the specific instance of the living room the differing profiles of the two graphs also support the assertion of the simulations that a large radiant heat source in this area is unnecessary and that it may simply provide a greater opportunity for wastage of heat energy.

While the monitored regime set limitations on the occupant's freedom to vary their internal comfort parameters, this type of behaviour – i.e. heat a space to comfort level then dump the heat once this level has been exceeded, is all too common a domestic practice. To this end the monitored scenario represents a fair reflection of this practice and a clear example of how occupant behaviour can negatively affect building performance. With thermally efficient housing, where occupant behaviour is becomes increasingly critical to the energy performance of the building, it highlights the need for good occupant education and understanding of their home's operating systems.

With the houses effectively being overheated due to the initial thermostat setting, the benefits of thermal mass, with its heat storage potential, are largely masked. Outwith the tested scenario it is, however, worth considering the behaviour of the dwellings during the summer season. In this scenario the house with the higher levels of thermal mass (i.e. Dwelling A) would be expected to perform better, in terms of thermal comfort, as the effects of temperature increases due to solar gain are mitigated by the buffering effect of the clay block superstructure.

6.3.2 Acoustic

While both dwellings received a very good rating for acoustic separation from the outside, Dwelling A was noted as having particularly poor acoustic insulation between floors. As one respondent noted;

"You can clearly hear what was going on in floors above and below. The wall blocked out more sound than the ceilings."

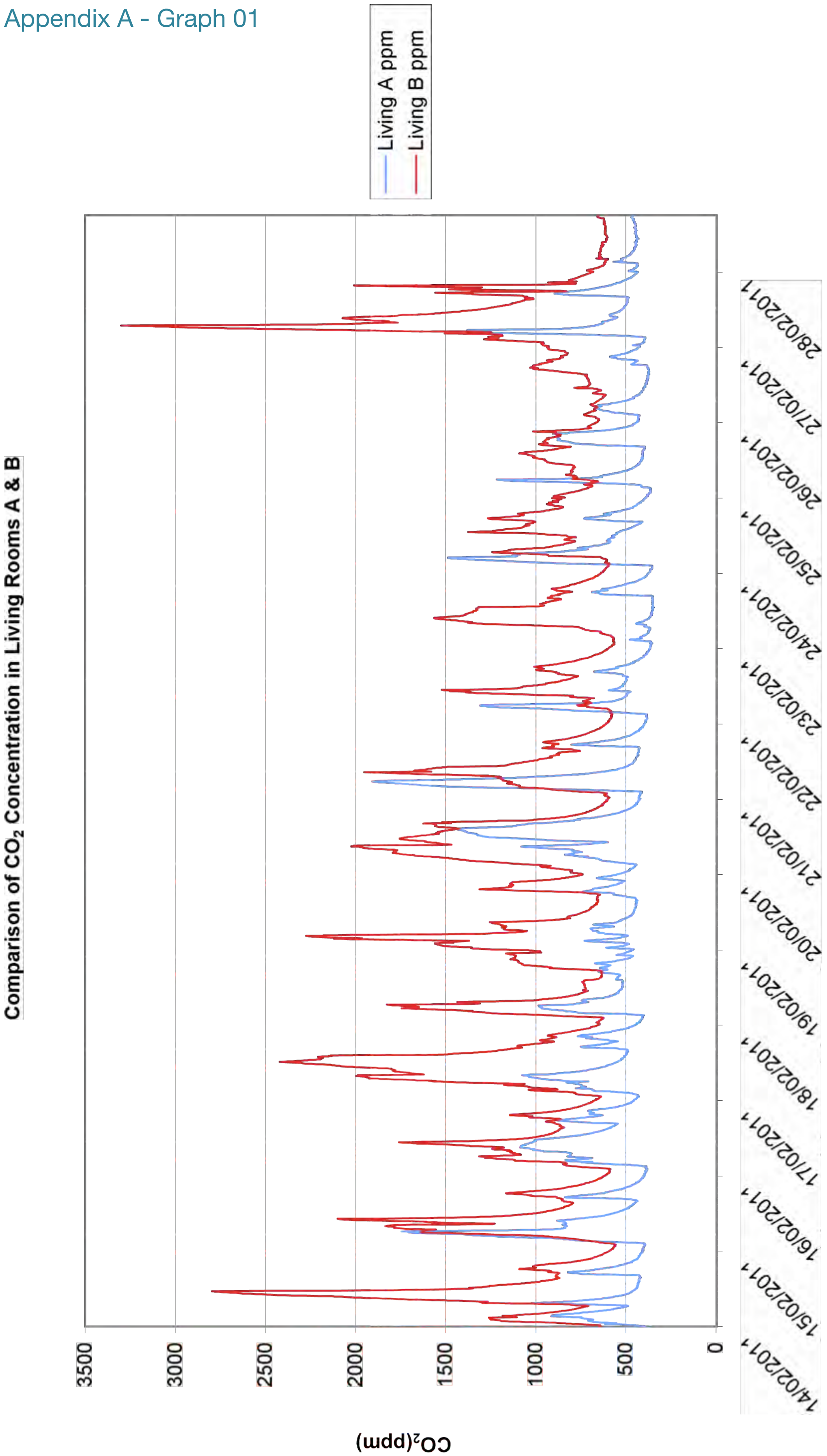
This sentiment was echoed by all other residents of this house and would suggest that the combination of the masonry walls, with cellular air spaces, and the lightweight timber floor construction may have resulted in a system which effectively channels impact and airborne sound between levels. This theory is supported by the fact that this phenomenon was not experienced in the timber kit dwelling.

While reassessing the floor to wall construction junction in future designs may improve the acoustic separation, another method for improving this could be to include a greater degree of mass within the floor zones. Ultimately this may also provide a greater degree of useful thermal mass in the dwelling and benefit the thermal performance as noted in 6.2.1 above.

6.3.3 Design

In terms of overall design, space provision, storage provision, appearance and comparison to the test occupant's own homes, both of the dwellings received very good scores and would indicate that the layout, design intent and execution of the Glasgow House is generally successful.

Appendix A - Graph 01



Appendix B – Collated Occupant Responses

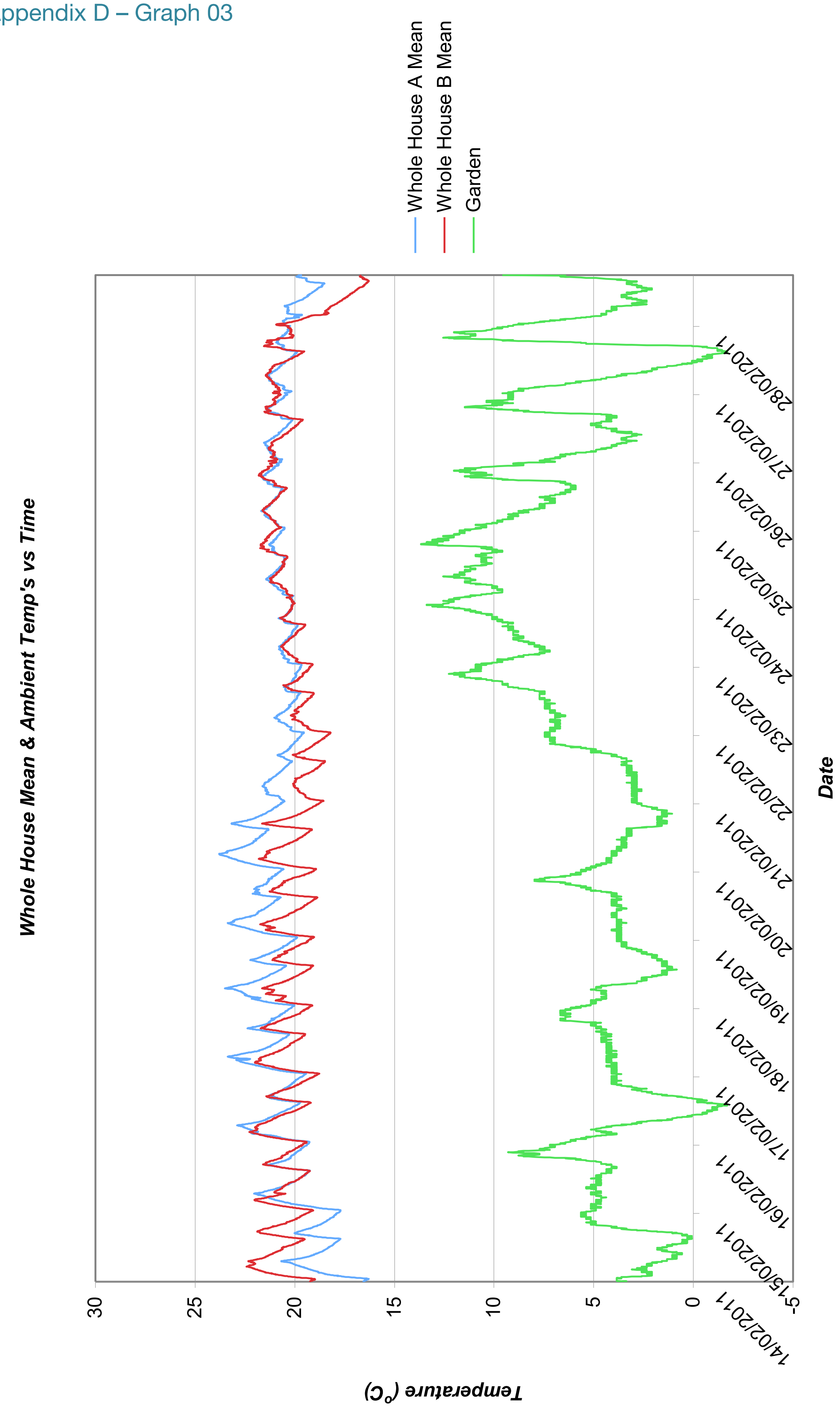
	DWELLING A (plot 1)					DWELLING B (plot 3)					COMBINED	OPTIMUM
	Occ 1	Occ 2	Occ 3	Occ 4	Mean	Occ 1	Occ 2	Occ 3	Occ 4	Mean	Mean	
TEMPERATURE WK 1												
Overall												
Uncomfortable ↔ Comfortable	2	4	2	2	2.5	5	5	4	5	4.75	3.625	5
Too Hot ↔ Too Cold	2	2	2	1	1.75	2	3	3	3	2.75	2.25	3
Stable ↔ Unstable	1	4	1	1	1.75	3	2	4	2	2.75	2.25	1
Living Room												
Uncomfortable ↔ Comfortable	2	3	2	2	2.25	5	5	4	5	4.75	3.5	5
Too Hot ↔ Too Cold	2	2	2	3	2.25	2	2	2	3	2.25	2.25	3
Stable ↔ Unstable	1	4	1	2	2	1	2	3	2	2	2	1
Bedroom												
Uncomfortable ↔ Comfortable	3	4	1	1	2.25	4	5	2	5	4	3.125	5
Too Hot ↔ Too Cold	3	2	1	1	1.75	3	3	4	3	3.25	2.5	3
Stable ↔ Unstable	2	4	1	1	2	3	1	4	2	2.5	2.25	1
AIR QUALITY WK 1												
Overall												
Satisfactory ↔ Unsatisfactory	4	4	3	4	3.75	2	1	2	1	1.5	2.625	1
Fresh ↔ Stale	4	3	3	5	3.75	2	2	3	1	2	2.875	1
Humid ↔ Dry	2	3	3	3	2.75	3	3	3	3	3	2.875	3
Still ↔ Good Ciculation	1	3	3	1	2	3	4	3	5	3.75	2.875	5
Smelly ↔ Odourless	2	4	4	2	3	5	4	4	5	4.5	3.75	5
Condensation												
Yes/ No	Y	Y	N	N	50%Y	Y	Y	Y	N	75%Y		
TEMPERATURE WK 2												
Overall												
Uncomfortable ↔ Comfortable	4	5	4	4	4.25	5	5	4	5	4.75	4.5	5
Too Hot ↔ Too Cold	3	3	3	3	3	3	3	3	3	3	3	3
Stable ↔ Unstable	4	3	1	4	3	2	4	3	2	2.75	2.875	1
Living Room												
Uncomfortable ↔ Comfortable	5	5	4	3	4.25	5	5	4	5	4.75	4.5	5
Too Hot ↔ Too Cold	3	3	3	3	3	3	3	2	3	2.75	2.875	3
Stable ↔ Unstable	1	4	1	3	2.25	2	4	3	2	2.75	2.5	1
Bedroom												
Uncomfortable ↔ Comfortable	3	5	3	3	3.5	4	5	3	5	4.25	3.875	5
Too Hot ↔ Too Cold	3	3	3	3	3	3	4	4	3	3.5	3.25	3
Stable ↔ Unstable	4	2	1	4	2.75	3	1	4	2	2.5	2.625	1
AIR QUALITY WK 2												
Overall												
Satisfactory ↔ Unsatisfactory	3	1	3	5	3	1	1	2	1	1.25	2.125	1
Fresh ↔ Stale	4	3	3	5	3.75	2	1	2	1	1.5	2.625	1
Humid ↔ Dry	3	3	3	3	3	3	2	3	3	2.75	2.875	3
Still ↔ Good Ciculation	3	3	3	2	2.75	3	5	4	5	4.25	3.5	5
Smelly ↔ Odourless	4	4	4	2	3.5	4	5	4	5	4.5	4	5
Condensation												
Visible? Yes/ No	Y	Y	N	N	50%Y	Y	Y	Y	NR	75%Y		
HOT WATER												
When Required? Yes/ No	Y	Y	Y	Y	100%Y	Y	Y	Y	Y	100%Y		
LIGHTING												
Overall												
Satisfactory ↔ Unsatisfactory	3	1	3	1	2	2	4	2	2	2.5	2.25	1
Natural												
Satisfactory ↔ Unsatisfactory	2	2	3	2	2.25	3	3	2	3	2.75	2.5	1
Artificial												
Satisfactory ↔ Unsatisfactory	4	3	3	3	3.25	3	1	3	3	2.5	2.875	1
NOISE												
Equipment Within House												
Not Noticable ↔ Annoying	2	2	3	1	2	3	2	2	1	2	2	1
People Between Rooms												
Not Noticable ↔ Annoying	5	5	5	5	5	4	2	2	2	2.5	3.75	1
Outside Noise												
Not Noticable ↔ Annoying	2	1	1	1	1.25	1	1	2	1	1.25	1.25	1
OVERALL COMFORT												
Unsatisfactory ↔ Satisfactory	4	5	3	2.5	3.625	5	5	4	5	4.75	4.1875	5
SPACE												
Not Enough ↔ Plenty	4	5	4	4	4.25	4	5	5	5	4.75	4.5	5
LAYOUT												
Poor ↔ Good	4	5	2	4	3.75	4	4	5	5	4.5	4.125	5
STORAGE												
Not Enough ↔ More Than Enough	5	5	4	5	4.75	4	4	5	5	4.5	4.625	5
APPEARANCE												
Poor ↔ Good	4	4	5	5	4.5	4	4	4	4	4	4.25	5
DESIGN												
Unsatisfactory ↔ Satisfactory	4	5	4	4	4.25	4	4	4	5	4.25	4.25	5
DRYING PRACTICE												
Drying Indoors? Yes/ No	Y	Y	Y	Y	100%Y	Y	Y	Y	Y	100%Y		
OWN DWELLING												
Glasgow House compared to own												
Worse ↔ Better	4	5	2	2	3.25	5	5	4	5	4.75	4	5

Appendix C – MVHR Flow Rate Results

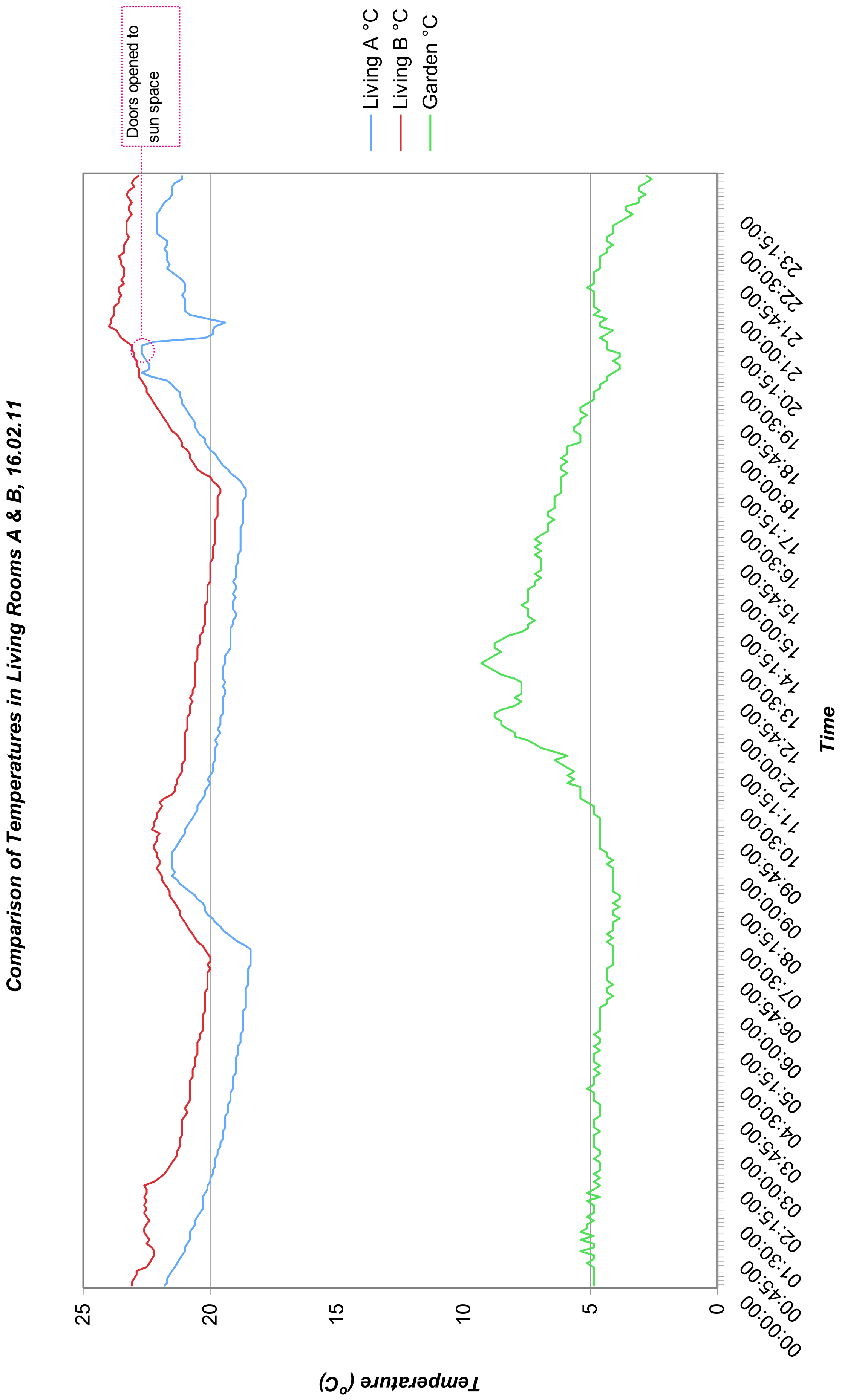
Note: Flow rates based on 100mm diam ducts as installed.

Date	Position	Vel	Flow	Flow (100mm duct)	Flow (100mm duct)	T	H	Boost On
		m/s	l/s	l/s/person (4 occupants)	l/s/person (7 occupants)	deg C	%rh	
30/03/2011	Living A	1.11	8.72	2.18	1.25	20.3	43.1	n
30/03/2011	Utility/ WC A	1.44	11.31	11.31		22.4	41	n
30/03/2011	Utility/ WC A	2.38	18.69	18.69		21.7	42.4	y
30/03/2011	Kitchen A	2.91	22.86	5.71	3.27	20.6	45.1	y
30/03/2011	Kitchen A	3.32	26.08	6.52	3.73	20.4	44.9	y (wc)
30/03/2011	Kitchen A	2.32	18.22	4.56	2.60	20.2	45.9	n
30/03/2011	Bathroom A	1.68	13.19	13.19		21.7	40.9	n
30/03/2011	Bathroom A	2.62	20.58	20.58		21.9	40.9	y
30/03/2011	Bed 2 A	0.94	7.38	3.69		20.9	42.9	n
30/03/2011	Bed 1 A	1.09	8.56	4.28		20.6	43.5	n
30/03/2011	Single Bed A	0.92	7.23	7.23		20.4	43.5	n
30/03/2011	Attic room A	1.5	11.78	5.89		20.4	44	n
30/03/2011	Living B	0.81	6.36	1.59	0.91	19.8	44.5	n
30/03/2011	Kitchen B	0.8	6.28	1.57	0.90	19.9	42.2	n
30/03/2011	Kitchen B	1.28	10.05	2.51	1.44	20	41.8	y
30/03/2011	Utility WC B	1.02	8.01	8.01		20.4	41.5	n
30/03/2011	Utility WC B	1.57	12.33	12.33		20.8	40	y
30/03/2011	Kitchen B	1.3	10.21	2.55	1.46	20.4	39.9	y (wc)
30/03/2011	Bathroom B	2.32	18.22	18.22		20.9	39.1	y
30/03/2011	Bathroom B	3.36	26.39	26.39		20.8	38.7	n
30/03/2011	Bed 1 B	1.19	9.35	4.67		19.9	45.7	n
30/03/2011	Bed 2 B	0.93	7.30	3.65		19.6	45.6	n
30/03/2011	Single Bed B	0.81	6.36	6.36		19.7	45.9	n
30/03/2011	Attic Room B	1.9	14.92	7.46		18.9	47.6	n

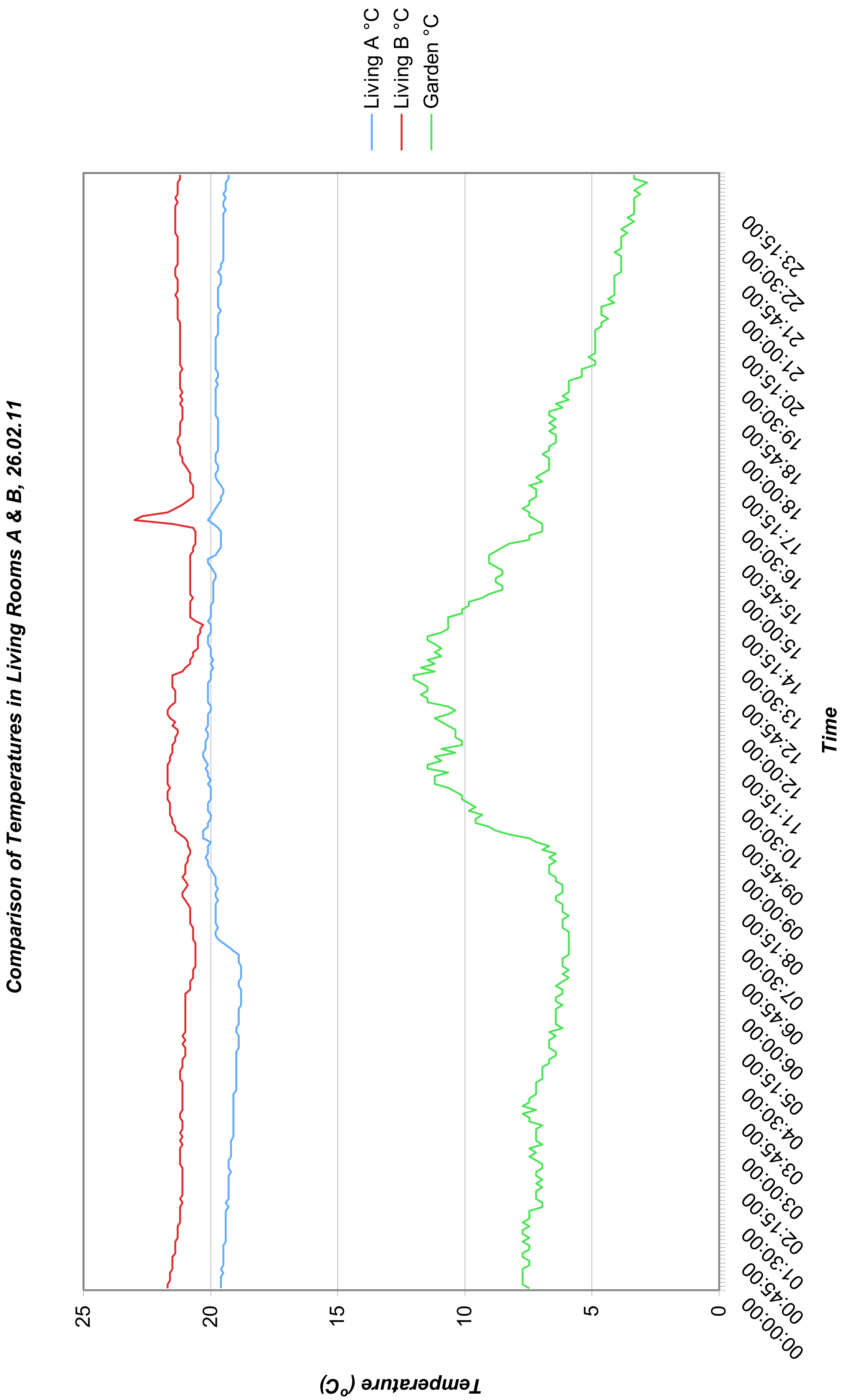
Appendix D – Graph 03



Appendix E – Graph 04



Appendix F – Graph 05



References to Section 2.0

Fung, W, 2008, 'The Unintended Negative Consequences of Decision-Making in Glasgow's Social Housing Sector', PhD thesis, Glasgow School of Art.
(Parts of Ch's 5-8 that deal with the retrofit of a Caledonia Road tower block contain interesting findings relative to glazed buffers and window sizing.)

Kondratenko, I V and Porteous C D A, 2005, 'SAP PLUS: Solar Enhancement to Standards Assessment Procedure', in proceedings North Sun 2005, 10th International Conference on Solar energy May 25-27, Vilnius, Lithuania.

Kondratenko, I V, Porteous, C D A and Sharpe, T R (2004) 'Why are new 'Direct Gain' dwellings underperforming in Scotland?', in proceedings Eurosun 2004 Sonnenforum, Freiburg, Germany, June, PSE GmbH, vol 2, pp370-375.

Page, J and Lebens R, 1986, 'Climate in the United Kingdom', HMSO.

Porteous, C, 1990, "Performance Characteristics of Solar Buffer ones for Scottish Housing, PhD Thesis, University of Strathclyde.

Porteous C D A and Ho, H M, 1997, 'Do sunspaces work in Scotland? Lessons learnt from a CEC solar energy demonstration project in Glasgow', International Journal for Ambient Energy, Vol. 18, No. 1, January, ed. J. C. McVeigh, pp. 23-35, ISSN 0143-0750.

Porteous C D A and Menon R, 2006, 'Problems of the Scottish/UK Building Industry vs. Energy-efficient New Build Passive Housing', proc. 10th International Passive House Conference 2006, May 19-20, Hanover, Germany, pp. 211-216.

Sharpe T and Porteous C, 2001, 'New energy efficient public housing in Glasgow - the Priesthill Project', proc. NorthSun 2001, Leiden, Netherlands.