Elm Tree Mews Field Trial – Evaluation and Monitoring of Dwellings Performance

Final Technical Report

Dr. Jez Wingfield, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Dr. Jenny Seavers, Centre for Urban Development and Environmental Management, Leeds Metropolitan University

January 2011

Executive Summary

1 This report summarises the technical results and monitoring data from the Elm Tree Mews field trial carried out by the Centre for the Built Environment at Leeds Metropolitan University on behalf of the Joseph Rowntree Foundation (JRF) and Joseph Rowntree Housing Trust (JRHT). The Elm Tree Mews Field Trial research programme was funded under JRF project No. 805319. This report details the technical data from fabric performance tests carried out on the completed dwellings, site observations and photographic records of the construction process and an analysis of available site documentation and drawings. Performance testing included pressure tests, a coheating test, thermal imaging, temperature and air flow measurements and heat flux measurements. A design retrospective of those aspects of the design and construction process related to energy performance was undertaken by an assessment of available documentation and through a series of semi-structured interviews with key individuals involved with the development. The report also contains the results of 12 months in-use monitoring of the occupied dwellings and data on the performance of the communal heat pump system.

2 This report should be read in conjunction with the main final policy report for the Elm Tree Mews project which is published by the Joseph Rowntree Foundation (Bell, Wingfield, Miles-Shenton & Seavers, 2010). The final policy report contains all the discussions, conclusions, recommendations and policy implications arising from the project.

Acknowledgements

3 The Elm Tree Mews project was supported by the Joseph Rowntree Foundation and the Joseph Rowntree Housing Trust, who were the scheme developers. The research was undertaken by the Centre for the Built Environment at Leeds Metropolitan University. The project was carried out over four years, and in that time we have been fortunate to have had the support of a large number of organisations and committed individuals who deserve our special thanks. The staff of the Housing Trust provided considerable support. In particular, we are grateful for the help and support given by Brian Jardine, Peter Giles and Nigel Ingram. From start to finish they have worked very hard to ensure that the project went as smoothly as possible. The design and construction team, subcontractors and others involved in the scheme deserve special thanks. In keeping with a general concern to maintain, as far as we can, the anonymity of the team, we are able to thank by name a few who have expressed a willingness to be identified. We would acknowledge the support and enthusiasm of Andy Watson, Andy Coates and Jason Kirby of the Strategic Team Group (main contractor) and Matthew Hill of Leeds Environmental Design Associates Ltd (services engineering). However, the contribution of all individuals and organisations involved in providing a pioneering scheme from which to learn was considerable and is gratefully acknowledged. This research project had the benefit of advice and support from an advisory group, the members of which we would also like to thank for their support. The range and depth of expertise available from the advisory group were considerable and their contribution invaluable. The advisory group consisted of Brain Jardine (JRHT), Dave Mitchell (HBF), Jayne Lomas (HCA), Prof. Bob Lowe (UCL), Prof. Kevin Lomas (Loughborough University), Richard Partington (Richards Partington Architects), Simon Corbey, (Good Homes Alliance) and Tanya Christensen (Consulting with Purpose).

4 No monitoring project can be undertaken without the cooperation and enthusiasm of the residents. They invite researchers into their homes, tolerate monitoring equipment in their daily lives and, in the process, facilitate the research. We are very grateful for their support and although anonymity prevents us from naming them, we acknowledge their considerable contribution. The staff at the Joseph Rowntree Foundation provided considerable support and advice to the research team and we would like to thank in particular the project officers Alison Jarvis and Katherine Knox for their help and unstinting enthusiasm throughout the project. In a project of the scale and complexity of Elm Tree Mews it is almost inevitable that we will have omitted to mention by name a number of people who have contributed. We can only apologise in advance to these individuals and express our general gratitude to all who have supported the project.

Table of Contents

Introduction

5 This report describes the technical data and results from the Elm Tree Mews field trial carried out by the Centre for the Built Environment (CeBE) at Leeds Metropolitan University on behalf of the Joseph Rowntree Foundation (JRF). The research programme was funded under JRF project No. 805319. This report details the findings of fabric and energy performance tests carried out on the completed dwellings, site observations and photographic records of the construction process, an analysis of available site documentation and drawings and the results from 12 months in-use monitoring together with a social survey. Performance testing included pressure tests, a coheating test, thermal imaging, temperature and air flow measurements and heat flux measurements. A design retrospective of those aspects of the design and construction process related to energy performance was undertaken by an assessment of available documentation and through a series of semi-structured interviews with key individuals involved with the development. This technical report is the companion report to the main policy report from the project which was also written by CeBE and is published by the Joseph Rowntree Foundation (Bell, Wingfield, Miles-Shenton & Seavers, 2010). The policy report details the main conclusions and policy implications arising from the project and should be read in conjunction with this technical report.

Background

The 21st Century Suburban Homes Competition

6 In February 2005, the Joseph Rowntree Foundation launched the "21st Century Suburban Homes" design and build competition for a small housing development on the site of a redundant used car showroom (Elm Tree Garage) in the JRF New Earswick model village in York (JRF 2005a). The site is adjacent to the grade 2 listed Folk Hall. The houses were to be constructed on behalf for the Joseph Rowntree Housing Trust (JRHT). The design competition was inspired by the 100th anniversary of the 1905 Letchworth "Cheap Cottages" exhibition. The aim of the development was to provide well designed houses of a mixture of tenures, with affordable, high quality houses and flats, both for rent and for sale (including part-ownership). The design was expected to reflect the "Arts and Crafts" vernacular of New Earswick and the Folk Hall. In addition, the development was required to be designed to higher than normal environmental standards and also meet the requirements of the JRF Lifetime Homes standard (Habinteg 2010). It was also expected that the development would provide practical ideas and technical data to support the design and construction process for the much larger 500 house Derwenthorpe scheme that the JRHT is developing on a site to the east of York. The winning design for Elm Tree Mews was selected from a short-of four entries by a panel of independent experts.

The Elm Tree Mews Field Trial

7 The main aim of the Elm Tree Mews field trial was to provide a comprehensive approach to the evaluation and monitoring of the Elm Tree Mews housing development in terms of design and construction process and performance, both on completion and when occupied. The data and results from the research have relevance for the design and construction of the proposed JRF Derwenthorpe development as well as other housing schemes both in the social housing sector and also in the private sector.

8 It is recognised by the housing industry that, despite the fact that solutions exist for the construction of very low and zero carbon housing, there is considerable concern that many of these solutions are untried and untested within the context of mainstream housing production in the UK. The lack of published performance data also shows that many schemes do not undergo comprehensive monitoring and evaluation to check whether the approaches chosen have achieved their designed performance targets. This research project was therefore designed to ensure that as much as possible was learned about the approaches, methodologies and systems used at Elm Tree Mews so that future schemes are able to benefit from the results and lessons learned. The research programme consisted of a retrospective evaluation of the design and construction process, performance measurements of the dwellings as constructed (compared with design expectations) and the monitoring of energy and other performance characteristics of the dwellings in use. The in-use monitoring was conducted over a 12 month period and included the measurement of energy flows for heating and hot water together with data for electricity consumption for lights and appliances, internal temperatures, humidity, carbon dioxide levels and hot water consumption. The occupants of the houses were interviewed at the end of the monitoring period in order to gather their views and opinions on thermal comfort and other issues such as the ease of use of the heating systems.

Competition Design Submission

9 The winning design for the 21st Century Suburban Homes competition was for a single block of 6 dwellings comprising four terraced houses and two apartments. The external appearance of the building design echoed the steeply pitched pantile roof and dormer windows of the adjacent Folk Hall and the general vernacular of the New Earswick village.

10 The winning design submission noted the innovative use of intelligent and environmental features with construction innovation, and a networking process of research and communication with stakeholders as demonstrated by the following quotation from the submission:

> *"We believe that we meet users' needs by designing adaptable, low-energy, low maintenance homes that respond to orientation, views, sunlight and daylight, along with Lifetime Homes principles in their planning and details. By using off-site fabrication methods, and using standard component parts, we believe that we can produce excellent 'intelligent and green' dwellings which offer far better value, amenity and comfort than standard traditional construction and standard house plans. Costs can be brought down to the same level as traditional construction, if not lower, given sufficient numbers such as the larger scheme at Derwenthorpe. Running costs are lower for energy, water and maintenance. Lifetime value is significantly greater. We have already provided various flagship demonstration schemes for Housing Associations and local councils, proving that high quality 'intelligent and green' homes can be affordable, attractive and can enhance neighbourhoods. We hope to have the opportunity to prove this again at New Earswick." (JRF 2005b)*

11 The design submission did not contain any supporting information, monitored data or references to provide evidence of actual performance when compared to design expectations. This is perhaps unsurprising as it is still relatively unusual for houses and housing developments to be monitored in any detail, or for the results of any monitoring that is carried out to be published in the public domain. It is likely that, in the future, clients will expect selection criteria in bids to be evidence-based and will require real energy performance data or other measurements that can demonstrate past performance. Indeed, with the UK's stated target of zero carbon homes by 2016, and with the energy and performance standards required by building regulations for new homes approaching very low levels of carbon emissions, it will become ever more critical that designers, developers and contractors can demonstrate that their designs, systems, processes and methodologies are actually able to deliver the promised performance targets.

12 The outline specification for the winning submission included brief descriptions of the major design components and systems. Those design aspects in the specification that are important for energy performance are listed in Table 1. The general design approach outlined was for a timber clad/rendered timber frame building with conventional gas fired central heating, passive stack ventilation, solar thermal hot water and a sunspace buffer zone on the south facing facade. The design targeted a base level Ecohomes[1] "Good" rating as a minimum, which would be upgradeable to Ecohomes "Excellent" with cost options such as photovoltaic panels. The building was designed to be oriented with a south facing roof and glazed façade in order to maximise solar gain and efficiency of the solar collector and also to allow for possible future upgrading with additional solar technologies such as the photovoltaic panels. It was noted in the submission that the building could be heated by a communal boiler, potentially with biomass, but this was discounted at the time due to the mixed tenure of the properties[2]. A mechanical ventilation system with heat recovery (MVHR) was also considered in the submission but was discounted due to the installation and maintenance cost.

13 The design submission noted several potential advantages of using timber frame with screw pile foundations as opposed to traditional masonry construction. The advantages stated included faster erection times, less site waste, reduced drying times (due to removal of wet trades), low embodied energy and better insulation values. A general statement was made about the use of "lean construction" without exploring in detail what was meant by this and how this might be achieved at Elm Tree Mews.

---

[1] Ecohomes is an environmental rating system for new homes and is based on the BRE BREEAM assessment system. In April 2007 it was replaced in England by the Code for Sustainable Homes.

[2] It is interesting to note that, following the recommendations from a separate study of heating options, a communal heating system was eventually used at Elm Tree Mews, albeit using a ground source heat pump rather than a biomass boiler.

Table 1 – Winning Competition Submission – Outline Specification and Design Details (JRF 2005b)

Foundation/Floor	Screw pile foundation (conditions permitting), ground beams, beam and block floor, blockwork to floor plate.
Main Construction Elements	Single skin timber frame with 180mm stud, external rainscreen cladding (timber and/or rendered board), internal battened dry-lined service void, timber floor cassettes, timber stud partitioning, timber frame roof structure.
Insulation	Wall insulation – Cellulose at 180mm to give 0.15 W/m^2K *U*-value, Roof insulation – 300mm cellulose or polyurethane, Floor insulation – not specified.
Thermal Performance	Estimated heat load for flats of around 1.5kW and houses of 3kW with inside-outside temperature difference of ~20K. Estimated balance temperature of 10°C.
Orientation	Main living spaces oriented to south, South facing roof slope for solar panels and/or photovoltaic panels.
Zoning of Internal Space	Main living spaces stacked over each other. Bathrooms stacked over each other to reduce pipework lengths and minimise deadlegs.
Heating System	Individual gas condensing boilers with radiators.
Hot Water	Solar panels to provide approx 50% to 70% of domestic hot water with rest provided by gas boiler.
Airtightness	Not specified.
Ventilation	Natural ventilation with passive stack to bathrooms.
Summer Cooling	Shading, brise-soleil and trees/hedges to cut out high summer sun but still allow low level solar gain in winter. Thermal mass in concrete floor. Provision for cross ventilation.
Windows	Maximise passive solar gain with south and west facing glazing. High specification timber windows stated but no detail given on type or performance.
Renewable Energy	Solar hot water panels.
Other Design Features	Solar sunspace to provide tempered air with aim of reducing heating in winter, Sunspaces to be provided with low & high ventilation to reduce summer overheating. Water butts to collect rain water. Dual flush/low flush W/Cs and flow restrictors. Intelligent controls such as multizone time and temperature heating controllers, lighting control system, ethernet/entertainment system wiring and home control system. Lifetime Homes standards.

14 The winning design proposal did not give any detailed information on the expected airtightness of the building fabric or the airtightness strategy. There were no specific requirements for performance testing, energy monitoring or feedback mechanisms.

15 The proposed design indicated that up to 70% of domestic hot water could be generated by the solar thermal panels. The actual performance of the solar system would be dependent upon the number and size of panels, panel orientation, volume of the solar store and hot water usage factors. The SAP worksheets for the solar panels on the dwellings as constructed give a predicted solar fraction of around 30%.

16 One key aspect of the proposed design was the use of passive measures in preference to mechanical or active systems. These measures include the use of solar panels, solar sunspaces, passive stack and cross ventilation, and careful orientation with shading to prevent overheating in the summer.

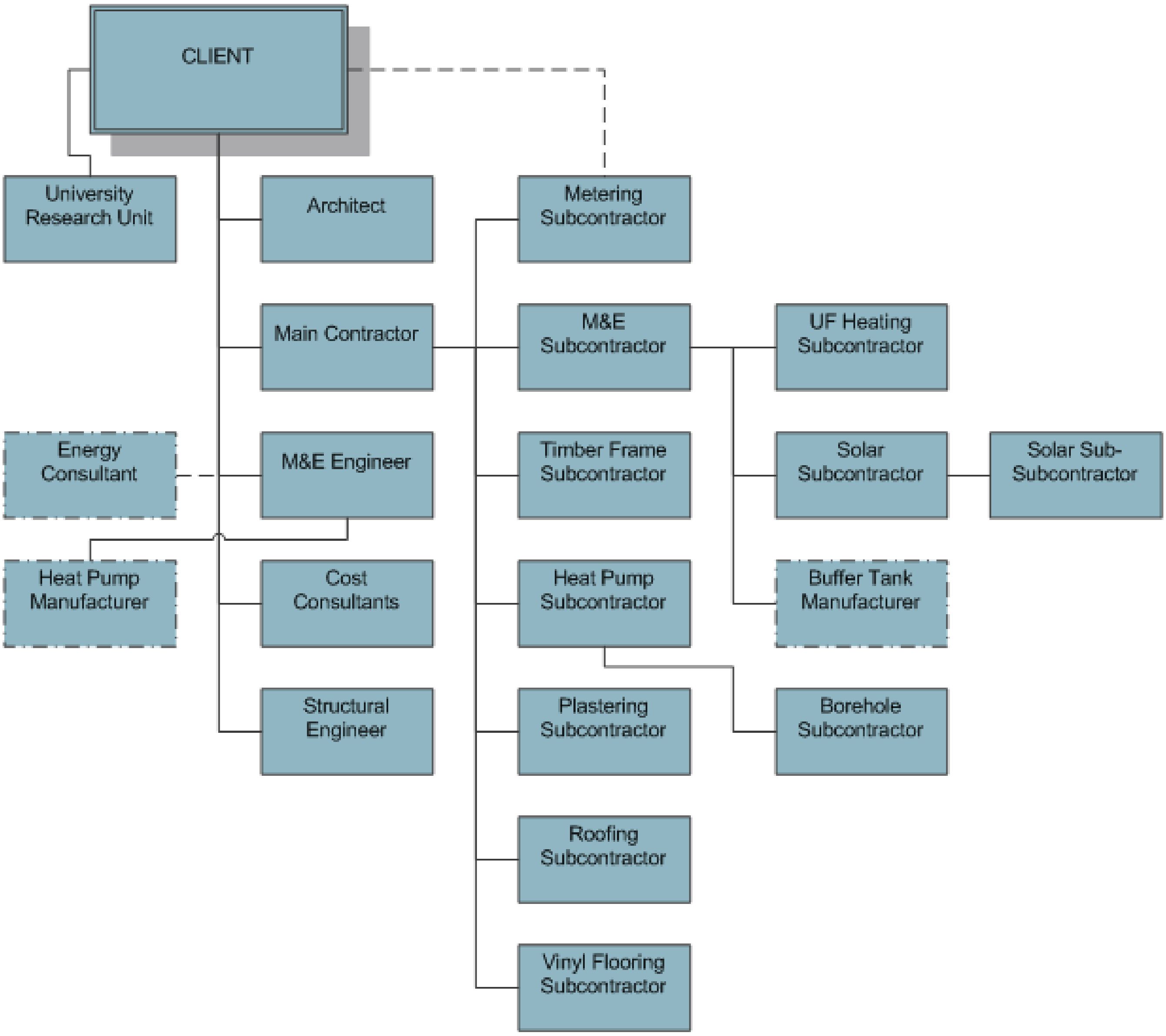
Other Initial Contract Issues

17 The 21st Century Suburban Homes competition was for a design and build turn key proposal, and the winning submission included named partners for the main contractor, quantity surveyor and various other roles such as M&E services, structure and ecology. However, although the Joseph Rowntree Foundation and Housing Trust appointed the winning architect to design the scheme, it appointed a different main contractor, quantity surveyor and other specialist consultants.

18 The organisational relationship between the JRHT as the client and the various consulting, contracting and subcontracting companies is illustrated by the chart in Figure 1. It is apparent from the large number of relationships shown by this chart that the organisation of the project was

relatively complex for a development of only 6 dwellings. In particular, the relatively high number of companies involved in the design, supply and installation of the heating and hot water system had the potential to give rise to issues with communication and final performance of the installed system if the project management structure, specifications and commissioning procedures were not carefully planned.

Figure 1 – Elm Tree Mews Project Organisational Chart



19 In addition to the changes to the design and construction team compared to that initially proposed, JRF/JRHT wanted to explore further the possible options for a low carbon heating system for Elm Tree Mews as an alternative to the gas boiler system recommended in the competition entry. To this end, a desk study was undertaken by consultants appointed by JRF to explore and assess the options available for the heating and hot water system at Elm Tree Mews in terms of capital costs, running costs and carbon emissions (Watson & Hill 2006). The heating options considered were individual ground source heat pumps (GSHP), a communal ground source heat pump, micro CHP, and a communal biomass boiler with/without a gas boiler back up system (see Table 2). The study concluded that a communal ground source heat pump with solar thermal hot water would provide the best balance of cost versus carbon emissions. There is some uncertainty in the report with respect to the definition of heat load. The report states that the heat load (defined on page 3 of the report as heating and hot water) will be less than the lowest output gas condensing boiler.

However, the calculated heat loads in the report are for space heating only. In the case of a dwelling with very low space heating demand, the maximum heating load with a gas boiler will more likely be determined by the hot water demand profile and hot water storage capacity and not the space heating demand, even when there is a solar thermal system. There are commercially available wall mounted gas condensing boilers with heat outputs as low as 4.5kW (e.g. Viessmann Vitodens 300) which would be suitable for even very low heat demands.

Table 2 – Heating Options Considered for Elm Tree Mews (Watson & Hill 2006)

Heating System	**Solar Panel?**	**Capital Cost (£/annum per dwelling)**	**Running Cost (£/annum per dwelling)**	**Carbon Emissions ($kgCO_2$/annum per dwelling)**
Individual Gas Boiler (Benchmark)	Yes	3700	110	1045
Communal Gas Boiler	Yes	4650	110	1045
Individual Ground Source Heat Pump	Yes	9000	113	815
Communal Ground Source Heat Pump	Yes	8900	108	775
Communal Biomass Boiler	Yes	12200	203	143
Communal Biomass Boiler	No	9200	298	210
Communal Biomass Boiler with Gas Boiler Back Up	Yes	12350	203	143
Communal Biomass Boiler with Gas Boiler Back Up	No	9350	298	210
Micro CHP	Yes	3500	110	1045

20 The calculations for the heat loads and energy use in the low carbon heating report assumed fabric U-values of 0.18 W/m^2K for the wall, 0.2 W/m^2K for the floor, 0.13 W/m^2K for the roof, 1.5 W/m^2K for the windows/doors and an air permeability of 3 $m^3/h.m^2$. The calculated design loads are listed in Table 3. The fabric data were obtained from an outline specification written in April 2006 (JRHT 2006b).

Table 3 – Elm Tree Mews: Design Heating Loads & Energy Use (Watson & Hill 2006)

Dwelling	**Space Heating Load (kW)**	**Space Heating Energy Use (kWh/a)**	**Hot Water Energy Use (kWh/a)**
House C (Ground Floor Flat)	1.41	2280	1698
House E (Duplex)	1.87	3019	1939
House B (Mid Terrace)	2.20	3504	2100
House A (Mid Terrace)	2.20	3504	2100
House D (Mid Terrace)	2.20	3504	2100
House F (End Terrace)	2.86	5047	2222
TOTAL	**12.74**	**20858**	**12158**

21 The predicted total space heating load for all six Elm Tree Mews dwellings combined was 12.7 kW (Table 3). The predicted total space heating consumption for all six dwellings of 20,858 kWh is very close to the average annual gas consumption for a single UK dwelling, which was 20,111 kWh per household in 2003 (DTI 2006).

Design & Construction Timeline

22 The timeline for the key stages in the design and construction process at Elm Tree Mews is outlined in Table 4. The original construction timeline was for a build programme of 26 weeks beginning in November 2006 and with first occupation expected in July 2007. However, although construction started on time in November 2006, the actual construction programme took around 18 months due to additional ground works required above those planned for, and due to a range of construction issues, mostly linked to the erection of the timber frame structure. This meant that the

first houses were not occupied until June 2008, nearly a year after the planned date. The first construction delays occurred during the ground remediation process. This was due to a higher level of ground contamination than expected and the presence of additional underground fuel tanks that were not identified on the old site plans. Further delays occurred with the discovery of an unmarked fibre optic telecommunications cable which was found running across the middle of the site.

Table 4 – Elm Tree Mews Design and Construction Timeline

Stage in Design and Construction Process	Original Planned Date	Actual Date
"21st Century Suburban Homes" competition announced	n/a	February 2005
Competition awarded to winning architect	n/a	September 2005
Selection of GSHP as heating system option	n/a	May 2006
Main contractor appointed	n/a	July 2006 (2nd stage tender)
Site remediation/decontamination works commenced	November 2006	November 2006
Foundation groundworks commenced	January 2007	February 2007
Foundation groundworks complete	Early March 2007	March 2007
Main structure completed	Late March 2007	November 2007
Practical completion	July 2007	March 2008
Building handover to JRHT	July 2007	May 2008
Occupation by residents	July – August 2007	June 2008 (rented properties)

23 Problems with the construction of the timber frame first became apparent around April 2007 where there were issues related to the erection of the roof panels. There were also issues with water damage to the panels that occurred during a prolonged rainy period in June and July 2007. In order to allow the frame to dry out fully, the internal OSB sheathing and cellulose insulation were removed from all external and internal panels during August 2007. The OSB sheathing was replaced and new cellulose insulation injected into the panel cavities during November 2007. It was also necessary during this time to insert additional supporting structural timber members into some of the separating party wall panels. Practical completion of the buildings was in March 2008 with final handover in May 2008. The first residents moved in to the rented properties during June 2008

24 A photograph of the original Elm Tree Garage prior to demolition is shown in Figure 2. Photographs of the completed houses at Elm Tree Mews are illustrated in Figure 3 and Figure 4. A photograph of the adjacent Folk Hall is shown in Figure 5.

Figure 2 – Elm Tree Garage in New Earswick Prior to Demolition

Figure 3 – Completed Building at Elm Tree Mews (View from North West)

Figure 4 – Completed Building at Elm Tree Mews (View from South West)

Figure 5 – Folk Hall in New Earswick (adjacent to Elm Tree Mews)

25 A site plan of the Elm Tree Mews development is shown in Figure 6. The shows the location of Elm Tree Mews relative to the Folk Hall, as well as the position and codes for the six dwellings. The adjacent road to the east of the development is Haxby Road which leads to the centre of York.

Figure 6 – Site Plan for Elm Tree Mews

Design and Construction Retrospective

Interviews with Key Members of Design and Construction Team

26 A series of semi-structured interviews were undertaken with some of the key members of the design and construction project team in order to better understand the team dynamics and to obtain background information on aspects of the process that had not been directly observed by the research team. The protocol used for these interviews is given in Appendix 1. The project team members that were contacted for interview are listed in Table 5.

Table 5 – Design and Construction Team Members Contacted for Retrospective Interview

Project Team Member	Organisation
Director of Development & Property Services	Client
Deputy Director of Development & Property Services	Client
Development Services Manager	Client
Project Manager	Main Contractor
Site Manager	Main Contractor
Project Architect	Architectural Practice
M&E Engineer	M&E Consultancy
Structural Engineer	Structural Engineering Consultancy

27 In general terms, the interview responses indicated that, although team interactions and communications worked well, there were some specific communication issues and it was suggested that more frequent site project meetings would have been helpful in this respect.

28 A common theme given by the interviewees was that the fact that the architects main office was located in London and that they believed that this meant that the architect spent less time on site and was perhaps unable to address site problems as quickly than perhaps a locally-based architect.

29 There was a common sense of disappointment from the interviewees with respect to the delays to the construction programme and the problems that arose during the erection of the timber frame. It was suggested that some of these issues could possibly have been avoided or minimised with better communication and on-site quality control processes, a more detailed analysis of potential risks at the design stage and a more rigorous process for selection of key sub-contractors based on an assessment of evidence of past performance rather than simple recommendations.

30 Another key issue that arose from the interviews were the potential benefits of the M&E consultant being involved in the design process at a much earlier stage than was the case at Elm Tree Mews. It was believed that this delay resulted in design choices for fabric and services that, in some cases, were perhaps not as well integrated as they might otherwise have been. This was in part unavoidable at Elm Tree Mews due to the relatively unusual nature of the procurement process being based around a design competition.

Design Specification

31 Following their appointment to the Elm Tree Mews scheme, the architects worked up the specification and design based on their initial design submission for the Suburban Homes competition. The outline specification and performance targets are listed in specification documents written in 2006 (JRHT 2006b, 2006c). The critical energy performance aspects from this outline specification are given in Table 6.

Table 6 – Elm Tree Mews Preliminary Outline Energy Performance Specification

Ecohomes Rating	Excellent
Walls	U-value 0.18 W/m^{2}K, timber panel with 200mm cellulose insulation
Roof	U-value 0.13 W/m^{2}K, timber panel with 240mm cellulose insulation
Floor	U-value 0.20 W/m^{2}K, concrete beam/block floor with 90mm BASF Neopor EPS insulation
Windows	U-value 1.41 to 1.57 W/m^{2}K, BFRC Band C, Rationel Domus timber frame, double glazed
Ventilation	Passive stack ventilation
Air Permeability	3 m^3/h.m^2 maximum
Thermal Bridging	Not mentioned
Summer Overheating	Louvers, sliding shutter, deep eaves, secure night ventilation via windows

32 A detailed specification for Elm Tree Mews was issued by the architect in July 2006 (2006d). In the main, the key energy performance criteria are the same as in Table 6 with the exception of the windows which are given a slightly higher U-value of 1.6 W/m^{2}K. The detailed specification does not include the airtightness target. There is also no discussion of airtightness measures (such as requirements for sealing service penetrations or panel joints) or any specific design requirements that would be needed to achieve the air permeability of 3 m^3/h.m^2 given in the outline energy performance specification. No reference is made in the detailed specification of any requirements for accredited construction details or any other specific construction detailing or procedures relating to thermal bridging, continuity of thermal insulation or thermal bypassing.

33 The make up of the various timber frame panels is given in the detailed specification, and these are described in Table 7. It is interesting to note that the specification does not detail the spacing of I-beams within the panels or the expected timber fractions as these would be expected to be provided by the specialist timber frame manufacturer. The specification does not detail requirements for additional structural timber required as this information would have been provided by the timber frame manufacturer and structural engineer. The specification required that the

timber panels be kept dry on site both during storage and erection, but does not specify a method for how this should be achieved.

Table 7 – Timber Frame Closed Panel Construction in Detailed Specification

Panel Type	Panel Make Up
External Wall Panel	Outer layer 9mm OSB, 200mm I-beam with 200mm factory applied cellulose insulation, Inner layer 9mm OSB
Party Wall	Outer layer 9mm OSM, 90mm factory applied cellulose insulation, Inner layer 2x15mm plasterboard
Walls to external staircase enclosure	Outer layer 11mm OSB, 140mm I-beam (no insulation), Inner layer 11mm OSB
Party Floors	Upper layer 18mm OSB, 240mm I-beam with 240mm factory applied cellulose insulation, Lower layer none
Roof	Outer layer 11mm OSB, 240mm I-beam with 240mm factory applied cellulose insulation, Lower layer 11mm OSB

34 The original detailed specification did not require the installation of a vapour control layer (VCL) on the inside face of the timber panels. However, the drawings and specification were subsequently altered to include a polythene VCL membrane fixed to the inner face of the panels.

Heating System Design, Installation and Commissioning

35 The heating and hot water system specified at Elm Tree Mews was based on a communal heat pump heating system with solar thermal panels providing a proportion of hot water to each dwelling as outlined in Table 8 (JRHT 2006e). Three 115m deep vertical bore holes were drilled for the ground source piping loops in preference to horizontally laid slinky pipes or flat panel ground collectors, mainly due to the limited land availability at the site. The location of the bore holes in relation to the building and plant room is shown by the plan drawing in Figure 7. A schematic of the heating and hot water system is illustrated in Figure 8.

Table 8 – Elm Tree Mews Heating and Hot Water System Specification

Heat Pump	Kensa 24kW 3-phase communal heat pump located in plant room building and connected to district heating system. Pump consists of two 12kW individual heat pump units in series.
Ground Source	Three 115m deep bore holes.
Buffer Vessel	300 litre specially manufactured mild steel buffer tank. 60 mm sprayed polyurethane insulation.
Communal Heat Main	The communal heat main runs from the plant room along the front of the building. Pre-insulated Calpex Uno 40/91 district heating pipe (25mm PU insulation).
Communal Main Circulation Pump	Grundfos Magna D 32-120F twin stage circulation pump with automatic variable speed control. Power range 25W to 435W.
Solar Thermal Panels	Schott ETC16 evacuated tube solar panels. Each panel 1.3m^2 with 2 panels specified per dwelling. This was reduced to 1 panel only for the flats during the cost engineering process. Resol DeltaSol-BS solar heating controller.
Hot Water Storage	210 litre Santon Premier Plus Solar twin coil unvented cylinder with 3 kW immersion heater on manually operated time switch (Ventaxia 2 hour electronic timer). 45 mm PU insulation on cylinder
Underfloor Heating	Velta Classic 17 system (17mm PEX pipe) with manifolds supplying individual zones. Zone control using zone thermostats and Honeywell CM707 programmable heating controller/thermostat

Figure 7 – Schematic of Elm Tree Mews Showing Location of Bore Holes and Plant Room

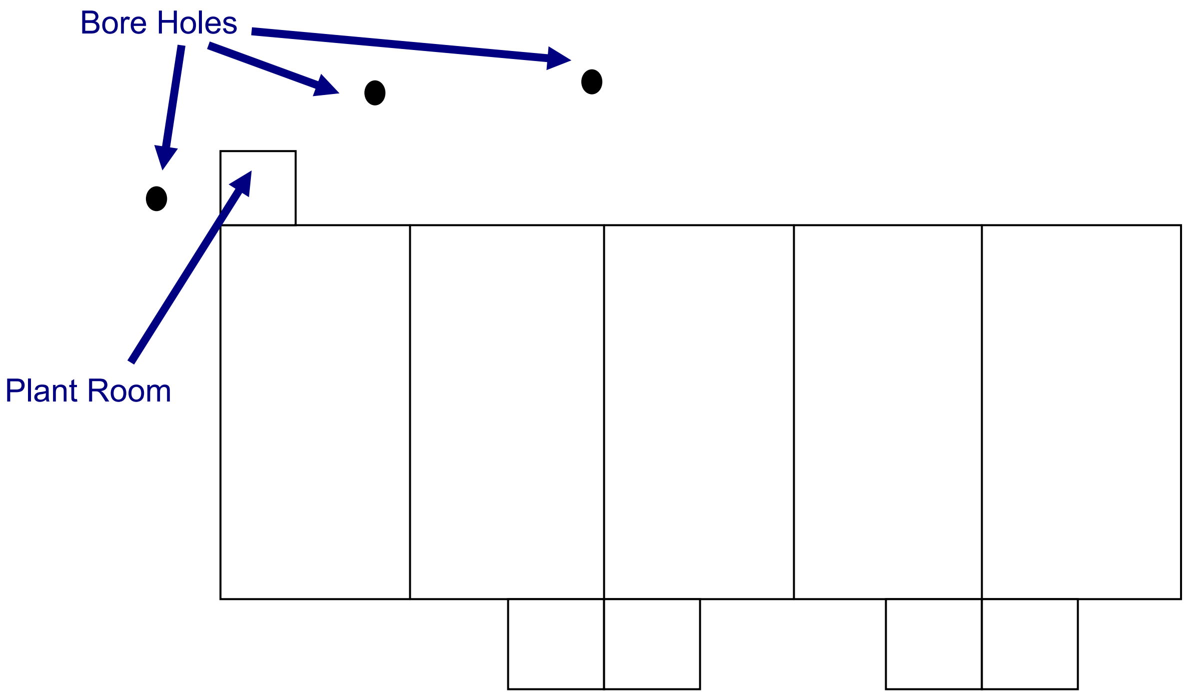
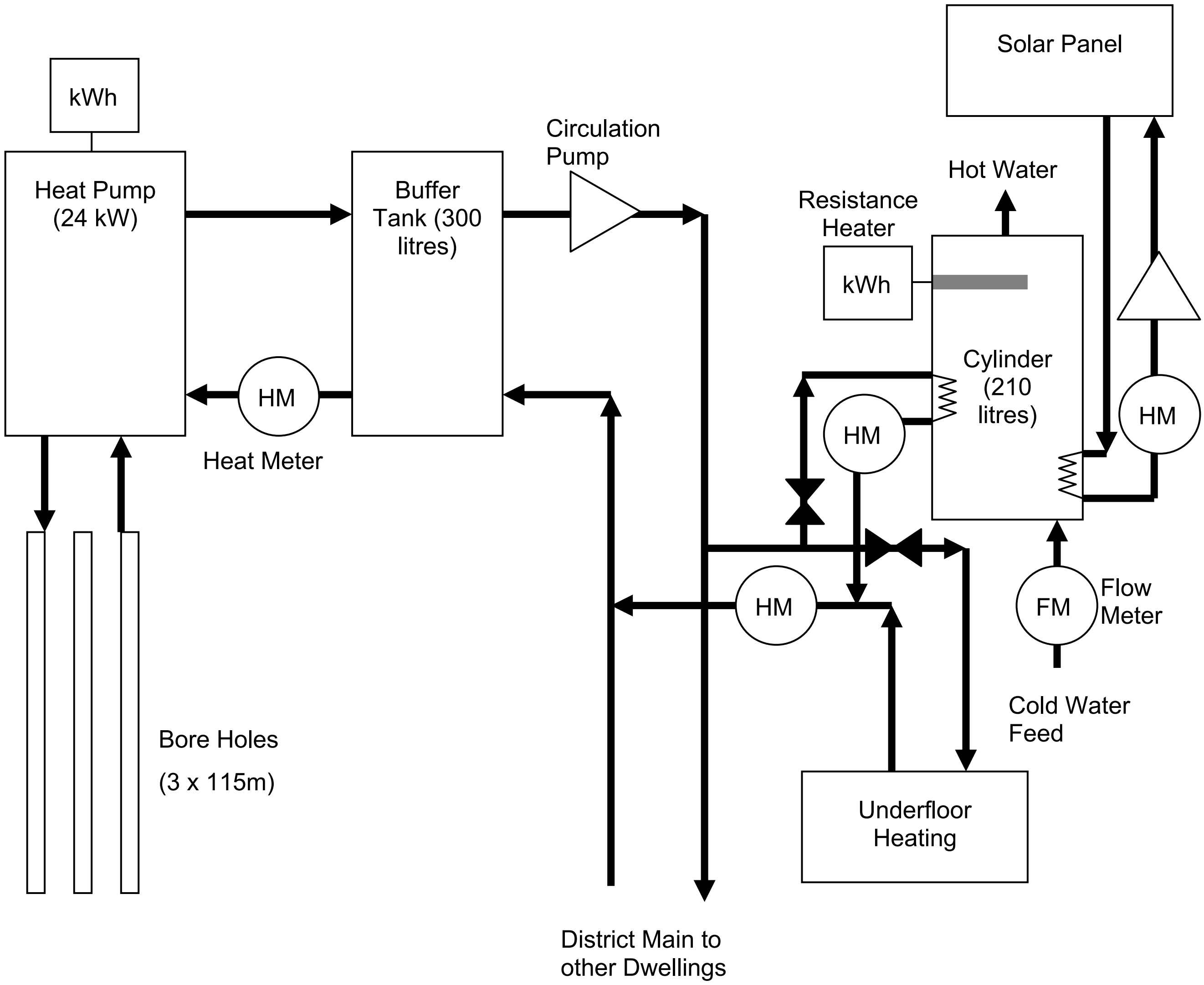


Figure 8 – Schematic of Heating and Hot Water System



36 Photographs of the plant room showing the heat pump system, buffer tank and other heating system components are shown in Figure 9, and Figure 10.

Figure 9 – Plant Room

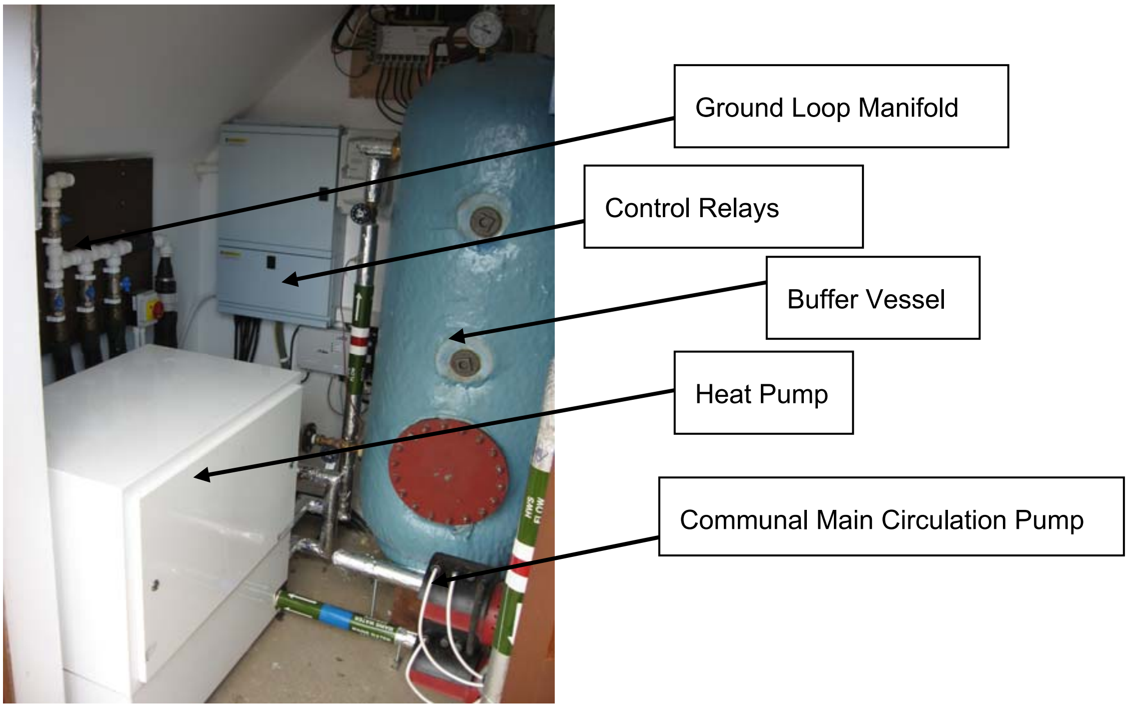
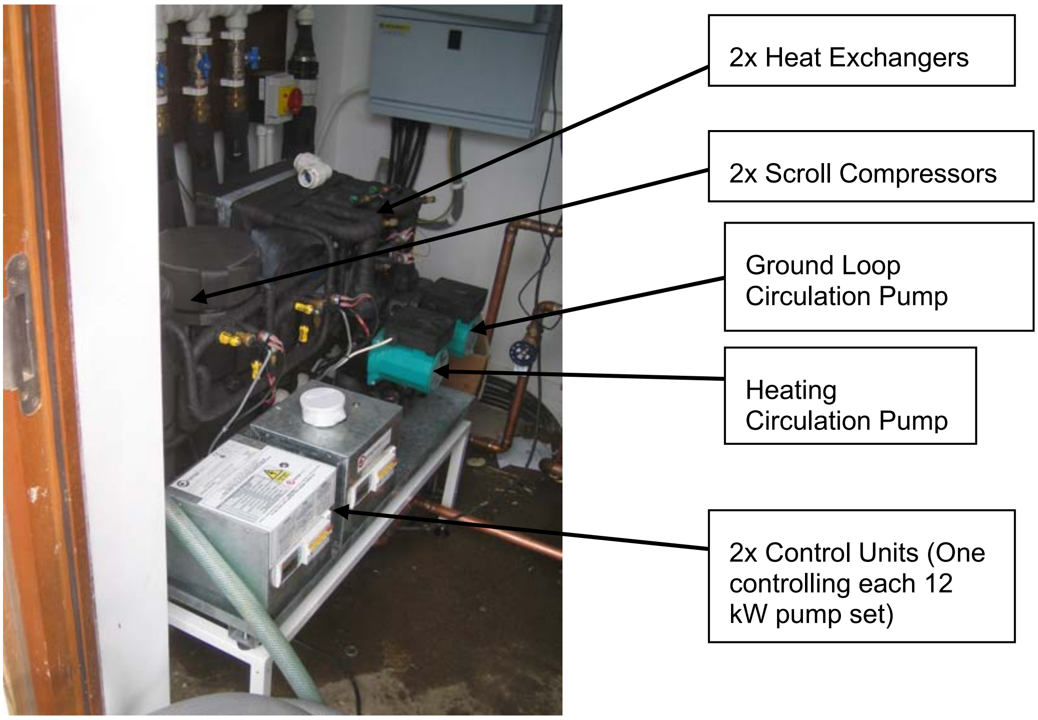


Figure 10 – Heat Pump Unit with Outer Casing Removed



37 The operation and control of the heating and hot water system can be summarised as follows:

a) The heat pump provides heated water to the buffer tank. Circulation is provided by a circulation pump inside the heat pump (Wilo Top S30/10 single phase pump with 3 speed settings at 345W, 390W and 400W). The purpose of the buffer vessel is to even out fluctuations in demand.

b) The operation of the heat pump is controlled by the return temperature of the water in the heating circulation system. The two control set points are the return temperature (pump on) and the temperature differential (temperature difference between pump on and pump off).

c) The heat pump is split into two 12kW compressor/heat exchange units which operate from independent electronic controllers. The system control points for return temperature in each controller are set such that only one compressor/heat exchange unit will operate when demand is low and both compressors/heat exchangers will operate when demand is high. This will reduce energy usage in low demand situations. The nominal return temperature set point recommended by Kensa is around 30°C (Kensa 2008a) which would be expected to give a flow temperature of around 35°C, depending upon the effectiveness of the ground source. (This is the factory setting for all units shipped by Kensa.)

d) Hot water is pumped from the buffer vessel and around the communal heat main by a twin head single phase variable speed circulation pump (Grundfos Magna Twin D32-120 F) with a power range of 25- 435W. The operation of the heat main circulation pump is controlled by a set of relays which receive signals from the two-way motorised valves on the heating and hot water circuits in each dwelling. When any of the two-way valves open in response to a signal from the dwelling heating or hot water controllers, then a relay switches on, activating the circulation pump. The speed of the pump is controlled by the head pressure in the communal heat main. The pump speed changes automatically in response to changes in hydraulic condition.

e) In each dwelling, a programmable thermostat heating controller (Honeywell CM707) operates the underfloor heating. When the heating timer is active, this operates the two-way motorised valve which allows hot water from the communal heat main into the heating system. The underfloor heating is zoned, with each zone controlled by individual thermostats which open and close the zone manifold valves as required.

f) The domestic hot water systems in the houses have a 210 litre twin coil unvented indirect cylinder (Santon Premier Plus Solar PP210B), with smaller 180 litre cylinders in the apartments. For the 210 litre cylinders, the dedicated solar volume is 63 litres and the auxiliary volume is 147 litres. The bottom coil is fed by the solar hot water circuit which is controlled by the solar controller (Resol DeltaSol-BS). The top coil is fed by the hot water from the communal heat main which is controlled by a hot water timer switch (Honeywell ST6100A) and the cylinder thermostat. When the hot water timer is active and the cylinder temperature is below the cylinder thermostat, then the two-way valve opens, allowing hot water from the communal main to heat the tank.

g) The cylinder also contains a 3kW immersion resistance heater located towards the middle of the cylinder. The immersion heater is activated by a manually operated 2 hour timer switch which can be used by residents to boost the hot water temperature. The timer can be set in 15 minute increments. Following concerns voiced by the research team, the hot water control design was adapted to prevent immersion resistance heating being used to heat the underfloor heating circuit. This involved adding a relay between the immersion heater timer switch and the Honeywell hot water controller circuit such that the hot water controller circuit will be interrupted if the immersion heater circuit is switched on.

h) The solar system in each dwelling uses Schott ETC16 evacuated tube panels. In the original design, all six dwellings were to have two solar panels each, but to reduce construction costs the number of panels on the flats was reduced to one each. The area of each panel is 1.3m^2 with an aperture area of 0.808m^2. The manufacturer's data sheet quotes an expected annual yield for hot water of 730 kWh per m^2 of aperture based on exposure conditions in mid-Germany (Schott 2008). The heat exchange fluid used in the solar hot water system was Tyfocor GLS which is based on 1,2-propylene glycol. The solar pump is a three speed model (DAB VA55/130 pump with 3 speed settings at 45W, 64W, 82W) which has been set to the lowest speed setting. A flow regulator located next to the pump controls the overall flow rate (nominal setting 1 litre/min). The operation of heat input from the solar panel to the cylinder is controlled by the solar controller (differential temperature controller) and three temperature sensors (one at the panel, one in the cylinder by the solar coil and one on the hot water flow pipe at the top of the cylinder). When the temperature in panel exceeds the cylinder temperature by the switch-on temperature differential (factory setting 6°C), then the controller switches on the solar pump. When the temperature in panel falls below the cylinder temperature by the switch-off temperature differential (factory setting 4°C), then the controller switches off the pump.

i) Energy consumption from the heat main used by each dwelling is measured by a heat meter (Landis and Gyr 2WR5 ultrasonic heat meter) located at the point of entry of the communal main into the dwelling. The residents at Elm Tree Mews are charged per kWh of heat that they use. Usage data from the heat meter in each dwelling is sent by M-bus communication protocol to a wired centralised energy logger in the plant room. JRHT have subcontracted the billing services to an energy management company. The energy management company download the meter readings daily via a modem attached to the logger. At the time of writing this report, the cost of heat charged to the residents was 4.474 p/kWh, together with an annual standing charge of £12.74 per dwelling.

j) Energy monitoring of the plant room includes a heat meter on the output from the heat pump (Landis and Gyr 2WR5 ultrasonic heat meter), a kWh meter on the 3-phase supply to the heat pump and a kWh meter on the 1-phase supply to the communal main circulation pump.

38 The commissioning of the ground source heat pump system was carried out by the heat pump subcontractor. This was conducted immediately after installation of the heat pump and before the communal heat main had been finished. This meant that, for the purposes of heat pump commissioning, the system was only being used to heat the water in the buffer vessel. The control settings on commissioning are shown in Table 9. These settings were changed (see Table 9) on the 12th May after a follow up visit by the subcontractor in conjunction with the M&E consultant (observed by the research team). The return temperature settings were reduced to improve CoP, and the temperature differentials increased to minimise the likelihood of short cycling. At the same time, the power setting on the hot water circulation pump inside the heat pump was reduced to its lowest setting of 345W. A return temperature of around 40°C will give a flow temperature of around 45°C. The heat pump start-up set point for the primary system is given by the return temperature set point minus the temperature differential (40.5-3.5 = 37°C). The heat pump switch-off set point for the primary system is given by the return temperature set point (40.5°C).

Table 9 – Heat Pump Commissioned and Revised Control Set Points

	Commissioned Setting (°C)	**Changed Settings after Visit on 12/5/08 (°C)**
Return Temperature on Secondary Compressor (Left Hand Side)	40.0	38.0
Return Temperature on Primary Compressor (Right Hand Side)	41.5	40.5
Temperature Differential on Secondary Compressor (Left Hand Side)	3.6	4.0
Temperature Differential on Primary Compressor (Right Hand Side)	3.0	3.5

39 The nature of the installation and commissioning of the various systems meant that there were no procedures or protocols to check the overall combined operation of the heating and hot water system.

Initial Performance of Heating System

40 Meter readings were taken in the plant room every couple of weeks following installation. These data were used to calculate the Coefficient of Performance (CoP) as shown in Table 10. It can be seen that the simple heat pump CoP ranged from 2.7 to 2.5 (getting lower over time) and the plant room CoP including the energy from the circulation pump ranged from 2.4 to 2.1 (again getting lower over time). This compares to the manufacturers stated average pump CoP of 3.5 and the nominal heating CoP used in SAP2005 of 3.2. It should be noted that during this period none of the dwellings were occupied and that these data will also include factors relating to the commissioning and installation process. These CoP data should therefore be considered with this in mind.

Table 10 – Heat Pump Measured Coefficient of Performance – Running Total CoP

Date	**Heat Pump Heat Output (kWh)**	**Heat Pump Energy Consumption (kWh)**	**Circulation Pump Energy Consumption (kWh)**	**Heat Pump Simple CoP**	**Heat Pump CoP including Circulation Pump**
02/05/2008	9122	3415	459.0	2.67	2.35
12/05/2008	9279	3548	563.9	2.62	2.26
23/05/2008	9652	3747	584.9	2.58	2.23
05/06/2008	9960	3937	598.8	2.53	2.20
11/06/2008	9968	3982	600.1	2.50	2.18
17/06/2008	10110	4070	611.0	2.48	2.16
26/06/2008	10316	4201	614.8	2.46	2.14

41 The distribution loss from the communal heating main for the period from installation to the first meter readings on the 2nd May 2008 was calculated from the difference in the total heat pump output (9122 kWh) and the sum of the incoming heat meters to all six dwellings on the 2nd May (7650 kWh). This means the heat loss from the communal main was 1472 kWh. The system CoP for the initial period is given by the sum of the dwelling heat meters divided by the total energy input (heat pump electricity + circulation pump electricity). This system CoP takes account of any distribution losses and also accounts for any heat input arising from the circulation pump. The system CoP for the period to 2nd May 2008 was therefore 1.98.

42 The variation in heat pump performance for the periods in between each set of meter reading is summarised in Table 11. It can be seen in Table 11, that the circulation pump energy for the first 10 day period (2nd May to 12th May) was very high at 104.9 kWh. This indicated that, over this period, the communal main circulation pump was operating at its maximum speed and power (435W) for 100% of the available time. The relays for the heating system were checked and found to be all in the open position, which explained why the pump was operating full time. Further analysis of the way the system had been installed and set up indicated two issues. Firstly, in all dwellings, the cylinder thermostat connected to the heating controller for the heat pump input to the secondary coil had been left at it factory default setting of 60°C. This meant that, as the heat pump could only ever supply hot water at a maximum temperature of 45°C, then at a thermostat setting of 60°C the hot water controller would always be demanding heat. This issue was overcome by adjusting the cylinder thermostat in all dwellings to 45°C. The second issue was identified after the change to the thermostat settings. It was found that the control relay for one of the dwellings was permanently in the on position, even when both heating and hot water controller were off. This was found to be as a result of faulty wiring of the relay and was subsequently rectified by the M&E subcontractor. The meter readings for the periods following these changes show much reduced energy consumption for the communal circulation pump, with mean pump power ranging from 9W to 79W. The occurrence of these faults indicates that the commissioning procedure for the heating system was not sufficiently robust. This could have been as a result of a lack of planning, poor communication or insufficiently detailed system specification. It is clear that the commissioning procedures for relatively complex heating systems such as that at Elm Tree Mews will need to be more detailed and comprehensively planned than those for a dwelling heated by a conventional gas boiler.

Table 11 – Initial Heat Pump CoP over Different Meter Reading Periods

Date Range	Number of Days	Heat Pump Heat Output (kWh)	Heat Pump Energy (kWh)	Circulation Pump Energy (kWh)	Heat Pump Running Simple CoP
02/05/2008 to 12/05/2008	10	157	133	104.9	1.18
12/05/2008 to 23/05/2008	11	373	199	21.0	1.87
23/05/2008 to 05/06/2008	12	308	190	13.9	1.62
05/06/2008 to 11/06/2008	6	8	45	1.3	0.18
11/06/2008 to 17/06/2008	6	142	88	10.9	1.61
17/06/2008 to 26/06/2008	9	206	131	3.8	1.57

43 It can be seen from Table 11 that the CoP values are very low, typically around 1.6. The period that stands out the most is that from the 5th June to the 11th June when the CoP was only 0.18. During this 6 day period the heat pump output was only 8 kWh, whilst the heat pump energy consumed was 45 kWh. The energy used by the communal main circulation pump during this time was only 1.3 kWh. This indicates that over this period there was no heat demand from any of the dwellings and that therefore the energy must have been consumed by the internal heating circulation pump within the heat pump itself running virtually full time (at 345W) and circulating hot water between the heat pump and buffer vessel. When questioned by the research team, Kensa stated that their heat pumps have been designed such that the internal circulation pump will always run all the time. This same issue has been picked up in a previous study of the performance of an IVT heat pump in

a single dwelling (BRECSU 2000), where an 87 W distribution pump was found to run continuously even when the system was not calling for heat. The M&E consultant for Elm Tree Mews investigated options to change the controls so that the internal circulation pump would switch off when there was no heat demand from any of the dwellings and these options are discussed later.

44 It is perhaps interesting to note that Kensa do not themselves recommend the use of buffer vessels with their heat pumps. Kensa argue that, although buffer tanks may be suitable for systems such as non-condensing oil boilers with high turn down ratios (50%) in order to avoid short cycling, the benefits are less for heat pumps where the turn down ratios are as low as 25% (Kensa 2008b). Kensa state that the use of buffer tanks in conjunction with heat pump systems that use return flow temperature as the control can give rise to cycling.

45 The heating systems in all six dwelling were fitted with a range of kWh meters and heat meters in preparation for the monitoring phase of the project. These meters are listed in Table 12. When visiting Elm Tree Mews during May and June 2008, the research team took the opportunity to take meter readings from the dwelling heat meters for all of the properties that were accessible (data given in Table 13).

Table 12 – Energy Monitoring in Dwelling

Dwelling Energy Use	Meter and Location
Supply Electricity	Secondary kWh meter (Iskra ME160 pulse output), Located next to consumer unit
Incoming Heat Main Energy	Heat meter on incoming supply (Landis & Gyr 2WR5 pulse output), Located in under stairs cupboard
Immersion Heater Energy	kWh meter (Iskra ME160 pulse output), Located in cylinder cupboard
Heat Pump DHW Energy	Heat meter (Landis & Gyr 2WR6 pulse output), Located in cylinder cupboard
Solar DHW Energy	Heat meter (Landis & Gyr 2WR6 pulse output), Located in cylinder cupboard
Hot Water Usage	Flow meter (Unico Qn2.5 pulse output) on cold water input to cylinder

46 It can be seen from the heat meter readings in Table 13 that there are some significant differences in the relative performance of the different dwellings. Some of this will be due to the fact the heating and hot water systems were installed and commissioned at slightly different times and also that some of the internal controls (heating timers, thermostats) would have been left at different settings. However, as none of the houses were occupied during this time any differences cannot be due to occupancy or usage effects. Of most interest is the dramatic difference between dwellings in the measured output of the solar hot water systems. This is most apparent in the difference between the solar heat meter readings in House F (ranging from 96 kWh on 1/5/08 to 285 kWh on 26/6/08) and House D (ranging from 2 kWh on 1/5/08 to 22 kWh on 26/6/08). Given that the solar systems in House F and D are identical, this indicates either a problem with the solar heating system in House D or a fault with the solar system heat meter in House D.

Table 13 – Dwelling Heat Meter Readings

	Dwelling	1/5/08	2/5/08	12/5/08	5/6/08	11/6/08	17/6/08	26/6/08
Incoming Heat Meter Reading (kWh)	**House F**	1864	1870			2263	2277	2277
	House D	1470	1473	1480		1698	1765	1875
	House A	1584	1592					
	House B	919	924					
	House C	819	839	839				
	House E	922	952					967
Heat Pump DHW Heat Meter Reading (kWh)	**House F**	25	26		29	29	31	31
	House D	26	27	30	32	33	34	34
	House A	23	24					
	House B	18	18					
	House C	8	9	12				

	House E	5	5					5
Solar DHW Heat Meter Reading (kWh)	**House F**	96	100		215	231	265	285
	House D	2	3	7	13	16	21	22
	House A	13	14					
	House B	51	54					
	House C	20	20	24				
	House E	14	15					94

Initial Performance of Solar Hot Water System

47 The main components of solar hot water system (solar panel, solar pump and controller) were installed by the solar heating subcontractor. The other key components of the domestic hot water system such as the cylinder, heat pump connection to cylinder, plumbing connections, timers, valves, electrical connections and the insulated pipework between the solar panel and cylinder were installed by the main M&E subcontractor (see Figure 11 and Figure 12 for photographs of cylinder cupboard and solar system components). The solar systems were filled with Tyfocor GLS heat exchange fluid at the end April 2008, when all other parts of the hot water system had been completed. The solar system commissioning certificates indicated that all six systems were operating correctly.

48 Concerns were raised about the performance of the solar system very soon after commissioning. Readings from the solar heat meters at the start of May showed a significant difference between the recorded solar inputs to the different dwellings. In particular, the solar heat meter readings in House D and House A are significantly below the other four dwellings. Observations made by the research team in House D in the first week of May suggested that the solar heat pump was short cycling and that the solar system pressures were only around 1 bar (compared to around 2.5 bar in House F). Initial diagnosis by the solar subcontractor indicated that there were no obvious faults and that all flow rates, flow temperatures, cylinder temperatures and pressures were operating within normal parameters. The research team subsequently conducted a short monitoring study on the solar systems in House F and House D between the 11th June and the 17th June in order to gather more data. The monitoring data confirmed that the solar pump in House D was short cycling at a frequency of around 1 minute (see graph in Figure 13) and was using around 2.6 kWh/day in electricity to run the pump compared to only 0.6 kWh/day for the pump in House F. It was also found that the heat up rate of the cylinder was much slower in House D than in House F. The underlying reason for the low heat meter readings in House D was thought to be related to the solar system delivering lower heat to the cylinder compared to House F together with the solar heat meter under recording the heat input to the cylinder (this is discussed further later in the report)..

Figure 11 – Cylinder Cupboard showing Heat Meters and Air Separator

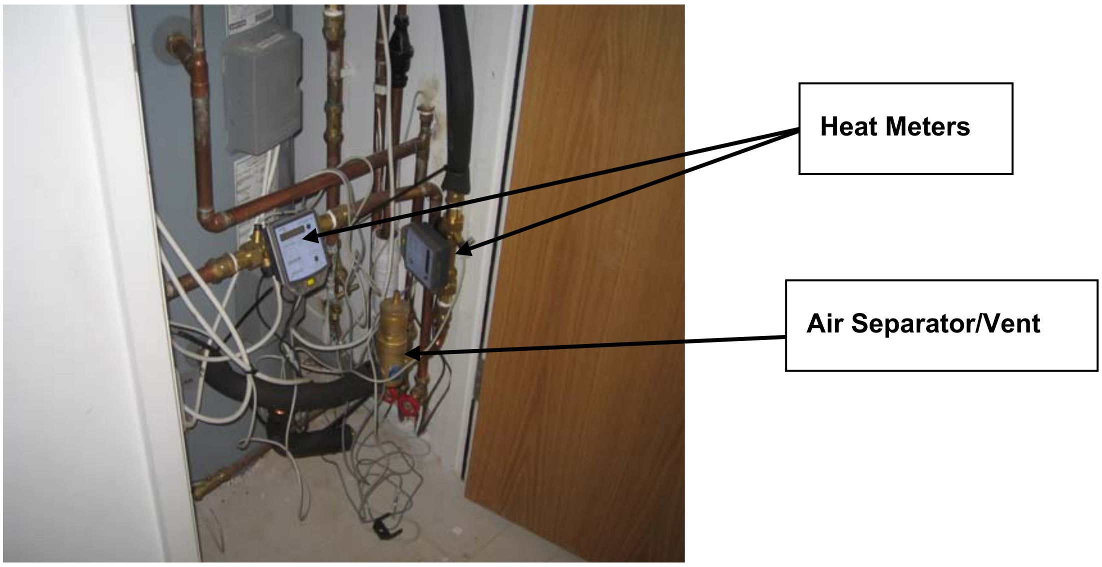


Figure 12 – Cylinder Cupboard showing Solar Pump, Filling Valves & Regulator

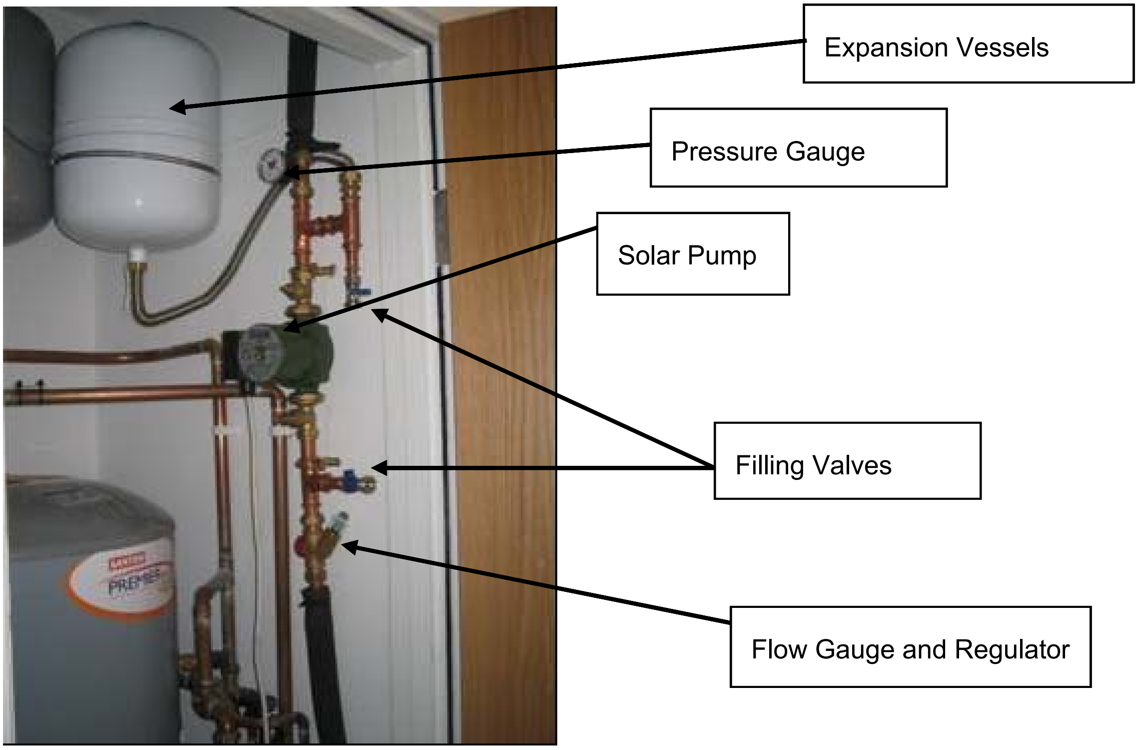
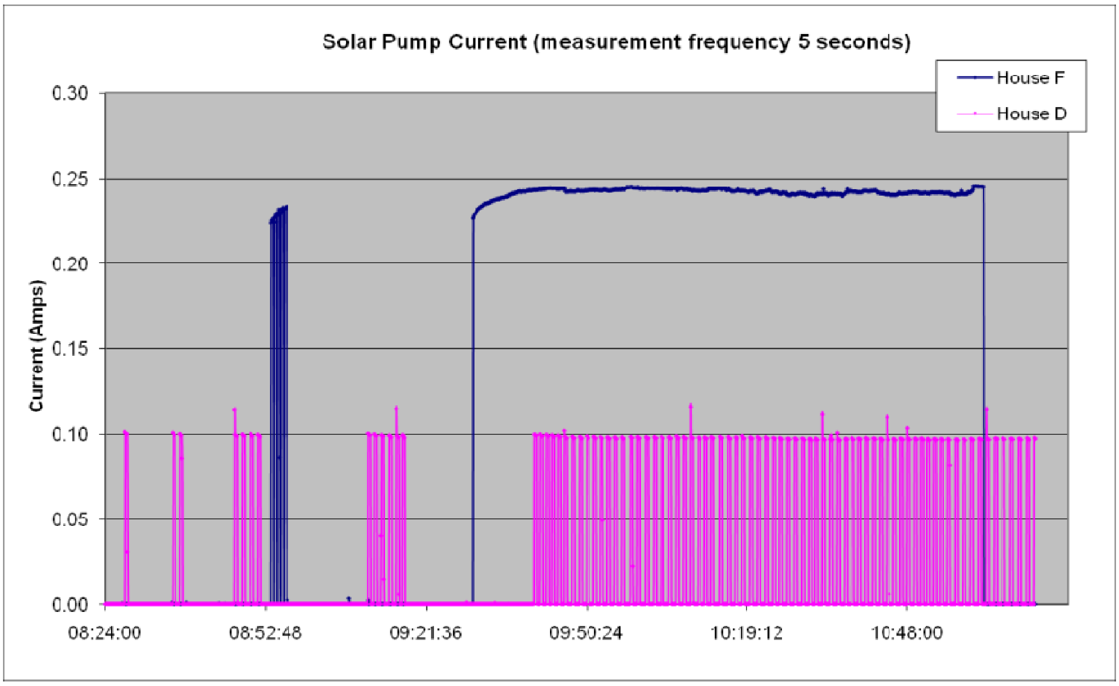


Figure 13 – Solar Pump Current House F and House D



49 In the light of the more detailed monitoring data, further investigations were carried out by the solar subcontractor using a more rigorous approach to diagnosis involving re-pressurising the system and using the external filling pump to monitor flow of the solar heat exchange fluid bypassing the solar pump. It is now known that there was a flow restriction in the solar circuit. This diagnosis correlates well with the observed low system pressures and pump cycling behaviour. Based on the meter reading data, a similar problem could exist in the solar system in House A and perhaps to a lesser extent in any of the other four dwellings. The pipework used to link the solar panels with the cylinder was 15mm malleable copper that had been pre-insulated with foam insulation (see Figure 14). Where this pipework had been bent to take it around corners then there is the possibility that any potential kinks may be disguised by the layer of insulation, and this was subsequently found to be the case.

Figure 14 – Solar System Pipework

50 Another issue was identified following measurements of the solar system in House E (duplex flat). Although the initial solar heat meter data for House E taken in May 2008 (see Table 13) indicated that the system was working according to expectations, a subsequent visit in June 2008 found that the cylinder had gone cold (cylinder temperature was 30°C) and that the system pressure had dropped. Further investigations by the solar engineer indicated that at some point in time following installation, the solar system had overheated and the system had released heat exchange fluid onto the roof via the pressure release valve. This problem was probably caused by the fact that the house had been unoccupied during a period of very sunny weather and that, as there was no hot water demand during this period, the only way for the system to protect itself was to release pressure. The system had to be re-pressurised with additional antifreeze solution. This risk could have been minimised with an automatic drain back facility, but this would have added cost to the installation. Alternatively, options in the solar controller, if active, could have reduced the risk by allowing the cylinder to heat to above 60°C during the day (and below the maximum safe limit) and then allow the solar pump to run in the evening to cool the cylinder down by using the solar panel as a heat sink. The system could also have been designed with the hot water system connected via controlled valves to the towel radiator in the bathroom, which could then be used as a heat sink in overheating situations. It would have also been beneficial if the client had been made aware of the potential so that occasional visits could have been made to unoccupied properties to draw off water and provide some heat demand for the system during sunny periods.

51 Another incident with the solar system that was observed during the filling of the solar circuit in House F highlights the potential benefit of using dedicated service risers to protect service pipe runs and allow easy access for maintenance. When the solar engineer began to fill the system in House with the heat exchange fluid it was found that there was a some damage to the solar pipework hidden somewhere either in the floor void or wall cavity. This was allowing substantial quantities of heat exchange fluid to leak out. The contractors had to pull down large sections of ceiling and wall plasterboard in order to locate the source of the leak. The leak was eventually found to be caused by a nail that punctured the solar pipe. The nail had been used to affix a piece of skirting board adjacent to where the vertical section of solar pipe ran up along the party wall. This situation could likely have been avoided with clearly labelled service ducts. It would have also been advantageous for the service risers and service floor voids had been designed with removable access panels which would have made tracing the source of the leak less damaging to the building. This would of course also make future maintenance easier. The inclusion of combined service risers and service floor voids is something that would have to be carried out at an early stage in the design process as it would require the optimal placement of plumbing service routes, wet rooms, cylinder cupboards, ventilation ducting and plant room areas.

52 The problems with the set-up of the solar system at Elm Tree Mews are further evidence of limitations in the commissioning process. This will be linked both to the complexity of the combined heating/hot water system and also to the way that the various contractors and subcontractors

worked together. The heating system at Elm Tree Mews is much closer to one that would be found in an office building than in a normal domestic property. The Probe studies of non-domestic buildings (Bordass, Leaman & Ruyssevelt 1999) have concluded that, although it is preferable to get the systems right first time, this is not always possible in very complex buildings and that "sea trials" of the building systems should be planned for and carefully monitored during the initial stages of occupation. It is likely that an approach such as "Soft Landings" framework (BSRIA 2009) would have been more appropriate for Elm Tree Mews than the traditional commissioning process used in housing.

Control of Legionella Bacteria

53 The original design of the hot water system did not appear to include any specific system measures to control legionella bacteria. The Approved Code of Practice and Guidance (ACOP) for the control of legionella (HSE 2000) provides guidance on system controls for hot water systems. Recent legislation changes (HSE 2003) mean that all providers of residential accommodation, including housing associations such as the Joseph Rowntree Housing Trust, are required to assess the risk of exposure to legionella bacteria and introduce appropriate prevention or control measures for any rented accommodation where the housing provider is responsible for the maintenance of the hot water system or provision of hot water. One of the key conditions for the multiplication of legionella bacteria is where hot water is stored between 20°C and 45°C (HSE 2000). The nature of the original design of hot water system at Elm Tree Mews was such that there was no control system that would guarantee to maintain the hot water stored in the cylinder at above 45°C. This would be most critical during the winter and swing seasons when the level of solar input into the cylinder will be low and the hot water system will rely on to a great extent the heat provided by the heat pump, which will have a relatively low flow temperature of between 40°C and 45°C. There is an electric immersion heater in the cylinder, but this is only activated by a manually operated 2 hour timer. The advice given in the ACOP for hot water systems recommends a thermal control procedure such that the whole water content of a calorifier is stored at a temperature of 60°C and that the water distribution system is designed such that water is delivered to the outlets at 50°C within 1 minute of operating a tap. Alternative control strategies could include the use of inspection regimes in conjunction with the regular use of biocide water treatments, ionisation or UV/ozone treatment. Following further work by JRHT and the contractors a solution to the issues of legionella was implemented at Elm Tree Mews that involved the installation of a shunt pump on the cylinder together with a 7 day immersion timer. This was set initially to give a weekly 4 hour pasteurisation cycle at 60°C. An ongoing programme of water checks is in place to monitor the water quality, and this is reviewed by JRHT on a regular basis.

Ventilation System

54 The ventilation system used for the dwellings at Elm Tree Mews consisted of individual extract fans (Ventaxia LoWatt WCBH and LoWatt Solo) located in the wet rooms (bathrooms and toilets) and either mounted through the wall or though the ceiling. There was also an extract cooker hood located in the kitchen. The extract fans were equipped with humidistat sensor controllers (Ventaxia Humidistat 563550) and manual override pull cord switches. No measurements were undertaken by the research team of the performance of the fans. It is interesting to note that the guidance in Part F of the building regulations (ODPM 2006) states that, although humidistat controller intermittent fans are suitable for use in moisture generating rooms they are not suitable for use in sanitary accommodation where the dominant performance requirement is one of odour control. However, in this case there is a manual override. In addition, the Lifetime Homes specification at Elm Tree Mews requires that the downstairs toilet should be upgradeable that a shower cubicle can be installed at a future date, so it is entirely appropriate that a humidistat control is installed in the WCs from the outset.

Predicted Energy Performance

55 The SAP2005 energy calculations for the 4 different dwelling types at Elm Tree Mews (using data contained from the provisional SAP2005 calculations) are summarised in Table 14 (with data from the design check sheet shown in parentheses) and the final submitted SAP 2005 calculations are summarised in Table 15. The calculations were carried out by using NHER Plan Assessor software (Preliminary calculations used NHER Plan Assessor V1.0.2 and the final calculations used NHER Plan Assessor V 4.0.28). The final submitted calculations used the measured air permeability rates (see section on pressure test results in Table 17). The official energy performance certificates for the four different dwelling types (based on the final SAP calculations) are shown in Appendix 2.

56 There are some inconsistencies in the SAP worksheet data. For example, the quoted cylinder size in the worksheet is 420 litres whereas the actual cylinder size is 210 litres (bottom solar capacity 63 litres and top secondary capacity 147 litres). The water heating efficiencies in the SAP worksheets are 152.4% for houses F, C and E and 224% for houses A, B and D. It would have been expected that the water heating efficiency would have been the same for all 6 dwellings. According to the requirements of SAP2005 (BRE 2005) the water heating efficiency would be either 320% (from Table 4a of SAP2005) multiplied by the efficiency adjustment of 0.7 in Table 4c of SAP2005 (which would be 224%) or alternatively would be the value calculated according to the equation in Appendix G1.1 of SAP2005 which would be 152.4%. Part of the problem here is that none of the water heating options available in SAP2005 actually match the situation at Elm Tree Mews where the primary water heating is supplied by solar water heating and there is secondary heating from both the heat pump and an electric immersion heater. The effect of the discrepancy in the water heating efficiency (224% versus 152.4%) on total predicted carbon emissions would be significant. Using the Leeds Met Parametric Domestic Energy Calculator (Lowe, Wingfield, Bell & Roberts 2008) the DER for the end terrace would be 14.9 $kgCO_2/m^2$ at 224% and 16.6 $kgCO_2/m^2$ at 152.4%, a difference of 1.7 $kgCO_2/m^2$.The discrepancies in the SAP calculations were due to input errors into the NHER software. However, it is also apparent that the nature of the software input fields and the information provided by the software at the point of input does not make clear the impact of the choice of response. This problem also highlights the limitations of SAP in its current form with respect to complex heating systems. These limitations will need to be addressed in future revisions of SAP and software implementations will also need to give due regard to user advice for situations that do not quite match SAP assumptions. Input errors in submitted SAP data are not unusual, with a recent study of Part L compliance showing errors in 68% of SAP assessments in a sample of 82 (Trinick, Elliott, Green, Shepherd & Orme, 2009).

Table 14 – Summary of Submitted Provisional SAP2005 Worksheet and Design Check Data

	House F	House No A, B, D	House C	House E
Dwelling Type	3 storey end terrace	3 storey mid terrace	1 storey ground floor	2 storey duplex
Gross Floor Area (m^2)	113.34	107.1	53.3	76.5
Exposed Area (m^2)	247.0	161.59	101.3	147.7
Dwelling Volume (m^3)	277.73	262.16	127.92	174.48
Thermal Bridging y-value (W/m^2K)	0.08	0.08	0.08	0.08
Air Permeability ($m^3/h.m^2$)	10	10	10	10
Ventilation	natural	natural	natural	natural
Cylinder Volume (litres)	420 (210)	420 (210)	420 (210)	420 (210)
Space Heating Efficiency (%)	320	320	320	320
Water Heating Efficiency (%)	152.4	224	152.4	152.4
Fabric Heat Loss (excluding thermal bridging) (W/K)	81.24	53.87	40.53	49.02
Thermal Bridging (W/K)	19.76	12.93	8.1	11.82
Ventilation Heat Loss (W/K)	62.09	56.56	35.44	38.18
Heat Loss Coefficient (W/K)	163.09	123.36	84.07	99.02
Heat Loss Parameter (W/m^2K)	1.44	1.15	1.58	1.29
TER ($kgCO_2/m^2$)	31.29	26.59	35.76	32.55
DER ($kgCO_2/m^2$)	14.42 (16.94)	11.26 (13.48)	19.04 (21.69)	15.22 (17.66)
SAP Rating	80.53 (80.53)	85.37 (85.37)	82.13 (82.13)	82.9 (82.9)
Space Heating Energy (kWh)	1780.2	1248.0	900.9	1117.75
Water Heating Energy (kWh)	1380.85	906.6	1061.06	1095.19

Table 15 – Summary of Submitted As-built SAP2005 Worksheet Data

	House F	**House No A, B, D**	**House C**	**House E**
Dwelling Type	3 storey end terrace	3 storey mid terrace	1 storey ground floor	2 storey duplex
Gross Floor Area (m^2)	113.34	107.1	53.3	76.5
Exposed Area (m^2)	247.0	161.59	101.3	147.7
Dwelling Volume (m^3)	277.73	262.16	127.92	174.48
Thermal Bridging y-value (W/m^2K)	0.08	0.08	0.08	0.08
Measured Air Permeability ($m^3/h.m^2$)	6.8	6.8	8.6	6.2
Ventilation	natural	natural	natural	natural
Cylinder Volume (litres)	420	420	420	420
Space Heating Efficiency (%)	320	320	320	320
Water Heating Efficiency (%)	152.4	224	152.4	152.4
Fabric Heat Loss (excluding thermal bridging) (W/K)	81.24	53.87	40.53	49.02
Thermal Bridging (W/K)	19.76	12.93	8.1	11.82
Ventilation Heat Loss (W/K)	54.77	50.64	33.22	33.59
Heat Loss Coefficient (W/K)	155.77	117.44	81.85	94.43
Heat Loss Parameter (W/m^2K)	1.37	1.10	1.54	1.23
DER ($kgCO_2/m^2$)	14.34	11.20	19.59	15.46
SAP Rating	81	86	81	83
EI Rating	86	89	86	87
Space Heating Energy (kWh)	1646.41	1152.82	860.34	1030.07
Water Heating Energy (kWh)	1495.38	986.48	1170.40	1225.34

57 As a comparison with the submitted SAP data, the Leeds Met Parametric Domestic Energy Model was used to calculate the carbon emissions for House F (end terrace) and Houses D, A and B (mid terrace) using the assumed design data. The resultant data are shown in Table 16. The dwelling emission rates were calculated to be 14.9 $kgCO_2/m^2$ for the end terrace and 13.5 $kgCO_2/m^2$ for the mid terraces. When the measured air permeability (6.8 $m^3/h.m^2$) is used instead of the default 10 $m^3/h.m^2$, these DER values drop to 14.4 $kgCO_2/m^2$ for the end terrace and 13.0 $kgCO_2/m^2$ for the mid terraces. It is also interesting to note that the space heating energy predicted using the Leeds Met Parametric Model was around 400 kWh higher than the data in the submitted SAP2005 calculations, which is probably a function of internal gains arising from the additional losses from the 420 litre cylinder assumed in the submitted SAP2005 calculation, rather than the 210 litre cylinder actually used. These discrepancies do not make any difference in terms of compliance with building regulations as the DER for the dwelling as designed would be significantly less than the TER in all cases. The predicted solar fraction (proportion of annual domestic hot water demand derived from solar energy) in both cases was only 0.26 meaning that 74% of the annual energy required for hot water will have to come from either the heat pump or the electric resistance heater in the cylinder.

Table 16 – Carbon Emissions Predicted using Leeds Met Domestic Energy Model

	House No F	House No D, A, B
Dwelling Type	3 storey end terrace	3 storey mid terrace
Gross Floor Area (m^2)	113	107
Exposed Area (m^2)	247.0	161.6
Dwelling Volume (m^3)	315	307
Thermal Bridging y-value (W/m^2K)	0.08	0.08
Air Permeability ($m^3/h.m^2$)	10	10
Ventilation	natural	natural
Cylinder Volume (litres)	210	210
Dedicated Solar Volume (litres)	63	63
Space Heating Efficiency (%)	320	320
Water Heating Efficiency (%)	224	224
Fabric Heat Loss (including thermal bridging) (W/K)	98.3	64.9
Thermal Bridging (W/K)	19.8	12.9
Ventilation Heat Loss (W/K)	65.3	63.7
Heat Loss Coefficient (W/K)	163.5	128.6
Heat Loss Parameter (W/m^2K)	1.4	1.2
TER ($kgCO_2/m^2$)	30.0	26.9
DER ($kgCO_2/m^2$)	14.9	13.5
Solar Hot Water Fraction	0.26	0.26
Space Heating Energy (kWh)	2035	1516
Water Heating Energy (kWh)	1005	968

Fabric Performance Tests

Airtightness

Pressure Test Results

58 All six dwellings at Elm Tree Mews were pressure tested at completion using a Minneapolis Type 3 blower door. The results are shown in Table 17 and Figure 15. In addition, the end terrace underwent pressure testing at two earlier stages, firstly at around a month before completion and secondly immediately before the coheating test (which took place during the first two weeks of March 2008). The air permeability results on completion ranged from 6.2 $m^3/h.m^2$ @ 50 Pa for the duplex apartment to 8.6 $m^3/h.m^2$ @ 50 Pa for the ground floor flat. The 4 houses ranged from 6.3 $m^3/h.m^2$ @ 50 Pa to 7.6 $m^3/h.m^2$ @ 50 Pa The mean completion air permeability for all 6 dwellings was 7.01 $m^3/h.m^2$ @ 50 Pa All six dwellings have air permeability rates that pass the 10 $m^3/h.m^2$ @ 50 Pa maximum air permeability limit in building regulations Part L1a 2006.

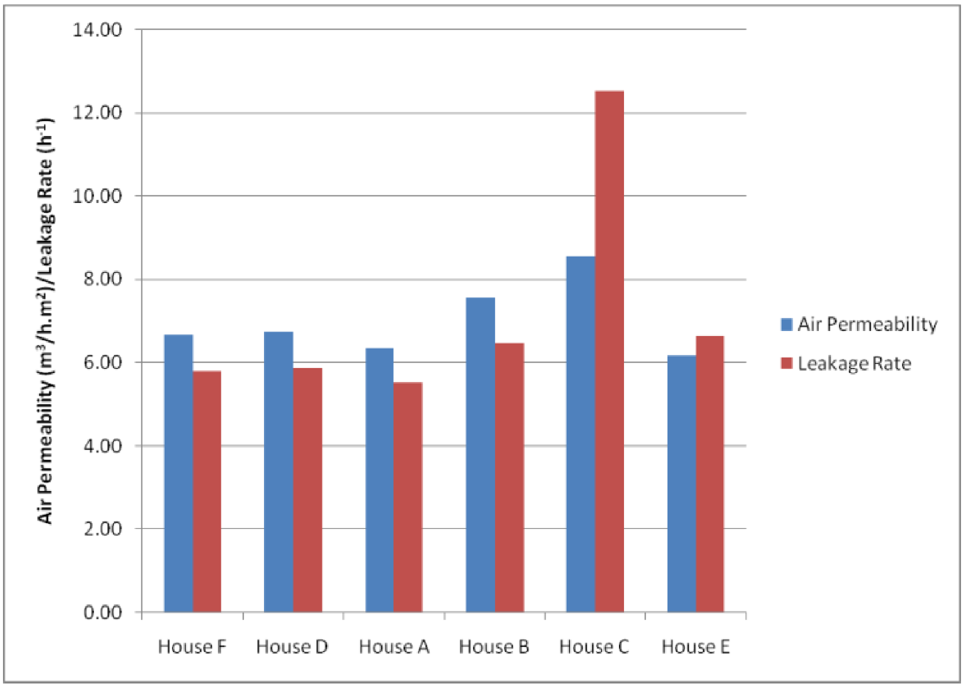
59 It is interesting to note that the volumetric air leakage rates for the four houses and duplex flat are of the order 5.5 h^{-1} @ 50 Pa to 6.5 h^{-1} @ 50 Pa. By contrast, the volumetric leakage for the ground floor flat is much higher at 12.5 h^{-1} @ 50 Pa This is a function of the shape and size of the ground floor flat which has a volume/surface area ratio of only 0.68. The volume/surface area ratios for the houses and duplex flat are much closer to unity, which means that air leakage and permeability will be numerically similar. The consequence of this is that the ground floor flat will be leakier in relative

terms than the other five dwellings.[3] Equivalent Leakage Areas (ELA) at 10Pa ranged from 0.07m^2 to 0.1m^2.

Table 17 – Pressure Test Results

House No	Type	Test Date	Mean Air Permeability (m^3/h.m^2 @ 50 Pa)	Mean Leakage Rate (h^{-1} @ 50 Pa)	ELA at 10Pa (m^2)	Volume (m^2)	Area (m^3)	Volume/ Surface Area Ratio	Comment
F	End Terrace	13/02/08	7.45	6.48	0.106	314.9	274.1	1.15	Initial unfinished
F	End Terrace	25/02/08	5.39	4.69	0.076	314.9	274.1	1.15	Pre coheating
F	End Terrace	17/03/08	6.67	5.80	0.093	314.9	274.1	1.15	Post coheating
D	Mid Terrace	18/03/08	6.75	5.87	0.078	307.3	267.2	1.15	
A	Mid Terrace	18/03/08	6.34	5.52	0.079	307.3	267.2	1.15	
B	Mid Terrace	19/03/08	7.56	6.48	0.092	307.3	267.2	1.15	
C	GF Flat	19/03/08	8.56	12.52	0.066	124.8	182.7	0.68	
E	Duplex Flat	19/03/08	6.17	6.63	0.068	242.0	260.3	0.93	

Figure 15 – Bar Chart of Air Permeability and Air Leakage on Dwelling Completion



60 The airtightness results obtained at Elm Tree Mews are fairly typical of current UK practice for mass housing which, in the experience of the Leeds Met research team, will generally lie in the range 4 m^3/h.m^2 @ 50 Pa to 12 m^3/h.m^2 @ 50 Pa (NHBC 2008). It can be seen from Table 17 that the air permeability of the end terrace increased by 1.3 m^3/h.m^3 following the coheating test. The increase is in line with what would be expected due to the accelerated cracking and shrinkage caused by the elevated temperatures used in the coheating test. This accelerated ageing would be equivalent to between 1 and 2 years normal shrinkage. It would therefore be expected that the air permeability of the five other dwellings will increase by a factor of the order 1 to 2 m^3/h.m^2 over the first 2 years. This increase should be taken into account when sizing any heating system.

---

[3] Typically single storey flats/apartments and bungalows will generally have volume to surface area ratios much less than unity (usually around 0.5 to 0.7). This means that the volumetric air change rate for single storey flats and bungalows can be up to 50% higher that the air permeability rate.

Air Leakage Paths

61 Identification of air leakage paths was carried out for all 6 dwellings using thermal imaging under depressurisation conditions (when the inside-outside temperature difference was sufficiently large) and using smoke detection during pressurisation conditions. The observed leakage paths were found to be common across all six dwellings and included the following:

a) **Intermediate Floor Junction with External Wall** – A major zone of leakage was found to be via the intermediate floor-wall junction. Air leakage was observed mainly via hidden leakage paths such a via the recessed light fittings in the ground floor ceiling, at the junction between the plasterboard lining and floor for external walls, party walls and partition walls, via sockets and light switches and via penetrations into the intermediate floor such as for drainage pipes in the bathrooms and soil stacks (see Figure 16 to Figure 20). The leakage at the party wall-floor junctions appeared to be worse than for the external wall-floor junction.

Figure 16 – Leakage via Recessed Light

Figure 17 – Leakage via Floor-Wall Junction

Figure 18 – Leakage at Wall Socket

Figure 19 – Thermal Image of Floor-wall Junction

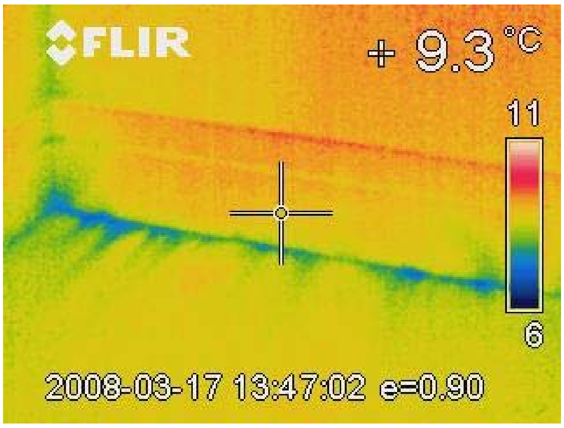
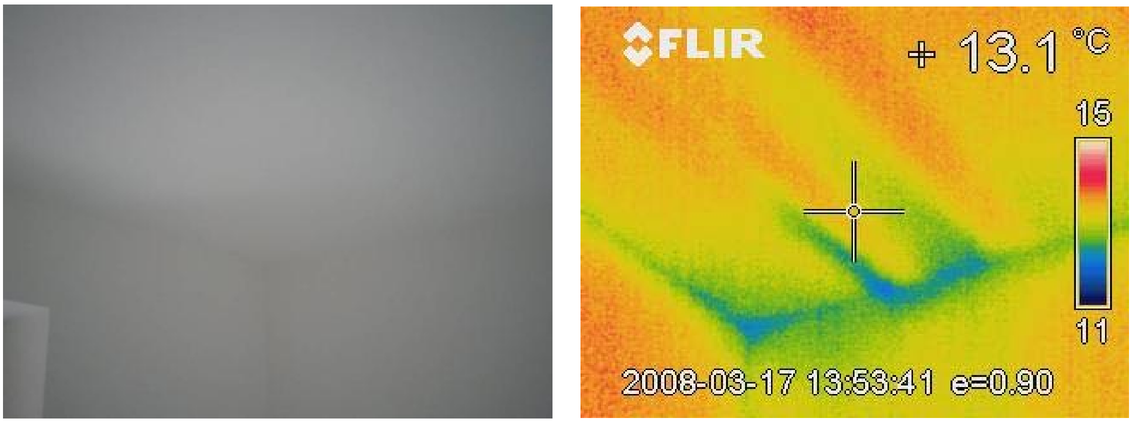


Figure 20 – Leakage at Bath Surround and Sink Boxing-in

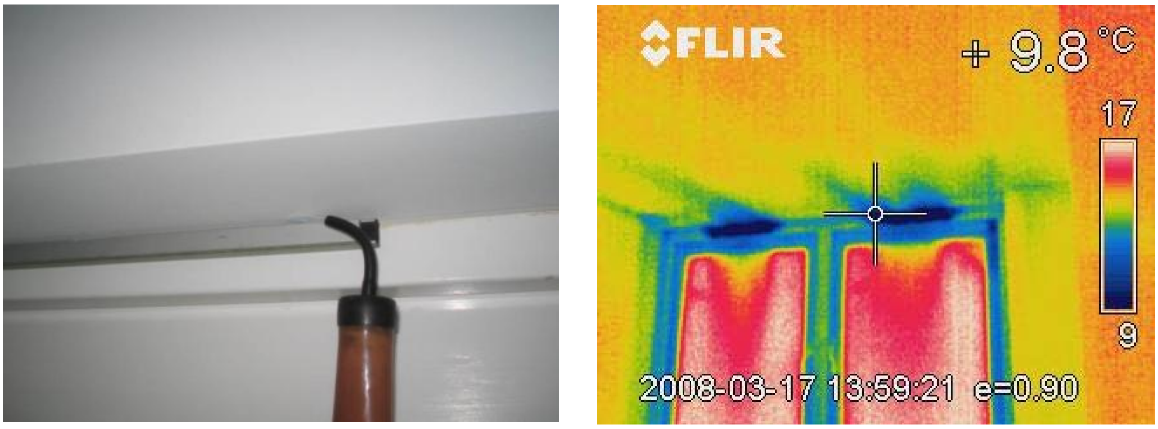
The flow of cold external air into the intermediate floor void can be seen in thermal images of the ceiling of the intermediate floor as shown in Figure 21. In this case the blue coloured colder air can be seen moving into the floor void from the external wall junction. The thermal image also shows the compartments in the floor void formed by the joists.

Figure 21 – Photograph and Thermal Image of Ceiling-Wall Junction



b) **Trickle Vents** – The fit of the trickle vent body into the window frame was not airtight. Consequently, even with the vent in the closed position, there was significant air leakage between the vent body and frame as illustrated in Figure 22. This is a function of the design of the trickle vent and not a result of poor fitting during construction.

Figure 22 – Leakage at Trickle Vent shown using Smoke and Thermal Imaging



c) **Ground Floor Slab Penetrations** – There was air leakage through the ground floor slab in situations where penetrations through the floor slab had not been effectively sealed, such as for pipework and drains. The example in Figure 23 shows leakage via the heat main penetrations, in particular between the insulation and pipe, and in Figure 24 air leakage can be seen around the boxed in pipework and soil pipe in the toilet on the ground floor.

Figure 23 – Leakage at Heat Main Floor Penetration using Smoke and Thermal Imaging

Figure 24 – Leakage at Boxing-in around Toilet on Ground Floor

d) **Through the Wall Penetrations** – Penetrations such as for the ventilation extract vents, electrical wiring and wiring connections for external lights were not sealed effectively at the primary air barrier (inner face of timber panel/plastic membrane). Such penetrations were found to be sources of air leakage as shown by the examples in Figure 25, Figure 26 and Figure 27.

Figure 25 – Thermal Image of Leakage at External Light Wiring and Photograph of Light Outside

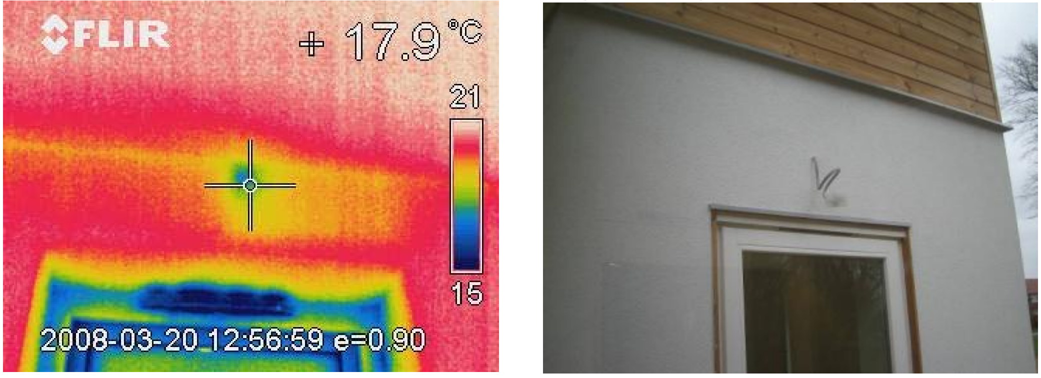
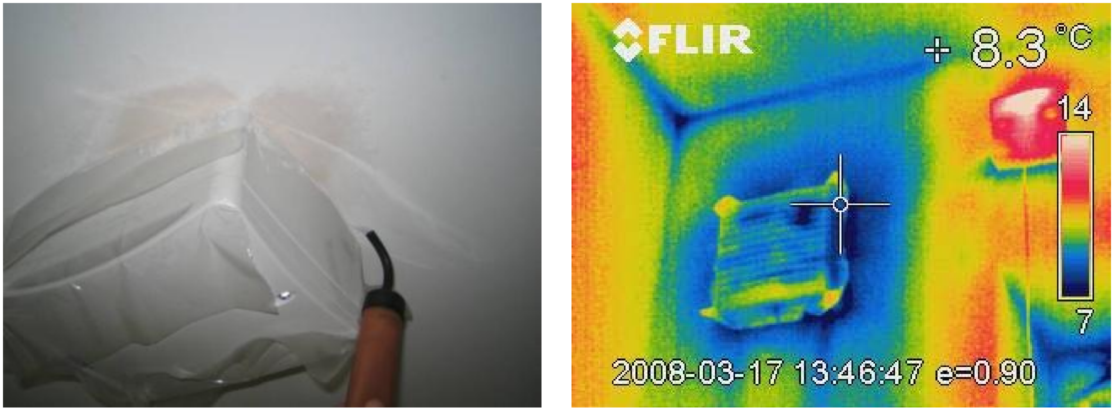


Figure 26 – Leakage at Electrical Junctions Boxes where Wiring Penetrates External Wall

Figure 27 – Leakage at Ventilation Extract Vents



e) **Window and Door Frames and Seals** – There was some leakage at the seals of both windows and doors, in particular where window seals met at frame corners and at the top and bottom of the seals between double patio doors (see Figure 28).

Figure 28 – Leakage at Door and Window Seals

f) **Door Thresholds and Full Height Window Sills** – Air leakage was observed at the thresholds of the patio doors and the sills of full height windows, and in particular at the corner of the threshold at the junction with the skirting board (Figure 29).

Figure 29 – Leakage at Thresholds

Coheating Test

62 A coheating test was conducted in the end terrace house during the period 25th February 2008 to the 12th March 2008. External weather data during the period of the coheating test (external temperature/humidity, vertical south facing solar insolation, wind speed/direction) were recorded by the Leeds Met weather station located on the side of a building at the Joseph Rowntree Housing Trust Tanners Yard site in York. The internal temperature during the coheating test was maintained at around 25°C with the heat provided by electric fan heaters and air mixing provided by circulation fans. The temperature of the adjacent mid terrace was also maintained at an elevated temperature of around 20 to 25°C in order to minimise heat flux across the party wall from the coheating test house, but this temperature was not controlled by the research team. Power input to the dwelling during the coheating test was recorded using kWh meters on each floor connected the fan heaters and circulation fans. For more detailed information of the test methodology refer to the standard Leeds Met coheating test protocols (Wingfield, Johnston, Miles-Shenton & Bell 2010). Additional measurements taken during the coheating test included temperatures in the party wall cavity (at 3 positions), heat flux through various construction elements (flux sensor positions changed during the coheating test) and carbon dioxide concentration (on the ground floor and top floor). Due to the construction work continuing during the coheating test, it was not possible to restrict access to the dwelling during the test. Consequently, several days' worth of data had to be discarded for those periods when construction activity inside the dwelling would have influenced the measured data. A plot of daily power versus delta-T for the coheating test is shown in Figure 30. The plot shows the predicted line, raw data and the data after correction for solar insolation. The results of a multiple regression analysis of the coheating data are shown in Table 18. This gives the heat loss coefficient for the end terrace as 196.4 W/K with an error of 5.7 W/K. The r^2 correlation coefficient for the analysis is 0.67 which indicates a good statistical correlation. The upper critical value of the t-statistic at a probability of 0.025 with 9 degrees of freedom is 2.26. The calculated t-statistic

values for both the solar insolation and Delta-T regression coefficients are higher than 2.26, indicating that the results are statistically valid in both cases.

Figure 30 – Coheating Data Plot – Power versus Delta-T

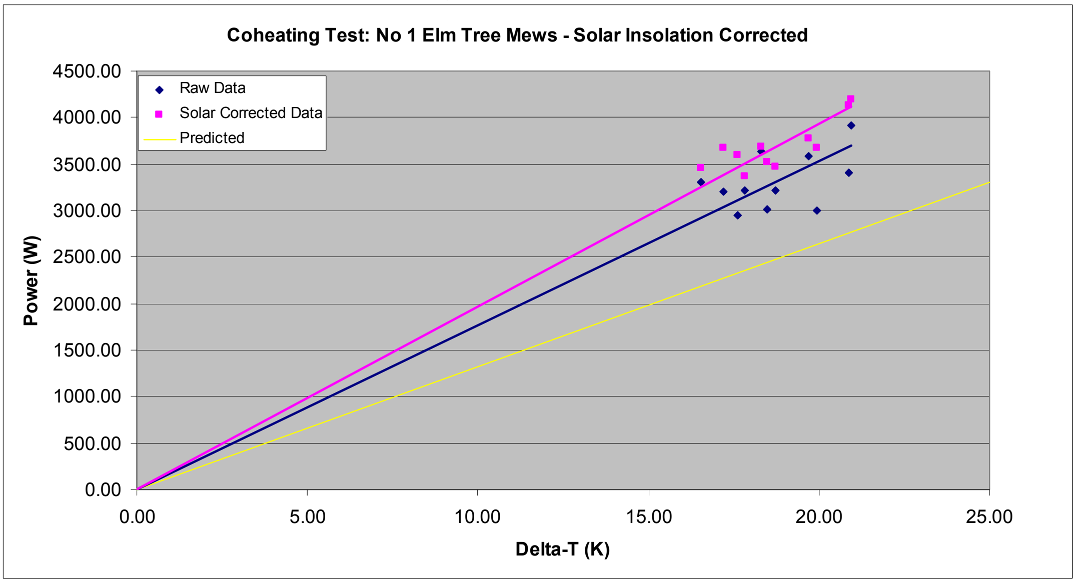


Table 18 – Coheating Test Data Multiple Regression Analysis Results

Regression Output		Error	t-statistic
y-intercept	0.00	-	-
Mean solar insolation regression coefficient	-3.58	0.88	-4.06
Delta-t regression coefficient	196.41	5.74	34.24
r^2 correlation coefficient	0.67	-	-

63 The predicted heat loss coefficient was obtained from the nominal fabric heat loss coefficient and the experimentally derived background ventilation heat loss coefficient (see Table 19). The nominal fabric heat loss (100.9 W/K) was calculated from the design nominal elemental U-values (wall 0.18 W/m^{2}K, floor 0.2 W/m^{2}K, roof 0.13 W/m^{2}K, windows 1.5 W/m^{2}K) and the SAP default thermal bridging y-factor of 0.08 W/m^{2}K (as declared in the SAP design worksheets). The background ventilation loss was derived from the mean air permeability test results before and after the coheating test (mean air permeability = 6.03 m^3/h.m^2) using the n/20 rule and a sheltering factor of 0.85 which gives a ventilation rate of 0.26 h^{-1} which in turn gives a ventilation heat loss coefficient of 26.6 W/K. At the maximum permeability (6.67) the ventilation rate would be 0.28 h^{-1} and at the minimum permeability (5.39) the ventilation rate would be 0.23 h^{-1}.

Table 19 – Predicted Heat Loss Coefficient for End Terrace

Nominal Fabric Heat Loss Coefficient (W/K)	Derived Ventilation Heat Loss Coefficient (W/K)	Total Predicted Heat Loss Coefficient (W/K)
100.9	26.6	127.5

64 It can be seen that there is a significant discrepancy of 68.9 W/K (+ 54%) between the measured whole house heat loss coefficient (196.4 W/K) and the predicted whole house heat loss coefficient (127.5 W/K). The reasons for the discrepancy are likely to be due to the nominal design fabric U-values, thermal bridging and thermal bypasses not reflecting the true heat losses of the elements as built. If we look only at the fabric heat loss (as the measured ventilation loss is the same in both the design prediction and measurement) then the measured discrepancy of 68.9 W/K is a 68% increase above the designed fabric heat loss. The possible reasons for this discrepancy and its implications will be discussed later in this report.

Heat Flux Measurements

65 Heat flux measurements were taken at various wall locations (external wall and party wall) in the end terrace during the period of the coheating test. Four Hukseflux HFP01 sensors were used and these were attached to the wall using masking tape and a thin layer of thermally conductive paste (Dow Corning 340) between the sensor and wall (locations shown in Figure 31). The sensors were always located on internal surfaces and, in the case of external wall panels, always on north facing walls to minimise solar heating effects.

Figure 31 – Heat Flux Sensors on North Facing Wall of Kitchen and Top Floor Bathroom

66 Heat flux measurements for sensors placed on the north facing wall of the ground floor kitchen (at a location with 100% insulation in the wall panel) and top floor bathroom (at a location with 100% timber in the wall panel) for a period of 1 week and with the flux recorded at 10 minute intervals are given in Table 20. Also given are U-values calculated from the heat flux and mean internal-external temperature difference. It can be seen that in all cases the measured U-values are higher than the nominal design U-value of 0.18 W/m^{2}K. In the case of the bathroom wall with 100% timber in the panel at the sensor location, the measured U-value is up to twice the nominal value. This indicates that, as expected, the proportion of timber in the wall panel will have a significant influence on the degree of heat loss. These data also indicate that the realised U-value for the external wall in the building as constructed is likely to be closer to 0.3 W/m^{2}K and not the 0.18 W/m^{2}K nominal design value. It is also interesting to note that the top sensors in each location show lower flux and lower U-values than the corresponding bottom sensors. This is thought to be due to stack air movement in the 38mm service void between the timber panel and plasterboard which will likely lead to higher void temperatures towards the top of the service void.

Table 20 – Mean Heat Flux Measurements from Kitchen and Bathroom

Heat Flux Sensor Location	Mean Heat Flux (W/m^2)	Mean U-value (W/m^{2}K)
Kitchen Bottom Sensor	4.6	0.25
Kitchen Top Sensor	3.7	0.21
Bathroom Bottom Sensor	6.5	0.36
Bathroom Top Sensor	5.1	0.28

67 Heat flux measurements over a period of 5 days were conducted with the sensors placed on the party wall on the ground floor close to the patio door, and the top floor at the top of the stairs as shown in Figure 32. The results are shown in Table 21. It can be seen that there is a significant amount of heat flux into the party wall which gives effective U-values for the party wall ranging from 0.25 to 0.44 W/m^{2}K. Given that the adjacent property was heated to a similar temperature to the coheating test house, this heat flow into the party wall cannot be being induced by any significant difference in internal temperatures between the two properties. The conclusion must be therefore that the temperature of the cavity in the party wall has been reduced by the flow of cold outside air into the cavity. These results show that there is some form of thermal bypass operating via the party wall. The magnitude of the thermal bypass is indicated by the mean U-value of 0.33 W/m^{2}K from the four flux sensor positions. This indicates that heat loss from the party wall is of the same

order, if not higher, than that from the external walls which have a mean U-value of 0.27 W/m^{2}K based on the measurements from the four heat flux sensors in the kitchen and bathroom[4].

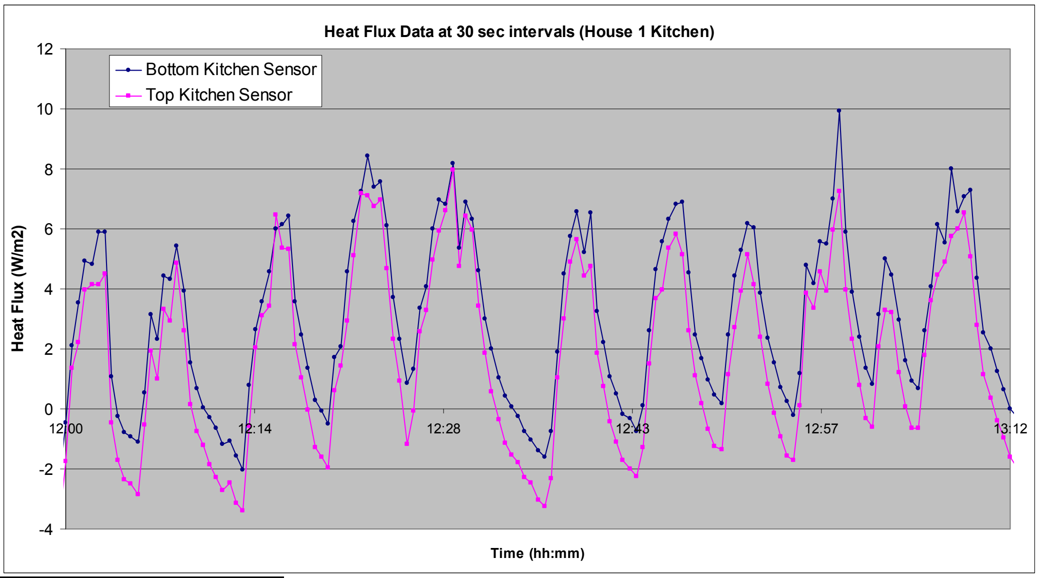
Table 21 – Mean Heat Flux Measurements from Party Wall

Heat Flux Sensor Location	Mean Heat Flux (W/m^2)	Mean Effective U-value (W/m^{2}K)
Ground Floor Right Sensor	8.6	0.44
Ground Floor Left Sensor	4.8	0.25
Top Floor Right Sensor	5.6	0.29
Top Floor Left Sensor	6.7	0.35

Figure 32 – Heat Flux Sensors on Party Wall on Ground Floor and Top Floor

68 The flux readings were mostly recorded at a 10 minute frequency. However, for a short period of test some of the heat flux data at the two sensors in the kitchen were recorded at 30 second intervals. A plot illustrating some of this more frequent data is shown in Figure 33. The saw tooth pattern of the data are indicative of heat pulses travelling through the wall and are likely a result of the response rate and control hysteresis of the thermostat controlling the operation of the fan heater. As heat flux rises to a maximum this will coincide with a period when the fan heater is switched on. As the heat flux then falls, this will coincide with a period when the fan is turned off. It can also be observed that at the bottom of the cooling phase there is actually a period of flux reversal where there is negative flux, indicating heat flow from the wall back into the room. This is likely due to the nature of the wall construction which has a 38mm deep service void between the plasterboard lining and the timber wall panel. This will mean that, as the heat pulses travel though the wall, there will be occasions when the air in the service void will be at a higher temperature than that in the room, giving rise to flux reversal.

Figure 33 – Heat Flux Data from Kitchen Sensors at 30 Second Frequency



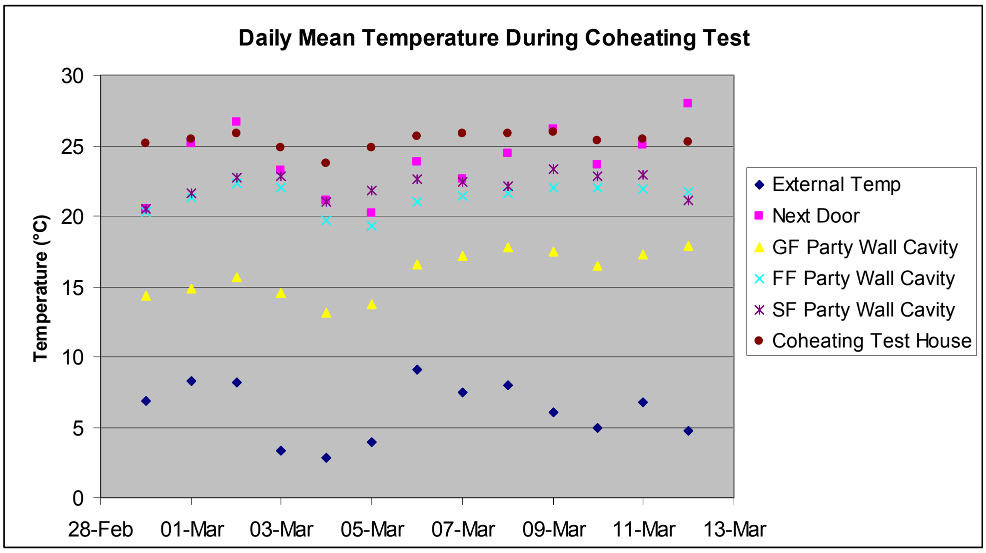
---

[4] It must be remembered, however that this is an indicative measure. A larger number of measurement points would be required in order to derive a much more precise estimate.

Party Wall Cavity Temperature Measurements

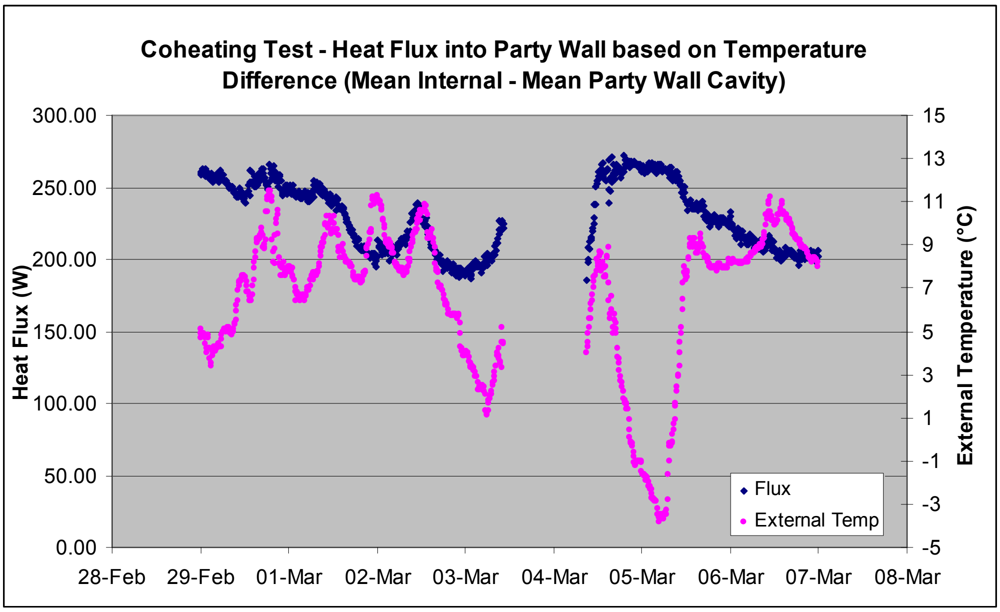
69 Three holes were drilled from the coheating test house into the party wall. These were located towards the centre of the party wall with one on the ground floor, one on the first floor and one on the third floor. Temperatures in the party wall cavity for the duration of the coheating test were measured using type K thermocouples inserted through these holes. The daily mean cavity temperatures are shown in Figure 34. It can be seen that the temperatures at the bottom centre of the cavity fluctuated around 15°C and increased to around 20 to 22°C for the two sensors located at the top of the cavity. If, as we believe, there is a thermal bypass operating in the cavity, then it is likely that the temperatures in the middle and top of the cavity will represent the maximum temperatures in the cavity and that temperatures at the sides and bottom are likely to be lower. Figure 19 provides further confirmation of very little inter-dwelling heat flow across the party wall as almost all party wall temperatures are less than internal temperatures in both dwellings.

Figure 34 – Daily Mean Temperatures during Coheating Test



70 The temperature difference between the internal space of House F and the party wall cavity will also give an indication of the size of the party wall thermal bypass. This is likely to be an underestimate due to the small number of temperature sensors in the cavity and their location in areas in the centre of the cavity where the bypass effect is likely to be smallest. The heat flux was calculated using the temperature difference and the nominal theoretical U-value of the single leaf of party wall (0.57 W/m^{2}K). The plot of heat flux and external temperatures during the coheating test period is shown in Figure 35. Based on these data the effective U-value of the party wall would be of the order 0.2 W/m^{2}K, which is at the lower end of the range of results obtained by direct measurement using heat flux sensors.

Figure 35 – Heat Flux into Party Wall based on Temperature Difference

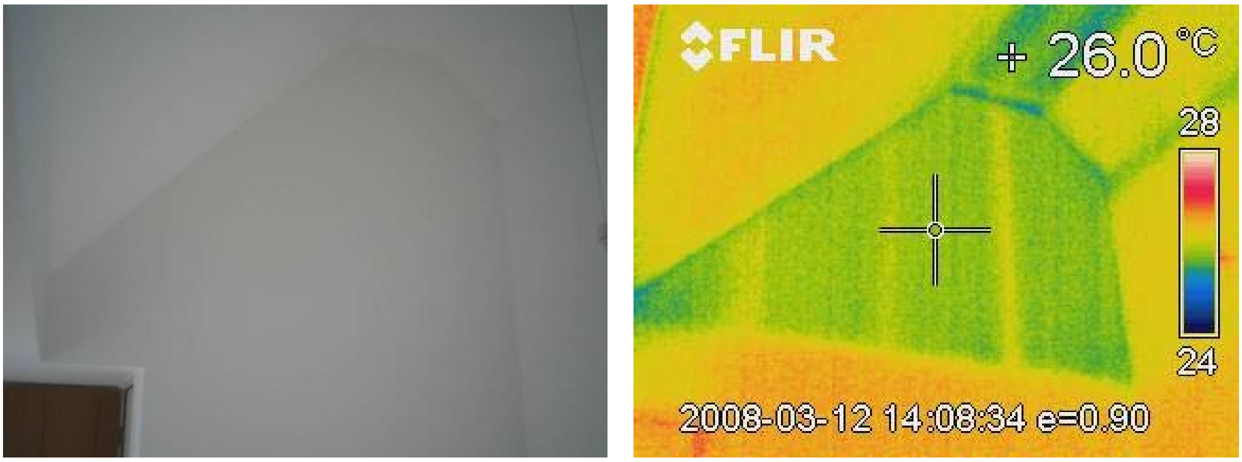


Thermal Imaging

71 Infra-red thermal images were taken using a FLIR Systems B4 camera, mainly from the inside and outside of the end terrace during the coheating test, but also from the inside of the other five dwellings when they were heated both before and following occupation. A selection of some of these images has been chosen to illustrate some of the thermal problems present in the dwelling as constructed. It should be noted that the service void on the inside surface and void behind the external cladding will tend to smear thermal effects due to air movement within and through the voids.

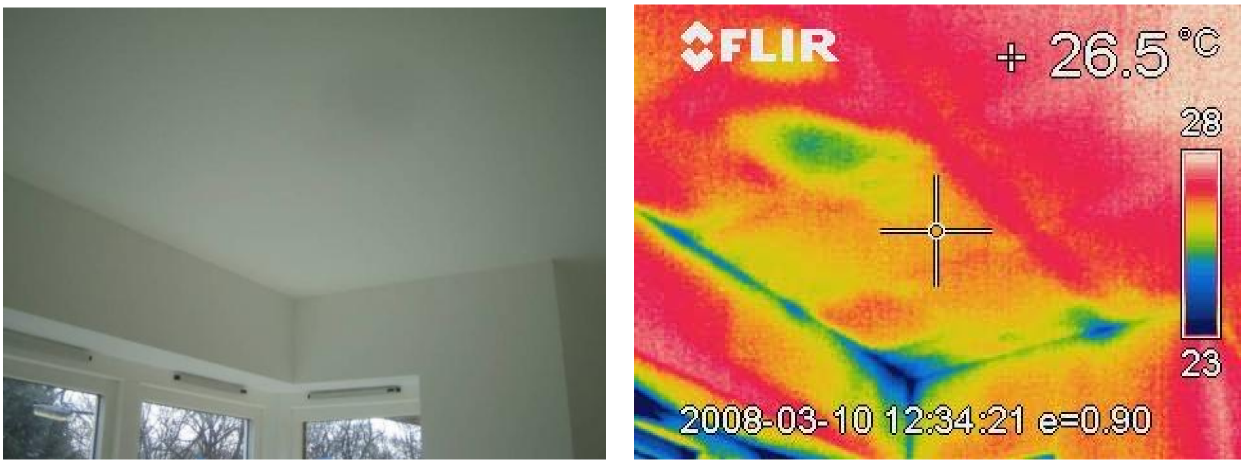
72 The images in Figure 36 show a view of the ceiling in the top floor bedroom of the end terrace. It can be seen from the thermal image that the surface of the boarded area just below the ridge beam and the boarded void above the stairs is at a temperature of 1 to 2°C less that the other surfaces. This indicates that the voids behind these areas are significantly colder than the internal temperature. If these voids were properly sealed and located inside the air barrier then they would be expected to be at the same temperature as the inside heated space. However, as they are in fact colder this would indicate that there is cold air infiltrating into these voids. These voids are therefore acting as a thermal bypass, probably as a result of the planes of the air barrier and thermal insulation layers being out of contact at these elements. It is also likely that the void at the roof apex above the ridge beam is linked with the identical voids in the other dwellings where the ridge beam crosses the party wall allowing cold air to move between dwellings at this point.

Figure 36 – House F: Top Floor Looking up to Ridge Void and Boarded Void over Stairs



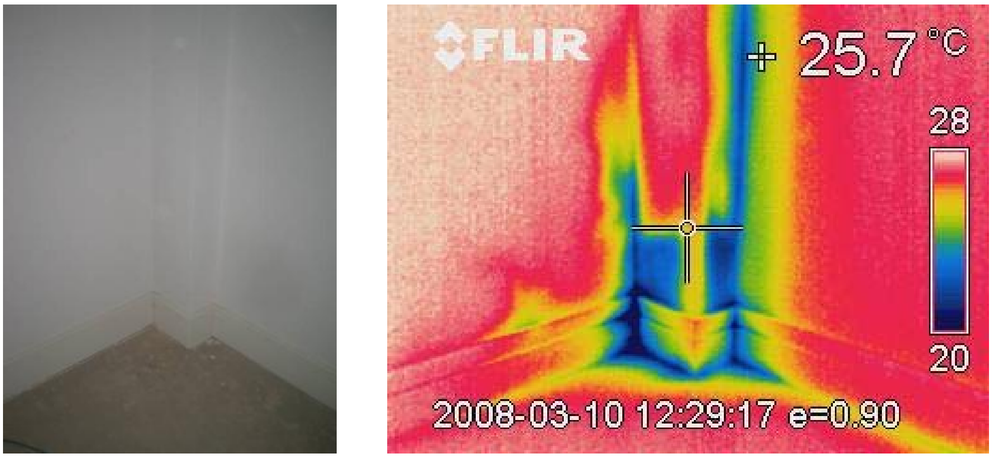
73 The thermal image of the bay window ceiling of the first floor bedroom in the end terrace (see Figure 37) shows a variable pattern of cold spots. This is likely to be due to the way that the mineral wool insulation has been packed in the void above the plasterboard. The insulation is likely to be loosely packed and pushed up into the void thus not making proper contact with the insulation. This would allow air to move around the insulation thus reducing its thermal performance.

Figure 37 – House F: Bay Window Ceiling on First Floor



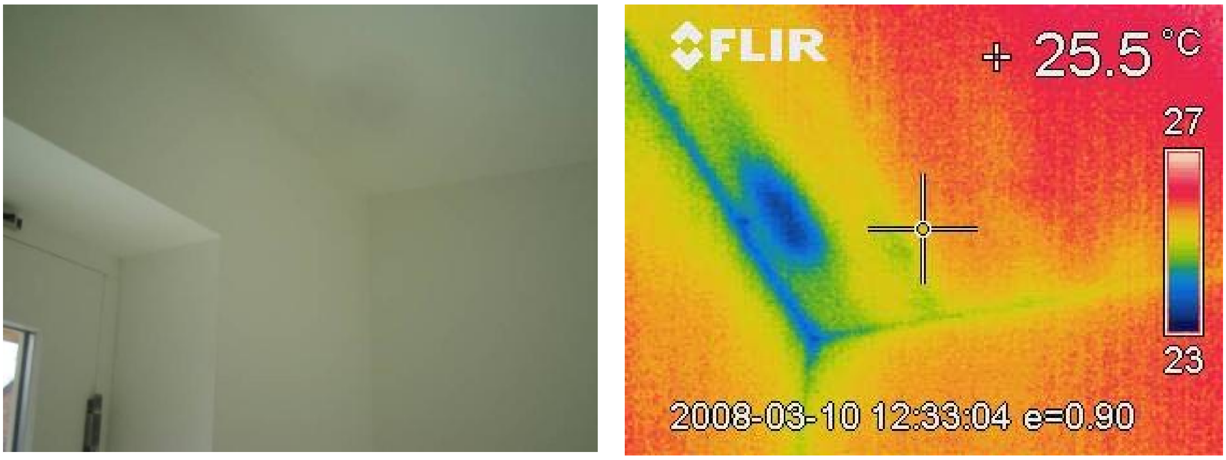
74 The boxed in service stack in the ground floor of House F shown in Figure 38 indicates that there is infiltration of cold air towards the bottom of the stack. This indicates that there is air leakage via an unsealed penetration through the floor slab for the waste pipe at this position.

Figure 38 – Boxed in Service Stack on Ground Floor of House F



75 The cold zone on the ceiling of the first floor bedroom in House F illustrated in Figure 39 is indicative of a cold zone inside the intermediate floor void. This heat loss area will likely be related to a thermal bypass and discontinuity in the air barrier formed at this junction.

Figure 39 – Ceiling of Bedroom on First Floor of House F

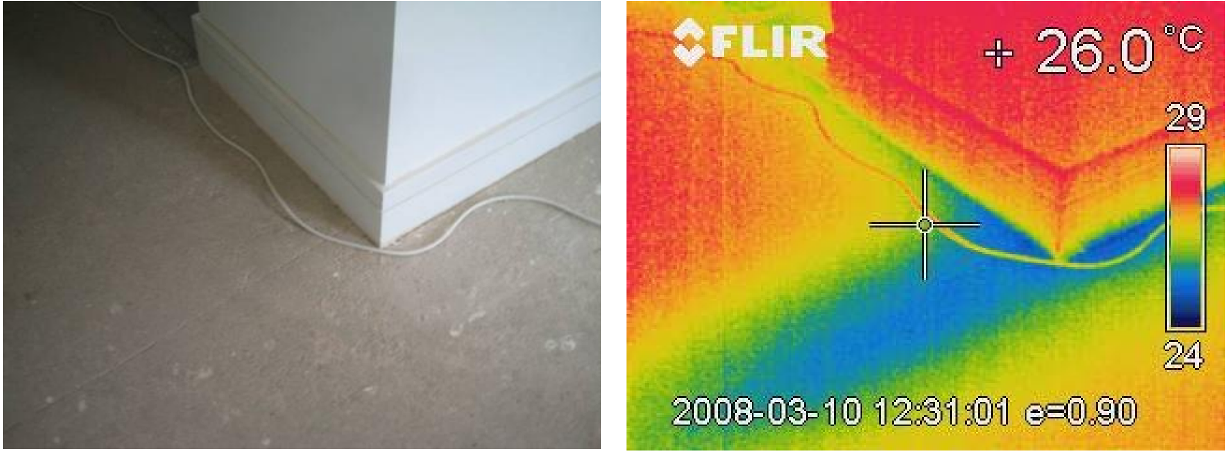


76 The images in Figure 40 show a cold zone in the floor parallel to the party wall (first floor bedroom I House F). This is likely to be related to the construction of the underfloor heating.

Figure 40 – Floor of Bedroom on First Floor of House F

77 The images in Figure 41 show a cold zone at a junction in the ground floor screed above the underfloor heating pipes in House F. There is clearly an air leakage path either along the side of the partition wall or up through the floor below the partition.

Figure 41 – Ground Floor Slab of House F



78 Thermal Images of the porthole window on the indicate higher than expected heat loss from the panel in which the window is fixed as shown in Figure 42 and Figure 43. This suggests that the area around the window has not been fully filled with insulation or that there is an air leakage path around the opening for the window. It is likely to be a combination of these effects.

Figure 42 – Porthole Window on Top Floor of House F – Viewed from Inside

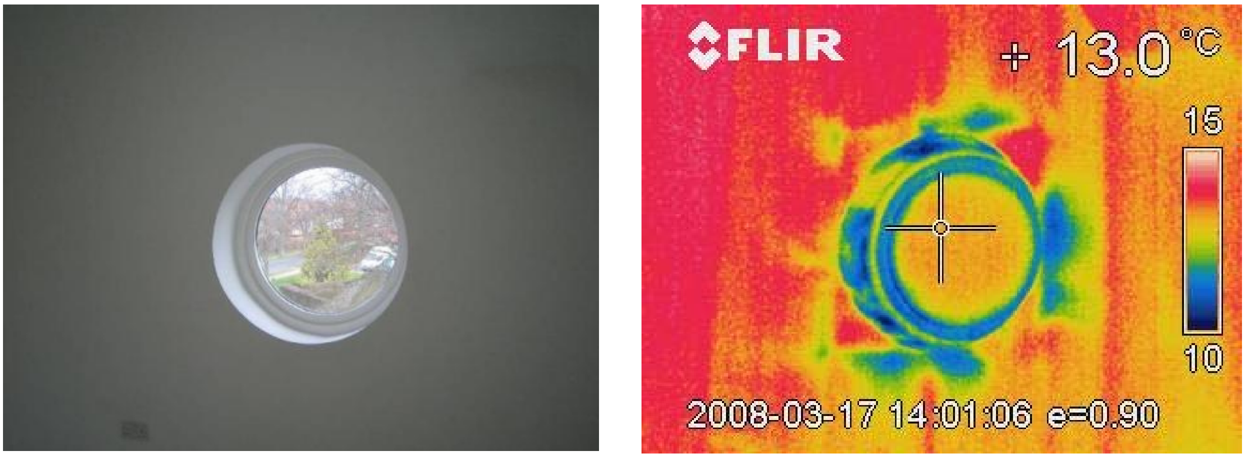


Figure 43 – Porthole Window on Top Floor of House F – Viewed from Outside

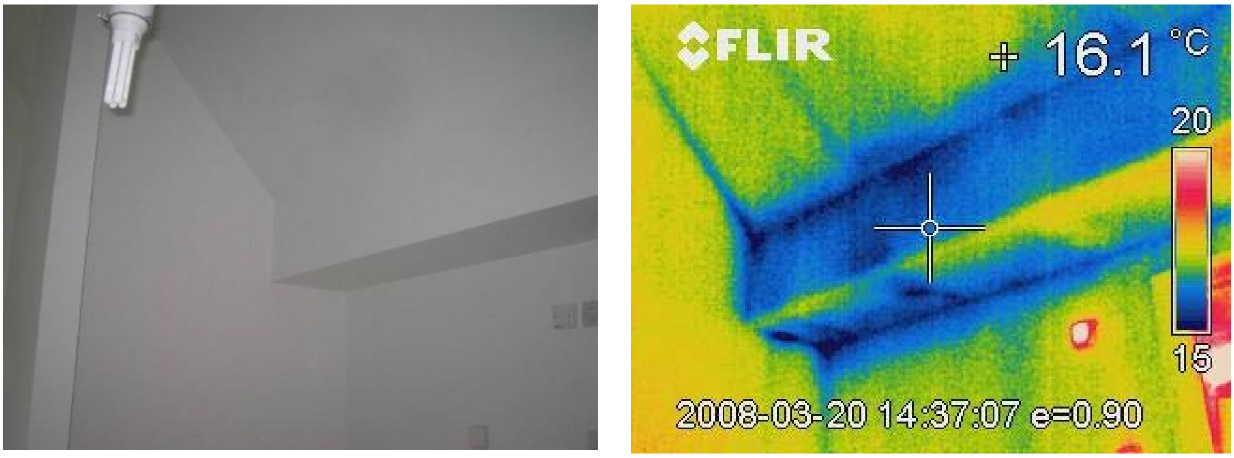
79 The external gable wall of the first floor bedroom of the duplex flat is illustrated in the images in Figure 44. The thermal image shows that there is a cold zone at the corner of the room where the

sloping roof section meets the knee wall. This is indicative of either missing insulation in the wall panels at this location or more likely the infiltration of cold air from the unheated plant room, which is situated directly below the knee wall.

Figure 44 – Gable Wall of House D in Bedroom above Plant Room

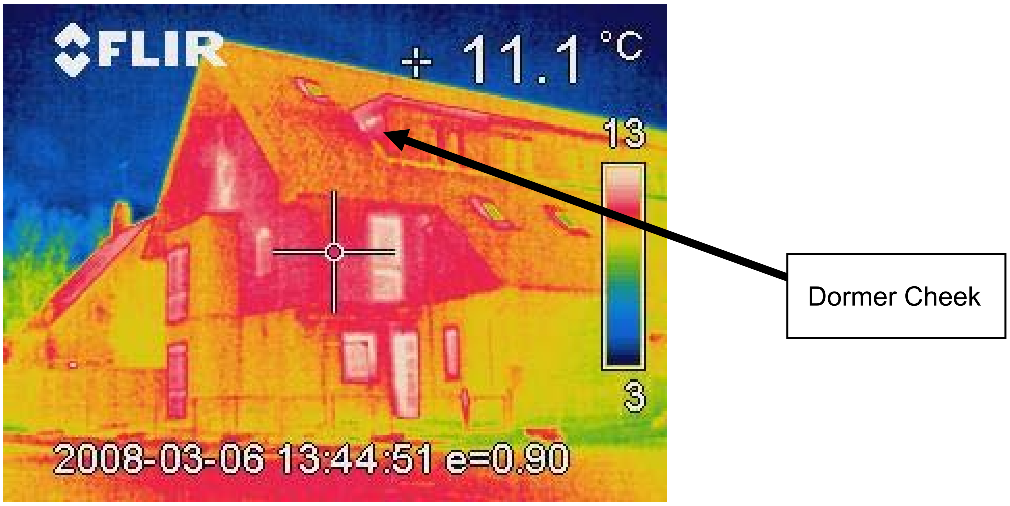
80 The thermal image of the soffit in the top floor bedroom of the duplex flat illustrated in Figure 45 shows cold surfaces along both sides of the soffit. This is indicative of infiltration of cold air at this point causing a thermal bypass. This soffit covers a roof purlin which crosses from the external wall to the party wall.

Figure 45 – Soffit in Top Floor Bedroom of House D



81 The heat loss from the dormer window cheek in the south facing dormer window of house F shown in Figure 46 appears to be higher than for other panels.

Figure 46 – Dormer Window Cheek in House F



Party Wall Air Flow Measurements

82 The air flow in the party wall cavity between the end terrace and mid terrace was measured during the coheating test by inserting a hot bulb anemometer through the holes in the party wall that had been drilled for the temperature measurements. The measured flow rates are given in Table 22. The external wind speed when these measurements were taken ranged from 2 m/s to 5 m/s. The air flow in the cavity ranged from 0.01 m/s up to 0.5 m/s, indicating that the cavity was not fully sealed at the outside edges, allowing the infiltration of cold, wind driven external air into the cavity. This would lower the temperature in the cavity and is consistent with the cavity temperature measurements given in Figure 34 and also the measured heat flux into the cavity.

Table 22 – Air Flow Rates in Party Wall Cavity

Location of Sensor	Vertical Flow (m/s)	Horizontal Flow (m/s)
Ground Floor	0.1 to 0.3	0.2
First Floor	0.01 to 0.03	0.01 to 0.03
Second Floor	0.05 to 0.1	0.1 to 0.5

Background Ventilation Measurements

83 Background ventilation during the coheating test was derived from the decay of carbon dioxide concentration. The coheating test dwelling was fitted with two calibrated CO_2 sensors, one in the ground floor living room and one in the second floor bedroom, with the CO_2 concentration (ppm) being measured every 10 minutes. The CO_2 concentration in the house became elevated due the build up of respiratory CO_2 from those weekdays when the researchers were in the test house downloading data or taking measurements. In the afternoon and evening after the researchers had vacated the house, the CO_2 concentration decayed at a rate determined by the background ventilation rate. The decay data (see example decay curve in Figure 47) could then be analysed by the method of Roulet and Foradini (2002) to calculate the background ventilation rate.

84 The measured background ventilation rates are given in Table 23. It can be seen that the ventilation rate varies from day to day. This is not unexpected and will likely be due to the variation in wind speed and wind direction. The mean ventilation rate averaged over both CO_2 sensors was 0.33 h^{-1}. This would be equivalent to an air permeability rate of 6.6 $m^3/h.m^2$ at 50Pa (assuming n/20 rule and ignoring any sheltering factor). This is in line with the air permeabilities for house F as measured using the blower door which ranged from 5.4 $m^3/h.m^2$ when measured immediately before the coheating test to 6.7 $m^3/h.m^2$ when measured immediately after the coheating test (see Table 17). This indicates that the predicted ventilation heat loss coefficient of 26.6 W/K given in Table 19 is likely to be close to the true figure. Also of interest is the fact that the measured ventilation rate on the ground floor (mean 0.39 h^{-1}) is around 50% higher than that on the second floor (mean 0.27 h^{-1}). This indicates that there is a higher area of potential leakage paths per floor volume for the ground floor than for the second floor. This is consistent with the measured air permeabilities given in Table 17 for the ground floor flat (8.6 $m^3/h.m^2$ @ 50 Pa) versus the duplex flat above it (6.2 $m^3/h.m^2$ @ 50 Pa).

Figure 47 – Typical Carbon Dioxide Decay Curve from Elm Tree Mews

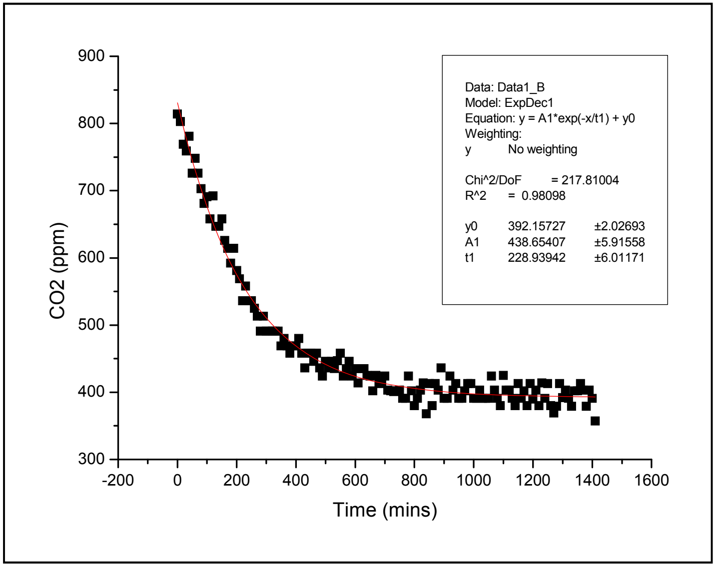


Table 23 – Background Ventilation Rates derived from CO_2 Decay

Date	Background Ventilation Rate (h^{-1})	
	Ground Floor	Second Floor
28/02/2008	0.36	0.26
29/02/2008	0.47	0.24
03/03/2008	0.29	-
04/03/2008	0.30	0.35
05/03/2008	0.44	0.27
06/03/2008	0.49	0.25
07/03/2008	0.42	0.26
10/03/2008	0.42	0.32
11/03/2008	0.29	0.23
Mean	**0.39**	**0.27**

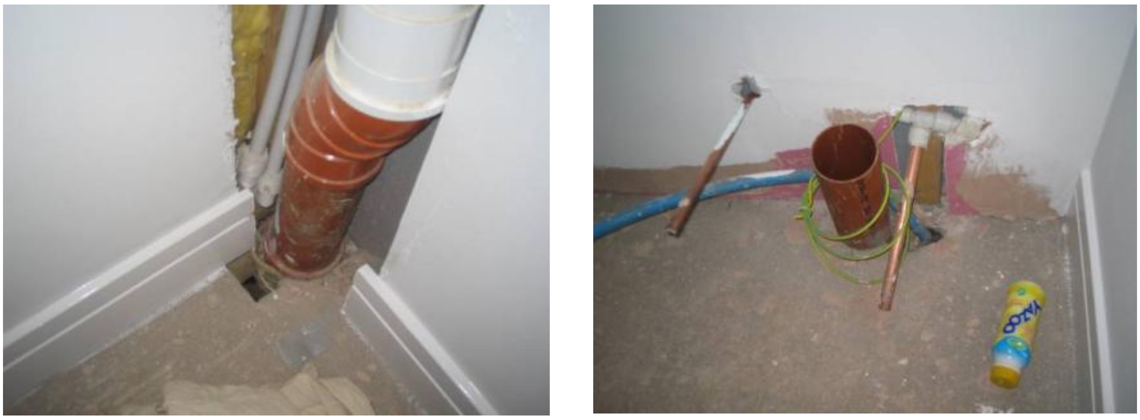
Construction & Design Observations

85 A series of site visits with photographic records were undertaken during the construction of Elm Tree Mews, with the first visit taking place on the 2nd March 2007 when the groundworks were under way.

86 The photograph in Figure 48 shows a typical soil pipe penetration though the beam and block floor at the stage prior to layer of the floor insulation and screed. It can be seen that there is a large gap between the pipe and floor block which would allow movement of air from under the floor into the dwelling if left unsealed. It was observed that these penetrations were indeed not sealed effectively as can be seen in Figure 49. This would give rise to the air infiltration paths that were observed by thermal imaging as shown in Figure 38.

Figure 48 – Soil Pipe Penetration through Floor Prior to Installation of Floor Insulation

Figure 49 – Soil Pipe Penetrations through Ground Floor Prior to being Boxed-in

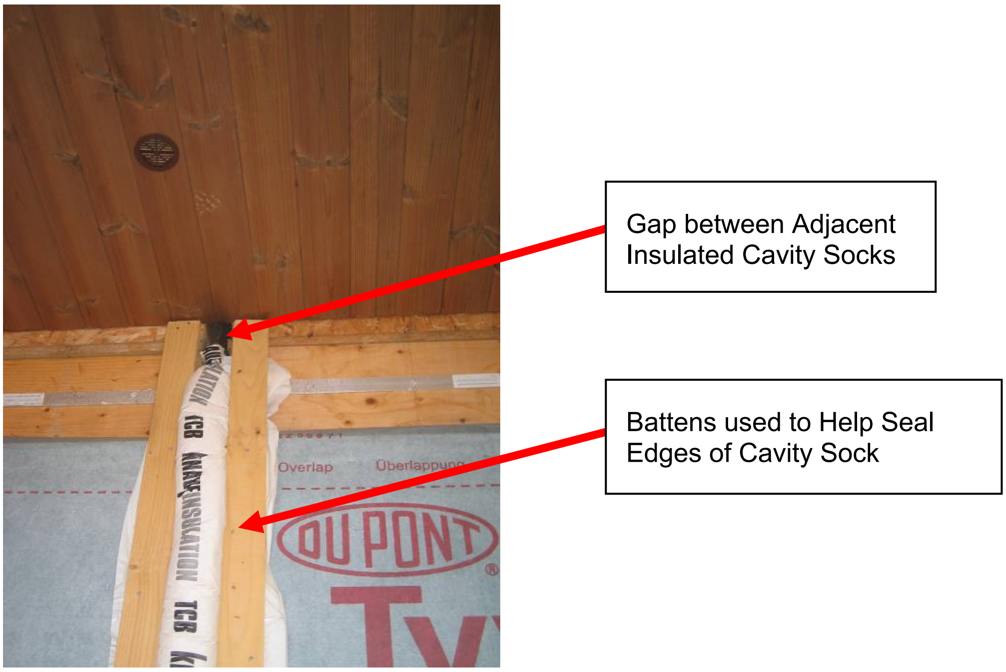


87 Observations were made of the construction of the party wall junction when the ground floor beam and block floor was being laid. Figure 50 shows the edge of the beam and block floors at the party wall between the ground floor flat and adjacent terrace. It can be seen that there are with gaps under the blocks which would allow air to move from the floor void into the party wall cavity. Conversations with the construction team confirm that there was no requirement in the construction specification to seal these gaps or to put any membrane or insulated sock at the bottom of the cavity. It is likely that air flow from the floor void into the party wall cavity at this point will be a major contributing factor to the party wall bypass at Elm Tree Mews as measured by the heat flux sensors (see paragraph 67).

Figure 50 – Construction of Beam and Block Floor showing Party Wall Junction

88 An additional contributing factor to the observed party wall thermal bypass would be gaps in the insulated sock used to seal the cavity edge. Although a reasonable attempt had been made to provide a good seal between the sock and the panels by battening the sock edges, there were still several gaps in the sock (see Figure 51) which would have allowed the ingress of external air into the cavity.

Figure 51 – Gap in Cavity Sock at Party Wall Junction

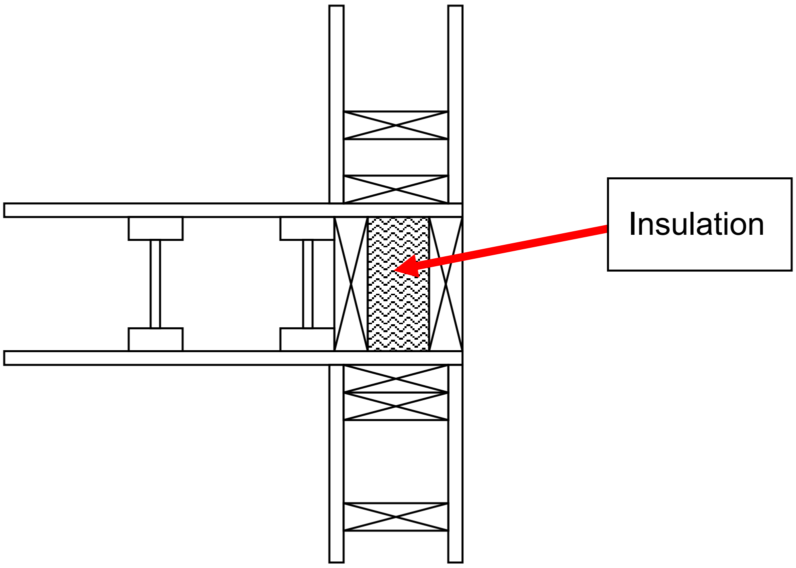


89 Observations of the construction of the timber frame panels for the first floor and the intermediate floor between ground floor and first floor showed that no sealant or gaskets were used to seal the

gaps between panel and flooring (Figure 52). Nor was a membrane used to wrap around the end of the intermediate floor. This indicates that there was no designed or constructed air barrier at these points and consequently the intermediate floor has the potential to be a major point of air leakage. It was also noted that edge section of the intermediate floor immediately above each panel did not seem to have been constructed with any insulation and would therefore potentially give rise to a significant thermal bridge. The drawing for this detail does show insulation at this point (Figure 53), so this suggests that the detail was not constructed as designed.

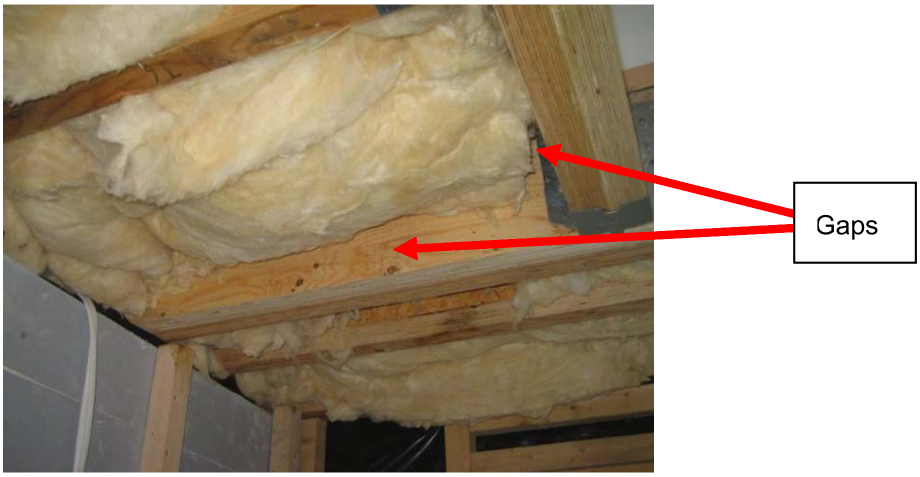
Figure 52 – Installation of First Floor Timber Frame Panels

Figure 53 – Schematic Drawing of Intermediate Floor-External Wall Junction



90 The installation of mineral wool insulation batts in the ceiling voids of the bay windows and winter gardens is illustrated in Figure 54. It can be seen that the insulation does not fully fill the gaps between the joists and that there are air gaps at the edges. The insulation is also pushed up into the ceiling void such that there will be air gaps between the insulation and the ceiling plasterboard when erected. The consequence of these gaps is that air will be able to circulate around the insulation which will reduce its effectiveness due to thermal bypass looping. This effect can be seen clearly in the thermal image of the bay window in house F shown in Figure 37. It is critical to the performance of insulated elements that the air barrier and insulation layer are in close contact at all times and that there are no gaps in either the air barrier or insulation that would allow the movement of air to bypass the insulation layer. It is likely that the construction team was unaware of the effect of such gaps or the potential consequence in terms of additional heat loss.

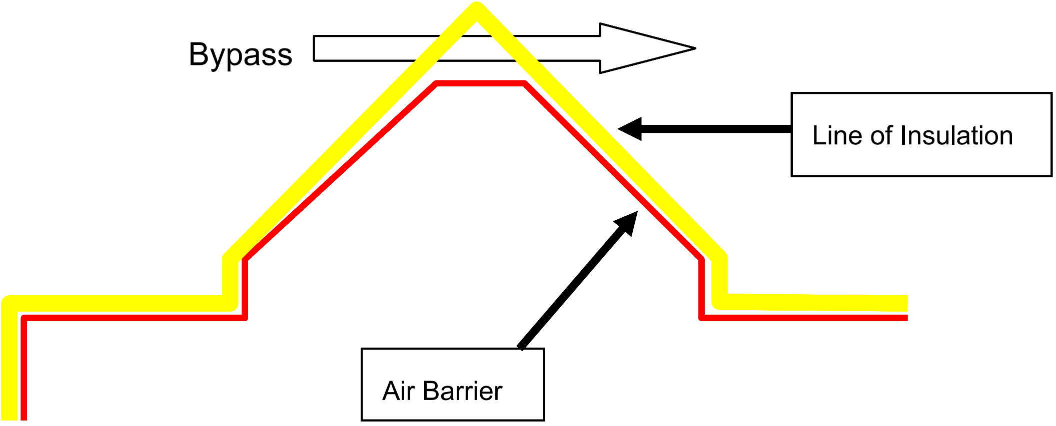
Figure 54 – Installation of Mineral Wool Insulation in Winter Garden Roof



91 Inspection of the timber frame panel drawings showed that in some locations internal partition walls had been specified at locations which were in fact external and would have full 200mm external wall panels. The best example of this was for the cheeks of the dormer windows on the north facing roof. Several potential thermal bypass routes were also identified during the retrospective design assessment. This included a bypass created by the small ceiling void formed by boxing out the main ridge beam as shown in Figure 55. This created a separation of the air barrier and insulation layer at this point, thus forming a potential for thermal bypassing by allowing free movement of air through the insulation layer into the ceiling void (see Figure 56). The bypass can be observed in the thermal image shown in Figure 36.

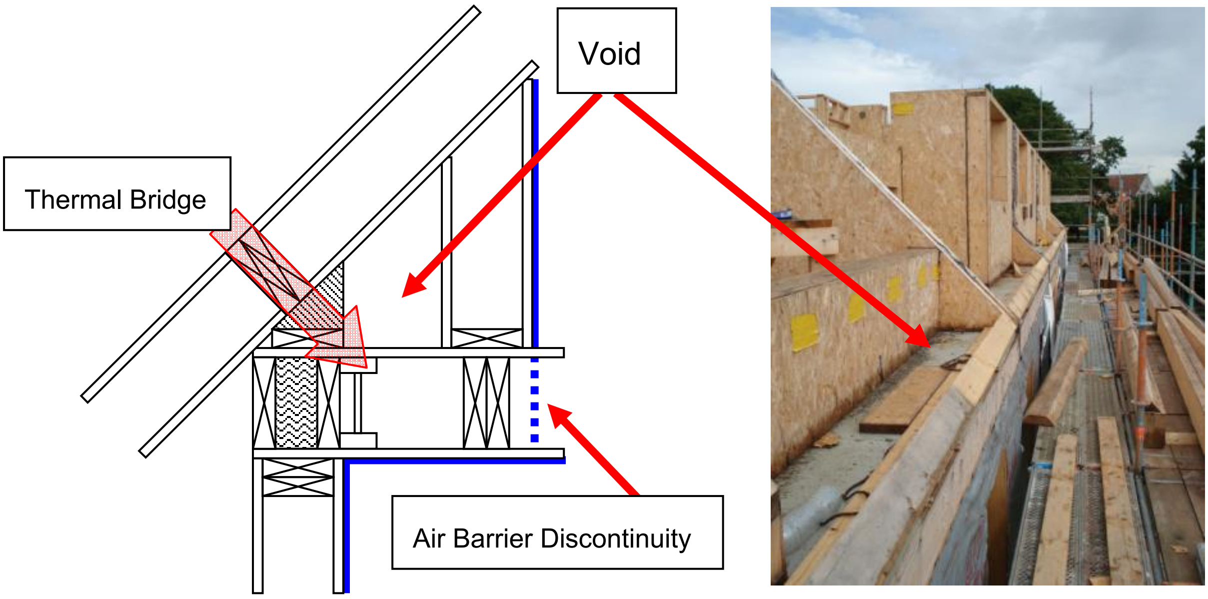
Figure 55 – Construction of Ceiling and Roof Void

Figure 56 – Schematic of Thermal Bypass at Ceiling Void



92 The complexity of the roof design and the detailing of the dormer windows resulted in the formation of a series of voids at the junction of the intermediate floor between the first and second floors as illustrated in the section and construction photograph shown in Figure 57. The design has resulted in a discontinuity in the air barrier (air barrier shown by blue lines in Figure 57 with the discontinuity shown as a dotted line). There is also significant thermal bridge formed by the additional solid timber where the wall meets the roof panel. A thermal bypass is also formed at this junction due to the separation of the insulation layer and air barrier, and the resultant heat loss due to the bypass can be observed in the thermal images of the ceiling below the void as shown in Figure 39. There is also potential for air movement from the intermediate floor void into the unheated space with associated condensation risk on the cold panel surfaces.

Figure 57 – Unheated Void Formed at Junction between First and Second Floor



93 Perhaps the most critical of the on site issues were the problems associated with the insulation in the wall and ceiling panels. This manifested itself in two ways. Firstly there was slumping of the factory-filled insulation, which would likely have been induced by vibrations during the road transport shipping of the panels from the factory to the site. Secondly, the insulation in the unprotected panels became wet and slumped further following several weeks of heavy rainfall. As a result, the inside facing OSB sheets were removed from all panels and the cellulose insulation removed (Figure 58). The panels were then allowed to dry before being refilled. The risk of water damage to the panels could perhaps have been reduced with better protection of the erected panels, but there will always be some level of risk using this sort of construction system.

Figure 58 – Roof Panel with Wet Insulation being Removed

94 Another area of concern relating to the erection of the timber frame was the incorrect placement and orientation of some of the party wall panels. This meant that some of the timber members

hidden in the panels that were there to support loads from above were not in the correct alignment. This had the potential to result in structural problems and was only noticed during the period when the internal facing panels were removed and an inspection carried out by the structural engineer. In order to rectify this situation, additional timber strands were inserted at the appropriate locations by the main contractor. The photograph in Figure 59 shows one of the party wall panels with the inner OSB facing board and cellulose insulation removed. It can be seen that there is no structural timber in the party wall panels to transfer the load from the load bearing timber beams. Structural timbers can be seen in the wrong locations. The markings made by the structural engineer can also be seen in the photograph where new timber members need to be inserted into the panels (red 3 and red 5). This problem could have been avoided with better training of the timber frame installation teams and with better labelling of the panels. Indeed, the use of Lean Manufacturing Poke-Yoke (fault proofing) techniques could have been used in this situation to make it impossible to erect the panels either in the wrong location or wrong orientation. The classical Poke-Yoke method for fault proofing the assembly of components is to create a series of unique cut-outs and/or inserts along the edges of components during their manufacture[5]. These are designed to ensure that components can only be assembled in one orientation and only with the intended matching piece.

Figure 59 – Photograph of Exposed Party Wall Panels Showing Missing Structural Members

95 The problems with the panel insulation and party wall panels were examples of a range of systems issues related to the erection of the timber frame structure. Other issues related to communication, delivery of panels, panels delivered in the wrong order and problems with the installation of the roof. This is perhaps an indication that this technology is relatively immature in the UK. It also shows that, despite the potential for so called Modern Methods of Construction (MMC) to improve construction process, if new construction technologies are simply implanted into existing design and production processes and systems, then the likely result will be a building that will not perform as expected nor be built to the required standards.

Nominal Panel U-value versus Actual Panel U-value

96 The nominal U-value of a “standard” Elm Tree Mews timber wall panel with 400mm spacing of I-beams, 10mm web thickness, 200mm I-beam depth and 9mm OSB facing is 0.18 W/m^2K based on a calculated timber fraction of 2.5% (I beam webs) and using the combined areas method to calculate the U-value. This is the same U-value as given in the detailed specification and that used in the SAP energy calculations. This method of U-value calculation for a timber panel ignores the effect of timber framing members around openings and does not take account of situations where the I-beam spacing is less than 400mm at the ends of the panels or where there are additional timber structural support members inside the panel. A U-value of 0.18 W/m^2K would therefore not

---

[5] A good example of a Poke-Yoke system is the UK 3-pin electrical plug and socket. The plug can only be inserted one way into the socket and, combined with colour coding of the wires inside the plug, this reduces the risk of connecting the wrong polarity of wiring.

represent the U-value of a typical panel as used with framing and support members and will give rise to a significant underestimate of heat loss from the building fabric.

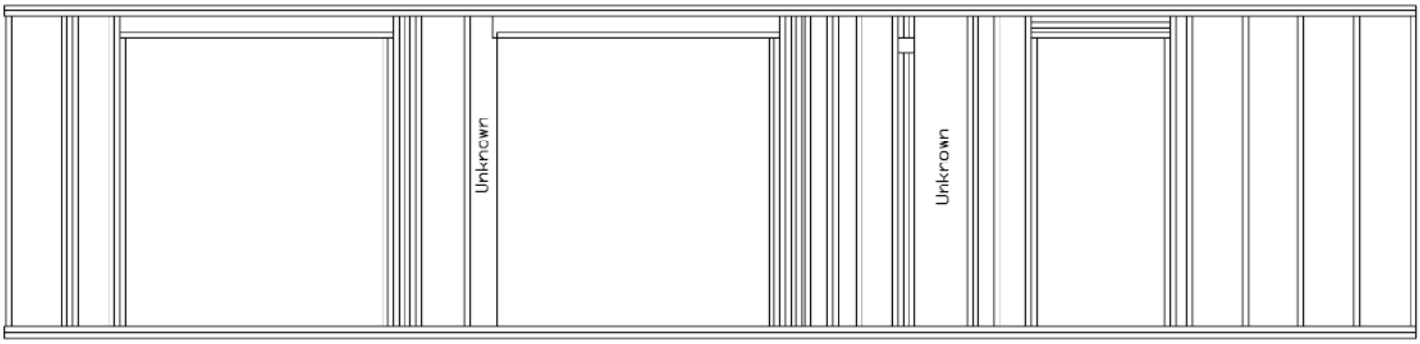
97 The opportunity to calculate a more accurate average U-value for the wall panels occurred when the internal OSB facing boards for all panels were removed and the cellulose insulation taken out. A series of panoramic photographs were taken of all rooms in all 6 dwellings whilst the OSB internal facing was removed. From these photos, a timber fraction for the opaque wall elements could be calculated based on the actual observed timber (see Ward 2008). On this basis the actual timber fraction was around 25%, averaged over all external wall panels. Based on a timber fraction of 25%, the nominal U-value for a typical panel would be of the order 0.27 W/m^{2}K, which is 50% higher than the nominal 0.18 W/m^{2}K given in the design submission. A nominal U-value of 0.27 W/m^{2}K correlates well with the external wall U-values measured using heat flux sensors as given in Table 20, which ranged from 0.21 to 0.36 W/m^{2}K.

98 Photographs taken of exposed external timber panels illustrated in Figure 60 clearly show some of the additional framing and structural supporting timber in the panels. In the photograph on the left hand side it can be seen that around a patio door opening there 7 timber members together immediately adjacent to an I-beam. In the photograph on the right there are 12 timber members in a part panel adjacent to an opening where the timber fraction of the part panel is around 80%.

Figure 60 – Exposed External Timber Panels Showing Additional Timber

99 As part of the timber survey, an example panel drawing was created from site measurements taken at the same time as the panoramic photographs. This acted as a check on the analysis of the panoramic photographs as well as providing an early indication of the issue. The extent of solid timber in the panels in the ground floor flat gable end wall is shown in Figure 61. This shows the additional timber at heads and the structural supporting members. In this particular case the timber fraction of the opaque elements (ignoring window and door openings) was calculated to be of the order 36% to 45% depending upon the proportion of timber in the unexposed unknown areas. This equates to panel U-values in the range 0.31 to 0.34 W/m^{2}K. The make up of the timber in this panel as observed compares well with the timber marked in the manufacturers panel layout drawings. The panel drawings indicated that one of the unknown areas from the observed drawing has no timber whilst the other has 100% timber.

Figure 61 – Drawing of Exposed Timber Panels (Ground Floor Flat Gable End)



100 The nominal U-value of a standard panel with nominal 400mm I-beam spacing was calculated using 2-dimensional thermal modelling with the Therm v5.2 finite element simulator and also by the combined area method. The model used is shown in Figure 62. The model showing the calculated colour flux magnitude is illustrated in Figure 63. The calculated U-value from this Therm model was 0.1878 W/m^{2}K, which is slightly higher than the value of 0.184 W/m^{2}K calculated using the combined areas method (see Table 24). This is likely due to the bridging effect of the flanges which would not be taken account of in the simple combined area method.

Figure 62 – 2d Model of I-beam Wall Panel: 400mm I-beam Spacing, 200m Wall Thickness

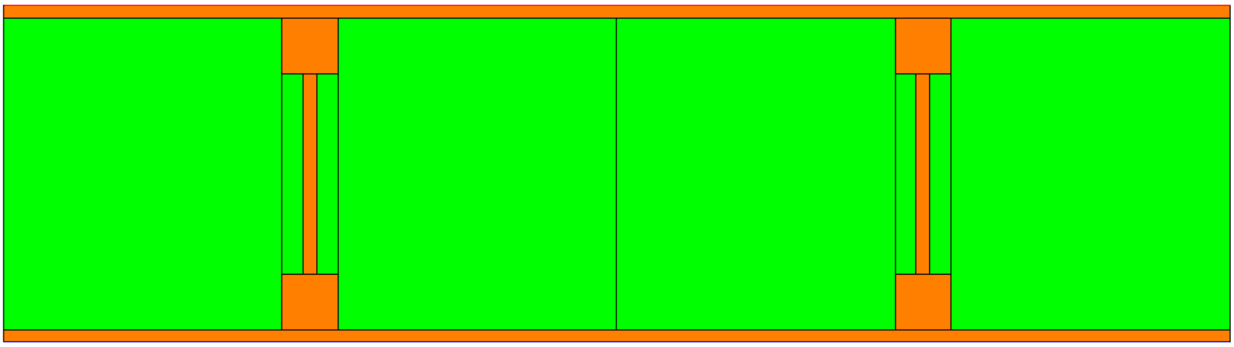


Figure 63 – Colour Flux Magnitude for Model I-beam Wall Panel

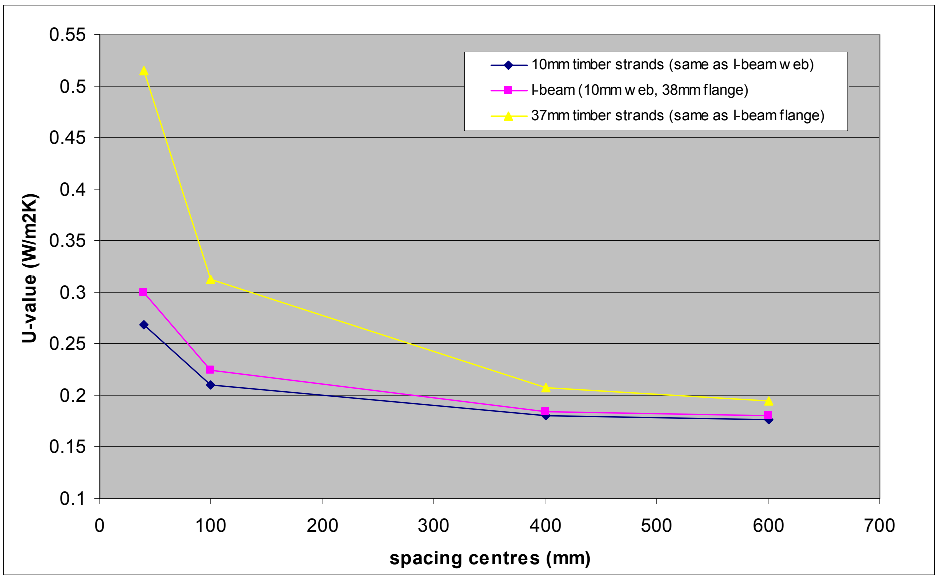
101 The U-values for a range of wall panel constructions is given in Table 24. The nominal U-value of a panel construction with I-beams spaced at 400mm and including the effect of the inner plasterboard layer and service void is 0.18 W/m^{2}K, both by the combined area method and using Therm. At a nominal 25% timber (solid timber not I-beams) and including the inner plasterboard layer and service void the U-value increases to 0.25 W/m^{2}K. Where the 25% timber is for I-beam webs, the effect of the flanges increase the nominal U-value to 0.29 W/m^{2}K.

Table 24 – U-values of Wall Panel Constructions

Wall Panel Make Up	U-value Calculated using Therm (W/m^{2}K)	U-value Combined Area (W/m^{2}K)	Comment
9mm OSB, 200mm Cellulose, 9mm OSB	0.1695	0.171	no timber
9mm OSB, 200mm Cellulose & I-beams at 400mm, 9mm OSB	0.1878	0.184	with 38mm flanges, 2.5% timber
9mm OSB, 200mm Cellulose & 10mm timber at 400mm, 9mm OSB	0.1807	0.180	no flanges, 2.5% timber
12.5mm PB, 38mm cavity,9mm OSB, 200mm Cellulose & 10mm timber at 400mm, 9mm OSB	0.1728	0.173	no flanges, 2.5% timber
12.5mm PB, 38mm cavity,9mm OSB, 200mm Cellulose & 10mm timber at 400mm, 9mm OSB, 25mm cavity, 21mm timber	-	0.165	no flanges, 2.5% timber
12.5mm PB, 38mm cavity, 9mm OSB, 200mm Cellulose & I-beams at 400mm, 9mm OSB	0.1792	0.180	with 38mm flanges, 2.5% timber
9mm OSB, 200mm Cellulose & 10mm timber at 600mm, 9mm OSB	-	0.177	no flanges, 1.67% timber
9mm OSB, 200mm Cellulose I-beams at 600mm, 9mm OSB	-	0.180	with 38mm flanges, 1.67% timber
9mm OSB, 200mm Cellulose & 10mm timber at 25% timber, 9mm OSB	-	0.268	no flanges, 25% timber
9mm OSB, 200mm Cellulose & I-beams at 40mm, 9mm OSB	-	0.300	with 38mm flanges, 25% timber
12.5mm PB, 38mm cavity, 9mm OSB, 200mm Cellulose & 10mm timber at 25% timber, 9mm OSB	-	0.250	no flanges, 25% timber
12.5mm PB, 38mm cavity, 9mm OSB, 200mm Cellulose, I-beams at 40mm, 9mm OSB	-	0.287	with 38mm flanges, 25% timber
9mm OSB, 200mm Cellulose & 10mm timber at 10% timber, 9mm OSB	-	0.210	no flanges, 10% timber
9mm OSB, 200mm Cellulose & I-beams at 100mm, 9mm OSB	-	0.224	with 38mm flanges, 10% timber

102 The effect of the spacing of the internal timbers of the U-value of a nominal 200mm thick panel with cellulose insulation and 9mm OSB facings is illustrated by the graph in Figure 64.

Figure 64 – Effect of I-beam/Timber Spacing on Panel U-value (200mm thick with Cellulose)



103 The standard construction specification for the roof panels at Elm Tree Mews detailed 11mm thickness OSB facing boards with a 240mm cavity and I-beams at 600mm spacing. The nominal design U-value of the roof panels was given as 0.13 W/m^{2}K, and this is the value used in all the SAP spreadsheets, heat loss calculations and design predictions. However, U-value calculations carried out by Leeds Met using both the combined area method and also using 2-d thermal modelling of a panel meeting this construction specification, give U-values of 0.14 and 0.15 W/m^{2}K respectively, not 0.13 W/m^{2}K (see Table 25). Allowing for the effect of additional structural and framing timber in the panels in excess of the nominal 1.7% (probably of the order 10% to 15%), a more realistic U-value of the roof will be significantly in excess of 0.15 W/m^{2}K. We have not been able to calculate the real timber fraction in the roof panels due to limited resources, but with a timber fraction likely to be of the order 10% this would give an actual U-value of ~0.18 W/m^{2}K.

Table 25 – U-values of Roof Panel Constructions

Roof Panel Make Up	U-value Calculated using Therm (W/m^{2}K)	U-value using Combined Area (W/m^{2}K)	Comment
11mm OSB, 240mm Cellulose, 11mm OSB	0.144	0.143	no timber
11mm OSB, 240mm Cellulose & I-beams at 600mm, 11mm OSB	0.153	0.150	with 38mm flanges
11mm OSB, 240mm Cellulose & 10mm timber at 600mm, 11mm OSB	0.150	0.148	no flanges, 1.67% timber
12.5mm PB, 38mm cavity, 11mm OSB, 240mm Cellulose & 10mm timber at 600mm, 11mm OSB	-	0.139	no flanges, 1.67% timber, with adjustment for unheated roof space

104 Photographs taken of the inside face of the roof structure during August 2007 when the inner OSB facing and insulation had yet to be refilled illustrate the level of additional timber in the roof panels (see Figure 65).

Figure 65 – Additional Timber in Exposed Roof Panels

Thermal Bridging

105 In low energy dwellings with relatively low whole house heat loss coefficients, such as those at Elm Tree Mews, thermal bridging at junctions becomes an important factor in overall heat loss. There are therefore opportunities to minimise heat loss by the effective design of junctions between elements and at door and window openings. However, it does not appear that any specific approach to address the issue of thermal bridging was taken in the design of Elm Tree Mews. The research programme has not carried out an in depth analysis of thermal bridging, so we cannot say for certain how Elm Tree Mews compares with similar buildings.

106 The building regulations SAP calculations for Elm Tree Mews used the default 0.08 W/m^{2}K thermal bridging y-factor in calculating heat losses due to thermal bridges. This factor is normally only

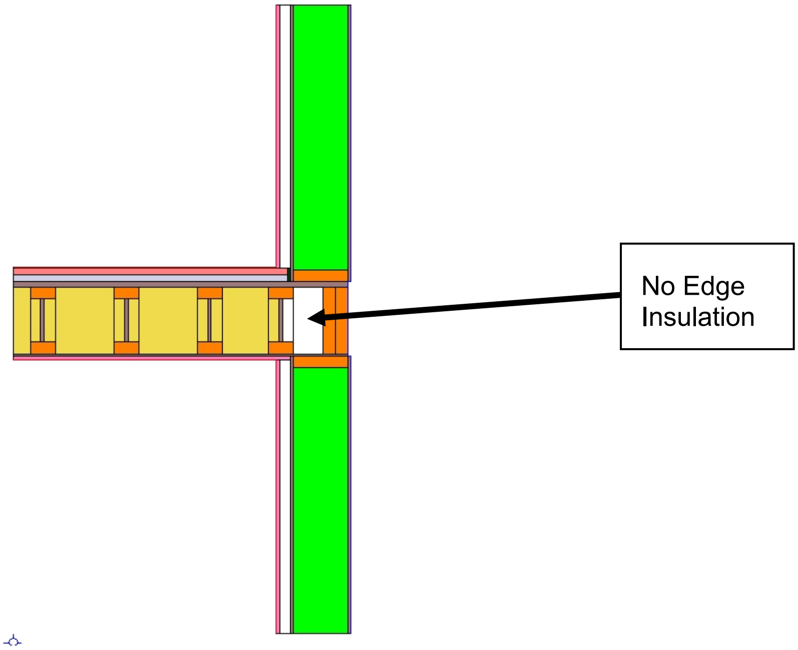
allowed for those dwellings that are built using details listed in the Accredited Details catalogue. However, although the catalogue contains timber frame details, no standard details are available for a closed panel system. It could therefore be argued that the use of the y-factor is inappropriate and that thermal bridging losses should be calculated either by modelling all the junctions or alternatively by using the default standard bridging values listed in Table K1 in SAP in combination with the calculated lengths of each type of thermal bridge in the dwelling. Using the table K1 method results in thermal bridging heat loss coefficients that are comparable to y = 0.08 for the 4 terrace dwellings (see Table 26). In the case of the ground floor flat the factor calculated using the K1 method is around twice that using y = 0.08 W/m^{2}K and for the duplex flat the K1 method gives a value around half that using y = 0.08 W/m^{2}K.

Table 26 – Thermal Bridging Calculations

Thermal Bridging Calculation Method	**Heat Loss Coefficient due to Thermal Bridging (W/K)**			
	End Terrace	**Mid Terrace**	**GFF**	**Duplex Flat**
Using Table K1 Ψ Values and Calculated Thermal Bridge Lengths	19.48	12.42	9.97	12.66
y = 0.08	19.76	12.98	4.26	6.12
y = 0.15	37.05	24.24	8.00	11.48

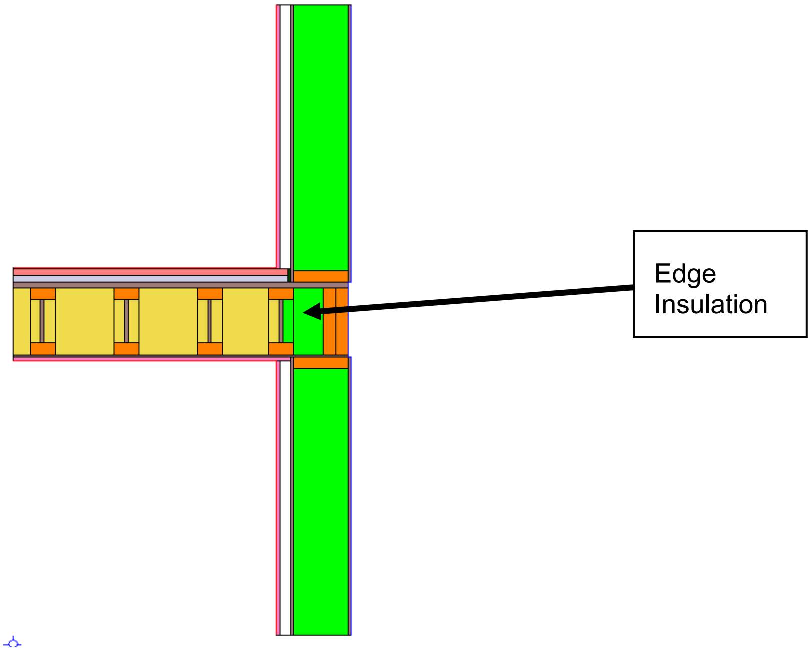
107 An example thermal analysis was undertaken of the standard intermediate floor junction as constructed at Elm Tree Mews (illustrated in Figure 66). Calculation of the thermal bridging losses using this model gave a linear thermal bridging Ψ value of 0.052 W/mK. In comparison, the Table K1 value in SAP for a nominal intermediate floor junction is 0.07 W/mK, whereas the design value at Stamford Brook was significantly lower at only 0.004 W/mK. Clearly there is significant scope for improvement at Elm Tree Mews in terms of thermal bridging.

Figure 66 – Model for Thermal Analysis of Intermediate Floor-Wall Junction As Built



108 It is interesting to note that by placing edge insulation in the cavity at the end of the intermediate floor (see Figure 67) as originally designed would more than half the Ψ value for the junction to 0.0222 W/mK. This highlights the importance of ensuring that junctions are built as designed, that the right materials are available and that short cuts are not taken on site. This requires an appropriate training regime for site-based staff and a rigorous quality control procedure.

Figure 67 – Model for Thermal Analysis Intermediate Floor-Wall Junction As-designed



109 Some of the thermal bridges that are present in the design at Elm Tree Mews are not actually mentioned specifically in appendix K of SAP (BRE2005). The most obvious of these is the geometric bridge at the roof ridge where the two sets of roof panels meet. This geometric bridge will be present in all room-in-roof/warm roof house designs but not in cold roof designs more typical of UK housing. The size of this thermal bridge was estimated using a Therm 2-d simulation (model shown in Figure 68). The calculated colour flux magnitude (Figure 69) shows the concentration of heat flux at the junction between the two panels at the ridge. The Ψ value of this junction as shown was calculated to be 0.012 W/mK.

Figure 68 – Therm Model of Ridge Junction

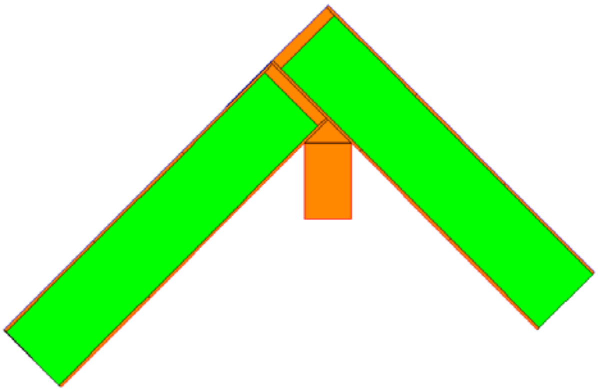
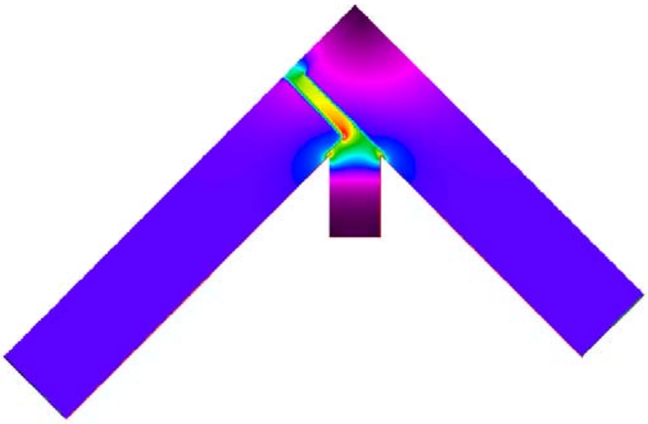


Figure 69 – Therm Model of Ridge Junction – Colour Flux Magnitude



110 The approach to thermal bridging taken at Stamford Brook was completely different to that at Elm Tree Mews. All common junctions at Stamford Brook were designed and optimised to reduce heat loss by thermal bridging and all major junctions were analysed using the Therm 2-d thermal modelling tool (Roberts, Bell & Lowe 2004). This resulted in nominal design heat loss due to thermal bridging at Stamford Brook equivalent to a y-factor of around 0.03 W/m^{2}K. This suggests that the lack of any thermal optimisation of junctions at Elm Tree Mews represented a significant lost opportunity to minimise heat loss. Future low energy housing designs will need to address the issue of thermal bridging much more rigorously, especially if it is intended to build at levels close to Passivhaus performance where y-factors would be expected to be of the order 0.01 W/m^{2}K.

111 The true level of thermal bridging at Elm Tree Mews is likely to be significantly in excess of the default accredited details y-value of 0.08 W/m^{2}K despite the apparent correlation for the terraced houses between y = 0.08 and the default Ψ values in Table K1 in SAP2005. Taking into account factors such as construction errors where details have not been built as designed (e.g. intermediate floor edge insulation), the effect of actual thermal bridge lengths, the influence of thermal bypasses at junctions (e.g. at the void between the first and second floors and the void below the ridge beam) and also the effect of unaccounted for thermal bridges such as the ridge, then the true thermal bridging factor is more likely to be of the order 0.15 W/m^{2}K. This is the nominal y-value in SAP2005 for constructions that do not meet the requirements of accredited details.

Predicted Heating System Performance

112 One of the important consequences of the measured whole house heat loss coefficient being around 50% higher than that predicted from the nominal fabric design values, is that this will mean that the communal heating system may not have sufficient output to match the heat demand from all 6 dwellings during a prolonged cold spell, especially if overcast. The heat pump for the communal heating system has a maximum rated output of 24 kW. The specification for the heat output was based on a design base heat load of 12.7 kW (Watson & Hill 2006) calculated from the nominal design U-values and airtightness, which gives a reasonable safety margin of around 11 kW between the design heat load and heating system output. However, the realised base design heat load for the end terrace calculated using the measured whole house heat loss coefficient excess over the prediction (71.5 W/K) and the measured air permeability (6.7 m^3/h.m^2) and using design internal and external temperatures of 20°C and -5°C respectively, would be 5.72 kW. If it is assumed, not unreasonably given the size of the party wall thermal bypass, that the heat loss from the other 3 houses and the two flats combined are also 5.72 kW each, then the total base heat load for all the dwellings together would be 28.6 kW. This exceeds the maximum rated output of the heat pump by more than 4 kW and suggests that the heating system would struggle to cope during periods of high heat demand when external temperatures fall below zero for any length of time. Another way to assess the impact of real construction compared to nominal design would be to use the realised heat loss coefficients for all four dwelling types at Elm Tree Mews calculated using the realised U-values and measured air permeabilities rather than the nominal values. Using realised U-values of 0.18 W/m^{2}K for the wall, 0.2 W/m^{2}K for the floor, 0.15 W/m^{2}K for the roof, 2.0 W/m^{2}K for the windows, 0.15 W/m^{2}K for thermal bridging and an air permeability of 7 m^3/h.m^2, the realised total design heat loads would be 27.3 kW using T-inside of 20°C and T-outside of -5°C (see Table 27), which is consistent with the initial prediction of 28.6 kW given above. These calculations ignore the effect of internal and solar gains, which would have the effect of reducing heat demand.

Table 27 – Design Heat Loads Calculated Using Design & Realised U-Values (T-in 20°C, T-out -5°C)

House Type	Heat Load using Design U-Values (W)	Heat Load using Realised U-Values (W)
End Terrace (House F)	3813	5737
Mid Terrace (House D, A, B)	2945	5094
Ground Floor Flat (House C)	1934	2445
Upper Duplex Flat (House E)	3010	3827
Total for all 6 Dwellings at Elm Tree Mews	17592	27291

113 In order to mitigate the potential for the system being unable to meet heat demand in very cold weather described above, bosses for additional resistance heating elements have been installed in

the system buffer tank. Two 3kW heating elements were fitted to the buffer tank during February 2009. The problem with the output of the heat pump highlights that one of the issues of low heat loss dwellings that have been designed with appropriate, closely matched heating systems, is that there is very little margin for error. If either the building fabric or heating system does not perform as expected, then the consequence will be that the system may not be able to cope under extreme conditions. In the past, heating systems have been oversized compared to the designed heat load and this allowed poorly performing heating systems or poorly performing fabric to go unnoticed. However, with rising energy prices and with designed system performance more closely matched to heat loads, residents will start to notice when systems are not working as they should, and will begin to complain about higher than expected energy bills or houses that are difficult to heat. This problem is especially critical for Passivhaus designs, which have very low output top-up heating systems.

Product and Material Substitution

114 It is normal in any construction process for changes to be made in the specification of products and materials. These can be as a result of a range of requirements such as lack of product availability, poor delivery times and cost engineering pressures, or due to changes in specification. Several instances of product specification were observed at Elm Tree Mews. The most critical of these in terms of thermal performance was the windows. The windows originally specified by the architect were timber frame double glazed units with a low-E coating (emissivity = 0.05) and argon fill, with a target whole window U-value range of 1.41 to 1.57 W/m^{2}K. It was originally specified that Danish Rationel windows would be used to meet this requirement. However, due to the cost of importing these windows from Denmark, an alternative local supplier was sought that could match the window specification at a lower price. The windows were ultimately sourced by the contractors from a local supplier. However, upon analysis of the manufacturer's window specification by the research team it became apparent that the windows did not actually meet the Elm Tree Mews specification requirements. There appears to have been confusion between the whole window U-value and centre pane U-value. The windows actually supplied were timber framed air filled double glazed units (with an unspecified low-E coating) and a quoted centre pane U-value of 1.5 W/m^{2}K. The actual whole window U-value for the units as supplied would range between 1.8 W/m^{2}K and 2.1 W/m^{2}K, depending upon the glazing gap[6]. This confusion between whole window U-value and centre pane U-value is a common occurrence and was not picked up by the contractors buying team, the Elm Tree Mews project team or at any site project meeting where this issue was discussed. This indicates a breakdown of the product approval process used at Elm Tree Mews. The consequence of this change in window specification versus the nominal design value of 1.5 W/m^{2}K would be to add around 10 W/K to the heat loss coefficient depending upon dwelling type. The consequent increase in carbon dwelling emissions of this change in window specification would be +0.8 kgCO$_2$/m^2 for the end terrace, +0.6 kgCO$_2$/m^2 for the mid terraces, +0.8 kgCO$_2$/m^2 for the upper floor duplex apartment and +0.9 kgCO$_2$/m^2 for the ground floor flat. These are clearly significant increases in emissions. If the same error had been made in the construction of a typical part L 2006 compliant dwelling then this error could have made the difference between the building either passing or failing to meet the dwelling target emission rate (TER).

115 Another issue related to the laying of the district heating main was the sequencing of the heating pipe relative to the main structure of the building. It would have been easier to lay the pipe work at the same stage as the building foundations and before the construction of the beam and block floor. However, the main structure of the building had already been completed when the district main was laid. This caused significant difficulties as the pipe had to be fed through holes in the foundation wall in the side of the building and under the beam and block floor to the entry point in the floor in the middle of each dwelling (see Figure 70). As the pre-insulated Calpex pipe is relatively inflexible with a minimum bend radius of 0.7m (Calpex 2006), the construction operatives found it impossible to feed the pipe where required without stripping back the insulation layer from the outside of the pipe. In some cases the outer protective sheath of the pipe was removed which would allow water ingress into the insulation layer and mean that the insulation layer is much more easily damaged. The reason for the laying of the district main so late into the construction process is unclear but it is know that there were significant delays in ordering the pipework.

---

[6] In SAP table 6e (BRE 2005) the nominal whole window U-value for a timber frame, double glazed, low-E coating (emissivity = 0.1) air-filled window with 12mm glazing gap is 2.1 W/m^{2}K and for a 16mm gap 1.9 W/m^{2}K. With a low E emissivity at 0.05 and 12mm glazing gap the U-value is 2.0 W/m^{2}K and at 16mm gap is 1.8 W/m^{2}K. The windows at Elm Tree Mews have either a 14mm gap or 16mm glazing gap, so the average nominal U-value for the windows used at Elm Tree Mews is likely to be of the order 2.0 W/m^{2}K.

Figure 70 – Installation of District Heating Pipework

District heating pipe being fed under ground floor of dwelling through hole in foundation wall

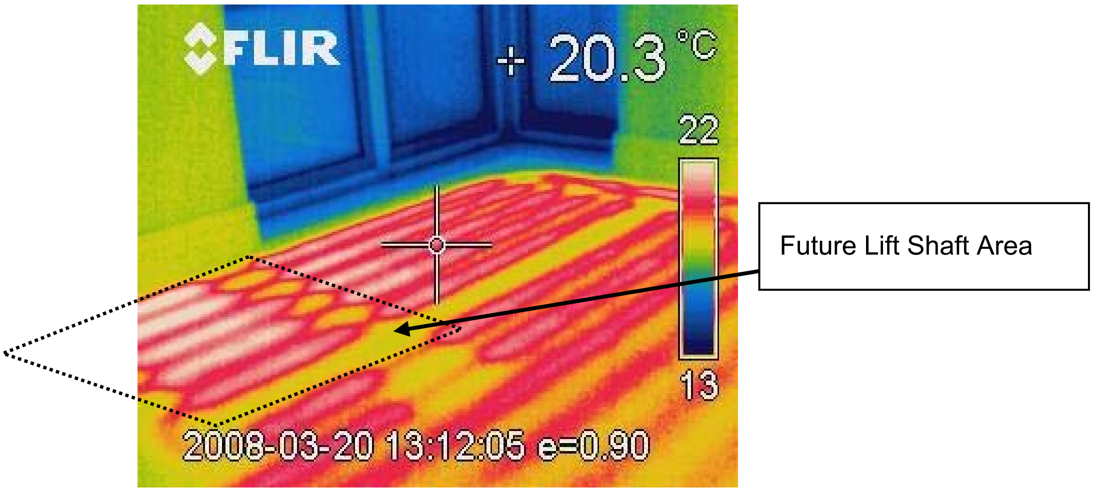
Outer protective sheath stripped away

Insulation layer stripped away

Lifetime Homes Requirements

116 Although the focus of the design and construction assessment for Elm Tree Mews has been on those aspects relating to thermal performance, it is pertinent to consider how other aspects of performance have been managed. In particular, the research team have observed that some aspects of the Lifetime Homes requirements have not been properly implemented. The best example of this was with the designed provision for a future lift shaft. In order to make the installation of a lift easier at a future point in time, an area of the first floor was designated as a future lift shaft and provision was made for this in the dwelling designs. It was therefore essential that the underfloor heating pipes were not laid across the floor in the location of the designated lift shaft area. However, this requirement was not well communicated to all members of the design and construction team. Consequently, the underfloor heating subcontractors designed and built the underfloor piping layout without any consideration for the future lift shaft. Confirmation that the heating pipes do cover the future lift shaft area is given by the thermal image of the floor in Figure 71. Another aspect of the Lifetime Homes requirements that was not built according to the specification was the provision of a capped foul water drain point in the downstairs WC. This would be used if the downstairs toilet needed to be converted into a shower room at a future point in time. However, it was found that this extra drain had not been installed in the floor. Both these issues are likely a result of poor communication of performance requirements. This is perhaps a reflection of the relatively complex nature, both of the building and also the organisational structure of the various consultants, contractors and sub-contractors involved in the project.

Figure 71 – Thermal Image in Bedroom of House F Showing Underfloor Heating Pipes



Future Lift Shaft Area

Party Wall Thermal Bypass Mechanism

117 Observations made during the construction of the beam and block floor and party wall at Elm Tree Mews give some clues as to part of the possible mechanism of the party wall thermal bypass that has been identified during this study. The ventilated underfloor void is now known to link directly with the party wall. The connection between the party wall cavity and floor void is formed by the gaps in the construction of the beam and block floor (see Figure 50). This means that cold air can move from the ventilated floor void into the party wall cavity and, conversely, warmed air can move from the party wall cavity into the floor void. Such air movement would be induced by pressure differences between the two spaces. Air gaps in the cavity sock at the vertical edge of the party wall cavity (Figure 51) will also allow horizontal flow of air across the cavity. Measurements taken using a hot beam anemometer confirm that there is both vertical and horizontal air flow in the cavity at a rate of up to 0.5 m/s. A schematic of the proposed thermal bypass mechanism is shown in Figure 72. A photograph of the heat plume due to the thermal bypass is shown in Figure 73.

Figure 72 – Elm Tree Mews Proposed Party Wall Thermal Bypass Mechanism

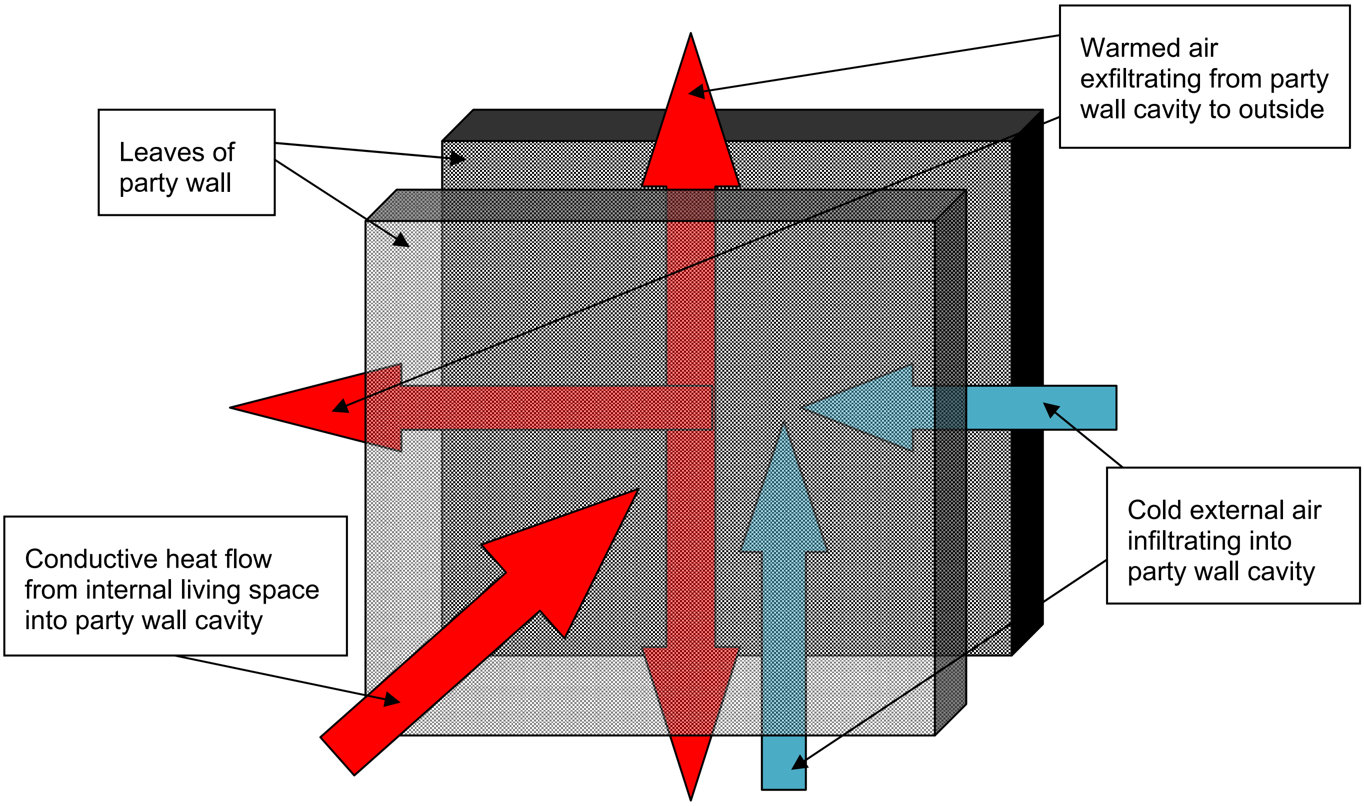
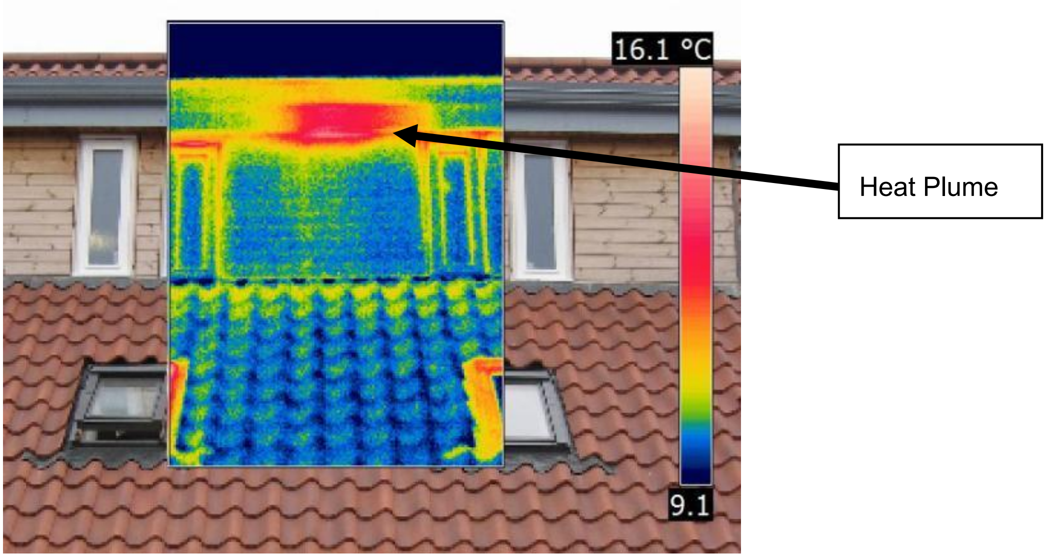


Figure 73 – Thermal Image of Heat Plume around Dormer Window due to Party Wall Bypass



Description of In-use Monitoring of Occupied Houses

118 It was the intention of the research project plan that all six dwellings at Elm Tree Mews would be subject to monitoring of household energy use and internal conditions over a period of one year following occupation, starting sometime in January or February 2008. In addition, it was planned that there would be a series of post occupancy evaluation interviews. However, due to the delays in the construction programme, the first dwellings were not actually occupied until the end of June 2008. The effect of this on the research programme was that it was not possible to contact the residents of the first three houses to be occupied to discuss participation in the project until September 2008. Further delays in the sale of the two part ownership properties meant that these residents could not be contacted until January 2009 and therefore monitoring did not begin in these two properties until the start of 2009. The remaining end terrace property designated for full sale tenure had still not yet been put on the market and was therefore not included in the monitoring programme. All five occupied households agreed to participate in the monitoring exercise. The start and end dates for the monitoring periods are shown in Table 28. The table also gives the dwelling code numbers that will be used to identify the houses in this report. These code numbers are needed to preserve the anonymity of the householders as far as is possible given the circumstances of the project. Three of the occupied dwellings (Dwelling Codes: A, B, C) were monitored for a full year or more, with the remaining two occupied dwellings (Dwelling Codes: D, E) being monitored for eight months, which covered only part of the heating season.

Table 28 – Occupation Dates of Dwellings at Elm Tree Mews

House Dwelling Code No.	House type	Tenure	Tenancy start date or sale completion date	Start date for monitoring	End date for monitoring and final interview
A	Mid terrace	Rented	24 June 08	3 Sept 08	23 Sep 09
B	Mid terrace	Rented	24 June 08	5 Sept 08	29 Sep 09
C	Ground floor flat	Rented	25 June 08	25 Sept 08	24 Sep 09
D	Mid terrace	Part-ownership	8 Dec 08	7 Jan 09	25 Sep 09
E	Duplex flat	Part-ownership	23 Dec 09	10 Jan 09	21 Sep 09
F	End terrace	Full sale	Unsold	n/a	n/a

119 Occupancy levels of the five occupied dwellings at Elm Tree Mews were ascertained from the initial discussions with the residents and from the final interviews, and are shown in Table 29. It should be noted that dwelling C was occupied intermittently, typically for only 1 or 2 days per week. This will significantly effect energy consumption and hot water use for this dwelling compared to the expected use.

Table 29 – Occupancy Levels of Dwellings at Elm Tree Mews

Dwelling Code	House Type	Occupancy
A	Mid terrace	4 + 1 dog
B	Mid terrace	5
C	Flat	1 (Intermittent occupation)
D	Mid terrace	3 + 1 cat
E	Flat	1

120 The performance and efficiency of the communal heat pump at Elm Tree Mews was monitored from July 2008 until the end of September 2009. A heat meter and kWh meters were installed on the heat pump and system components, and a series of temperature sensors were located on the flow and return pipework to and from the heat pump, buffer tank, communal main and ground loop.

121 In addition to the energy data collected directly by the research team, access was also given by the Joseph Rowntree Housing Trust to the metered data from the heat meters used to charge the residents for their use of heat from the communal heating system. This data was collected by the

metering subcontractors on a daily basis and was provided to the research team in the form of spreadsheet which was updated every month. These metered data were collected for the period June 2008 to September 2009 inclusive.

122 The original intention was to conduct a short interview with the residents a month or two after installation of the monitoring equipment and then to follow this up with a longer final interview at the end of the monitoring period. However, due to technical problems with the heating and hot water systems at Elm Tree Mews over the first 6 months of occupation, it was decided not to conduct the initial interviews in order to avoid any negative bias in the interview responses as a result of the technical issues, and also to minimise any further disturbance to the householders. The effort was therefore concentrated on the final interviews which took place at the end of the monitoring period.

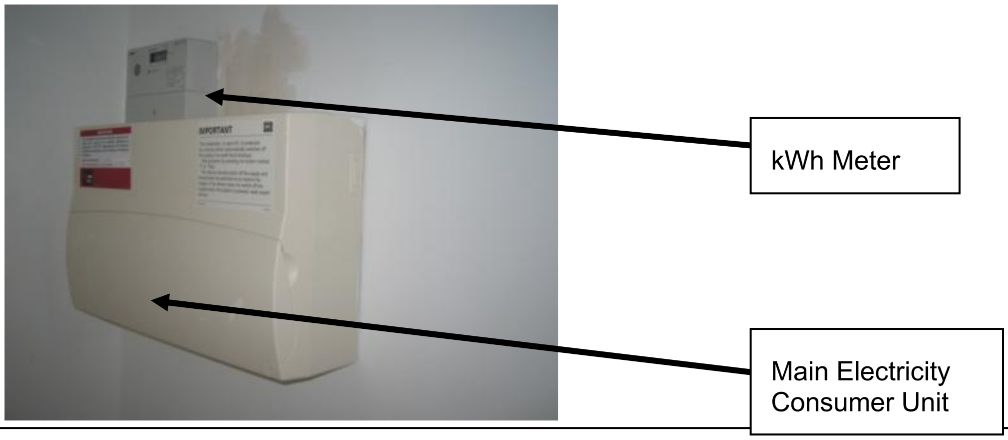
Technical Performance

123 The five occupied houses at Elm Tree Mews were equipped with a range of sensors and additional meters as shown in Table 30. The meters were preinstalled during construction when the electrical, heating and hot water systems were installed. Secondary electricity meters were installed between the main utility meter and the consumer unit as shown by the example in Figure 74. The energy input to each dwelling from the communal heat main was recorded using a pulse output on the main heat meter used to charge the residents for their energy use. These heat meters also relayed meter data on a daily basis to a data integrator located in the plant room. These data were then used by the subcontract meter management company to calculate the householder's heat pump energy bills. The data from the sensors and meters in the houses were collected by several wireless dataloggers. These loggers were located in the heat pump plant room on the ground floor at Elm Tree Mews so that they could be accessed without disturbing the residents. See Appendix 4 for details of the specific equipment used.

Table 30 – Sensors and Meters used for Monitoring Households

Sensor/Meter Details	No. per Dwelling	Location in Dwelling
Electricity kWh meter	2	1 on mains supply 1 on electricity supply to hot water immersion heater
Ultrasonic heat meter	3	1 on communal heat main input to house 1 on communal heat main input to hot water cylinder 1 on solar panel input to hot water cylinder
Water meter	1	1 on cold water supply to hot water cylinder (equivalent to domestic hot water use)
Wireless temperature and relative humidity sensor	5	1 in living room 1 in hall or downstairs toilet 1 in kitchen 1 in a bedroom 1 in main bathroom
Wireless Carbon Dioxide sensor	1	1 in kitchen or bedroom

Figure 74 – Secondary kWh Meter Adjacent to Consumer Unit



124 A typical installation of the main heat meter in the cupboard under the stairs is shown in Figure 75 (photograph taken during the construction process). The main heat meter body comprised the flow meter, return temperature sensor, energy integrator and was located on the return flow pipework. The second flow temperature sensor for the heat meter was located on the pipework just before the flow splits between the underfloor heating and hot water systems. A typical installation of heat meters and flow meter on the hot water inputs in the cylinder cupboard is shown by the photograph in Figure 76.

Figure 75 – Typical Main Heat Meter Installation

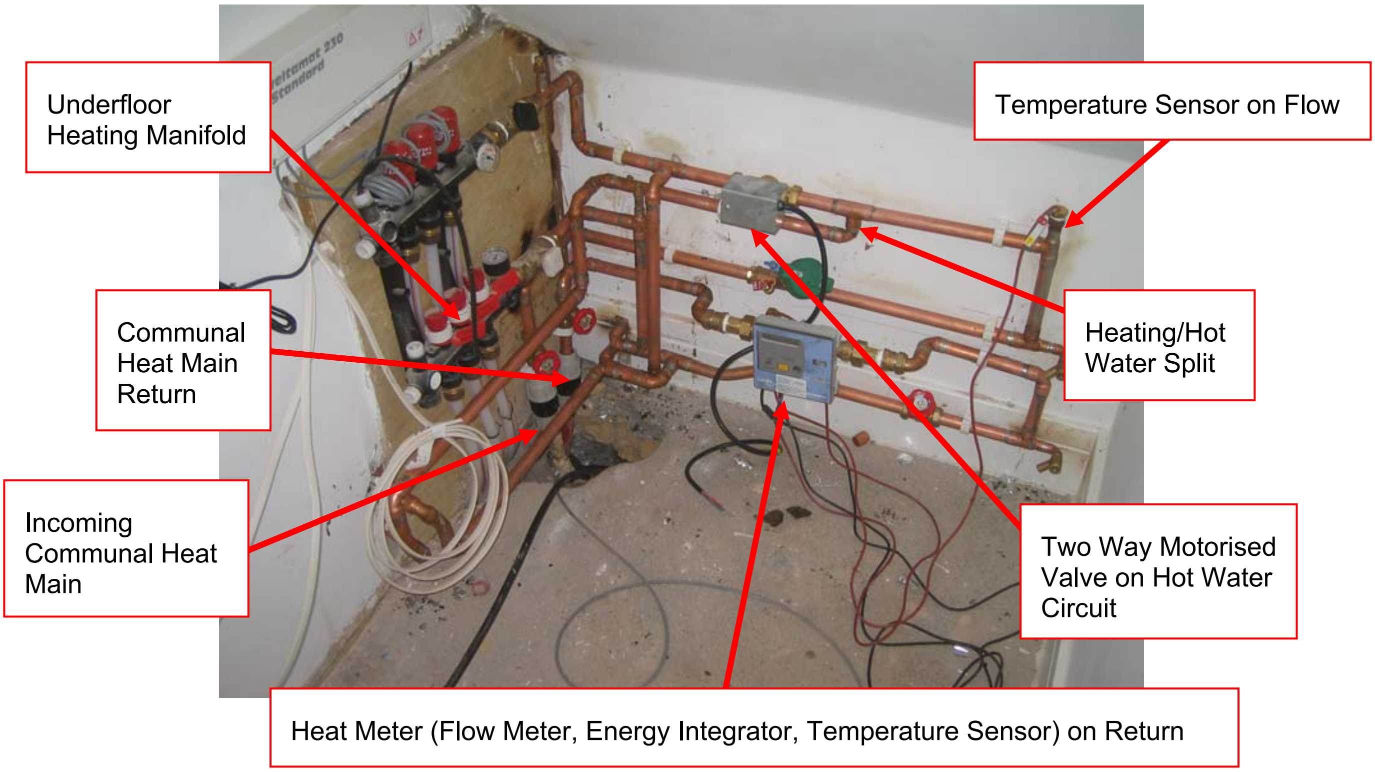
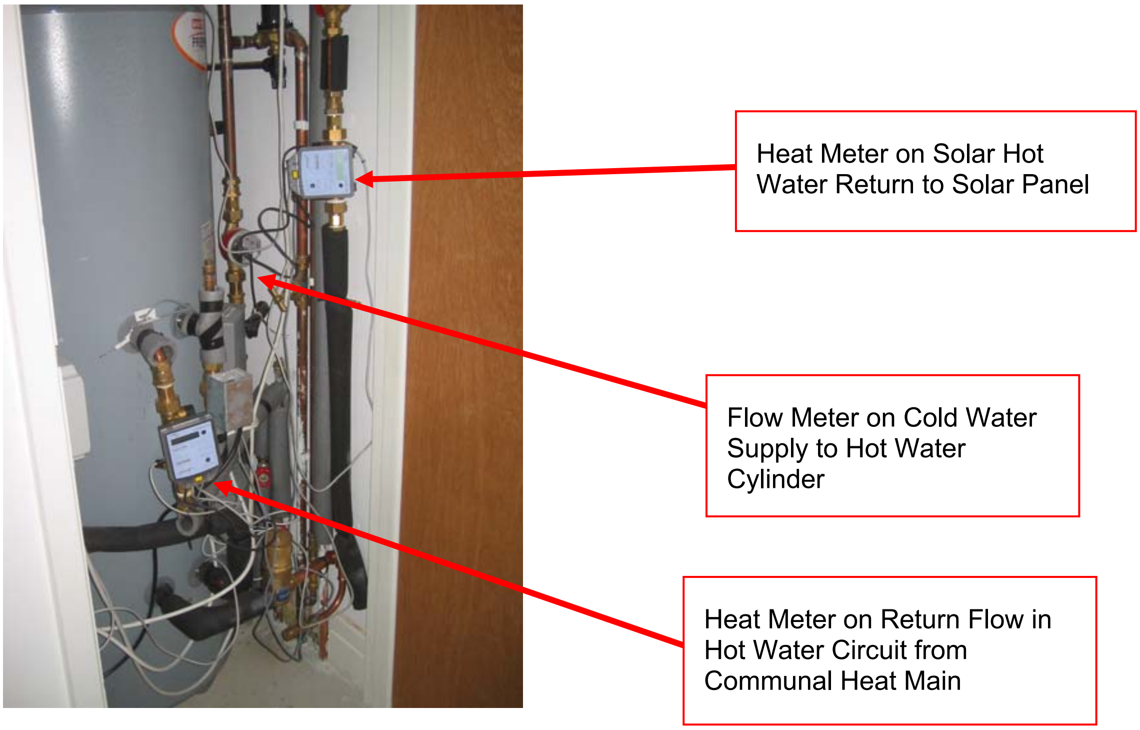
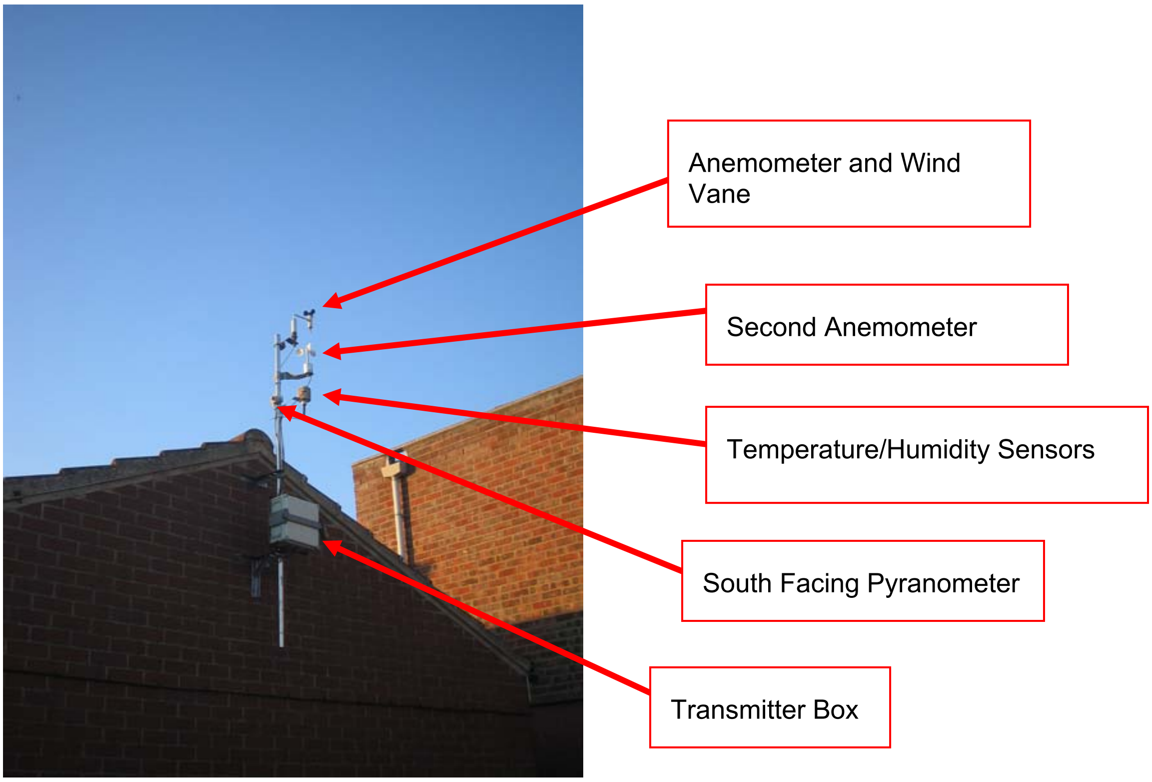


Figure 76 – Typical Heat Meter Installation in Hot Water Cylinder Cupboard



125 A weather station was erected at York in February 2008 to provide data on external conditions during the monitoring phase. For security reasons, the weather station was located on a building in the secure compound at the Joseph Rowntree Housing Trust depot at Tanners Yard in York, which is approximately 500 metres from the Elm Tree Mews site. A photograph showing the weather station on location at Tanners yard is shown in Figure 77. The weather station comprised sensors for external temperature and relative humidity, wind speed, wind direction, and vertical south facing solar insolation. The weather station data was collected using wireless datalogger, which was located in the offices at Tanners Yard. See Appendix 4 for details of the specific equipment used.

Figure 77 – Weather Station at Tanners Yard in York



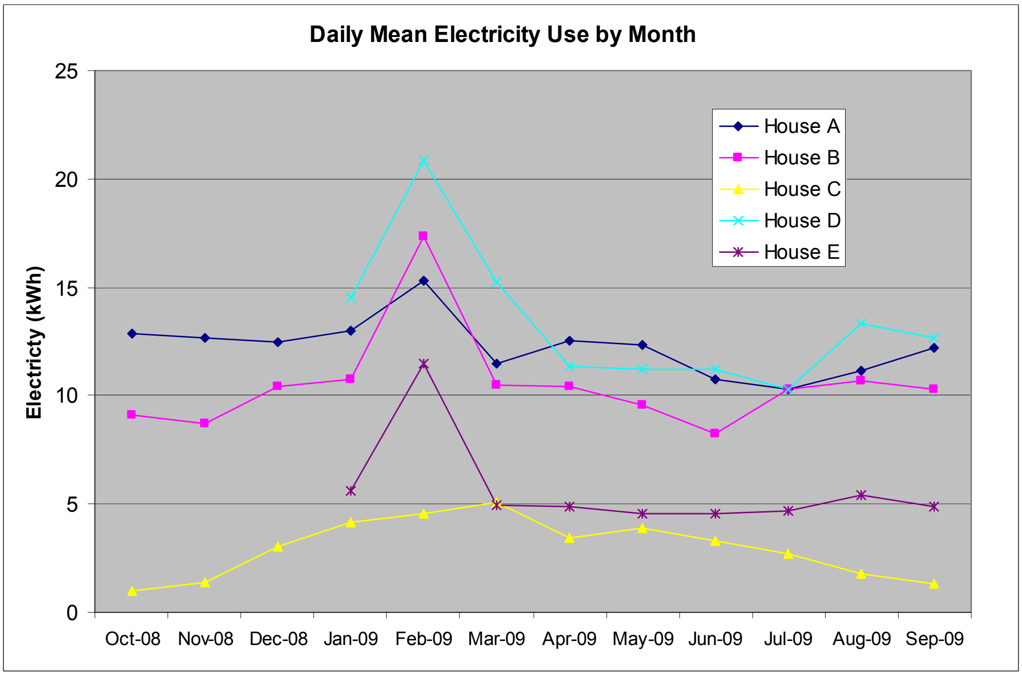
In-use Energy Performance

126 The daily mean electricity use by the five occupied are given in Table 31 and illustrated by month in Figure 78. These data give a daily average for the annual monitoring period for Houses A, B and C and also by month for all five dwellings. It can be seen from the data that electricity use peaks in February. This is a direct consequence of a failure of the communal heat pump at this time, with the residents having to use electric fan heaters to heat the houses and to use the immersion heater to supplement the solar input to the hot water cylinder. Ignoring February, the highest electricity consumption over the winter period was in House D at around 15 kWh/day. The lowest consumption was in House C at around 4 kWh/day, which reflects the intermittent occupation pattern in this household. During the spring and summer, the electricity use for the three mid terraced properties (A, B and D) ranged from around 9 to 12 kWh/day. The consumption in Houses C and E was much lower at between 1 and 5 kWh, reflecting the lower occupancy and smaller floor area of the flats compared to the mid terraces.

Table 31 – Mean Daily Electricity Use – Annual and by Season

	Mean Daily Electricity Use (kWh)				
Period	**House A**	**House B**	**House C**	**House D**	**House E**
Annual	12.1	10.3	3.0	-	-
Oct-Apr	12.9	11.0	3.2	-	-
Jul-Aug	10.7	10.5	2.3	11.8	5.0

Figure 78 – Plot of Daily Mean Electricity Use by Month



127 The equivalent annual electricity use for the three Elm Tree Mews houses with annual data ranges from 1082 kWh/annum for House C, 3762 kWh/annum for House B and 4430 kWh/annum for House A. Based on the available monthly data, is likely that the annual consumption in House D would have been the highest at around 5040 kWh/annum if we extrapolate for the missing months. By comparison, DECC data show that the mean domestic electricity consumption for Yorkshire in 2007 (see Table 32) was 4080 kWh/annum, although this would include properties that only had electrical heating, which would skew the results slightly higher than if the data were for gas or oil heated dwellings only. The median electricity data (3350 kWh/annum for Yorkshire) is likely a better comparison to the Elm Tree Mews results for the mid-terraced houses. As the electricity consumption in all 3 mid-terraces was higher than the median, this suggests that the annual electricity consumption at Elm Tree Mews is towards the higher end of typical domestic electricity consumption. This will be party due to the electricity requirement for the hot water cylinder immersion heater, but will also reflect the usage patterns of the occupants and the need to use electricity rather than gas for all cooking. When the electricity data are adjusted for the measured and extrapolated use of the immersion heater, then the annual use for the dwellings drops to 4196 kWh/annum for House A, 3495 kWh/annum for House B, 526 kWh/annum for House C, 4492 kWh/annum for House D, and 1458 KW/annum for house E. The data can then be corrected for estimated use of electricity for cooking using standard use algorithms and also adjusted for the extra electricity used in February to supplement the lack of heat from the broken heat pump.

128 These relatively crude adjustments give the annual electricity use for the three mid-terraces at 3196 kWh/annum for House A, 2477 kWh/annum for House B and 3785 kWh/annum for House D. Another comparison for the electricity data from the mid-terraces can be made with the annual electricity consumption of three similarly sized mid-terraced houses measured by Leeds Met as part of the Stamford Brook field trial, which ranged from 2100 kWh/annum to 3100 kWh/annum (Wingfield, Bell, Miles-Shenton, Lowe & South 2008) putting the Stamford Brook houses at the lower end of typical consumption. This is a useful comparison, as the houses at Stamford Brook were designed to have a similar fabric performance to Elm Tree Mews but with a deliberate design focus that avoided renewable energy and the houses at Stamford Brook were therefore fitted with condensing gas boilers as the main heating energy source. Given that all the permanent light fittings at Elm Tree Mews were low energy bulb fittings, one might have expected the electricity use to be lower by around 300 to 400 kWh compared to the UK median and the Stamford Brook houses, but this was not found to be the case. With hindsight, it may have been useful to measure the electricity use by the individual power and lighting circuits in the dwellings.

Table 32 – Mean Annual Electricity Consumption from Domestic UK Meters in 2007 (Chan 2009)

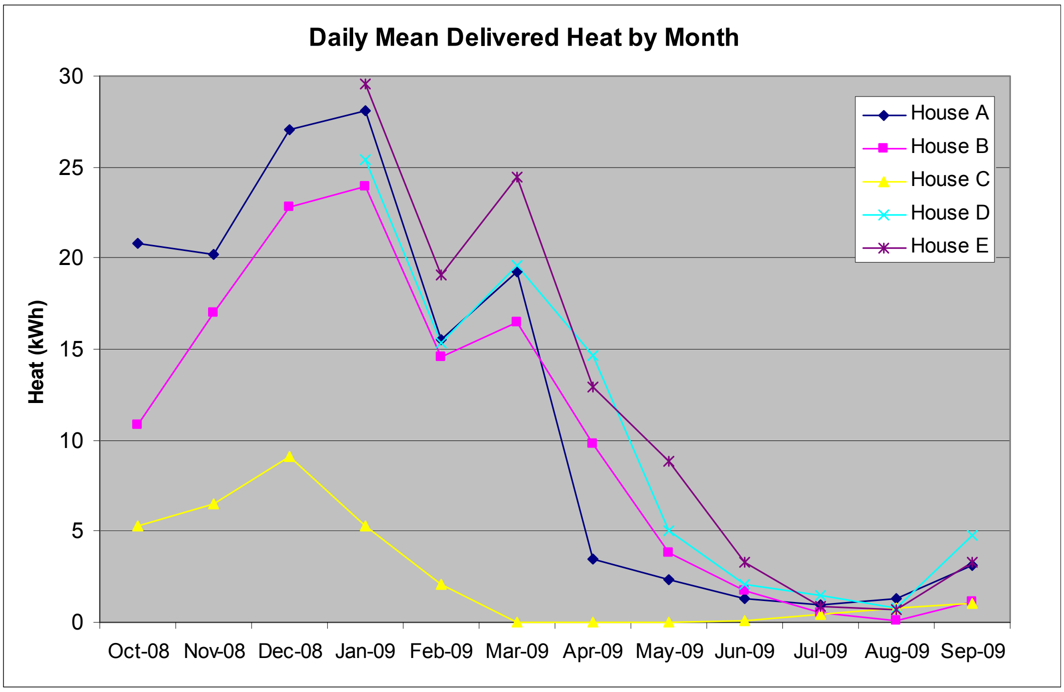
	Annual Electricity Consumption (kWh)					
	All Domestic Meters		Standard Meters Only		Economy 7/10 Meters Only	
Meter Area	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**
Yorkshire and Humber	4080	3350	3817	3240	6589	5610
Great Britain	4392	3550	3934	3320	6191	5050

129 The daily mean heat inputs from the communal main into the five occupied houses are given in Table 33 and illustrated by month in Figure 79. It can be seen that there is a reduction of around 10 kWh/day in the measured heat input for Houses A, B, D and E during February when compared to either January or March. This is consistent with the reduced input during the period of around seven days when the communal heat pump was out of action. It is interesting to note that the corresponding increase in electricity consumption over the same period in February was only 5 kWh/day, indicating that the residents were either unable or unwilling to replace the missing heat input, perhaps due to concerns about the potential cost of the electricity. Excluding February, the peak heat input during the winter months was of the order 30 kWh/day for the terraced houses. During the summer months the communal heat input fell to around 1 kWh/day per dwelling, being the residual requirement for hot water that was not being satisfied by the heat input to the hot water cylinders from the solar panels and immersion pasteurisation cycles.

Table 33 – Mean Daily Communal Heat Input – Annual and by Season

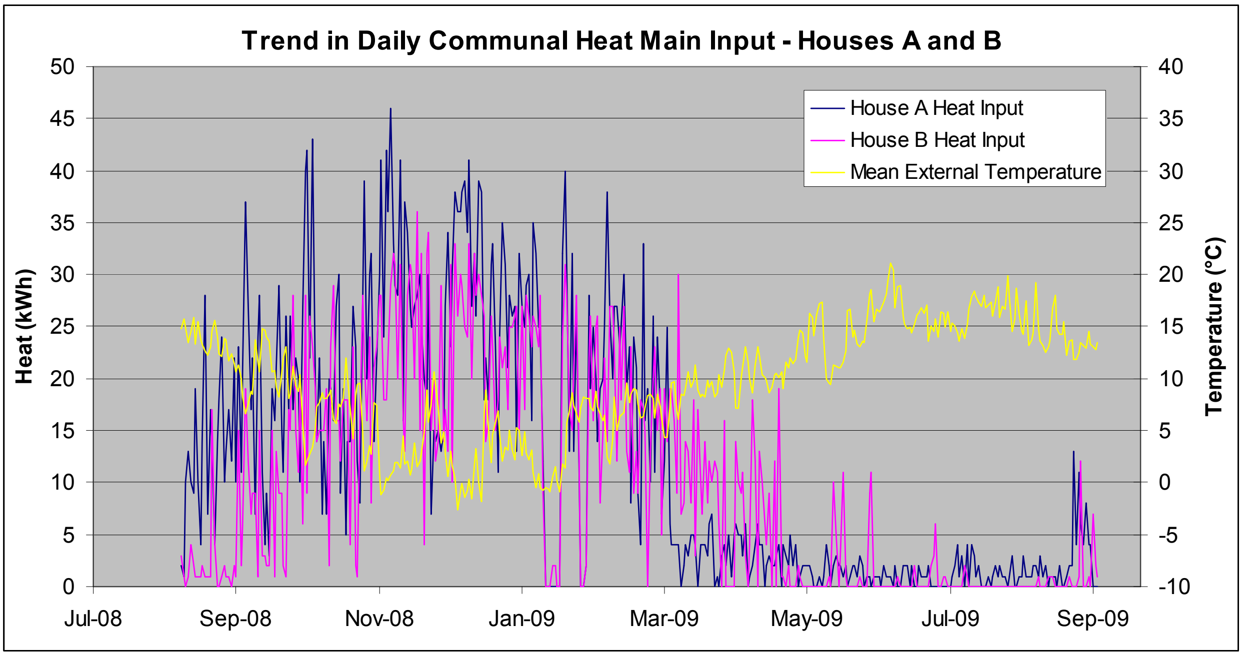
	Mean Daily Heat Input from Communal Main (kWh)				
Period	**House A**	**House B**	**House C**	**House D**	**House E**
Annual	12.2	9.8	2.6	-	-
Period October to April	19.2	16.6	4.1	-	-
Period July to August	1.1	0.3	0.6	1.1	0.8

Figure 79 – Mean Daily Communal Heat Input to Dwellings by Month



130 A graph illustrating the daily total heat main input to dwellings A and B for the whole monitoring period is shown in Figure 80. This graph shows that the general trend for the heat energy required is similar for both dwellings. As would be expected, the heating trend is the inverse of the trend in daily mean external temperature. It can also be seen that the heat input drops to zero for a short period in February. This coincides with the breakdown of the heat pump. The plot shows that external balance temperature when the heating system was turned off for the summer and on again in the winter was between 10°C and 12°C. It can be seen that the heating in house B came on several times during May when the external temperature dropped to close to 10°C. This would suggest that the residents of this dwelling did not turn off the heating completely for the summer, but instead left the system on to control itself using the system thermostat.

Figure 80 – Heat Main Daily Energy Input to Houses A and B



131 The mean daily hot water usage (litres/day) for the occupied dwellings at Elm Tree Mews is given in Table 34 and the monthly trend is illustrated in Figure 81. The data are compared in the table to the estimated usage using the hot water algorithm in BREDEM-12 model[7]. The data indicate that dwellings A, D and E are generally in line with the predicted use. Dwelling C has a much lower usage (~19 litres/day) which will be a result of the intermittent occupation pattern for this dwelling. Hot water consumption in house B (average of 88 litres/day) is much lower than the BREDEM-12 estimate of 138 litres/day, which would indicate that this household is very cautious with their use of hot water when compared to a typical UK household. The monthly trends show that all the dwellings except House C show a reduction in hot water use over the summer of around 30% compared to usage during the winter.

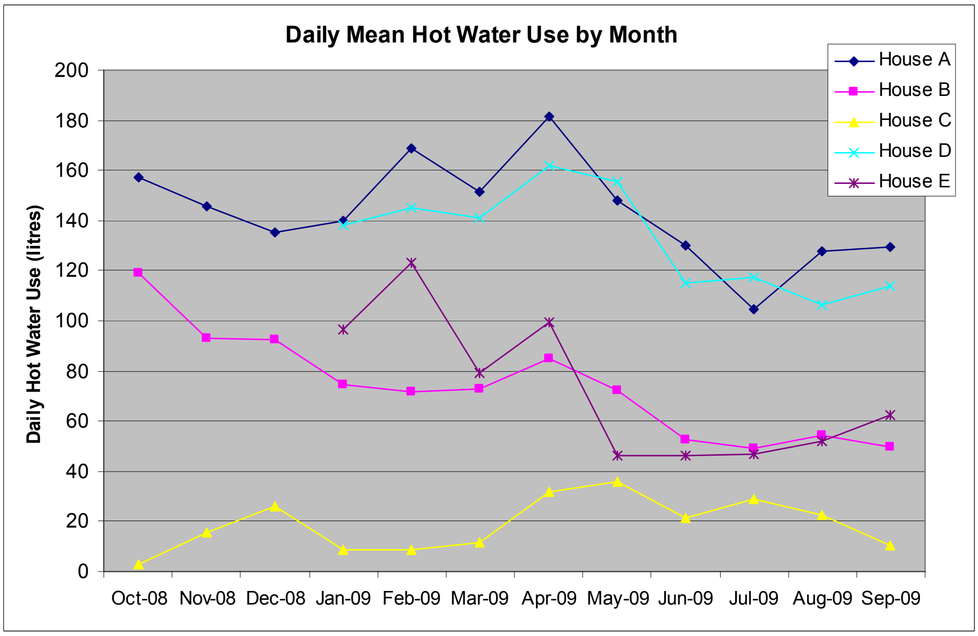
Table 34 – Mean Daily Hot Water Use Occupied Dwellings

	Mean Daily Hot Water Use (litres)				
Period	**House A**	**House B**	**House C**	**House D**	**House E**
Annual Mean	145.1	74.9	18.6	-	-
BREDEM-12 Model Estimate	138.0	163.0	63.0	113.0	63.0
Period October to April	153.8	87.1	15.0	-	-
Period July to August	116.2	51.7	25.7	111.7	49.6

---

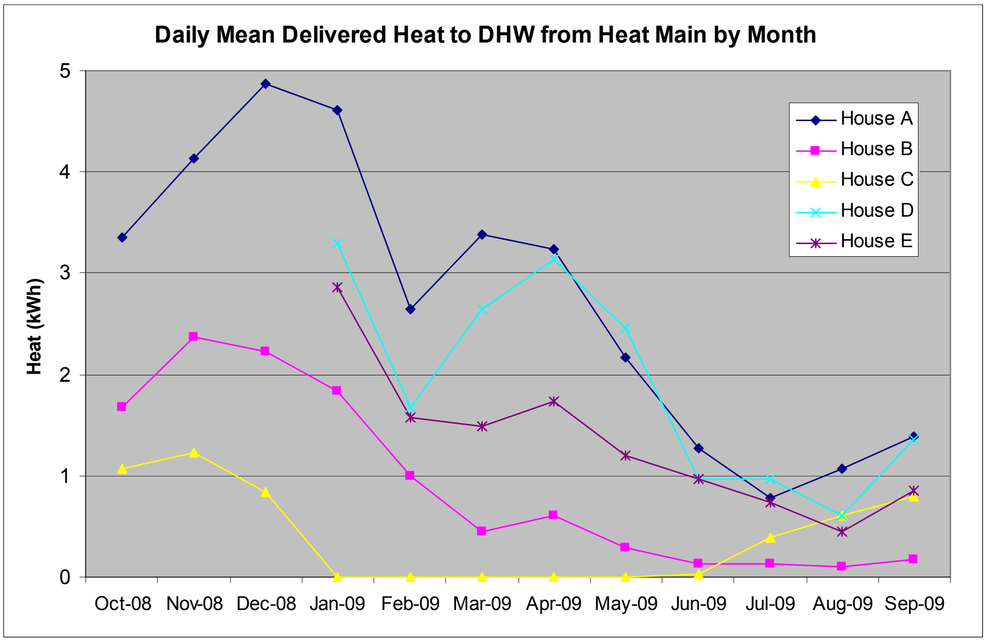
[7] Typical daily hot water consumption in litres calculated according to the BREDEM-12 domestic energy model is given by the equation: Hot water use = 38 + [occupancy x 25] (Anderson et al 2002).

Figure 81 – Daily Mean Hot Water Use by Month



132 The energy used to heat the domestic hot water in the cylinders comes from three sources. In the summer the heat will come mainly from the solar thermal panels on the roof, whereas in winter it would be expected that the energy will come from a mixture of solar, heat pump input and the immersion heater. The mean daily input to the cylinders for each month is shown in Figure 82. This graph shows that the demand for communal heat input for hot water is greatest during the winter when the solar input will be at its highest.

Figure 82 – Daily Mean Delivered Heat from Heat Main to Cylinder by Month

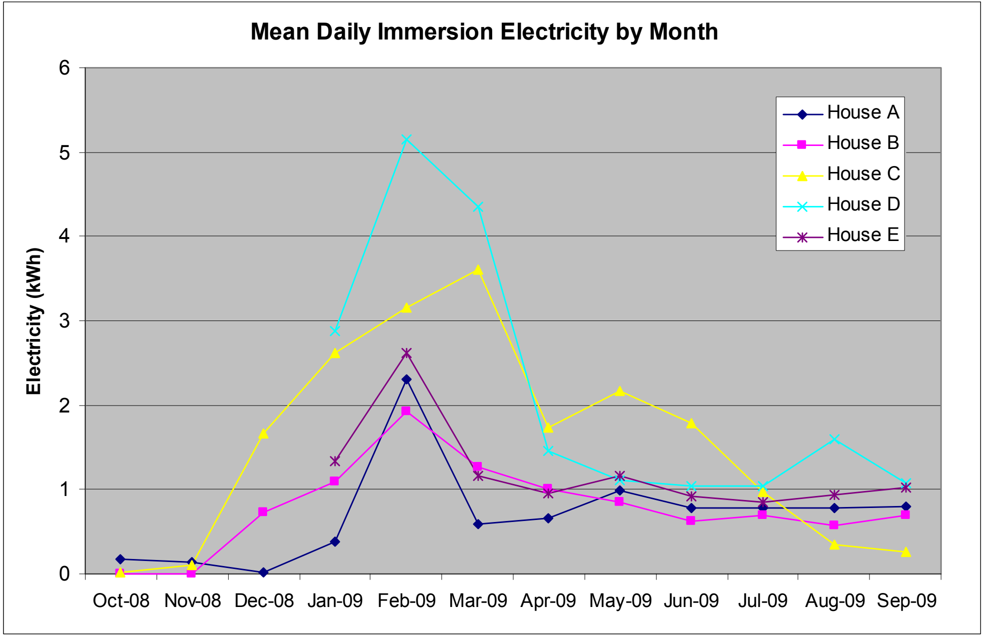


133 The communal main hot water input to the cylinder in mid-terrace House B is much lower than the other two mid terraces. This is most likely a function of the lower hot water use by the residents in B. The lower water use will mean that the water in the cylinder will be at a higher temperature than in the other houses and so is more likely to be higher than the temperature of the communal main water which is only at around 40°C compared to around 70°C to 80°C for the output from a domestic gas boiler. This highlights one of the main problems when trying to use low temperature heat sources to supplement the heating requirements for domestic hot water which is generally stored at 60°C. It can also be seen in Figure 82 that the heat main input to the cylinder in House C fell to zero in January and did not pick up again until June. This issue was identified by the

research team at the time and the information passed on to the Housing Trust and main contractor. However, the cause of the problem was not diagnosed until June. It was found that a time clock for the immersion heater installed at the request of the resident in House C had been set up in such a way that it interfered with the proper operation of the solenoid valve designed to prevent feedback of heat from the cylinder immersion heater into the communal system. This fault had the effect of closing off all input from the communal main into the cylinder. Once the timer was correctly re-installed, then the heat input from the communal main returned to normal. The operation of the communal heat input to the cylinders was controlled by a programmable timer located in the cylinder cupboard. The controllers were capable of up to two heating periods per day, and were initially set up by the system installers to come on between 6:00am and 8:00am in the morning and again between 6:00pm and 8:00pm in the evening. The responses from all the householders in the final interviews indicated that these settings were not changed from these set points over the monitoring period.

134 The hot water cylinders at Elm Tree Mews were fitted with an immersion heater to provide boost heating when required by the residents. The immersion heater was operated by a manual timer located in the cylinder cupboard next to the hot water controller. The timed heating period was for up to 2 hours in 15 minute increments. A graph of the mean daily immersion heater energy for each month is shown in Figure 83. This shows a peak in the use of the immersion heater in February which was a result of the problems with the communal heating system. It can also be seen that immersion heater use in October and November was very low when compared to use in the spring and summer of 2009. This is a direct result of the introduction of an automatic weekly pasteurisation cycle that used the immersion heater to boost the temperature of the stored hot water to 60°C as part of measures to mitigate the risk of contamination by legionella bacteria. This is discussed in more detail later in this chapter. It can be seen that the use of the immersion heat by Houses C and D over the winter period was significantly higher that the other three dwellings. This can be related to problems with the performance of the solar system in House D and to the solar system, heat pump input to hot water and low hot water use in House C. It is interesting to note that when the householder in House D was questioned by the researchers at the time about the excessive use of the immersion heater they replied that they had not been using the heater. It subsequently transpired that the children in House D had been switching on the immersion timer without the knowledge of their parent, the reason being given that this was the only way they knew to get reliable hot water when they wanted to take a shower (from their experience in their previous home).

Figure 83 – Daily Mean Electric Immersion Heat Main to Cylinder by Month

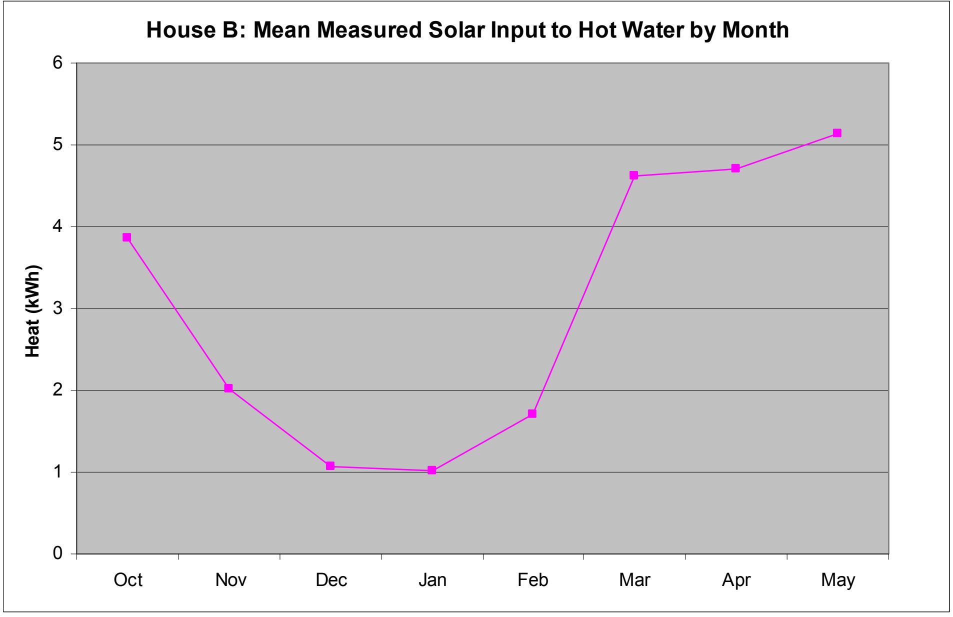


135 The performance of the solar system has been difficult to analyse properly. This is due in part to problems with the heat meters that had been installed to monitor the heat output from the solar panels into the hot water cylinders. However, it was subsequently discovered that the ultrasonic meters specified were unsuitable for use in solar heating systems that used glycol antifreeze mixtures as is the case at Elm Tree Mews. Discussions with engineers from the manufacturers of

the heat meters indicated that the meters will give unreliable data at low liquid flows due to the density difference between glycol and water. This issue demonstrates that the research project itself was not immune from problems that arise due to inadequate process controls and poorly defined performance specifications. In this case the research team did not properly check the specification of the proposed metering solution and assumed that what was being installed was suitable for the task. As it turned out, the issue with the solar heat meters was in someway fortuitous, as it was possible to use the data obtained to identify at an early stage that there were significant problems with the solar installations in four of the dwellings at Elm Tree Mews. If the heat meters had been working as expected, then the likely observable differences in solar output could just as easily have been ascribed to differences in the usage patterns of hot water.

136 Of the 5 monitored dwellings, the solar system in House B was the only one that was free from known installation problems. Reliable solar heat meter data from House B was obtained for the period from October 2008 to May 2009 as shown in Figure 84. Using these data, together with the solar data from the weather station, it is possible to calculate a relationship between solar insolation and heat input to the hot water cylinder. This calculation gives an average input of 0.034 kWh of heat per W/m^2 of solar insolation as measured using a vertical south facing pyranometer. The measured mean daily solar insolation at the York weather station over the period October 2008 to September 2009 was 95 W/m^2 which would give a total annual solar input for House B of 1179 kWh. This is in line with the manufacturers claimed typical annual output of 730 kWh per m^2 of solar aperture (Schott 2008), which is equivalent to 1180 kWh/annum for the 2-panel systems installed on the terraced houses at Elm Tree Mews. The realised performance is also in line with that predicted by the SAP energy model for the mid terrace houses (1097 kWh/annum). It is unlikely that the other dwellings at Elm Tree Mews would have achieved a similar level of solar input to hot water as was achieved in House B due to the various technical problems with the solar systems that were not fully rectified until July 2009.

Figure 84 – Plot of Mean Daily Solar Input for House B by Month



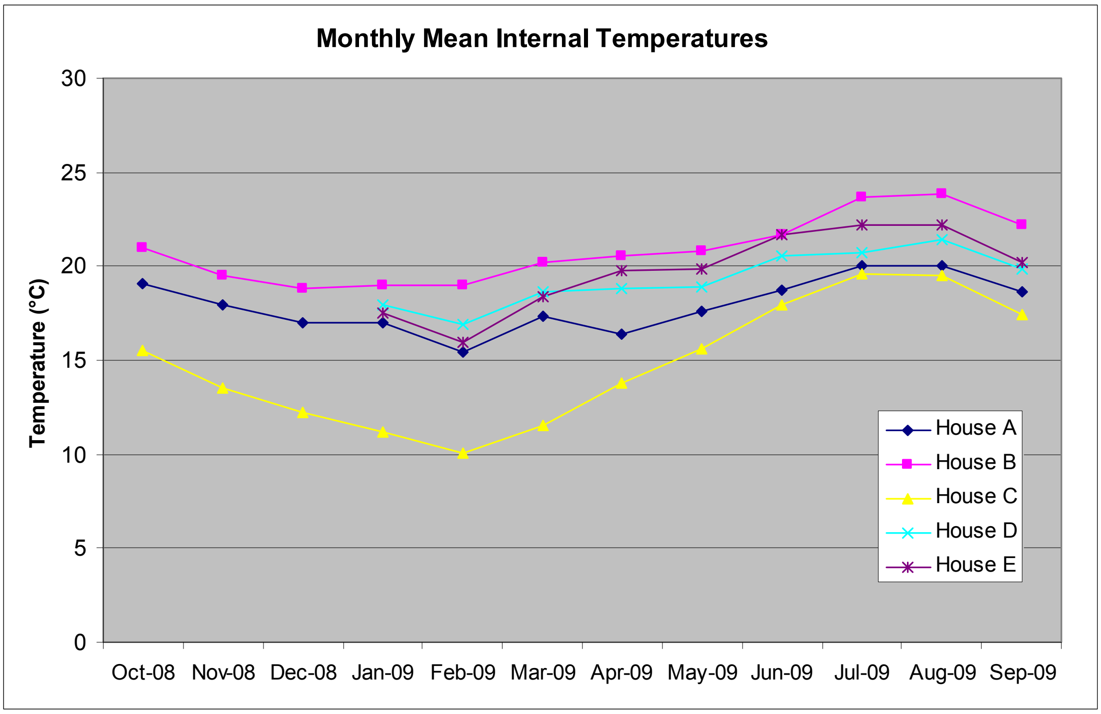
Internal Conditions

137 A comparison of the mean internal air temperature for all five dwellings by is illustrated by the seasonal data in Table 35 and by the monthly data in Figure 85. The graph shows that there are significant differences between the temperatures that the householders are living at. In particular it can be seen that mean heating season temperature in House C drops to as low as 10°C during February, with a mean of 12.6°C. This will be mostly due to the intermittent occupancy of this house as the resident turned the heating off when they were not in the house and therefore does not reflect any specific issues with the heating system. There was some noticeable variation in the preferred internal temperatures for the other dwellings over the winter. The mean temperatures in House B was the highest at 19.7°C which is slightly above the typical internal temperatures that are assumed in the standard SAP model of around 18.5°C. The mean temperature in House A at 17.2°C is at the lower end of internal conditions for a typical UK household. There is a dip in the internal temperatures in February which coincides with the breakdown of the communal heat pump.

Table 35 – Seasonal Mean Internal Temperatures

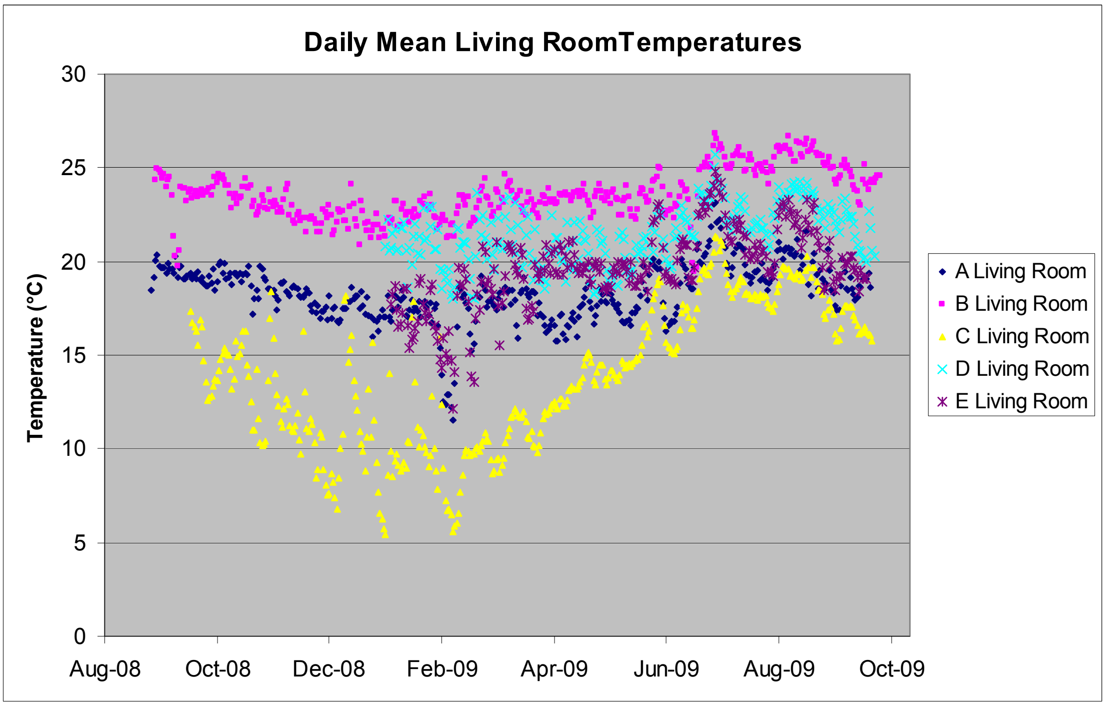
Period	Mean Internal Temperature (°C)				
	House A	House B	House C	House D	House E
October to April	17.2	19.7	12.6	-	-
July to August	20.0	23.8	19.6	21.1	22.2

Figure 85 – Monthly Mean Internal Temperatures



138 The data showed that there was considerable variation between the temperatures of the living rooms in the different dwellings as shown in Figure 86. Ignoring House C, typical winter temperatures in the living room ranged from around 17°C in House A up to around 22°C in House B.

Figure 86 – Trend in Living Room Temperatures



139 The pattern of temperature variation between rooms varied between the different dwellings. In House A, all the rooms were being maintained at a similar temperature with the exception of the downstairs toilet which was up to 5°C colder than any of the other rooms (see Figure 87). By comparison, there was much more variation in room temperatures in House B with the living area being much warmer than the rest of the house (see Figure 88), and with again the coldest room in the house being the downstairs toilet. A drop in internal temperatures can be seen during February when the heat pump was off. This indicates that, even though the residents were heating their homes during this period with fan heaters supplied by the Housing Trust, they were unable to heat their houses effectively without the underfloor heating system.

Figure 87 – Daily Mean Internal Air Temperatures House A

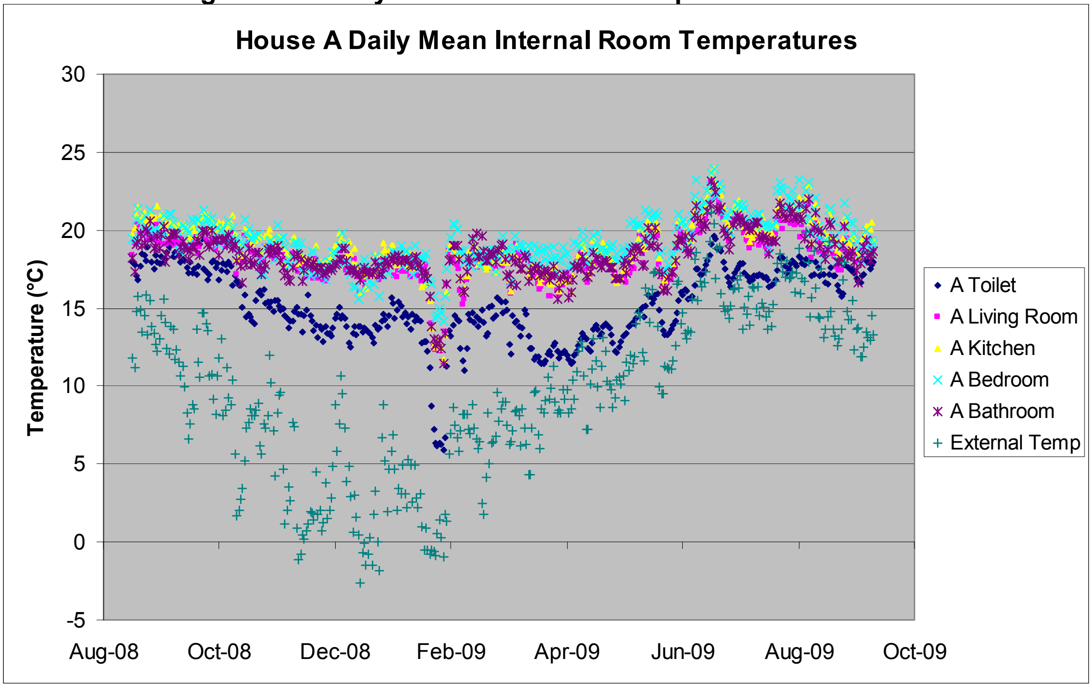
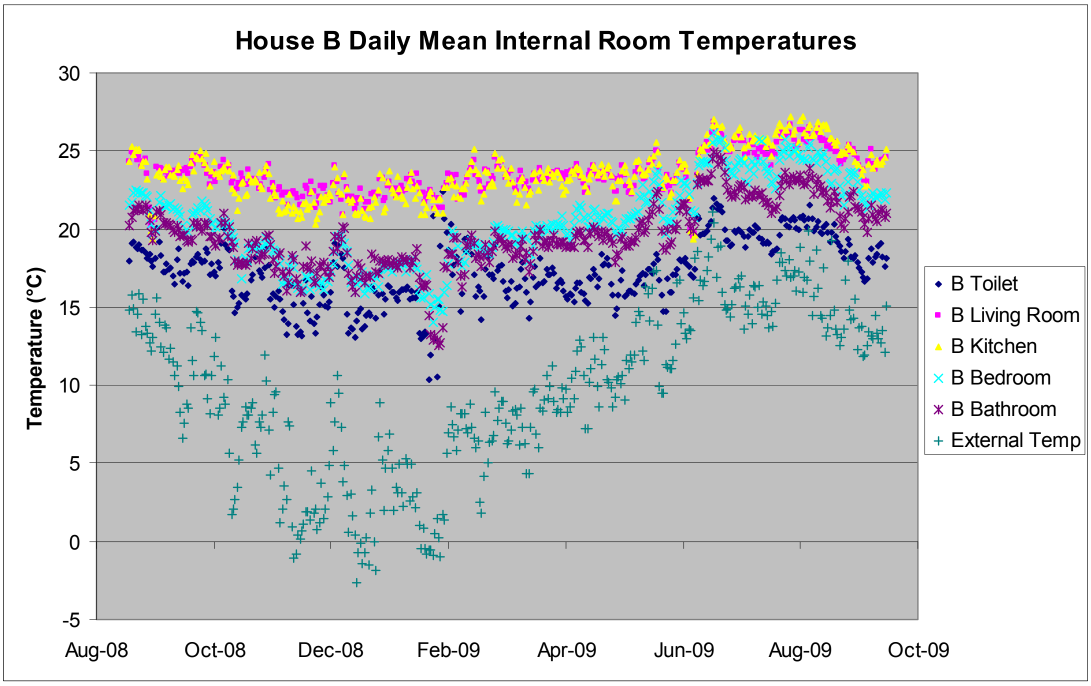


Figure 88 – Daily Mean Internal Air Temperatures House B

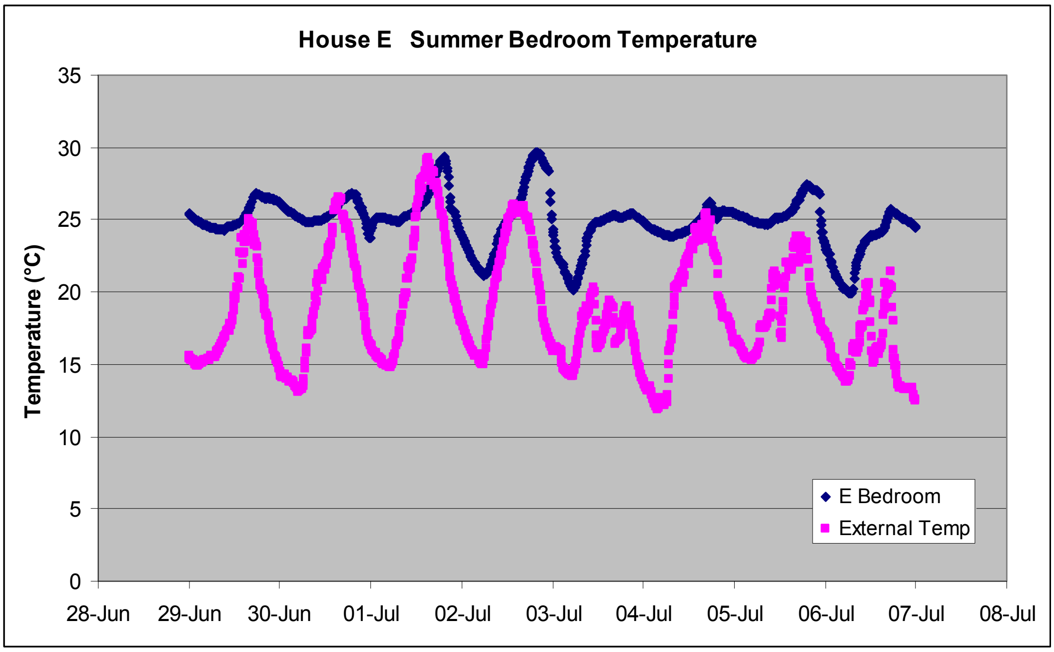


140 The pattern of a much colder downstairs toilet compared to other rooms was also observed in House D. In addition the residents of all three terraced houses commented in the final interviews

that they had noticed that the toilet was much colder than the rest of the house, but that there did not appear to be a way to improve the heating. A review of construction photos showed that the correct underfloor heating pipework had been installed in the hall and toilet. The photos also showed that the timber fraction in the wall panels in the toilet was lower than in the rest of the house which would actually mean lower heat loss would be expected when compared to other rooms. Further investigations by the research team showed that there was no heating thermostat in either the hall or toilet for the terraced houses, even though one was marked on the drawings. Instead the thermostat controlling the underfloor heating zone in the hallway and toilet had instead been placed on a wall in the living area adjacent to the main heating controller. It would have been impossible for the residents to have any proper control on the temperature in the hallway zone as it was being influenced by the temperature in the living area. The main contractor has since been asked to move the thermostat to the correct location.

141 The highest internal temperatures were observed in the upstairs rooms of House E during the early part of July 2009 when the external temperatures were at the highest for the year reaching a maximum of 29.3°C on the 1st July. The temperature in the top floor bedroom of House E peaked at 29.4°C at around 8:00pm on the 1st July, and peaked again at 29.7°C on the 2nd July at around 8:00pm (see Figure 89). The indications are that there is some potential for overheating at Elm Tree Mews, but that given the relatively cool summer during 2009 it would be difficult to draw any firm conclusions about the tendency for the dwellings to overheat in the summer overheating. The interview feedback from the residents did not suggest any great concern with overheating, although the resident of House E did say that some evenings were very warm and that it was sometimes necessary to open windows and patio doors to provide the necessary cross ventilation.

Figure 89 – Summer Temperature Trend for Bedroom in House E



142 A comparison of the mean internal relative humidity by month for all five dwellings is shown in Figure 90. This shows that the highest relative humidity in House C and the lowest in House E. However, the difference in internal temperatures of the dwellings means that it is difficult to make any comparisons using relative humidity, as the air in the warmer houses is able to hold much more moisture than that in the colder houses. In order to account for this difference in internal temperature, the relative humidity readings have been converted into an absolute humidity in grams of water per m^3 of air (see Figure 91). From these data it can be seen that the water content of the air in House B is much higher than the other dwellings containing around 3 grams more moisture per m^3 air than any of the other dwellings. This high level of internal moisture in House B is a very strong indication of low ventilation rates. Some of the humidity levels in individual rooms in House B were very high by normal standards, with the mean daily relative humidity in the bedroom and bathroom regularly exceeding 70% RH during the winter. This would give rise to concerns about mould growth and potential health issues, as it is normally expected that to maintain a

healthy internal environment at typical temperatures the relative humidity should preferably be kept in the range 40% RH to 60% RH.

Figure 90 – Mean Daily Relative Humidity

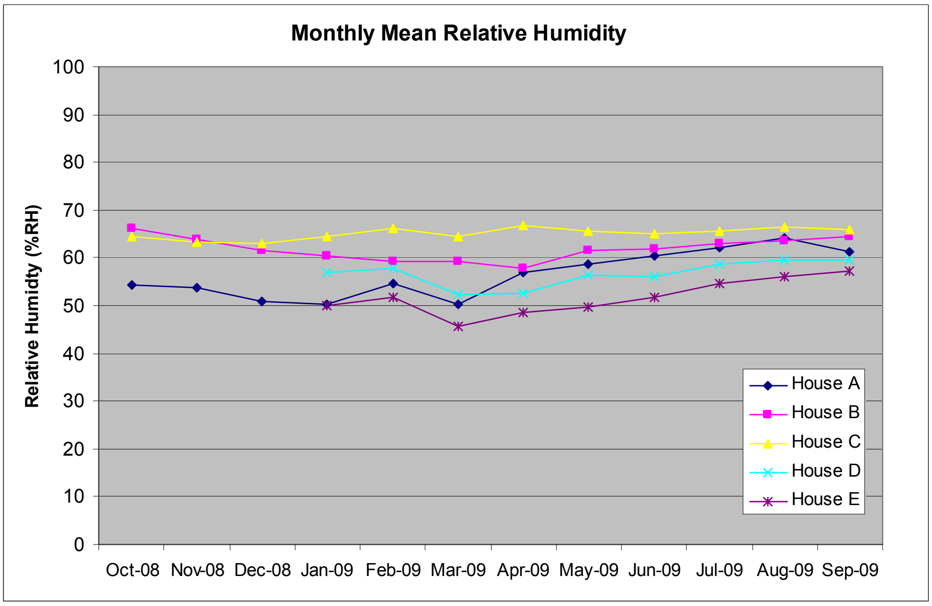
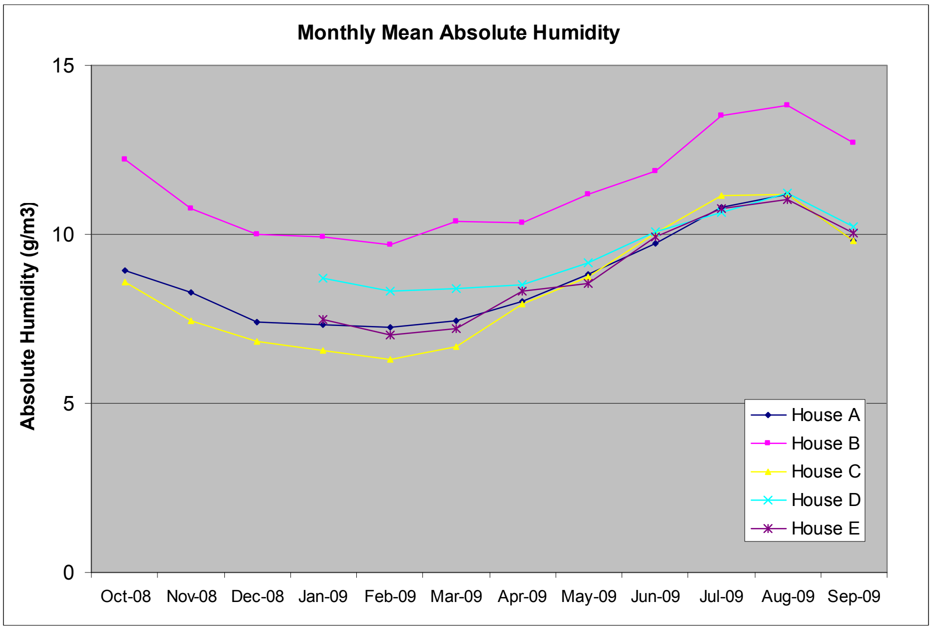


Figure 91 – Mean Daily Absolute Humidity



143 The internal carbon dioxide concentrations are illustrated by the monthly data in the graph in Figure 92 and by the seasonal data in Table 36. These data show that the mean carbon dioxide concentration in House B is very high compared to the other four dwellings. In the winter the mean CO_2 levels in House B range from around 1200 to 1400 ppm compared to between 500 and 800 ppm in the other dwellings. Even in the summer the mean CO_2 in House B exceeds 1000 ppm, whereas in the other dwellings it drops below 600 ppm. The daily data for House B also show that the carbon dioxide concentration who frequently exceed 2000 ppm ,which is the measurement limit of the sensors that were used at Elm Tree Mews. The very high levels of CO_2 are indicative of low ventilation rates and correlate well with the high humidity levels that were also observed in House B. The implication is that the occupants of House B are not ventilating the house using the provided trickle vents and humidistat controlled fans. This was confirmed during the final interviews where it was found that the residents of House B had turned off the fans in the bathrooms and toilet at the electrical isolation switch, and had also closed most of the window trickle vents. Despite the lack of ventilation the householders of House B did not complain of feeling stuffy or uncomfortable. This

demonstrates that the perception of what is comfortable in terms of temperature, humidity and internal air quality can vary significantly from household to household, and from person to person.

Figure 92 – Daily Mean Carbon Dioxide Concentration – Houses A, B & D

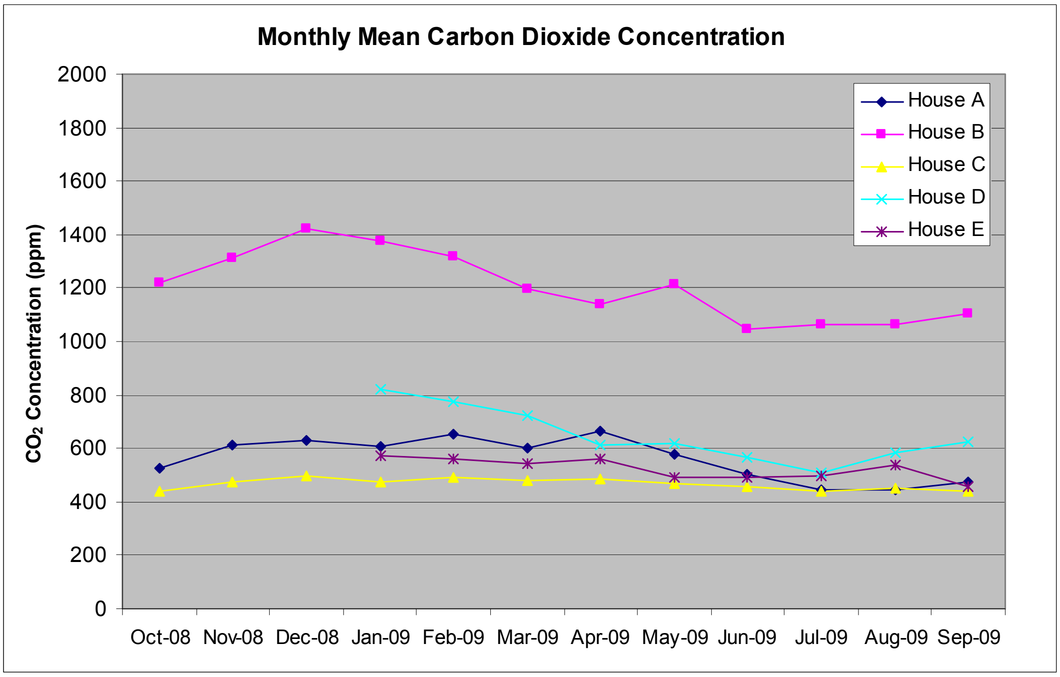


Table 36 – Seasonal Carbon Dioxide Concentration

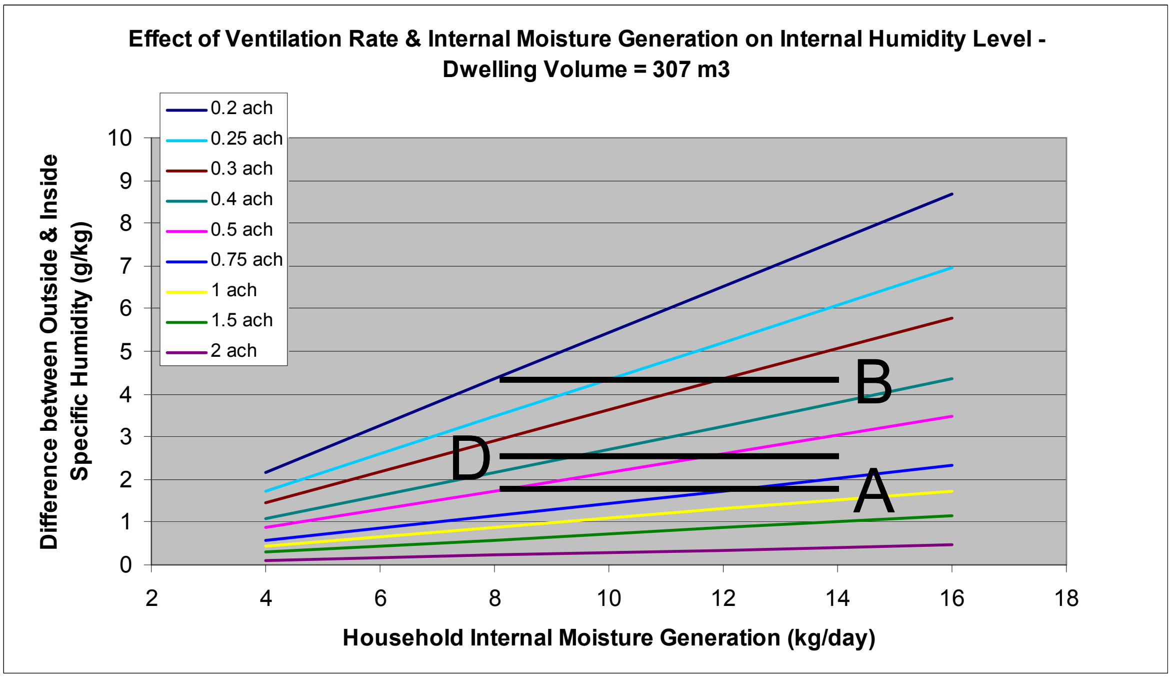
Period	Mean Carbon Dioxide Concentration (ppm)				
	House A	House B	House C	House D	House E
October to April	613.7	1283.4	477.7	-	-
July-Aug	445.6	1063.5	444.5	546.1	516.1
Annual Mean	558.9	1194.5	466.9	643.8	522.6

144 It is possible to estimate the actual mean ventilation rate in the occupied dwellings by comparing the internal humidity with the external humidity and allowing for the expected moisture generation due to the occupants inside the dwelling. The ventilation rates calculated using this humidity excess are shown in Table 37 and are compared to the effective ventilation rate calculated in the SAP energy model using the measured air permeability. The data show that the actual ventilation rates in House D (0.5 h^{-1}) and House A (0.6 h^{-1}) are general agreement with the effective ventilation rate calculated using the SAP energy model. By contrast, the measured ventilation rate in House B (0.25 h^{-1}) is much lower than would the expected effective ventilation rate which assumes a typical pattern of window opening and ventilation behaviour. The graph of internal moisture generation rate versus the humidity excess for the mid-terrace dwellings (internal volume 307 m^3) is shown in Figure 93. The graph shows a range of curves for various ventilation rates from 0.2 h^{-1} to 2 h^{-1}. The mean ventilation rate in the three dwellings (A, B and D) can then be estimated using the measured humidity excess and a knowledge of the occupancy level, occupancy patterns and use of water in the occupied houses.

Table 37 – Estimated Household Ventilation Rates

	Modelled Effective Ventilation Rate Calculated from Air Permeability (h^{-1})	Actual Ventilation Rate Estimated from Humidity Excess (h^{-1})
House A	0.56	0.60
House B	0.58	0.25
House D	0.57	0.50

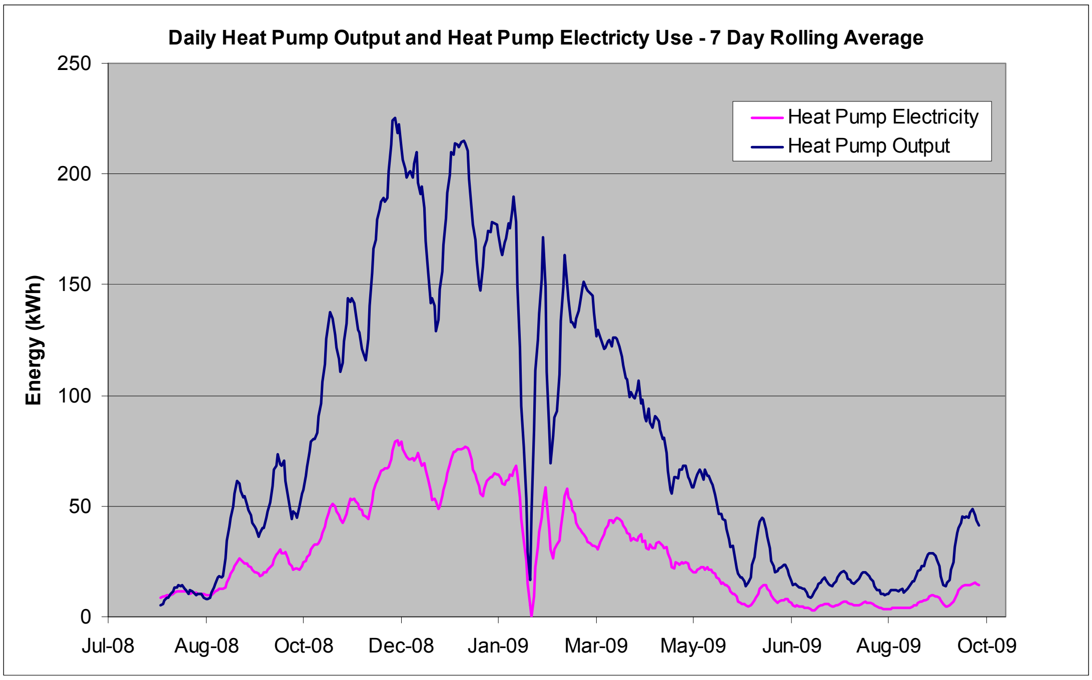
Figure 93 – Internal Moisture Generation Rate versus Humidity Excess for Elm Tree Mews Mid-terrace Dwellings at Different Ventilation Rates



Performance of Communal Heat Pump

145 A plot showing the trends in daily output from the communal heat pump and the daily electricity consumption by the heat pump (7 day rolling average) is given in Figure 94. This shows that, during the winter period of highest heat demand, the peak output from the heat pump was between 200 to 250 kWh/day, which is equivalent to a mean daily power of around 10 kW. Analysis of the daily trend in power shows that the heat demand in winter is concentrated for around 2 hours in the morning and then again for about 6 hours from late afternoon till about 10 in the evening, and during these periods the heat pump was sometimes running at close to its maximum capacity of 24 kW. The two periods when the heat pump was out of action for around 2 weeks in February can be seen as a sharp drop in output. Over the summer months the residual demand for communal heat to supplement the solar input to the hot water cylinders dropped to around 10 to 20 kWh/day. The electricity used by the pump to supply the heat can be seen to be around 30% of the energy output, reflecting the high coefficients of performance that can be achieved using heat pump technology.

Figure 94 – Daily Output from Communal Heat Pump (7 Day Rolling Average)

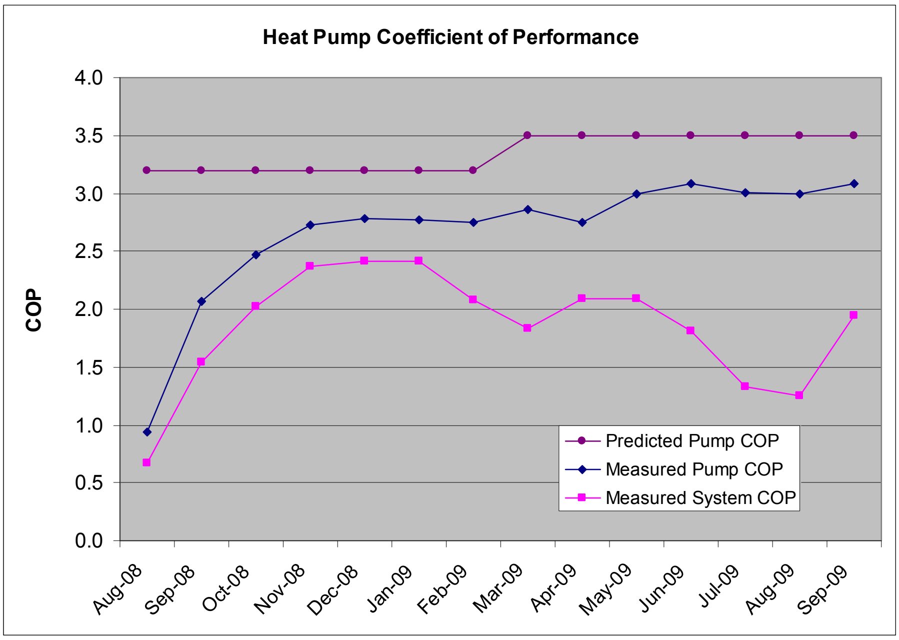


146 The key performance characteristic of any heat pump is its coefficient of performance (CoP). The Pump CoP is a measure of the efficiency of the heat pump in isolation from the rest of the heating system and is calculated by dividing the energy output of the pump by the electrical energy needed to run the pump. The System CoP takes account of other system factors such as the energy used to run circulation pumps and any storage or distribution losses up to the point of delivery. In the case of Elm Tree Mews, the system boundary for the System CoP is defined as the heat meters at the point of entry of the communal heat main into each dwelling. Annual and monthly performance data for the heat pump are listed in Table 38 together with the Pump CoP and System CoP. The nominal predicted Pump CoP using manufacturers bench test data for the period up to February was 3.2, and following changes to the heat pump made during February the predicted Pump CoP increased to 3.5. It can be seen from Table 38 and Figure 95 that the heat pump never achieved its expected performance, with an annual Pump CoP of around 2.7 and a System CoP of around 2.1. Indeed, during August 2008 both the Pump CoP (0.94) and System CoP (0.67) were less than 1, making the heat pump performance for that month worse than could have been achieved with gas condensing boilers in the dwellings. The main cause of this inefficiency in August 2008 was found to be the electrical energy required to drive the hot side circulation pump located inside the heat pump. The design of the heat pump control system meant that the hot side circulation pump was required to run continuously in order to provide the return flow temperature as a control signal. The daily energy requirement for this circulation pump was measured at 7 kWh which is clearly an inefficient use of energy if there is little or no heat demand on the system, as would be the case in summer. It can also be seen that that the distribution and storage losses were significant at around 17% for the year, ranging from around 12% in the winter to as high as 55% in the summer. These losses will be a result of standing heat loss from the buffer tank storage vessel and also heat losses from the insulated communal distribution pipework that runs from the plant room to the houses. Numerous interventions and suggestions to improve the performance and efficiency of the heat pump were made by the research team over the monitoring period. This action research approach means that the measured CoP will have tended to improve over time as a result of these interventions.

Table 38 – Heat Pump Annual and Monthly Performance and Efficiency Data

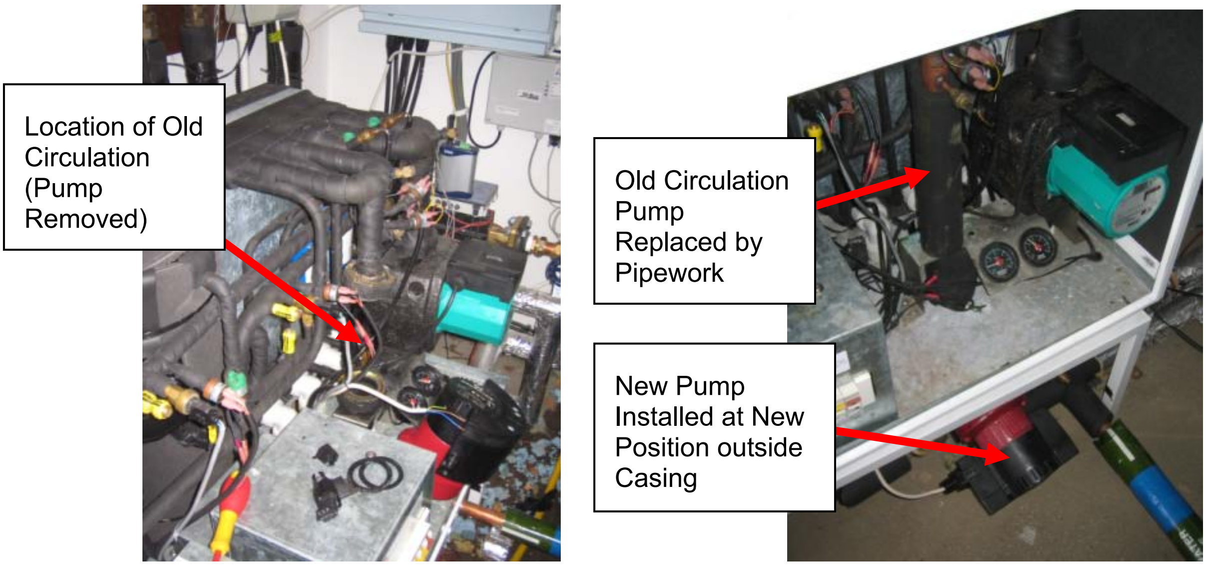
Period	Total Heat Output (kWh)	Total Electricity Used (kWh)	Total Delivered Heat (kWh)	Total Distribution Loss (kWh)	Pump CoP	System CoP	Distribution Loss (% of Output)
Aug-08	301	329	219	82	0.94	0.67	27.2%
Sep-08	1251	664	1025	226	2.06	1.54	18.1%
Oct-08	2444	1012	2044	400	2.46	2.02	16.4%
Nov-08	4396	1642	3886	510	2.72	2.37	11.6%
Dec-08	5778	2106	5080	698	2.78	2.41	12.1%
Jan-09	5658	2070	4993	665	2.77	2.41	11.8%
Feb-09	3154	1304	2708	446	2.75	2.08	14.1%
Mar-09	4018	1807	3312	706	2.86	1.83	17.6%
Apr-09	2486	920	1919	567	2.75	2.08	22.8%
May-09	1412	486	1013	399	3.00	2.09	28.3%
Jun-09	729	249	449	280	3.08	1.80	38.4%
Jul-09	488	175	232	256	3.01	1.33	52.5%
Aug-09	453	165	206	247	2.99	1.25	54.5%
Sep-09	977	331	644	333	3.09	1.94	34.1%
Aug 08 - July 09	32115	12764	26880	5235	2.68	2.11	16.3%
Sep 08 - Aug 09	32267	12600	26867	5400	2.73	2.13	16.7%
Oct 08 - Sep 09	31993	12267	26486	5507	2.78	2.16	17.2%

Figure 95 – Monthly Trend in Pump CoP and System CoP



147 The most important intervention to improve heat pump performance was to replace the hot-side circulation pump with one with lower power consumption, whilst at the same time changing the system control parameter from the return flow temperature to the buffer tank temperature to include a control mechanism to turn off the hot-side circulation pump when not required. A previous attempt to control the system using a thermostat strapped to the buffer tank and connected to a relay managing the electrical power to the heat pump was found to be ineffective due to the poor temperature control. The work to change the hot-side pump was carried out during February 2009. However, difficulties were encountered by the contractor when trying to fit the new circulation pump and they were not able to reattach the old pump. The heat pump was out of action for a week whilst the contractors waited for a replacement component from the heat pump manufacturer. In the end the new pump had to be fitted to the outside of the heat pump casing (see Figure 96).

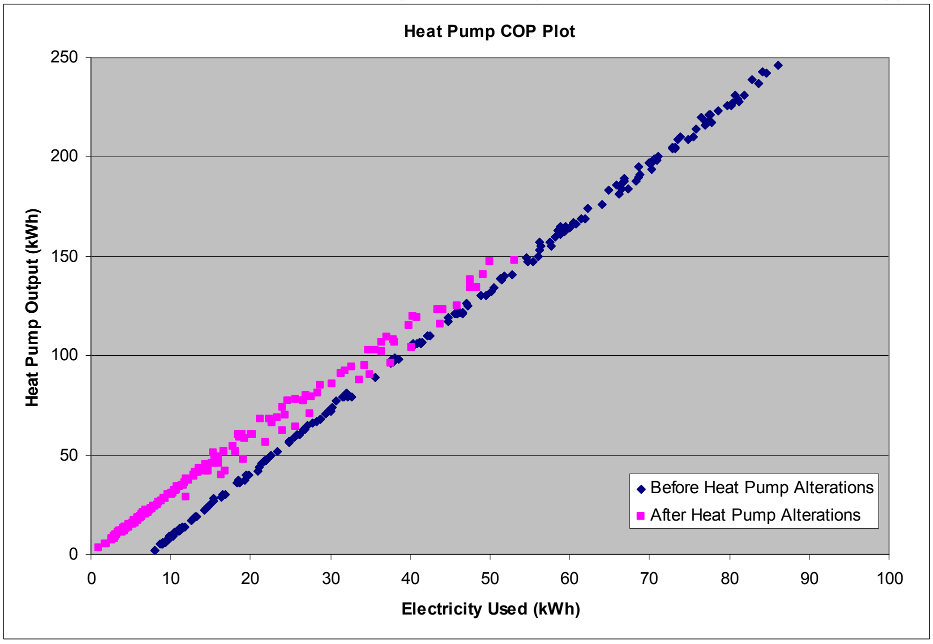
Figure 96 – Photographs of Alterations to Hot-side Circulation Pump



148 The effect on heat pump efficiency of the changes to the hot-side circulation pump can be seen in the graph of daily heat pump electricity used versus heat output shown in Figure 97. The plot of data before the alterations does not pass through the origin and has an intercept on the x-axis showing that around 8 kWh of electricity is consumed when there is no heat output. Following the alterations, the data line shifts to pass through the origin, showing that the residual electricity demand of the heat pump is negligible when there is no heat output. The heat pump energy

consumption data show that the residual standby energy of the heat pump used to run the internal control systems is very small and of the order 7.5 W. The slope of the plots will give the underlying Pump CoP. It can be seen that the slope is lower after the alterations indicating that the underlying Pump CoP has actually got worse, dropping from around 3.1 to 2.8. It would have been expected that there would have been an increase in Pump CoP, as the energy consumption of the internal hot-side circulation pump had reduced from 345 W to a maximum of 85 W, which would have reduced the underlying energy consumption of the heat pump by at least 260 W. The reduction in underlying performance indicates that the change in control strategy from the return flow to the buffer tank has degraded efficiency. This is almost certainly an effect due to start up inefficiencies and short cycling of the heat pump as it tries to maintain the temperature in the buffer tank on a 24 hour basis. This problem raises the question of how best to control the system and what effect buffer tanks can have on performance. Further alterations to the system at Elm Tree Mews were not contemplated as it would have been extremely difficult to justify any further disturbance to the householders. However, it is clear that the system interactions in communal heating systems such as that at Elm Tree Mews are highly complex and that simplified design assumptions about heating system performance can lead to large discrepancies between designed energy use and that achieved by the system in-use.

Figure 97 – Heat Pump CoP Plot: Daily Electricity Used vs. Heat Pump Energy Output

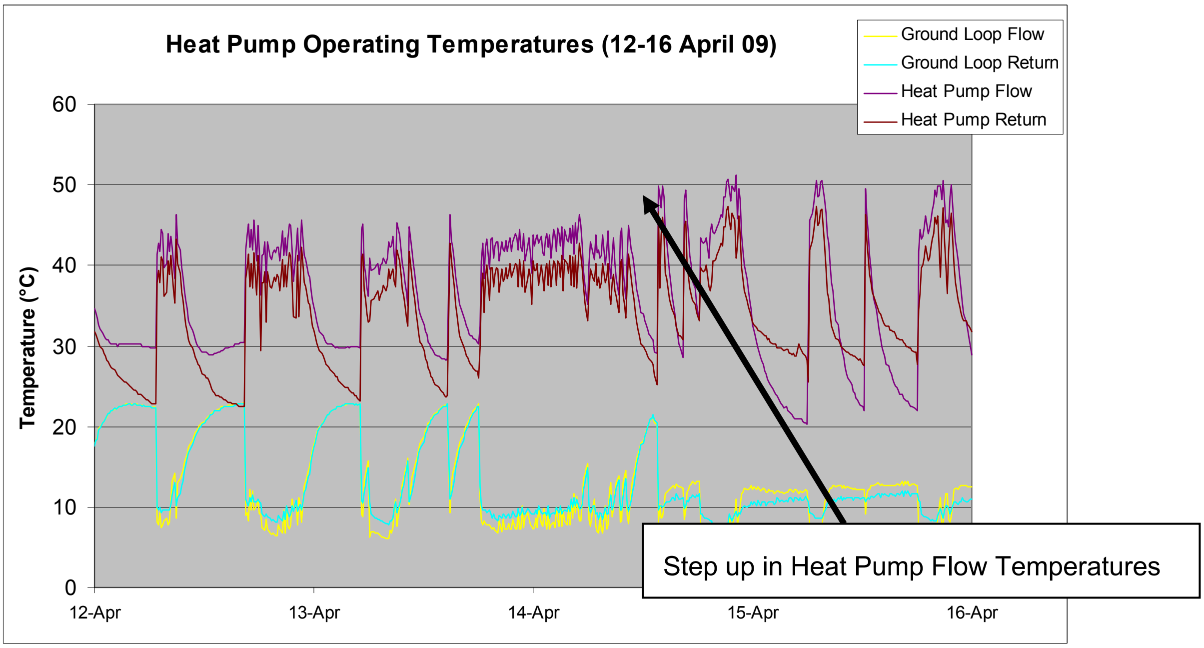


149 The heat pump manufacturer’s data sheet gives a thermodynamic CoP of 3.91 based on bench tests in the factory, with an estimated thermodynamic CoP after run in of 4.25. This factory test is generated using an input temperature of 0°C and an output temperature of 35°C, giving a Δ-T of 35K. After allowing for the power consumption of the two internal circulation pumps at 345 W each, this is equivalent to a Pump CoP of 3.19 when one 12kW heat pump compressor is running and 3.51 when both compressors are running. For the situation following the alterations to the hot-side circulation pump, if we recalculated the efficiencies using a hot-side pump power consumption of 85 W, then the predicted CoP for one compressor increases to 3.43 and for two compressors it increases to 3.66. If we assume a run-in thermodynamic CoP of 4.25, then the Pump CoP would increase to 3.41 for one compressor and 3.78 for two compressors. Given that the designed delta-T for the heat pump at Elm Tree Mews is also of the order 35K (input temperature ~5°C and output temperature ~40°C), then we would expect the underlying Pump CoP to be in the region of 3.2 to 3.5 when the system was first installed, rising to 3.4 to 3.8 after a years service or more. It is apparent that the measured underlying Pump CoP is at the bottom end of this expectation, and there is no evidence of any improvement in CoP due to the system having been run in.

150 Following the changes to the internal circulation pump, there were still some minor issues relating to the control of the output flow temperature from the heat pump. Before the alterations the peak flow temperatures were of the order 40 to 42°C but immediately after the alterations this had risen to ~45-47°C with a consequent drop in CoP. This increase was due to the change in location of the control temperature sensor from the return pipe to the buffer tank. This was resolved by reducing the temperature set points on the heat pump controllers by 4°C so as to maintain the flow

temperatures at the desired 40-42°C. Further problems with the heat pump flow temperature were also recorded during April 2009, when there was a sudden increase in flow temperatures to 50°C (see Figure 98) and a corresponding drop in CoP to ~2.5. This sudden change in temperature coincided with a visit to the plant room by an engineer who was maintaining the communal TV aerial system. Further investigations found that the engineer had knocked and displaced the temperature sensors on the buffer tank. Once the sensors had been repositioned back on the buffer tank, the flow temperatures returned to their normal level.

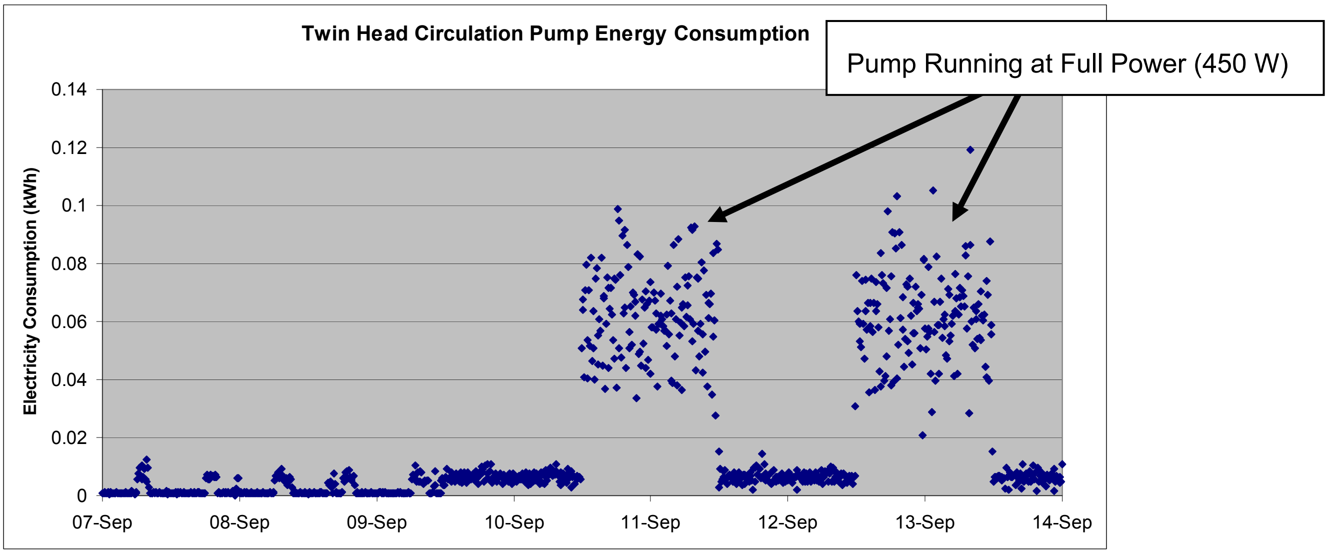
Figure 98 – Heat Pump Flow and Return Temperatures April 2009



Step up in Heat Pump Flow Temperatures

151 Another heating system problem diagnosed by the research team was related to the set up of the external twin head circulation pump on the communal heat main. The initial heat pump data in July 2008 highlighted the fact that the external circulation pump had not been set up correctly, having been left in manual mode at full power (450W). This was quickly rectified by the M&E contractors at the time by altering the pump control settings so that it was in automatic mode. This was thought to have solved any issues with the external circulation pump. However, unusual circulation pump data were again observed in September 2008, when the circulation pump energy use increased 10 fold on certain days (see Figure 99). Investigations by the research team showed that this problem was related to the settings on the second standby pump on the twin-head pump set, which was found to be still in manual mode, and also that the duty/standby settings on the twin-head pump set were also incorrectly set. These problems were readily fixed by altering the settings on the circulation pump.

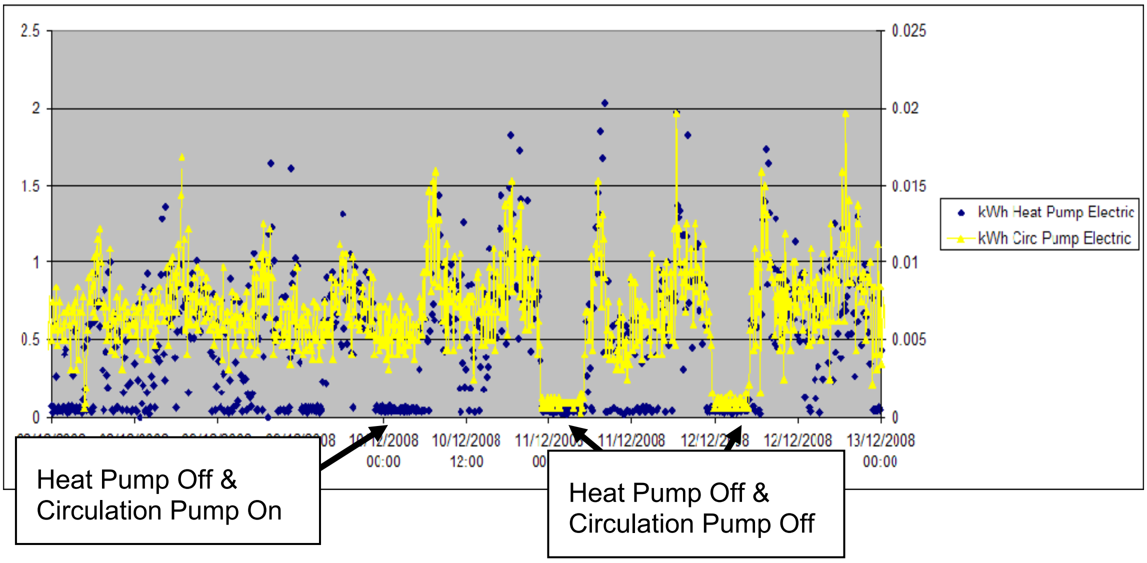
Figure 99 – External Circulation Pump Energy Consumption September 2008



Pump Running at Full Power (450 W)

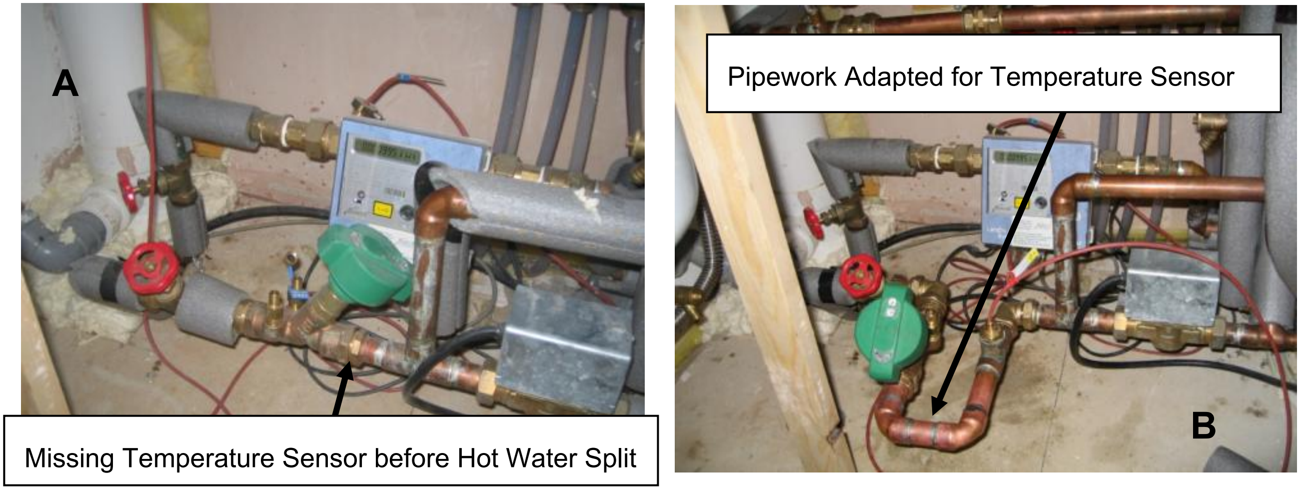
152 Several months following the alterations to the heat meter temperature sensors some unusual behaviour was recorded for the external circulation pump. The data showed that the external circulation pump was running for long periods even though the heat pump was off and there was no increase in temperature in the communal main flow pipes (see Figure 100). It was found that in one of the dwellings, the plumbers had forgotten to open the gate valves after they had finished doing some work on the heating system. This had probably not been noticed before as the effect would have been masked if any other dwelling had been calling for heat at the same time. It was also apparent that the communal heating system had not been designed with a system bypass. This was confirmed by the M&E engineer. Subsequent analysis showed that this same pump behaviour occurred intermittently afterwards, indicating that perhaps some of the two way valves in the properties were not opening and closing properly.

Figure 100 – Heat Pump and Circulation Pump Energy Use December 2008



153 When the first monitored heat meter data were available from occupied dwellings in September 2008 it was found that the overall total heat input to some of the individual dwellings could not be resolved with the hot water input to the cylinders for those dwellings (on some days the hot water input was higher than the total input). Investigation of the installation of the heat meters in these dwelling showed that the incoming flow temperature sensor on the main charging heat meter was incorrectly positioned on the heating circuit after the split for the hot water circuit (see Figure 101A). The M&E contractors adapted the pipework and moved the flow temperature sensor to the correct position in the affected dwellings (see Figure 101B). If this problem had not been spotted then it would have resulted in some residents being undercharged for the heat that they had used.

Figure 101 – Location of Charging Heat Meter Thermocouple Sensor in House E

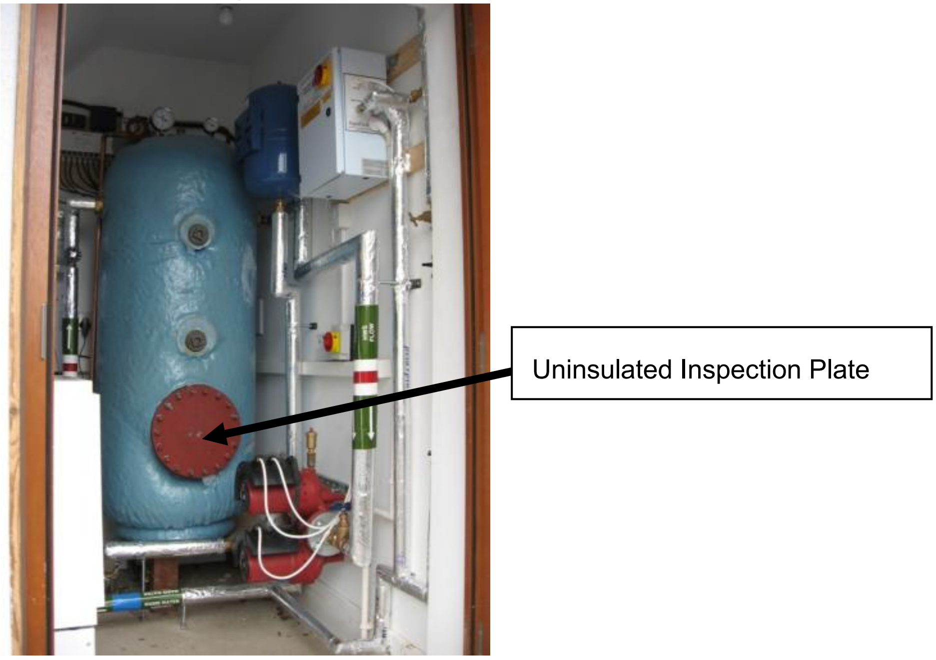


154 In order to avoid any future problems with the potential for lack of heat pump capacity due to the fact that the heat loss from the dwellings was higher than predicted, two 3 kW electric immersion heaters were installed in the buffer tank at the same time as the heat pump alterations. These

heaters were designed to provide back up heat if the heat pump was unable to maintain the buffer tank temperature above 35°C during prolonged periods of extreme cold weather. There were some initial problems with the immersion heaters coming on when not required as the thermostats were set too high. This was picked up very quickly in the monitored energy data, and the thermostats adjusted by the Housing Trust maintenance team accordingly to avoid unnecessary electrical heat input into the system. Feedback from JRHT on the performance of the heat pump during December 2011 indicates that the backup immersion heaters were not needed even when the mean external temperatures dropped to around -5°C for at least a week.

155 The heat loss coefficient for the buffer tank was calculated to be 14 W/K from the decay curve of the water temperature inside the buffer vessel during periods where there was no heat demand from the communal system. So if we assume a typical temperature for the stored water of 40°C and the temperature of the plant room as 20°C, then the daily energy lost from the buffer tank will be of the order 6.7 kWh/day, which equates to 2445 kWh/annum. The total annual distribution losses from the communal system were of the order 5400 kWh/annum (Table 38), so losses from the buffer tank could account for up to 45% of all distribution losses. The losses from the buffer tank could be reduced by improving the insulation around the tank where there is a large exposed metal access plate (see Figure 102). It can also be seen from the data in Table 38 that the proportion of heat lost during the summer of 2009 at around 30-50% of heat output is much higher than that during the summer of 2008 where the losses were only around 20-30% of heat output. It is believed that this relates the way that the temperature in the buffer tank is being controlled. Prior to the heat pump alterations in February the buffer tank was not directly controlled and could drop significantly when heat was not being demanded. Following the alteration, the buffer tank temperature was controlled directly using the differential controller in the heat pump, which resulted in more energy being required to maintain the temperature. Indeed, it can be argued that before February, the buffer tank was not being used like a true buffer vessel as the temperature was too variable. During winter, the impact of losses from the buffer vessel are much reduced as the heat demand from the houses for heating means that the heat pump is on for much more of the time. It remains unclear as to the performance benefits of having a buffer vessel in the heating system compared to not having one. It is perhaps interesting to note that Kensa do not themselves recommend the use of buffer vessels with their heat pumps. Kensa state that the use of buffer tanks in conjunction with heat pump systems that use return flow temperature as the control can give rise to cycling (Kensa 2008b).

Figure 102 – Heat Pump Buffer Vessel



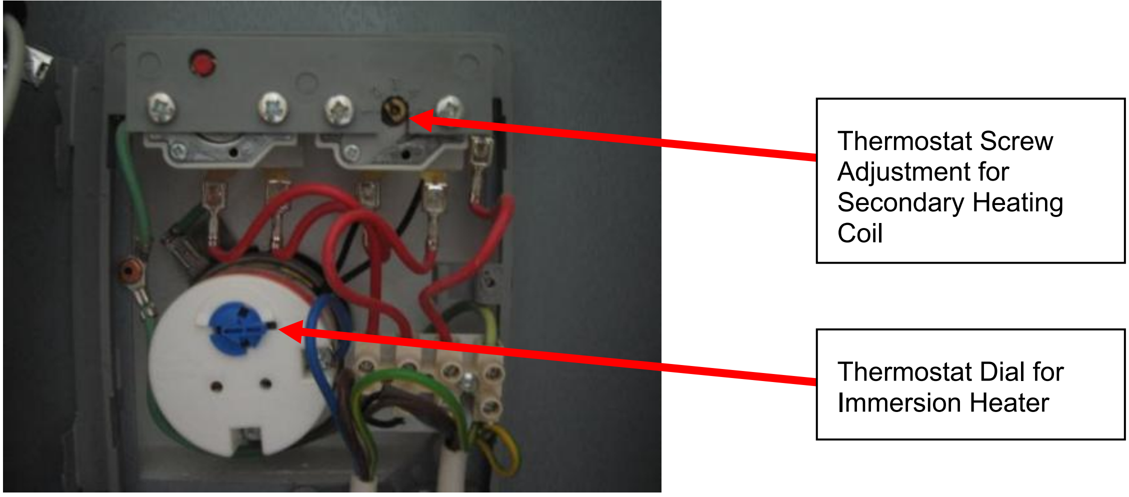
Uninsulated Inspection Plate

Hot Water Control Issues

156 One of the main concerns with the provision of hot water to the dwellings at Elm Tree Mews is that the combination of the three different hot water inputs (solar, communal heat, immersion) needs a complex control strategy for the system to be efficient and to provide a reliable supply of hot water to the residents when required. However, the measured data from monitoring of the occupied

houses and feedback from the residents indicates that this is not always being achieved during the winter months when the solar input will be at its lowest. Part of this problem relates to the reliance on the communal main to provide the majority of hot water during the winter months. If the temperature inside the cylinder is relatively high at the times when the hot water controller is demanding heat, then there will be no heat input. This could occur more frequently in some households compared to others depending upon the usage patterns. In addition to this problem there are some fundamental problems with the control of communal hot water to the cylinders. The input temperature thermostat set point for the secondary heating coil in the hot water cylinder is set using a small slotted brass screw housed in a casing on the side of the cylinder (see Figure 103). The screw is marked with a scale 1 to 5 which represents a temperature range of 30°C to 70°C. It would be very difficult to set the temperature set point using this screw with any accuracy, and one would expect that if one was trying to set the input temperature at 40°C, then it would only be possible to achieve this to no better than be ± 1°C. In addition, the temperature differential for a capillary thermostat is typically around 5% of the range, so this would be ± 2°C in this case. Combining the temperature differential with the set point accuracy gives a potential temperature range for the cylinder temperature at the secondary coil of 40 ± 3°C. The monitored data show that the temperature of the water in the incoming heat main can vary from as low as 33°C up to around 42 °C, depending on the heat demand on the system and the temperature of the buffer tank. This gives rise to a mismatch between the temperature of the incoming main and the temperature in the hot water cylinder which means that there is a significant risk that heat will be fed back from the cylinder into the heat main for at least some part of any heating cycle. This risk could be overcome with the use of a differential temperature controller combined with RTD (e.g. PT100) temperature sensors in the buffer tank and flow pipework.

Figure 103 – Hot Water Cylinder Thermostatic Control Dials



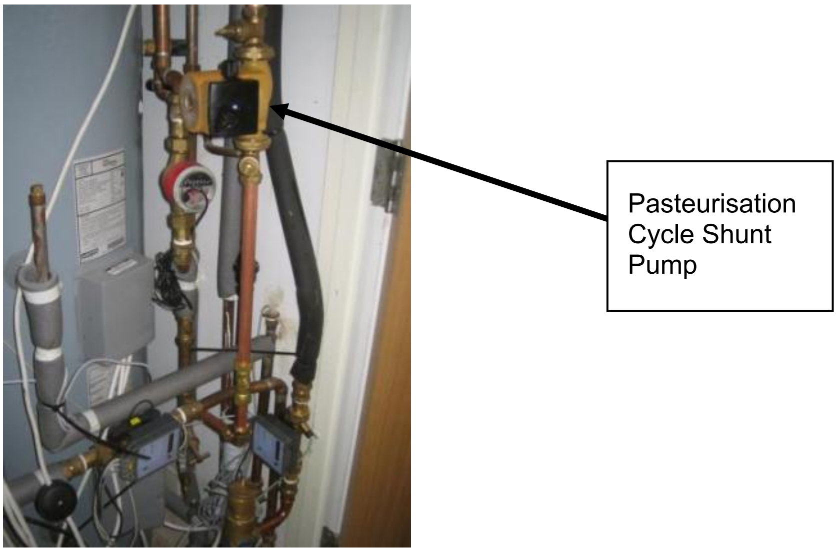
Thermostat Screw Adjustment for Secondary Heating Coil

Thermostat Dial for Immersion Heater

157 The research team identified early on in the project that there was a potential risk for legionella contamination of the stored hot water in the dwellings as the heating system design lacked a method to ensure that the temperature of the stored hot water was raised to 60°C on a regular basis. New legislation means that all providers of residential accommodation, including housing associations such as the Joseph Rowntree Housing Trust, are required to assess the risk of exposure to legionella bacteria and introduce appropriate prevention or control measures for any rented accommodation where the housing provider is responsible for the maintenance of the hot water system or provision of hot water (HSE 2003). One of the key conditions for the multiplication of legionella bacteria is where hot water is stored between 20°C and 45°C (HSE 2000). The nature of the hot water system at Elm Tree Mews is such that there is no control system that will guarantee to maintain the hot water stored in the cylinder at above 45°C. This will be most critical during the winter and autumn when the level of solar input into the cylinder will be low and the hot water system will rely on to a great extent the heat provided by the heat pump, which will have a relatively low flow temperature of between 40°C and 45°C. There is an electric immersion heater in the cylinder, but this is only activated by a manually operated 2 hour timer. The advice given in the ACOP for hot water systems recommends a thermal control procedure such that the whole water content of a calorifier is stored at a temperature of 60°C and that the water distribution system is designed such that water is delivered to the outlets at 50°C within 1 minute of operating a tap. The research team contacted the Joseph Rowntree Housing Trust in April 2008 to outline their

concerns. The Housing Trust subsequently carried out a legionella risk analysis and also arranged for an external environmental consultant to carry out a series of bacteriological tests on the water. The results of the initial tests indicated that there were no legionella bacteria in the water, but that general bacteriological levels in the water were higher than normal indicating that these was some risk of contamination. To minimise any residual risk, it was therefore decided to modify the hot water cylinders in all the houses with equipment designed to perform automatic pasteurisation cycles. These alterations were carried out towards the end of 2008 and involved the installation of a shunt pump to pump hot water from the top of the cylinder to the bottom of the cylinder in order to mix the stored water (see photograph of installed shunt pump shown in Figure 104). A 24-hour 7-day timer was connected to both the immersion heater and shunt pump. The initial recommendation from the environmental consultant was that the pasteurisation cycle should involve heating the cylinder to 60°C for 4 hours once per week with the shunt pump operating continuously during this time. Monitored data showed that the energy used by the immersion heater for a typical pasteurisation cycle varied from around 4 kWh to around 9 kWh, and would be dependent upon the water temperature in the cylinder at the start of the cycle. The typical shunt pump flow rate was measured at around 80 litres/hour. It was also recommended by the environmental consultant that monthly sampling of the hot water should continue for the foreseeable future and that the pasteurisation cycle timings be kept under review. The stored hot water has since been retested several times and, as a precaution, the hot water systems in all the dwellings have undergone a sterilisation process. The issue of how to control levels of legionella and other bacteria in stored water will become more important in domestic housing as hot water system designs become more complex and use combinations of low carbon heating inputs with lower input temperatures than is the norm for gas heating. It is interesting to note that some of the residents have adapted their use of hot water to coincide with timing of the pasteurisation cycle. One resident complained that the noise from the shunt pump was loud enough to disturb them when they were asleep in the bedrooms adjacent to the cylinder cupboard.

Figure 104 – Cylinder Cupboard Showing Installation of Shunt Pump



Solar System Performance Issues

158 The operation and performance of the solar hot system suffered from a range of issues relating mainly to the installation of the system. It took around a year to resolve most of these problems, meaning that the in-use monitoring results will have been affected in some way by the relative underperformance of solar input to the domestic hot water demand in the occupied dwellings. The main components of the solar system (solar controller, solar panel, solar pump) were installed by the solar system sub-contractor. However, other components such as the twin coil cylinder, thermocouple leads and the insulated solar pipework between panel and cylinder were installed by the main M&E subcontractor. Whilst this situation is not in itself unusual, it does give rise to an increased risk for confusion, miscommunication and error.

159 The main problems observed with the performance of the solar system can be summarised as follows:

a. **Installation Leaks**: When the solar system in House F was first filled with the solar fluid, the system was found to leak at the wall-floor junction with the party wall, with the fluid causing damage to the ceiling and wall below. The cause of the leak was found to be a nail used to attach the skirting board. This is clearly avoidable had there been better temporary marking of service routes so the following trades were less likely to cause damage. Better still, the use of designated and accessible service routes in walls and floors would make it easier to inspect, repair and maintain pipework. Other leaks in the solar systems were found once the dwellings were occupied. Some were due to kinked pipework and some to failed joints. The leaks were usually associated with a drop in system pressure.

b. **Kinked Pipework**: The monitoring data indicated potential problems with the restricted flow rates in at least 2 of the dwellings. Further investigations by the main contractor and solar system sub-contractor found that some of the solar pipework was kinked where the pipes changed direction from the wall to floor. Kinked pipe was found in two of the properties (House D and House B) and the faulty sections were replaced by the main contractor. An example of a kinked pipe is shown in Figure 105. In one case the pipe was also cracked at the kink which meant the there was also a leak of glycol fluid which had stained the ceiling and also gave rise to a reduction in system pressure (See photograph of stain on ceiling plasterboard shown in Figure 106). It was suspected from the data that there were minor kinks at 2 of the other properties but it was decided that the reduction in performance was not serious enough to justify disturbing the residents. The piping material used was a pre-insulated copper which would be prone to kinking if the correct procedures are not used to bend the pipe or if elbow connectors are not used. It is likely that the insulation material covering the pipe would have prevented the plumbing engineer from seeing the damage at the time of installation.

Figure 105 – Kink in Solar Pipework (Pipe Insulation Removed)

Figure 106 – Plasterboard Stained by Leak from Solar Pipe

c. **Solar Pump Cycling**: The solar pump for the system in house D was found to be short cycling at a frequency of around once per minute (see Figure 13). It is thought that this was due to a combination of problems related to the system controls and pipework restrictions.

d. **Incorrect Placement of Thermocouples**: It was found that the thermocouple sensors for the solar panels in the two flats had been located in the wrong panels. This gave rise to the systems not operating correctly as the solar controllers were receiving the wrong panel temperature data. It took several months to correctly diagnose this problem.

e. **Thermocouple out of Sensor Pocket**: One of the temperature sensors on the panels was found to have come out of the sensor pocket in the manifold. It was believed that this occurred sometime after the initial installation suggesting that it had not been secured properly. The solar engineer suggested that a bird could have pecked the sensor out of the pocket.

f. **Solar Pump Left in Manual Mode**: One of the solar pumps was found to have been left in the manual mode rather than the normal automatic control. In manual mode the solar pump will run continuously and will not respond to temperature differential signals from the controller. The manual mode is used for commissioning and system diagnosis and could therefore have been left that way during the initial installation or any subsequent visit by the solar engineer. It would not have been possible for any of the other contractors or the residents to activate the manual mode as access to the relevant parts of the controller menu was protected by a password. The impact on energy consumption of the system running in manual mode would be significant as it would both use excessive pump energy and also take heat out of the cylinder and dissipate this heat at the panel on the roof.

g. **Solar Controller Left in Freeze Protection Mode**: One of the solar controllers was set so that the freeze protection mode was active. This mode is normally for use with systems in southern European climates which do not use antifreeze solutions in the solar hot water system. They instead use some of the stored heat in the cylinder to prevent the exposed parts of the system freezing on those few days in the year where the external temperature might drop below zero overnight. The freeze protection system is activated when the external temperature drops below a certain threshold which will turn on the solar pump to circulated heated water from the cylinder. The freeze protection mode is not required for the systems at Elm Tree Mews which are protected from freezing by the Tyfocor propylene glycol antifreeze solution which prevents freezing down to -28°C (Tyforop Chemie, 1999). The system was reset so that the freeze protection mode was inactive.

h. **Heat Meter**: The ultrasonic heat meters (Landis & Gyr 2WR6) provided by the metering subcontractor were found to be unreliable when used with glycol based fluids. It was expected by the research team that it would be necessary to correct the heat meter energy data for the difference in density and heat capacity between water and the Tyfocor solar heat exchange fluid. However, the research team were told initially that the meters would be suitable for use in the solar systems at Elm Tree Mews. The unusual heat data from the houses with kinked pipework and other spurious data such as heat meter pulses during the night raised concerns about the performance of the heat meters at an early stage but the cause of the problem was not finally identified until a large part of the monitoring programme was already complete, and it was too late to make any changes to the metering set up. Subsequent discussions with the German engineers at Landis and Gyr indicated that the problem with the ultrasonic flow meters and glycol/water mixtures is related to the higher viscosity of glycol solutions compared to water (Viscosity comparison at 25°C: water = 1 mPa.s, 50% ethylene glycol = 2.8 mPa.s, 100% ethylene glycol = 16.1 mPa.s, 100% propylene glycol = 40.4 mPa.s) . The speed of sound of propylene glycol (~1500 m/s at 20°C) is within the specifications of the ultrasonic meter. However, the flow pattern of the liquid inside the measuring tube of the ultrasonic meter becomes critical at low flow rates, and this is exacerbated for smaller meters such as the Landis & Gyr 2WR6. The calibration of the flow meter is related to the Reynolds number, and as such the heat meter data become unreliable when the flow rate drops below a value equal to the minimum calibrated flow for water multiplied by the factor difference in kinematic viscosity. For future monitoring projects involving heat metering of heating systems containing high viscosity solutions such as glycols, heat meters will need to be carefully selected to ensure that they will work correctly with heat medium other than water. It would also be preferable if the energy integrator could be programmed with the density and thermal characteristics of the heating medium. An example of a heat meter suitable for use with glycol and similar antifreeze solutions is the Sontex Superstatic 440 (Sontex, 2007). This particular heat meter utilises a flow meter based on fluid oscillation principles in conjunction with a programmable energy integrator (Sontex Supercal 531).

160 It is probable that, had the houses not been part of the monitoring project, then many of the faults observed in the solar systems at Elm Tree Mews would have gone undetected and unresolved for some considerable time, perhaps never. It is therefore concluded that there need to be

improvements in the way that such systems are installed and commissioned. There is also scope for integrated measurement and self diagnostics, so that such systems are self checking.

System Complexity Issues

161 It was apparent from the monitored performance data and the numerous interventions made by the research team, that the complex nature of the communal heating system and controls gave rise to a number of performance problems and associated inefficiencies. Many of these issues had their roots in the design of the system, assumptions about fundamental performance and a lack of control of the commissioning procedures. This is perhaps unsurprising as one of the underlying objectives of the Elm Tree Mews development was for it to act as a research case study to help understand performance issues in the construction and operation of low carbon heating systems. Perhaps the most important system parameter impacted by the system complexity issues was the coefficient of performance and seasonal performance factor of the communal heat pump. The lack of understanding of the impact of commissioning processes on the various factors such as heat pump flow temperature settings and circulation pump set up, led to very low efficiencies during the first few months of operation. It is unlikely that these factors would have been picked up by the Housing Trust or contractors had the research team not been monitoring the system performance and at the same time analysing the data on at least a weekly basis. Indeed, had the research team not been involved then it is also unlikely that the necessary meters and sensors such as the heat meter and kWh meter on the heat pump would have been installed.

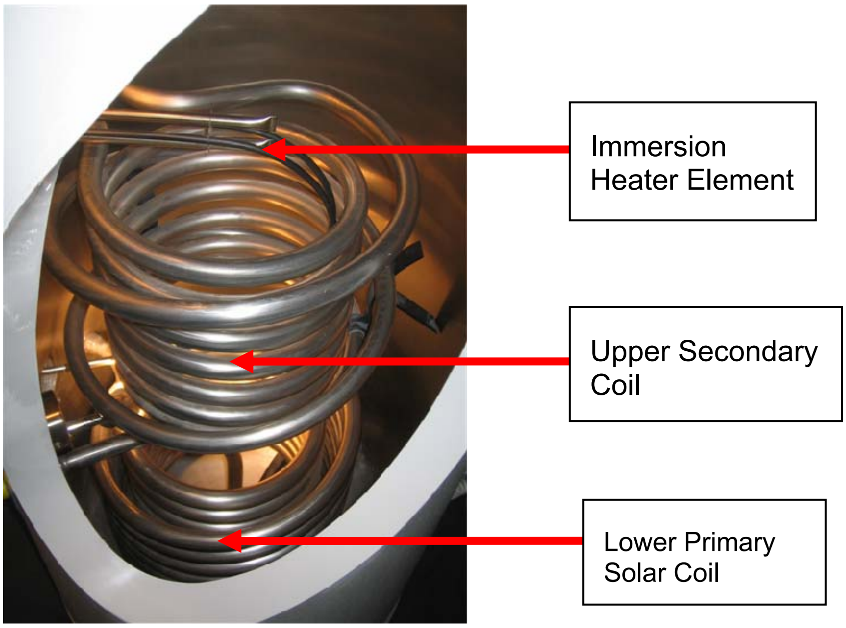
162 The design requirement for the heat pump to supply heat input to both underfloor heating and the domestic hot water cylinders had serious implications for system efficiency. The CoP of a heat pump is determined by its uplift temperature, that is to say the difference between the input temperature from the ground loop and the output temperature from the heat pump. The lower the uplift temperature, then the better the CoP. For underfloor heating systems then the target temperature for the floor would be of the order 29°C or less which would require a flow temperature of between 30°C to 35°C compared to a typical flow temperature from the ground loop of 5°C. However, the design of the system at Elm Tree Mews required there to be a single flow temperature of around 42°C to provide heating to hot water cylinders as well as the underfloor heating. Temperatures lower that this would have been of little use for hot water. This compromise meant that the heat pump temperature was between 5°C and 12°C higher than needed for heating alone. This increase in uplift temperature reduced the maximum efficiency of the system but without any obvious significant benefit to the residents in terms of the quality and quantity of the hot water supply. The requirement for a fixed heat pump output temperature also meant that it was not possible to use temperature compensation to improve the performance of the heat pump outside of the main heating season. The heat pump at Elm Tree Mews had the capability to use weather compensation using external temperature sensors together with control algorithms that would reduce the flow temperature during milder external conditions. However, it was not possible to use the supplied temperature compensation system at Elm Tree Mews as the flow temperature could not be reduced if the system was still to provide domestic hot water as well as space heating.

163 An alternative heating strategy for Elm Tree Mews would have been to have a second heat pump system to supply the hot water heat at a higher temperature, or to use a heat pump with a control system to vary the output flow temperature. Variable output would have been difficult to implement in a communal system where there may be conflicting requirements for heating and hot water at any particular time. In retrospect, it would have perhaps been better to use the heat pump to supply underfloor heating input only and to find another way to supplement the solar hot water input to the domestic hot water. The lack of any gas supply to the houses would have meant that the simplest approach in this case would have been to use the immersion heater as the main secondary input to hot water, which would have also avoided the problems with the need for a legionella pasteurisation cycle. Alternatively, individual heat pumps in each dwelling could have been used which were capable of supplying both space heating at 35°C and hot water at around 55°C. This would have removed the need for any immersion heater input.

164 It should be acknowledged that the twin coil cylinder used at Elm Tree Mews was designed for a low temperature solar heat input at the bottom primary coil and a higher temperature input (typically around 70°C from a gas boiler) to the upper secondary coil. Correspondingly, the size of the coils in the cylinder is matched to the expected heat input with the secondary coil (0.61 m^2) being around half the area of the primary solar coil (1.1 m^2) as can be seen in the cutaway photograph of the cylinder (Figure 107). The situation at Elm Tree Mews was that the temperature of the input to the secondary coil from the communal heat main was between around 35°C and 42°C, and as such is much lower than the designed input temperature of around 70°C. This would significantly reduce

the effectiveness of heat transfer from the communal heat main. Perhaps a better solution would have been to have a bespoke cylinder manufactured for Elm Tree Mews with a twin coil arrangement more suited to the expected heat inputs.

Figure 107 – Cutaway of Hot Water Cylinder Showing Twin Coils



165 The impact on the householder of the complex nature of the heating and hot water systems is that they were faced with a bewildering array of controls including a main heating controller, hot water controller, immersion timer, room thermostats and solar controller. It is perhaps unsurprising that the residents reported that they were confused as to how best to operate the system so that they could maintain comfortable living conditions and an acceptable supply of hot water at the times that they needed it (Bell, Wingfield, Miles-Shenton and Seavers, 2010).

Impact of Space and Water Heating Efficiency Assumptions

166 During the design development phase a heating options desk study was commissioned (Watson and Hill 2006). This concluded that there would be energy and carbon benefits from changing the space and water heating systems from individual gas boiler systems to the communal heat pump installed. The efficiency of heat pumps, which is usually referred to as a coefficient of performance (CoP[8]), can be very high since they make use of the release of latent heat when a fluid in vapour form is compressed into its liquid state. In effect the electrical energy used to drive the compressor releases considerably more heat energy than the electricity input. This results in a CoP that can be much greater than 1 or, in percentage terms, over 100%. The stated CoP of the communal heat pump at commissioning was quoted as 3.5 (350%) but, in design calculations, the standard CoPs contained in SAP 2005 were used. In the case of heat supplied for space heating, a value of 3.2 (320%) was applied but in the case of water heating two different values were shown. The different values would appear to reflect some uncertainty as to the extent to which the system was designed to provide all or only part of the residual hot water energy requirement (after deducting the contribution from the solar thermal system). Guidance in SAP suggests that where all of the water heating is from the heat pump then a simple adjustment factor (0.7) is applied to the space heating CoP, which results in a value of 2.44 (244%). Where this is not the case, SAP assumes that water heating is split on a 50-50 basis between heat pump (operating at a CoP of 3 (300% efficiency) and the immersion heater with an efficiency of 100%. The combined efficiency is then derived using a weighted average, which gives a value of 1.524 (152.4%).

167 The efficiency values and solar input predictions contained in the building regulations submission are set out in Table 3. The possible uncertainty over water heating efficiencies is evident from the

---

[8] The terminology used for "efficiencies" of heat pumps and for other systems can be confusing. Indeed the overall annual (seasonal) coefficient of performance of a heat pump is often referred to as a "seasonal performance factor" (SFP) and expressed as a percentage or as a real number. In this report the term CoP will be used but where appropriate its equivalent in percentage terms will also be included.

value used for the mid terrace, which uses the higher figure than other dwelling types despite the fact that all dwellings are heated by the same heat pump. Of course it is quite likely that the inconsistency is a simple oversight and would not have an impact on regulatory compliance since the dwellings were designed to a much higher standard than that required by regulation. A further difficulty in understanding the design expectation is the fact that the SAP design sheets do not use the communal heating algorithms in SAP 2005 but treat the heating system as if it were provided by an independent GSHP in each dwelling. Although this was not a particular difficulty for regulatory purposes, the fact that the calculation did not take into account the heat losses from the communal hest main would over estimate the theoretical system CoP by around 5%.

168 In a communal system where there is no separation of delivered heat to space and water systems, there is no difference in the efficiency of heat supplied. However, the problem still remains as to how a water heating system that takes some of its heat from the communal system and some from an immersion heater should be treated. Table 39 sets out the impact of changing the calculation method to apply the communal algorithms and compares the communal water heating CoP's based on the standard 50-50 split and the actual split for House A (80% GSHP 20% Immersion). The net effect of the different modelling assumptions is to generally reduce the CoP of the delivered heat from 3.2 to 3.05 and for hot water the design value could be anywhere between 1.5 and 2.2 depending on the assumptions made about the split. Interestingly the figure for the actual split in house A is close to that used in the submitted SAP sheets. As shown by the monitored data from the occupied houses, the actual split between heat pump input and immersion heater input varied considerably from around 55-45 to 80-20 depending on usage. The design expectation for the proportion of water heat from the solar system was reasonably consistent at around 30% depending on property type.

Table 39 - Heating Efficiencies and Solar Input to Hot Water

Dwelling Type	End terrace	Mid terrace	Ground Floor Flat	Duplex Flat
Space Heating CoP – from SAP as submitted	3.2	3.2	3.2	3.2
Water Heating CoP – from SAP as submitted	1.524	2.24	1.524	1.524
Alternative space heat CoP – communal heating algorithms	3.05			
Alternative water heat CoP – communal heating algorithms @ 50-50 split – HP – Immersion	1.506			
Alternative water heat CoP – communal heating algorithms @ 80-20 (House A actual split) HP – Immersion	-	2.2	-	-
Solar input to water heating (kWh)	1117	1097	692	981
Solar input as a percentage of the total water heating requirement	33%	33%	28%	34%

Closing the Loop - Predicted Energy Use vs. Measured Energy Use

169 In order to assess that actual performance of the systems at Elm Tree Mews, the measured annual heating energy data for House A and B were analysed over the same heating period (24th September 2008 to 23rd September 2009) and were compared to the performance that would be predicted using the Leeds Met parametric domestic energy calculator. The relevant performance data are given in Table 40. It can be seen that the measured annual delivered heating energy input was 3463 kWh for House A and 3409 kWh for House B. After allowing for adjustments to allow for heating gains due to electricity compared to the model and for the heating that would have occurred in February when the heat pump was broken, these values increase to 4509 kWh for House A and 4282 kWh for House B. This compares to an unadjusted modelled heating input requirement of 3439 kWh and 3505 kWh using the design fabric U-values and calculated using the standard modelling assumptions for ventilation, internal temperature, weather and occupancy. After adjusting the model inputs for the actual measured values for these parameters, the modelled heating input falls to 1776 kWh for House A and 1878 kWh for House B. The modelled heating input is therefore around 2500 kWh lower than that actually measured. This discrepancy can be

explained by the fact that the design values for the fabric do not reflect the performance of the buildings as constructed. If we therefore adjust the model using U-value data that better reflect the houses as built and also allow for heat losses due to the party wall bypass, then the modelled values increase to 4308 kWh for House A and 5128 kWh for House B, which are in closer agreement with the measured data.

Table 40 – Modelled and Measured Annual Heating Performance: House A and House B

For annual monitoring period 24/9/08 to 23/9/09	House A	House B
Delivered Energy from Heat Main (kWh)	4482	3750
Measured Hot Water from heat main (kWh)	1019	341
Delivered Heating Energy from Heat Main (kWh)	3463	3409
Hot Water Used (litres)	52507	27602
Mains Electricity (kWh)	4455.1	3824.4
Immersion Electricity Used (kWh)	245.7	285.1
Electricity Excluding Immersion (kWh)	4209.4	3539.3
Assumed Energy Lights, Appliances, Fans, Pumps in Model (kWh)	3286	3192
Extra Electricity in Heating Season versus Model (kWh)	538.65	289.42
Additional Electrical Heat vs. Model (kWh)	545.67	373.48
Heating Start Date	12/09/2008	01/09/2008
Heating Finish Date	29/03/2009	15/05/2009
Mean Internal Temperature in Model (°C)	18.8	18.8
Measured Mean Internal Temp Oct 08 to Apr 09 (°C)	17.2	19.7
Difference Model Heat Demand & Measured Heat Demand (Degree Days)	-250	0
Assumed Occupancy in Model (Persons)	3.3	3.3
Actual Occupancy (Persons)	4	5
Assumed Ventilation Rate in Model (h^{-1})	0.58	0.58
Actual Ventilation Rate (h^{-1})	0.6	0.25
Estimated Heat Not Used in February when Heat Pump Broken (kWh)	500	500
Total Annual Measured Heating Input after Adjustments (kWh)	4509	4282
Modelled Heating Input with Standard Assumptions (kWh)	3439	3505
Modelled Heating Input Adjusted for all Factors except Fabric (kWh)	1776	1878
Modelled Heating Input Adjusted for all Factors (kWh)	4308	5128

170 It is interesting to note that if one had just looked at the delivered energy data, and then compared this to energy predictions based on the model calculated using only the standard assumptions, then these data would have been in very close agreement. On this basis, it can be seen how one might make the erroneous conclusion that the building was performing as expected from the design assumptions. However, the fabric performance measurements tell us that this is not the case. This demonstrates why one needs to be very careful when using energy performance models and the need to fully understand what assumptions are being used in the model. This is especially true for low energy housing where factors such as internal gains and solar gains can have a significant impact on heating energy demand.

Relative Energy Performance

171 Data for typical UK domestic energy consumption for gas and electricity can vary depending upon the organisation publishing the information. The current standard annual gas and electricity consumption data used by OFGEM are given in Table 41 (OFGEM 2010). Alternative data for

annual domestic energy consumption are produced by DECC, Consumer Focus and Eurostat as shown in Table 42 (OFGEM 2010). A regional breakdown of consumption data by DECC (Table 43 and Table 32) gives the mean and median annual consumption data for the Yorkshire and Humber region. An analysis of changing trends in domestic energy consumption between 2005 and 2009 along with input from other energy datasets has led OFGEM to review their standard consumption figures and they have recommended changes to the low, medium and high usage as shown in Table 44. The new OFGEM data shows medium level gas consumption has reduced from 20,500 kWh to 16,500 kWh reflecting the improved performance of new dwellings built to the higher energy efficiency standards required under the 2001 and 2006 reviews of Part L of the building regulations. This is in line with the median gas consumption for the Yorkshire region in 2007 (16,860 kWh, see Table 43).

Table 41 – OFGEM Standard Annual Domestic Energy Consumption (OFGEM 2010)

Fuel	Average Annual Consumption (kWh)		
	Low User	Medium Use	High User
Gas	10,000	20,500	28,000
Electricity (standard)	1,650	3,300	4,600
Electricity (Class 2 – economy 7/10)	3,300	6,600	9,900

Table 42 – Alternative Annual Domestic Energy Consumption Data (OFGEM 2010)

Data Source	Annual Gas (kWh)		Annual Electricity (kWh)	
	Median	Mean	Median	Mean
DECC - Quarterly Energy Prices	-	18,000	-	3,300
DECC – Energy Trends	16,210	17,614	3,550	4,392
Eurostat	-	23,250	-	3,500
Consumer Focus	-	20,500	-	3,300

Table 43 – Mean Annual Gas Consumption from Domestic UK Meters in 2007 (Chan 2009)

	Annual Gas Consumption (kWh)	
Meter Area	Mean	Median
Yorkshire and Humber	18,099	16,860
Great Britain	17,614	16,210

Table 44 – Recommended Changes to OFGEM Domestic Energy Data (OFGEM 2010)

Fuel	Average Annual Consumption (kWh)		
	Low User	Medium Use	High User
Gas	11,000	16,500	23,000
Electricity (standard)	2,100	3,300	5,100
Electricity (Class 2 - economy 7/10)	2,900	5,000	8,300

172 In order to compare the measured energy consumption of the Elm Tree Mews dwellings with that of a typical UK house heated by a gas condensing boiler, it is necessary to convert the communal heat main input into electricity consumed by the equipment in the plant room. For this purpose a system efficiency of 2.13 has been assumed (see Table 38). Using the annual heat and electricity data for Houses A and B given in Table 40, the total annual electricity consumption for the two

houses has been calculated as shown in Table 45. The total energy consumption for House A was 6559 kWh and for House B was 5585 kWh. The annual energy totals for the two Elm Tree Mews houses are around 50% less than a typical low use gas heated dwelling in the UK (13,100 kWh) and around 70% less than a typical medium use gas heated dwelling (19,800 kWh).

Table 45 – Annual Energy Consumption for Elm Tree Mews Houses A and B

Dwelling	Annual Electricity used for Communal Heat Input (kWh)	Annual Electricity on Utility Meter (kWh)	Total Energy Consumption (kWh)
House A	2104	4455	6559
House B	1761	3824	5585

Carbon Emissions

173 The submitted energy requirements from the as-built SAP worksheets for space heating, hot water, fans/pumps and lighting for the 4 dwelling types at Elm Tree Mews are given in Table 46. Using these data the total predicted space heating and hot water energy requirement for all six dwellings is 13,846 kWh which is equivalent to 5.84 tonnes CO_2/annum using the SAP 2005 carbon emission factor of 0.422 $kgCO_2$/kWh for grid electricity. From the monitored energy data for the heat pump, together with the immersion heater consumption for the dwellings (including some manual meter readings for those dwellings that were not monitored for the whole year), the total electricity used by all six dwellings for space heating and hot water over the year September 2008 to October 2009 was of the order 15,100 kWh (12,600 kWh for the heat pump and 2,500 kWh for the immersion heaters). This is equivalent to 6.37 tonnes CO_2/annum. However, we know from the fabric performance tests and heat pump CoP calculations that the energy consumption and carbon emissions would have been much lower if the building fabric and heating system had performed as designed.

Table 46 – Energy Requirements from Submitted SAP Worksheets

	End Terrace	Mid Terrace	Ground Floor Flat	Duplex Flat
Space heating (kWh)	1646.4	1152.8	860.3	1030.1
Hot water (kWh)	1495.4	986.5	1170.4	1225.3
Fans/pumps (kWh)	205	205	205	205
Lighting (kWh)	506	497.8	237.9	341.5
Total (kWh)	3852.8	2842.1	2473.6	2801.9

174 The likely effect of real fabric performance on carbon emissions can be estimated by applying a correction factor based on the relative performance of the modelled heating input to House A and House B. This shows that the effect of fabric factors such as the party wall bypass and actual U-values on the modelled performance was an increase of around 160% on the delivered space heating input. Applying this factor to the measured total delivered space heating for the 6 dwellings at Elm Tree Mews of 23,500 kWh gives an adjusted space heating input of 9,038 kWh. If we then add in the measured hot water input from the heat main (3,100 kWh), the total delivered heat from the heat pump would have been 12,138 kWh. If the heat pump had met the expectations of the design intent and achieved a system CoP of 3.2, then the heat pump system electricity consumption for this adjusted total annual communal heat input would have been 3,793 kWh. If we then add in the measured annual immersion heater input to the 6 dwellings (2,500 kWh), then the total electricity consumption for space heating and hot water for the houses would have been 6,293 kWh had the fabric and heat pump performed as expected from the design assumptions. This is equivalent to 2.66 tonnes CO_2/annum with a carbon emission factor of 0.422 $kgCO_2$/kWh for grid electricity. This compares to the 6.37 tonnes CO_2/annum that were actually measured, giving an increase in actual carbon emissions of 3.71 tonnes CO_2/annum as a result of the underperformance of the fabric and systems relative to the design assumptions.

175 The design decision to use a heat pump at Elm Tree Mews rather gas condensing boilers would have been heavily dependent upon the assumptions made about the CoP of the heat pump and the relative carbon coefficients for mains gas and grid electricity. In SAP 2005 the carbon

coefficient for grid electricity is given as 0.422 $kgCO_2/kWh$ and for mains gas is 0.194 $kgCO_2/kWh$. However, these factors have been reviewed for the latest version of SAP (BRE 2010), and have increased to 0.517 $kgCO_2/kWh$ for grid electricity and 0.198 $kgCO_2/kWh$ for mains gas (BRE 2010)[9]. If we assume a nominal delivered energy input for space heating and domestic hot water of 15,000 kWh (approximately equivalent to the measured consumption of all 6 dwellings at Elm Tree Mews), then we can calculate and compare the effect of different assumptions about CoP and carbon emission coefficients on the overall carbon emissions for Elm Tree Mews heated using either individual gas boilers or a communal ground source heat pump. For this comparison we have assumed the system efficiency for a modern gas condensing boiler to be 85% based on monitoring work carried out by the Leeds Met research team at Stamford Brook (Wingfield et al. 2008). If we use the SAP 2005 carbon coefficients (BRE 2005) and assume a nominal system CoP for the heat pump of 3.2, then the relative carbon emissions for Elm Tree Mews would be 2.7 tonnes CO_2/annum for the communal heat pump and 3.42 tonnes CO_2/annum for gas condensing boilers (see Table 47). On this basis, the decision to use a communal heat pump would be the most effective in terms of carbon emissions for space heating and hot water. However, if the calculation is repeated using the latest SAP 2009 carbon coefficients (BRE 2010) together with a more realistic system CoP for the communal heat pump of 2.15 based on the measurements from Elm Tree Mews, then the situation is reversed, with the calculated emissions for gas boilers at 3.49 tonnes CO_2/annum being lower than those for the communal heat pump at 4.30 tonnes CO_2/annum (see Table 48). This example clearly demonstrates the importance of using appropriate factors for system efficiency and emission rates. There is of course little that designers or developers can do to change the carbon coefficient of grid gas or electricity supplies. However, they can influence the performance and efficiency of the designed and installed heating systems.

Table 47 – Comparison of Individual Gas Boilers versus Communal Ground Source Heat Pump – SAP 2005 Carbon Coefficients

	Individual Gas Condensing Boilers	Communal Ground Source Heat Pump
Main Heating System Efficiency %	85	320
Immersion Heating Efficiency %	n/a	100
Delivered Heat from Main Heating System (kWh)	15,000	12,500
Delivered Immersion Heating Input (kWh)	n/a	2,500
Total Energy Used (kWh)	17,647	6,406
Carbon Coefficient ($kgCO_2/kWh$)	0.194	0.422
Heating/Hot Water Carbon Emissions (tonnes CO_2/annum)	3.42	2.70

Table 48 – Comparison of Individual Gas Boilers versus Communal Ground Source Heat Pump – SAP 2009 Carbon Coefficients

	Individual Gas Condensing Boilers	Communal Ground Source Heat Pump
Main Heating System Efficiency %	85	215
Immersion Heating Efficiency %	n/a	100
Delivered Heat from Main Heating System (kWh)	15,000	12,500
Delivered Immersion Heating Input (kWh)	n/a	2,500
Total Energy Used (kWh)	17,647	8,314
Carbon Coefficient ($kgCO_2/kWh$)	0.198	0.517
Heating/Hot Water Carbon Emissions (tonnes CO_2/annum)	3.49	4.30

---

[9] It should be noted that in the original Pout review of the carbon emission factors were 0.591 $kgCO_2/kWh$ for electricity and 0.208 $kgCO_2/kWh$ for gas (Pout 2009a and 2009b). Following consultation these factors were reduced to those currently given in SAP 2009.

Closing the Loop – Fabric Heat Loss

176 It is clear from the measurements and observations carried out at Elm Tree Mews that the heat loss from the various construction elements and junctions as constructed did not match the theoretical values calculated in the original design estimates that used nominal U-values and thermal bridging factors. The consequence of this was to increase the realised whole house fabric heat loss coefficient compared to that calculated using the nominal design values. It is possible to modify the calculation of whole house heat loss by using elemental U-values and thermal bridging factors that more closely reflect those of the dwellings as-built. A set of conservative as-built U-values for Elm Tree Mews based on measurements by the research team are given in Table 49 together with the nominal design values. The as-built values used are 0.3 W/m^{2}K for the wall, 0.18 W/m^{2}K for the roof, 2.0 W/m^{2}K for the windows, 0.15 W/m^{2}K for the thermal bridging y-value and additional heat loss for the party wall having an effective U-value of 0.3 W/m^{2}K. No evidence was found to justify any adjustment to the U-value of the floor which was therefore left unchanged at the nominal design value of 0.2 W/m^{2}K. The adjusted values have then been used to calculate the fabric heat loss for the end terrace dwelling (House F) as shown in Table 50.

Table 49 – As-built and Nominal U-Values and Thermal Bridging Factors

Heat Loss Element	Designed U-Value or y-value (W/m^{2}K)	Conservative As-built U-value or y-value (W/m^{2}K)
External Wall	0.18	0.30
Party Wall	0	0.30
Roof	0.13	0.18
Windows/Doors	1.50	2.00
Rooflights	1.68	1.68
Thermal Bridging	0.08	0.15
Floor	0.20	0.20

Table 50 – As-built and Nominal Fabric Heat Loss for End Terrace (House F)

Heat Loss Element	Heat Loss Using Conservative As-Built U-value or y-value (W/K)	Heat Loss Using Designed U-Value or y-value (W/K)	Difference between As-built and Designed Heat Loss (W/K)
External Wall	31.1	18.7	12.5 (+ 66.7%)
Party Wall	20.7	0.0	20.7
Roof	12.7	9.2	3.5 (+38.5%)
Windows/Doors	56.5	42.3	14.1 (+33.3%)
Rooflights	2.4	2.4	0.0
Thermal Bridging	37.1	19.8	17.3 (+87.5%)
Floor	8.6	8.6	0.0
TOTAL	169	100.9	68.1 (+67.5%)

177 The realised fabric heat loss coefficient for the end terrace as-built was calculated to be 169 W/K. The difference between the nominal fabric heat loss (100.9 W/K) and the realised fabric heat loss was 68.1 W/K, which is an increase of 67.5%. This difference compares very favourably with the experimentally derived fabric heat loss coefficient discrepancy of 68.9 W/K obtained from the coheating test conducted on the end terrace. This leads to the conclusion that the measured difference between the coheating test result and designed heat loss can be explained fully by the observed variability in the thermal performance of the building elements and junctions as-constructed. The data suggest that the biggest contributor to the increase in fabric heat loss for the

end terrace was the party wall thermal bypass which accounted for 20.7 W/K (some 30% of the 68.1 W/K difference). This illustrates the importance of eliminating thermal bypassing in the design and construction of low energy dwellings. The cumulative effect of the various discrepancies in designed and as-built heat loss for the various elements can be seen in the bar chart shown in Figure 108. The percentage contribution for each factor to the total discrepancy is shown in Table 51.

Figure 108 – Cumulative Effect on Fabric Heat Loss Coefficient of Designed versus As-built U-values & y-value for End Terrace Dwelling (House F)

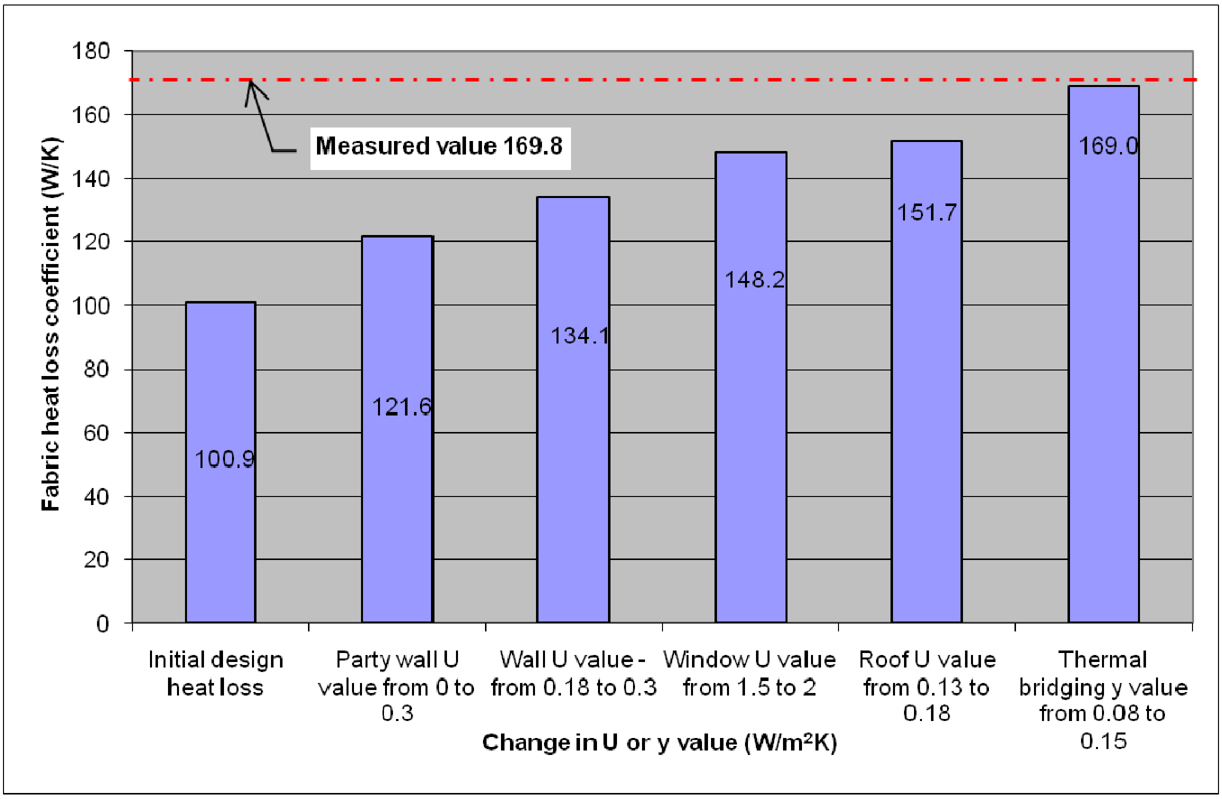


Table 51 – Percentage Contribution of Heat Loss Factors to Discrepancy is Measured Fabric Heat Loss for End Terrace (House F)

Change in U-value or y-value for Element	**Discrepancy in As-built Heat Loss versus Designed Heat Loss (W/K)**	**Discrepancy as % of Total**
External Wall (0.18 to 0.30 W/m^{2}K)	12.5	18.3 %
Party Wall (0 to 0.30 W/m^{2}K)	20.7	30.4 %
Roof (0.15 to 0.18 W/m^{2}K)	3.5	5.2 %
Windows/Doors (1.5 to 2.0 W/m^{2}K)	14.1	20.7 %
Rooflights (no change)	0	0
Thermal Bridging (0.08 to 0.15 W/m^{2}K)	17.3	25.4 %
Floor (no change)	0	0
TOTAL	68.1	100 %

178 The calculated as-built fabric heat losses for the mid-terraces, ground floor flat and duplex flat are shown in Table 52, Table 53 and Table 54 respectively. It can be seen that in the case of the mid-terraced dwellings, the discrepancy between as-built and designed fabric heat loss is likely to be of the order 70 W/K, representing an increase of 104% compared to the designed heat loss. This

higher discrepancy compared to the end terrace is an effect of the party wall bypass, as mid-terraces have two party walls. The party wall is also the biggest contributor to the additional heat loss in the duplex flat, but in the case of the ground floor flat it is the windows that are the largest contributor to the heat loss discrepancy.

Table 52 - As-built and Nominal Fabric Heat Loss for Mid-terrace (Houses A, B and D)

Heat Loss Element	Heat Loss Using Conservative As-Built U-value or y-value (W/K)	Heat Loss Using Designed U-Value or y-value (W/K)	Difference between As-built and Designed Heat Loss (W/K)
External Wall	9.5	5.7	3.8 (+66.7%)
Party Wall	41.4	0.0	41.4
Roof	12.7	9.2	3.5 (+38.5%)
Windows/Doors	38.5	28.8	9.6 (+33.3%)
Rooflights	2.4	2.4	0.0
Thermal Bridging	24.2	12.9	11.3 (+87.5%)
Floor	7.7	7.7	0.0
TOTAL	136.4	66.7	69.7 (+104.4%)

Table 53 - As-built and Nominal Fabric Heat Loss for Ground Floor Flat (House C)

Heat Loss Element	Heat Loss Using Conservative As-Built U-value or y-value (W/K)	Heat Loss Using Designed U-Value or y-value (W/K)	Difference between As-built and Designed Heat Loss (W/K)
External Wall	9.6	5.8	3.8 (+66.7%)
Party Wall	6.0	0.0	6.0
Roof	0.0	0.0	0.0
Windows/Doors	32.0	24.0	8.0 (+33.3%)
Thermal Bridging	15.2	8.1	7.1 (+87.5%)
Floor	10.7	10.7	0.0
TOTAL	73.5	48.5	24.9 (+51.4%)

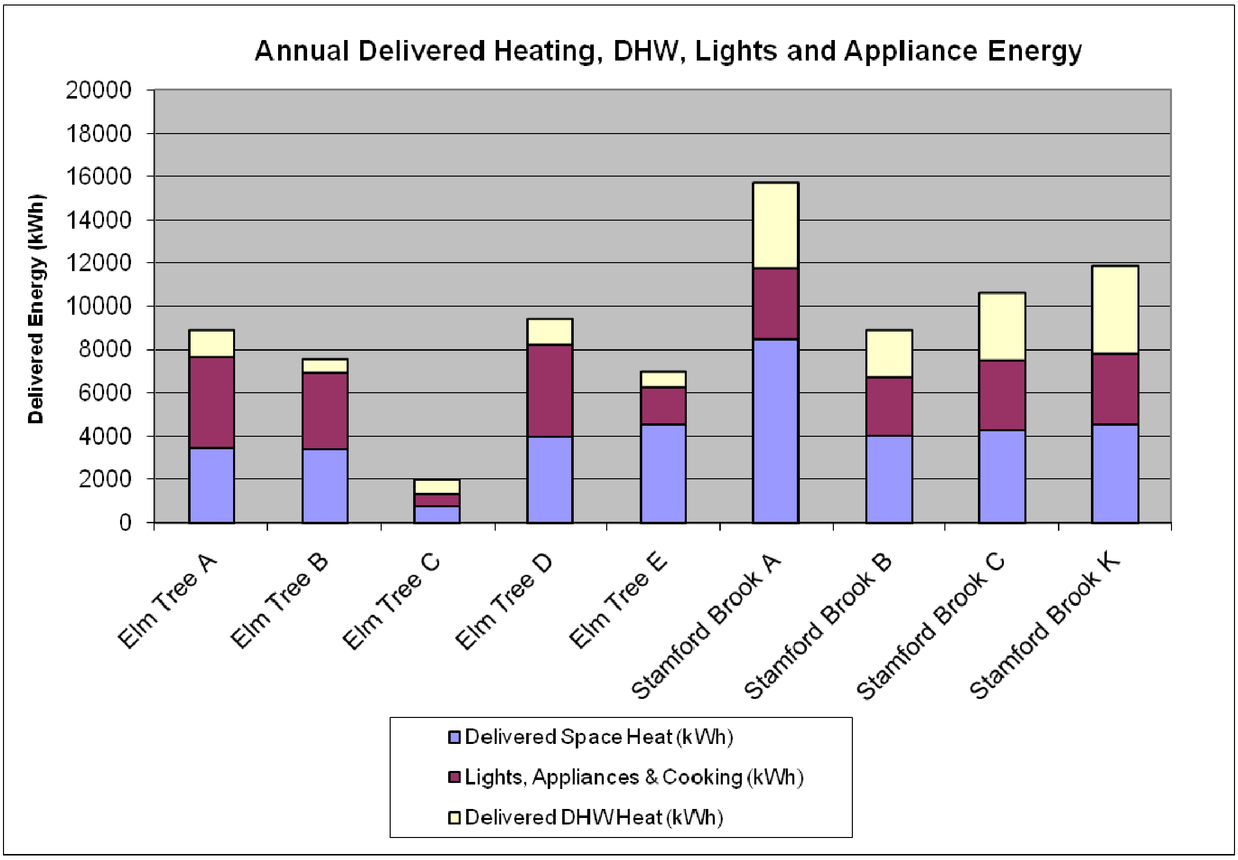
Table 54 - As-built and Nominal Fabric Heat Loss for Duplex Flat (House E)

Heat Loss Element	Heat Loss Using Conservative As-Built U-value or y-value (W/K)	Heat Loss Using Designed U-Value or y-value (W/K)	Difference between As-built and Designed Heat Loss (W/K)
External Wall	22.5	13.5	9.0 (+66.7%)
Party Wall	14.7	0.0	14.7
Roof	9.7	7.0	2.7 (+38.5%)
Windows/Doors	38.0	28.5	9.5 (+33.3%)
Thermal Bridging	22.2	11.8	10.3 (+87.5%)
Floor	0.0	0.0	0.0
TOTAL	107.0	60.8	46.2 (+76.1%)

Comparison with Stamford Brook Energy Consumption Data

179 A useful comparison for the Elm Tree Mews in-use energy consumption data are the in-use data obtained by the Leeds Met research team from the Stamford Brook field trial. The Stamford Brook project monitored the performance of four occupied cavity masonry dwellings that were built to an energy standard that was around 15% better than that required under Part L 2005 of the building regulations (Wingfield, et al., 2008). The houses at Stamford Brook were monitored for at least a year during 2006 and 2007. A comparison of the annual delivered energy for space heating, domestic hot water and lights/appliances for the five Elm Tree Mews dwellings and the four Stamford Brook dwellings is illustrated by the bar chart shown in Figure 109. It can be seen that Elm Tree Mews C and Stamford Brook B are both outside of the typical range, but that all the other dwellings have total delivered energy in a similar range from ~7,000 kWh to 12,000 kWh. It is noticeable that the delivered energy for domestic hot water at Elm Tree Mews was significantly lower than that for the dwellings at Stamford Brook. This will be due to the availability of solar hot water at Elm Tree Mews but also because the average temperature of the stored hot water at Elm Tree Mews would almost certainly be less than that at Stamford Brook. Some of the differences in delivered electricity for lights and appliances will be due to occupant behaviour. However, in general terms it can be concluded that the energy performance of the Elm Tree Mews dwellings when compared to those at Stamford Brook does not represent that of dwellings that, in design terms, should have had much lower heat and energy demand than those at Stamford Brook.

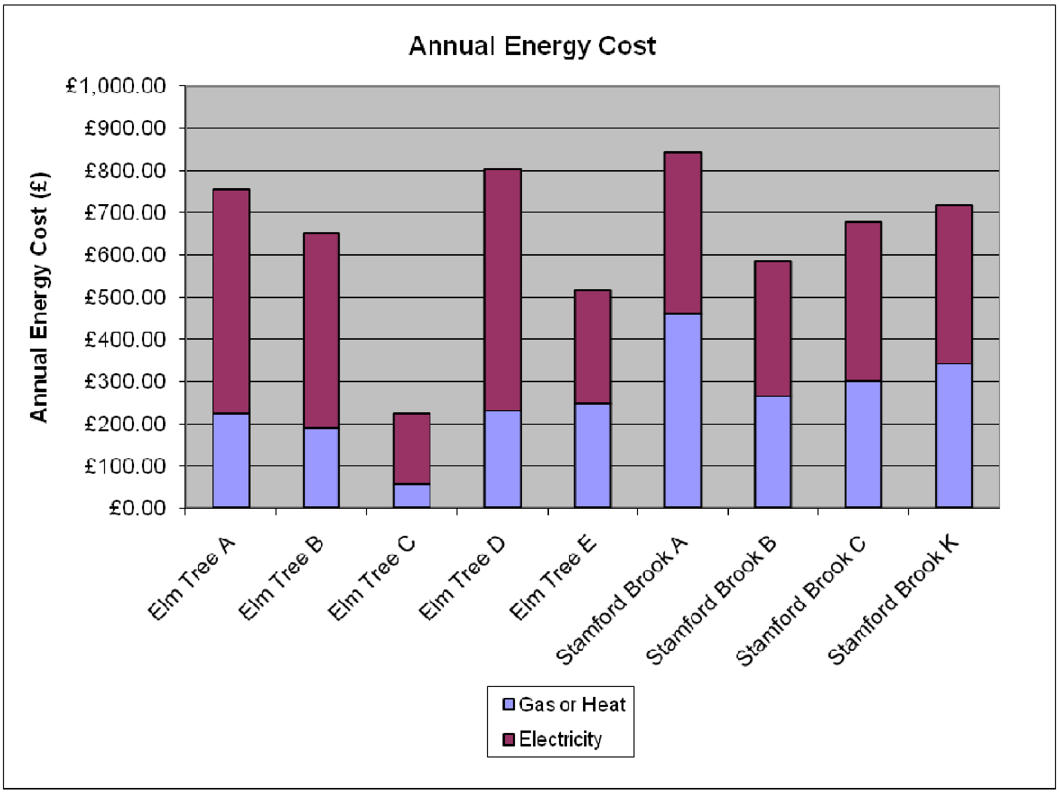
Figure 109 – Comparison of Annual Delivered Energy for Elm Tree Mews and Stamford Brook



180 It is also interesting to compare the total energy costs for the monitored dwellings at Stamford Brook and Elm Tree Mews as shown by the bar chart in Figure 110. To ensure a fair comparison, the illustrated costs were calculated using the same electricity prices typical for the Yorkshire region in 2010 (10.25 p/kWh, 48.69 £/annum service charge, 5% VAT). The Elm Tree Mews heat prices are those charged to the householders during 2009 (4.47p/kWh, 12.74 £/annum service charge, 5% VAT). The gas prices are those typical for the Yorkshire region in 2010 (3.03 p/kWh, 57.38 £/annum service charge, 5% VAT). It can be seen that the total energy costs for Elm Tree Mews are no better than those from Stamford Brook (ignoring the outlier data for Elm Tree Mews C) and are typically in the range £500 to £800 per annum. The efficiency benefit of the ground

source heat pump is being offset by the higher price of communal heat relative to natural gas, and also the higher usage of electricity in the houses at Elm Tree Mews, which will be party driven by the need to use the immersion heater for pasteurisation of the domestic hot water.

Figure 110 – Comparison of Annual Energy Costs for Elm Tree Mews and Stamford Brook



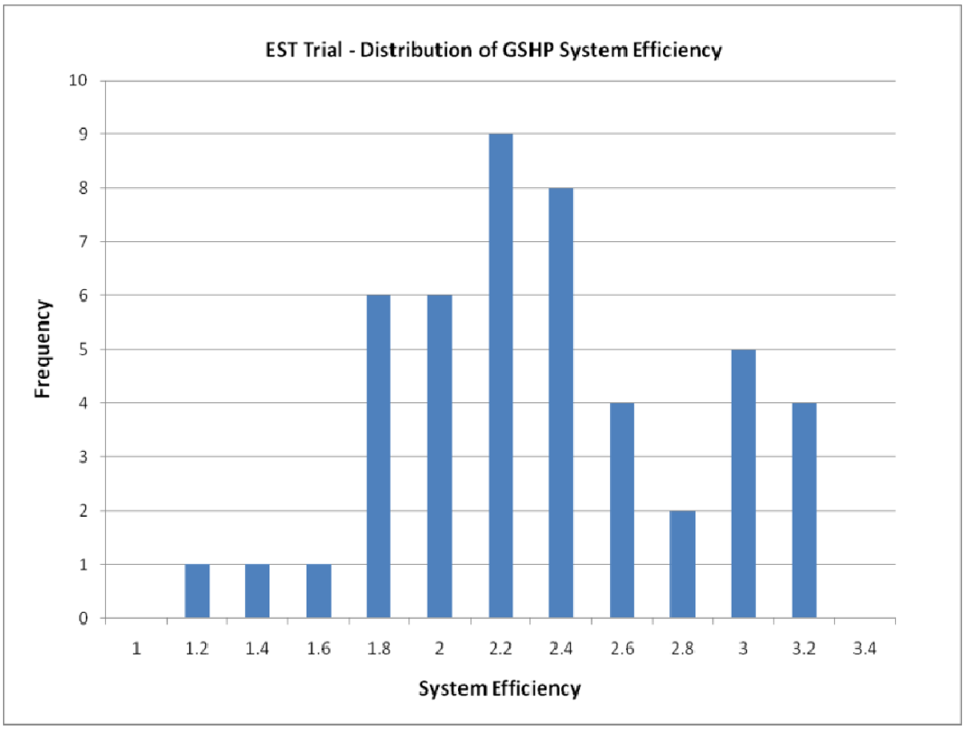
181 A typical gas-heated dwelling with annual gas consumption of 16,500 kWh and electricity consumption of 3,300 kWh (see Table 44) would have an annual energy cost of £880, comprising £525 for gas and £355 for electricity (using typical 2010 Yorkshire region prices of gas at 3.03 p/kWh with a 57.38 £/annum service charge and electricity at 10.25 p/kWh with a 48.69 £/annum service charge). The annual cost of energy for the residents of Elm Tree Mews ranged from £500 to £800 (ignoring House C), and is therefore less than that of a typical gas heated dwelling using the same energy price for electricity. However, the difference in cost is not as marked as it might be due to the much higher cost of electricity (10.2 p/kWh) and communal heat (4.5 p/kWh) compared to the cost of natural gas from the grid (3.0 p/kWh).

Comparison of Elm Tree Mews with other Heat Pump Field Trials

182 The Energy Saving Trust (EST) recently published the final report from a year-long field trial of the performance of 83 domestic heat pump installations in the UK (EST 2010). Of these installations, 54 were ground source heat pumps and 29 were air source heat pumps. The range of measured heat pump CoP's for the ground source heat pumps was from 1.3 to 3.6, with the system efficiencies ranging from 1.3 to 3.3. The distribution of ground source heat pump system CoP data is shown in Figure 111. The EST report quotes a "mid-range" system CoP for the ground source heat pumps of 2.4. The report does not contain any detailed information on the type of ground source heat pumps, whether the systems are providing space heating or both space heating and hot water, or what the typical flow temperatures and temperature uplifts are for the various installations. The report is also unclear as to what is included in either the pump CoP or the system CoP. It is therefore difficult to make a direct comparison with the results from Elm Tree Mews. However, in general terms, the measured system CoP from Elm Tree Mews of around 2.15 (Table 38) is comparable with the mid-range performance of the data from the EST field trial. The EST report concluded that the measured efficiencies were generally worse than expected and that this was due to a range of factors relating to design, installation and commissioning problems together with issues of complexity of controls and the interaction of the householders with the controls.

These conclusions echo those made in this report regarding the performance of the Elm Tree Mews communal heat pump.

Figure 111 – EST Heat Pump Field Trial – GSHP System Efficiency Distribution (after EST 2010)



183 The Fraunhofer-Institut für Solare Energiesysteme (ISE) in Germany has published the initial data from an ongoing field trial of domestic ground source and air source heat pumps. The trial includes, 34 new build ground source heat pumps, 35 retrofit ground source heat pumps, 6 new build air source heat pumps and 34 retrofit air source heat pumps. The measured CoP results from the first year of the field trial (2008) are shown in Figure 112. The definition of annual CoP used for the ISE field trial includes the electricity input to the heat pump (excluding the heating loop circulation pump) relative to the energy output to the radiators/underfloor heating and the hot water storage tank (The typical system boundary is shown in Figure 117). The mean CoP for the new build ground source heat pumps was 3.8. This compares to the measured annual pump CoP for Elm Tree Mews of 2.7. Even allowing for the improvement in pump CoP to around 3.1 following the interventions at Elm Tree Mews, these data indicate that the Elm Tree Mews heat pump CoP is lower than that of a typical German system. The ISE data also indicate that difference is not due to variations in the temperature uplift. The mean temperature uplift for the ISE ground source heat pumps was 33 K (see Figure 113) compared to a similar uplift temperature of around 35 K for the Elm Tree Mews system.

184 To allow a better comparison of the ISE data with Elm Tree Mews, the energy used by the internal hot-side circulation pump has been calculated and removed from the calculation of the Elm Tree Mews pump CoP for the year September 2008 to August 2009[10]. This gives a seasonal pump CoP for Elm Tree Mews of 3.11 with the hot-side circulation pump energy excluded. Following the changes to the hot-side circulation pump carried out in February 2009, the energy consumed by the circulation pump has been significantly reduced. This means that the impact on the pump CoP of excluding the hot-side circulation pump energy in the CoP calculation (hot-side circulation pump energy estimated at approximately 100 kWh/annum following the heat pump alterations) would not be significant, and would only increase the pump CoP by a factor around 0.02 to 0.03.

---

[10] For the period before the alterations to the internal hot side circulation pump in February 2009, the hot -side circulation pump was running continuously for 24hours/day at a power of 345 W. Excluding the 2 weeks of heat pump downtime in February this gives an energy use of 1395.2 kWh for the 6 months from September 2008 to February 2009. For the 6 month period after the alterations the hot side pump power was reduced to 85 W. The circulation energy used was calculated by assuming an average power for the heat pump of 16kW. This gives an energy use of 44.9 kWh for the 6 months from March 2009 to August 2009. The annual energy consumption of the hot-side internal circulation pump for September 2008 to August 2009 was therefore 1443 kWh.

Figure 112 – Frauenhofer ISE Field Trial CoP Results for First Year (after Russ 2009)

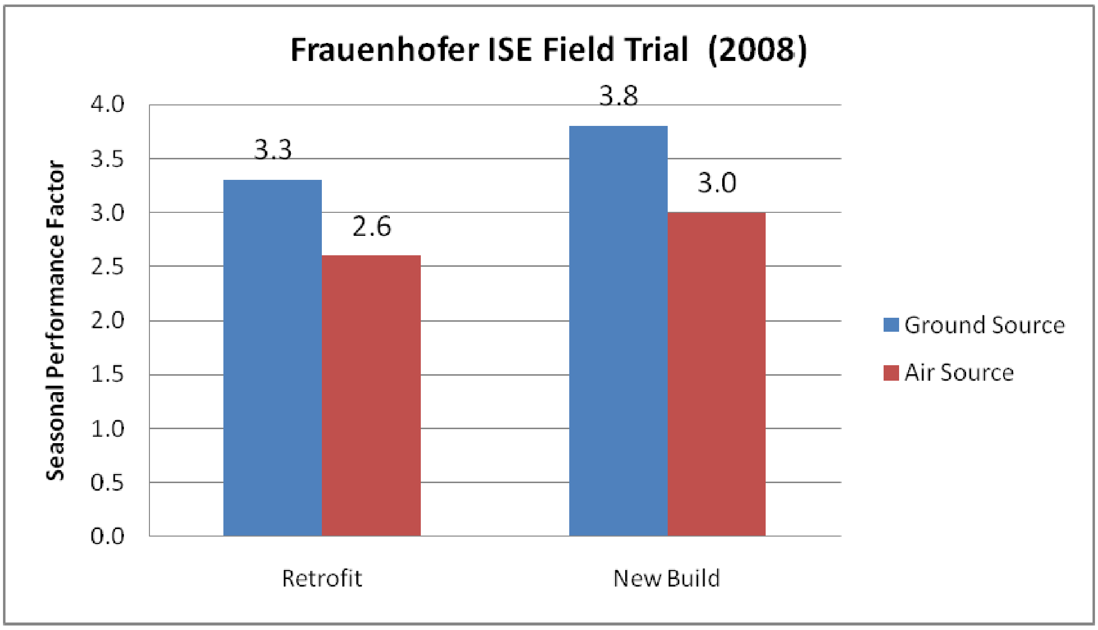
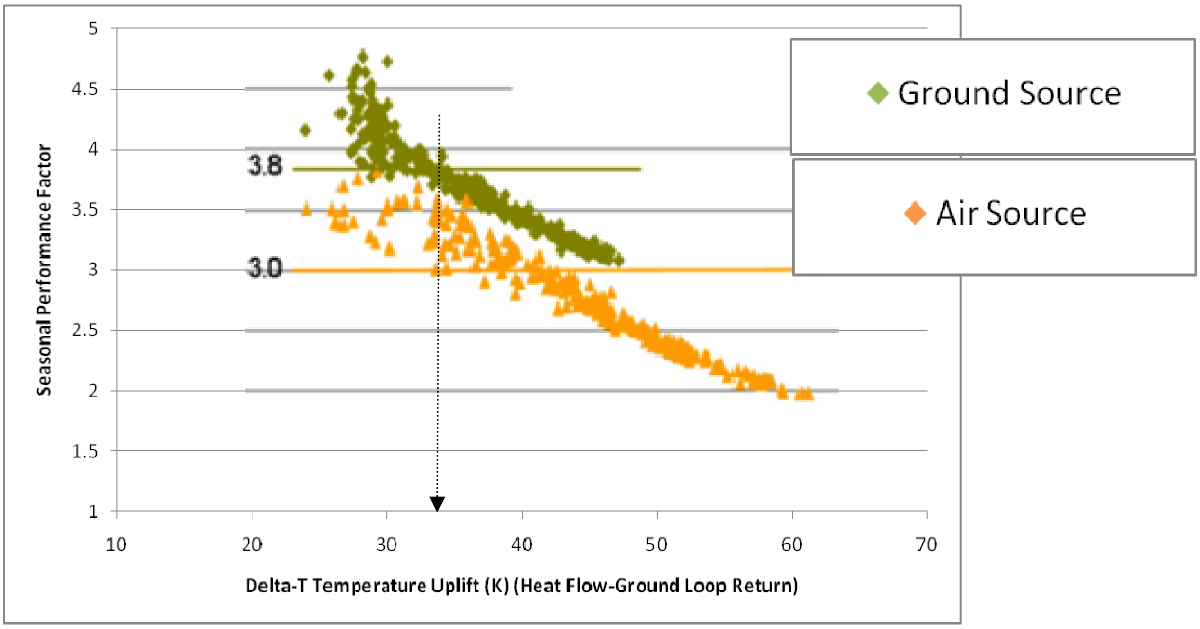


Figure 113 - Frauenhofer ISE Field Trial CoP versus Δ-T Temperature Uplift (after Russ 2009)



185 The research team at Leeds Met is currently working on another heat pump field trial. This is part of the EPSRC-Eon funded Carbon, Control and Comfort project, and is investigating the performance of ten retrofit ground source heat pump installations in rented properties owned by Harrogate Borough Council (Leeds Metropolitan University, 2010). The project is expected to finish in 2012, and will eventually have heat pump CoP data from 2 years monitoring.

System Boundaries

186 Comparisons with the data from other field trials demonstrate the importance of knowing and understanding the system boundaries used in defining the performance of heat pumps, and other heating and hot water systems. Schematic diagrams of the system boundaries used in the calculation of CoP at Elm Tee Mews are given in Figure 114 (Pump CoP) and Figure 115 (System CoP). For comparison, typical system boundaries used for the CoP calculations for the EST heat pump field trial are shown in Figure 116 and for the ISE heat pump field trial in Figure 117. The EST field trial system boundary was derived from direct observations by the Leeds Met research team of the monitoring equipment (heat meters and kWh meters) installed on the heat pump in a dwelling in Yorkshire that is taking part in the EST trial.

Figure 114 – Heat Pump System Boundary at Elm Tree Mews – Pump CoP

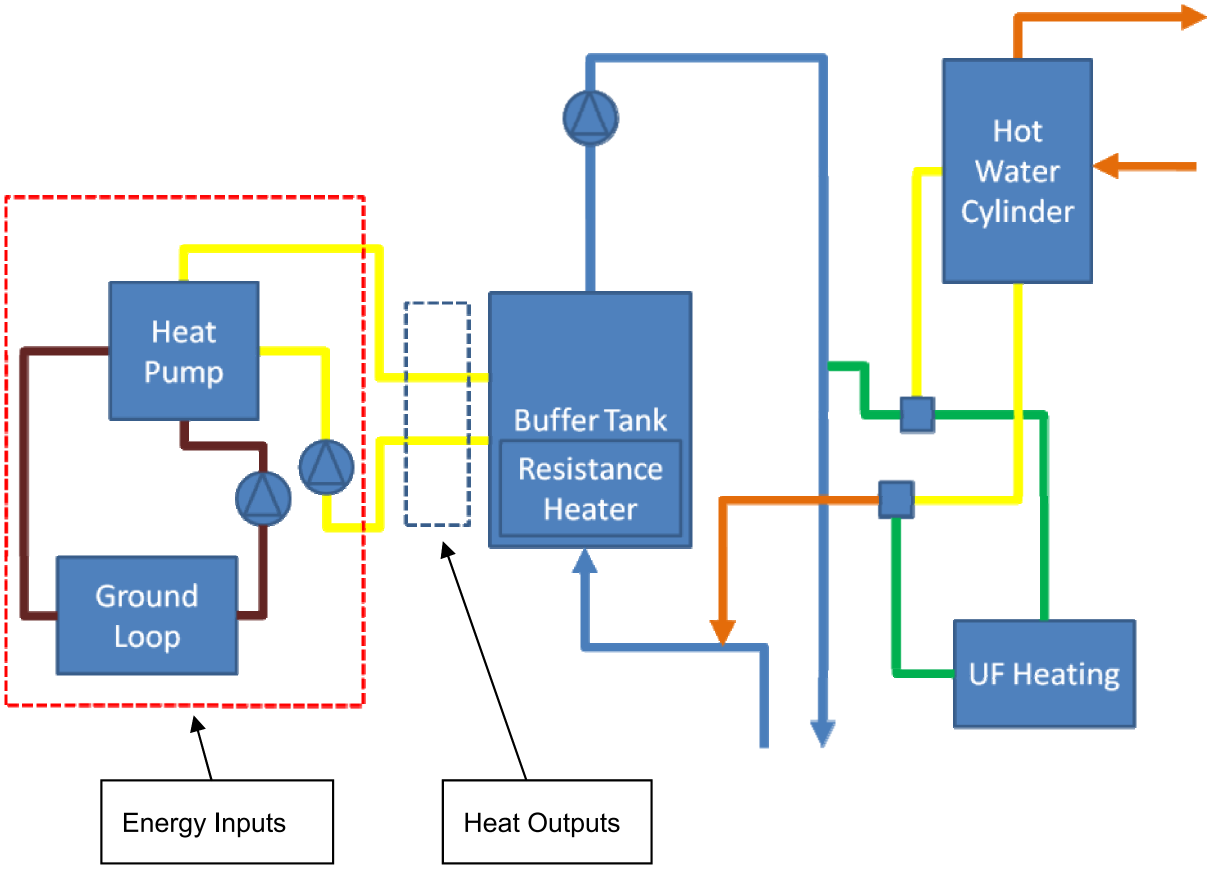


Figure 115 – Heat Pump System Boundary at Elm Tree Mews – System CoP

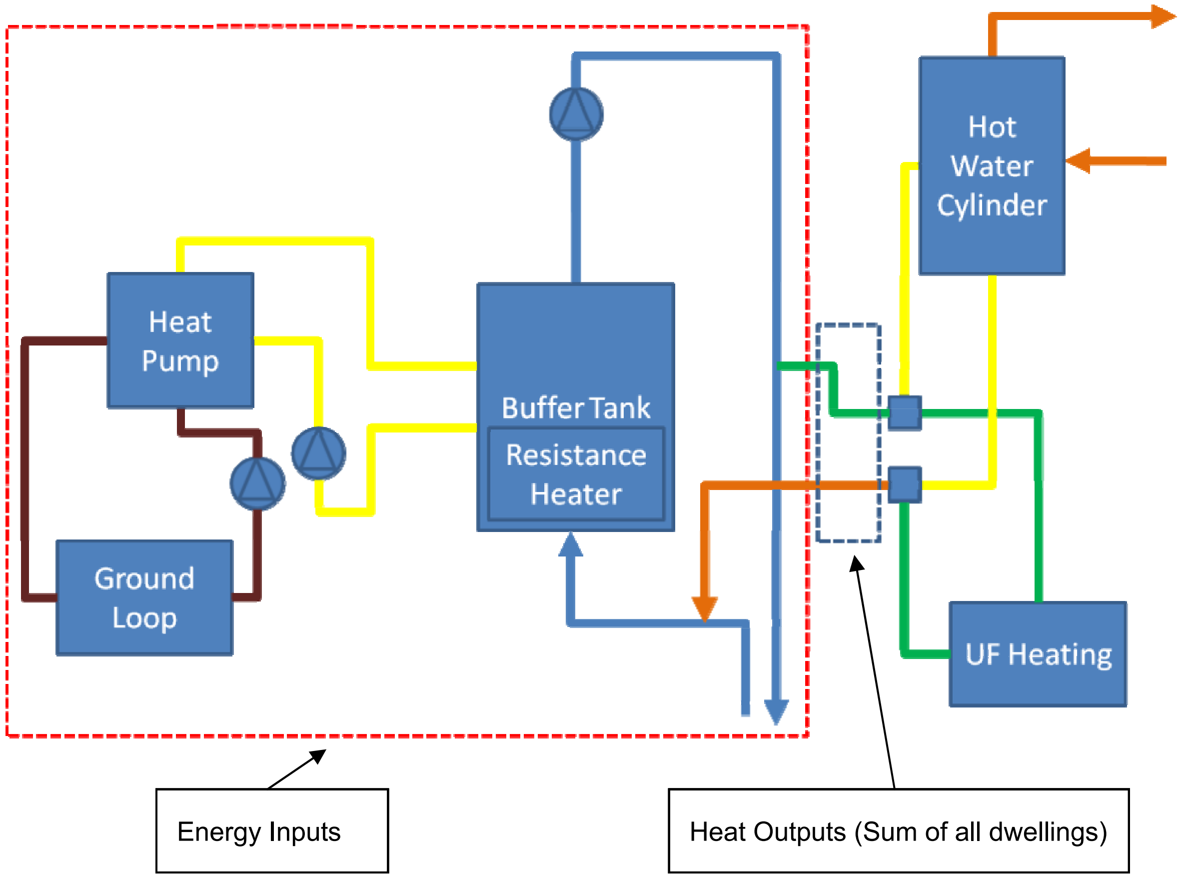


Figure 116 – Typical System Boundary – EST Heat Pump Field Trial (Installation in Yorkshire)

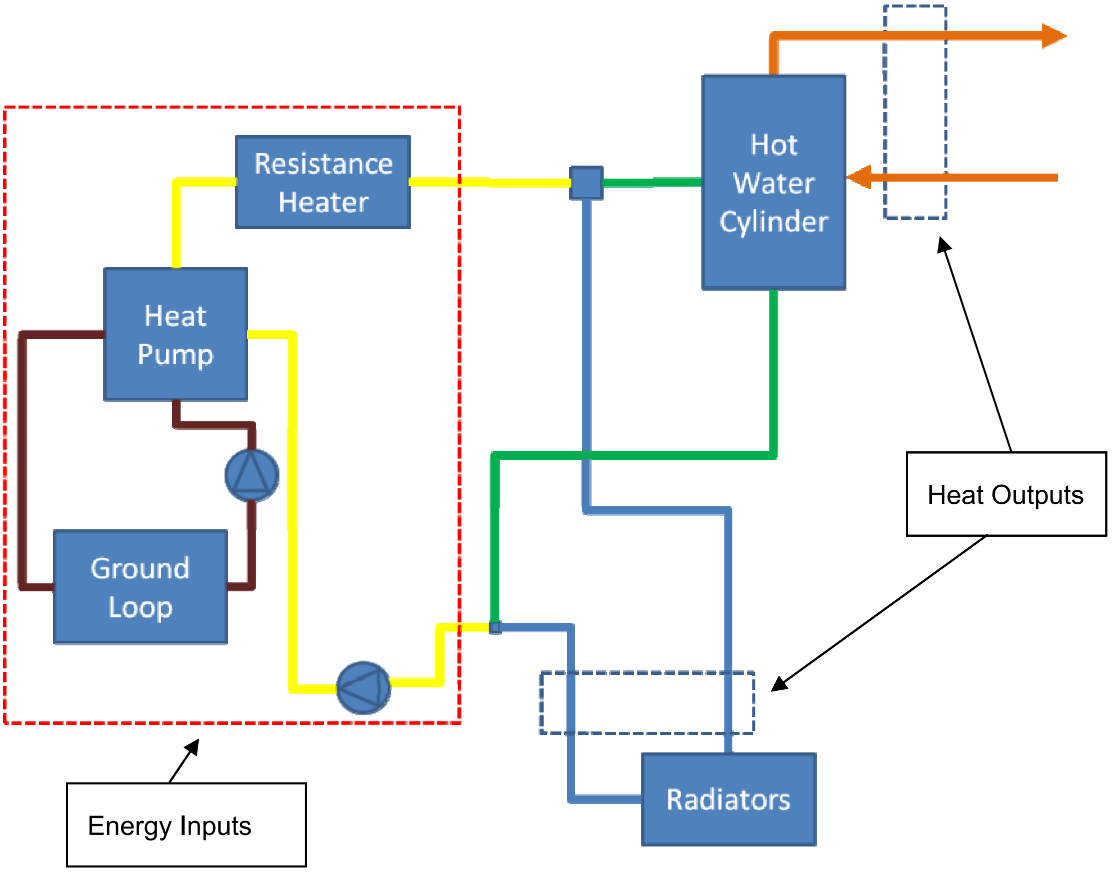
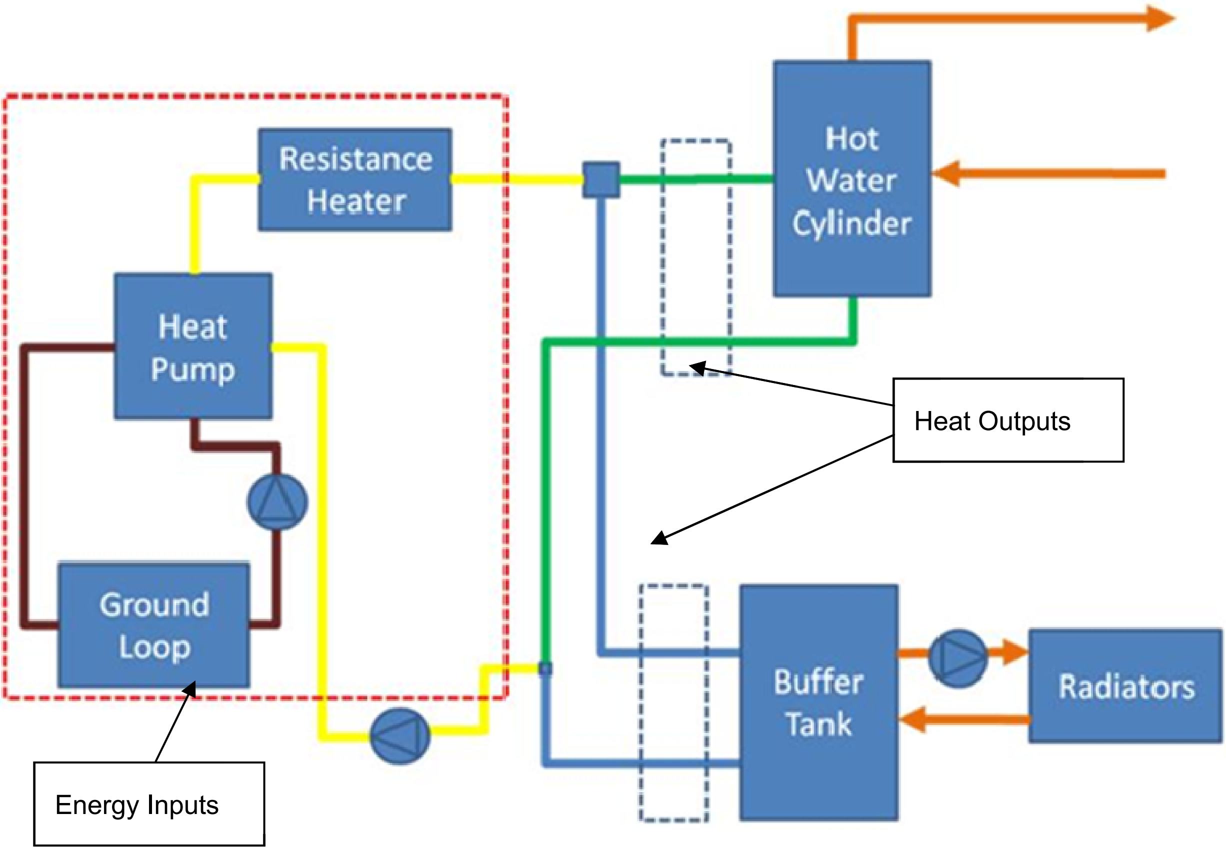


Figure 117 – Typical System Boundary – Frauenhofer ISE Heat Pump Field Trial (after Russ 2009)



187 It can be seen that there are some significant differences in the system boundaries for the various field trials. Of particular note is the use in the EST project of data from the heat output from the hot water cylinder as opposed to the heat input to the cylinder (see Figure 116). The consequence of this is that the EST trial CoP will include the effect of storage losses and will therefore be influenced not just by the performance of the system but also by the way that the householders use the stored hot water. Such potential variations between definitions in CoP between different trials and energy models suggests that the most prudent approach in designing any future monitoring programmes for heat pumps (or other energy systems) would be to include sufficient measurements of the various energy inputs and outputs at different points in the system so that it would be possible to disaggregate the data in a number of ways so as to calculate a range of different CoP numbers. For example, it may be that the heat loss from the hot water cylinders is an important parameter. In such a case it would be possible to calculate the heat loss by measuring the temperature decay rates of the stored water. If this was done for a range of mean cylinder temperatures then it is possible to develop a set heat loss curves such as those shown in Figure 118 and Figure 119 from houses D and F at Elm Tree Mews.

Figure 118 – Elm Tree Mews House D Cylinder Heat Loss vs. Mean Cylinder Temperature

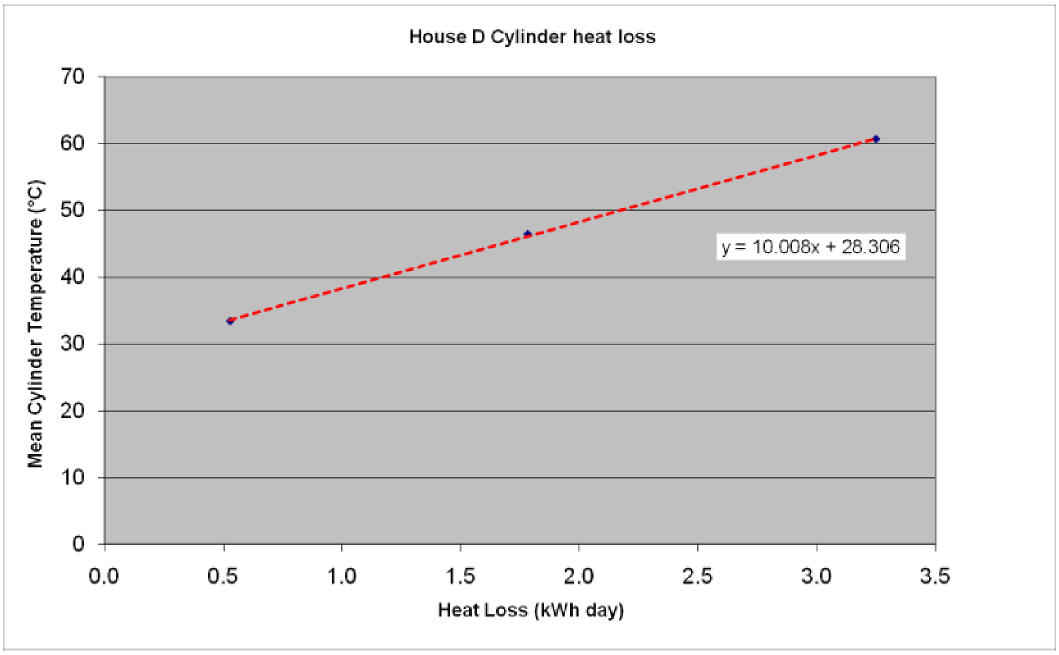
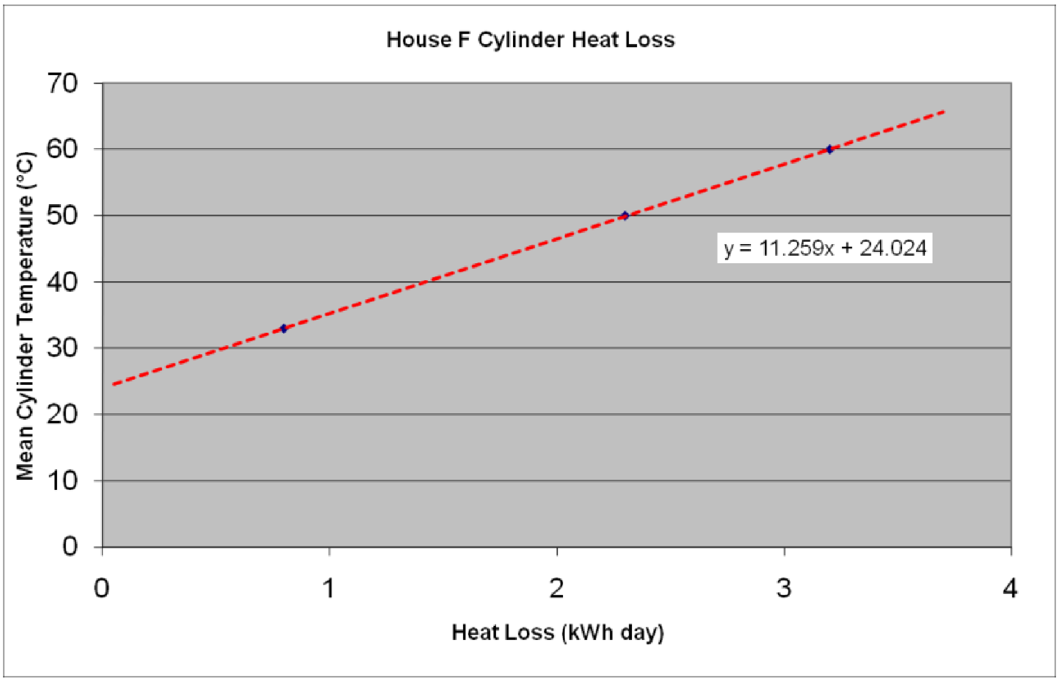


Figure 119 – Elm Tree Mews House D Cylinder Heat Loss vs. Mean Cylinder Temperature



188 It is recommended that the following parameters are measured in any future heat pump trials:

a) Total electricity consumption of the heat pump unit including compressors, pumps, controls and electrical resistance heaters.

b) Electricity consumption of all individual circulation pumps including ground loop pump, hot-side pump and any additional circulation pumps on the heating circuit. This may be difficult to do if the pumps are integrated into the heat pump unit but it is critical that the various pumps energies are measured wherever possible.

c) Electricity consumption of all individual electrical immersion heater elements whether in the heat pump unit, hot water storage tanks or buffer vessels.

d) Total heat output from the main heat pump system before any split between heating and hot water. The heat output should include any immersion heater input from in-line electrical heaters located inside the heat pump.

e) Heat output to the space heating circuit after any split between space heating and hot water.

f) Heat input to any hot water storage vessel.

g) Temperatures of any storage vessels such as hot water cylinders or buffer vessels, preferably at multiple points to determine the level of stratification.

h) Temperatures in all flow and return pipes to and from the heat pump (ground loop and heating loop) and in addition the flow and return temperatures to and from any buffer vessel.

i) Consumption of domestic water using flow metering on the cold supply to the heat storage vessel or cylinder.

j) It may also be useful to monitor the temperature of the heat sink used for the heat pump. So for example, if the heat pump is a ground source heat pump, then this would require temperature sensors in the ground.

k) In order to be truly effective, any trial of the efficiency of heat pumps, or indeed any other heating system, should be part of a wider study that investigates the performance of all other aspects of the building in-use.

Social Survey

189 A key focus of the study has been concerned with the performance of the dwellings following occupation by the residents. The in-use monitoring of energy and the heating and hot water systems has shown that the performance of the various energy systems in place in the dwellings has been influenced to some degree by the residents using them, highlighting the importance of taking the relationship between the residents and the systems seriously. This section provides a more discursive examination of this relationship and considers what this means for policy and practice in low carbon housing supply. The discussion is based on feedback from residents obtained from a series of semi-structured interviews that took place at the end of the monitoring period. The interview protocol is given in Appendix 3. The demographic makeup of the five households is described in Table 55.

Table 55 – Description of Monitored Households

Dwelling Code	House Type	Occupancy Level	Household Type	Employed?	Number of children under 16	Member of household with a disability?
A	Mid terrace	4 + 1 dog	Family	No	2	Yes
B	Mid terrace	5	Family	No	3	No
C	Flat	1 (Intermittent occupation)	Single	Full time	n/a	No
D	Mid terrace	3 + 1 cat	Single Parent Family	Part time	2	No
E	Flat	1	Single	Full time	n/a	No

190 Figure 120 illustrates the four key themes that can be drawn out from the analysis of the quantitative data and the qualitative interviews. These themes are “design and resident needs”,

"engaging with new technologies", "knowledge and confidence", and "affordability". As the diagram suggests, these themes are not mutually exclusive and tend to be interconnected. In addition, the former two themes are more clearly measured, whilst the latter two are less tangible though none the less important, and highlight the problems of understanding this complex relationship between a structure and the way it interacts with human behaviour in all its facets.

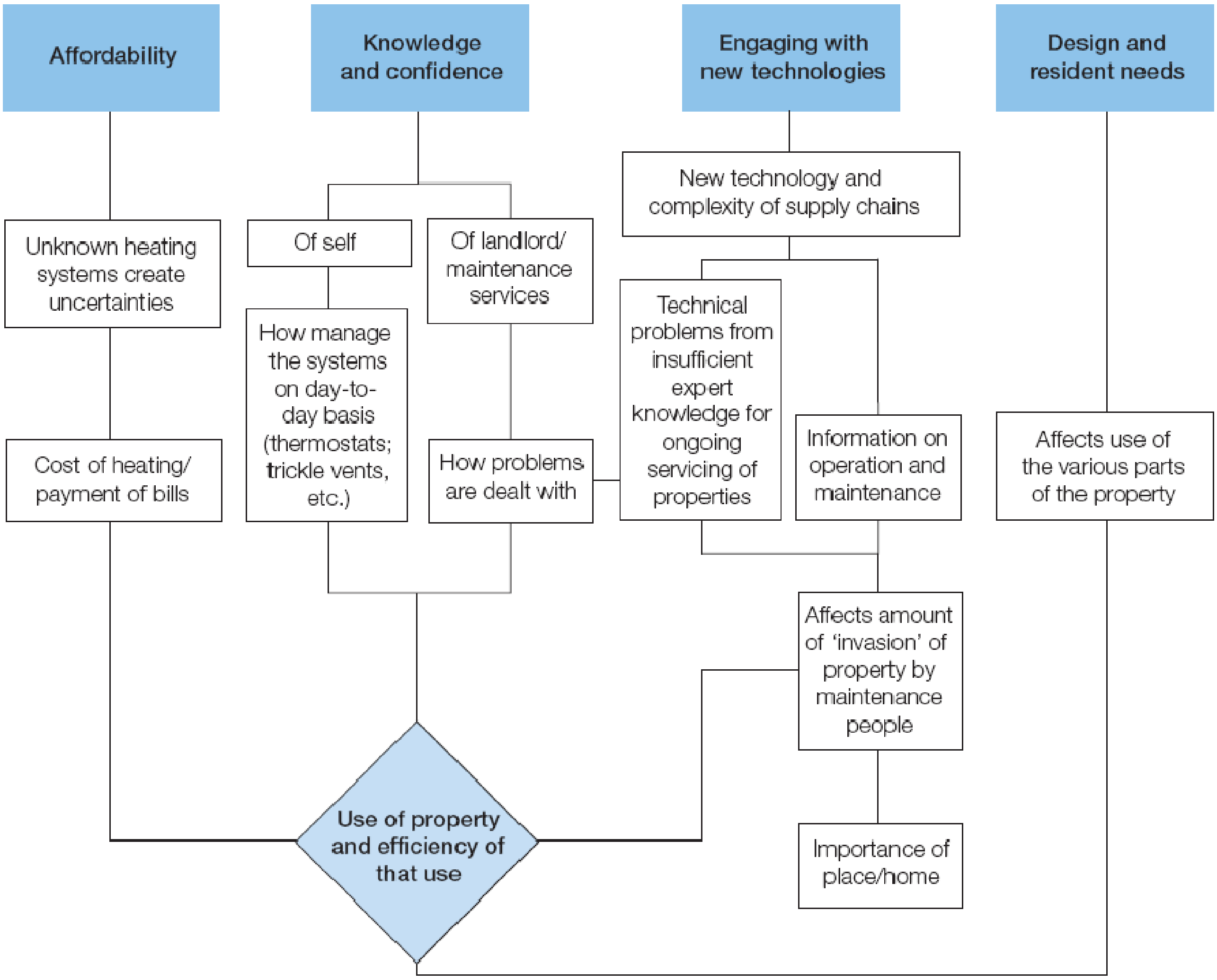
Design and Resident Needs

191 Fundamentally, the success of any property design relates to how it affects the lived experiences of those who occupy it. Indeed, this is less about the aesthetic or ecological value, although this may form a key factor in the initial decision to purchase or rent, but is more about its utility value; how it works for any given household at that stage of their lives. The critical concern about any lifetime home is that this design will accommodate the changes in lifestyle over time and still provide the same utility value needed by the household.

192 For example, using the loft space to provide additional living space was an interesting design feature, but in practice removed valuable storage space. This lack of storage space was a common complaint from the residents, and was particularly an issue for families as one female respondent pointed out,

"The other house had a loft, an attic, so, I mean we could put all our stuff up there, where as this one doesn't have any of that…. once we've got rid of some things it's somebody's birthday and we're back to square one again."

Figure 120 – Key Themes Arising from Social Survey



193 Similarly, the usefulness of the winter garden space[11], which is illustrated in Figure 121, was questioned by the residents of the mid-terraced properties. As one male tenant pointed out:

"You can't use it because there is no heating in it. We just use it as a dumping bin at the moment because you can't sit in it. You can't use it as a conservatory sort of thing. There's not heating in it. And it takes up [space], and the gardens very small anyway. It takes up a massive lump of the garden... If they came in and said, "We're asking people, would you have that or would you not?" I would say 'Knock it down. Today'."

194 Another resident pointed out that the winter garden would be used more if the temperature was higher. Indeed, he noted that it might be used for family dining, which in their property they don't have anywhere for at the moment. However, the solution that the resident has adopted is less than ideal in an eco-home:

"We have got a little kilowatt heater that we got over the winter and it might be that we use that to warm it up in there before we have dinner and then we can use it"

195 Spaces and design have to work for those who live in them otherwise the residents will adopt solutions that often negate the positive effects that the designers have gone to great lengths to provide such as heat and insulation. It is worth reminding ourselves that sustainability is a human conservation term and this is particularly pertinent when contemplating the homes we create. They must provide a living space that is sustainable in terms of their usage as well as their construction and appliances; if due care is not taken then all the effort to preserve heat and minimise energy use will be to little avail.

196 For example, the residents felt that they did not have a suitable inside space in which to dry clothes on wet days or during the winter, and this was exacerbated by the lack of radiators which they were used to hanging clothes over to dry in previous homes. Indeed, the main use of the winter garden (apart from as a general storage area) was as a drying area, with the residents putting up clothes horses to dry clothes. As one resident put it:

"…we're supposed to be saving energy but we have no way of drying clothes now so we have to have a tumble dryer. Because in the other house we had radiators so in the winter time the big things went in front of the radiator to dry your clothes. We can't do that here. So it's all defeated itself. The saving that you were getting there you're now losing because you've got the tumble dryer…"

197 This is a key need for households with children who need to do a wash each day compared to the single person households who were washing once a week. The concern then about access to drying spaces is a significant one when families are expected to be able to dry a wash each day throughout the year.

198 Households will adopt coping strategies to resolve problems and these are not always appropriate in terms of energy consumption: *"A tumble dryer is something we've been thinking of getting just because it would be so handy. And I know last winter there were times when it took quite a while for stuff to dry."* (Male resident with a family)

---

[11] A winter garden is a type of conservatory normally attached to the south facing façade of a building and designed to act as a buffer zone with potential for passive storage of solar energy. This type of feature is also sometimes called a sun space. The winter garden at Elm Tree Mews would be expected to provide some energy benefits in terms of reduced heat loss from the south facing wall on sunny days during the heating season. Although the walls of the winter garden are insulated and the glazing is of the same specification as the rest of the dwelling, the space is considered to be outside the thermal envelope and no provision was made for heating of the space using the under floor heating system. The patio doors between the winter garden and the living room are classed as external elements and are therefore also the same specification as the rest of the glazing. The nature of the site, which is over shaded by a tree belt on the boundary and a high wall, reduces the availability of solar energy in the winter and the lack of heating may make it a difficult space to use during the winter months, especially on cloudy days.

Figure 121 – Winter Garden on South Facade.

Winter Garden

Floor plan

Engaging with New Technologies

199 To a certain extent, many of the concerns raised in the qualitative interviews were the type that could be applied to any form of housing. However, critically low carbon housing of this sort introduces residents to a new set of systems for which they are unlikely to have any experiential knowledge to draw on as a guide.

200 In the case of one Elm Tree Mews resident, feedback indicated that the operation of the heating and hot water controls was very confusing. The potential confusion is demonstrated in Figure 122 which shows the four main heating controllers in the dwellings, all of which have different displays and approaches to their operation. Residents need to feel that they are in control of their property and can ‘manage it’ on a day-to-day basis. This lack of clarity reduces this sense of control and their confidence and contentment in the property. In terms of the property’s performance it is more likely to result in residents using the properties less effectively. Among residents, there were obvious concerns about the lack of technical knowledge of how things function and what to do to put them right, as one male tenant suggested,

“I think what they should’ve done was got a little patch of ground somewhere, built one, tested it …put people in it that were willing to, maybe free, just for the sake of testing it…then get their reaction of how they felt about it. But instead, they’ve moved us all in and everything is going pear shaped.”

201 This system has been further complicated by the thermostatic controls which are the only part of the heating system which has the potential appearance of normality. Since the operation of the heating and hot water controls is very confusing several of the residents used the thermostats to adjust the room/property temperature in preference to having the timer set to come on and off. This is clearly similar to many households more generally providing the potential for some form of understanding among residents. However, the thermostats themselves have been an added source of concern to the residents, since the controls which appear in most rooms in each property do not have any numbers on them so that determining where 20 °C is on the dial is left to guesswork (see Figure 123). This has led to unnecessary frustrations. As one tenant’s discussions with a plumber who had come on site indicates:

*“The plumber came and he says to me well we work them [the heating timer] on these hours and if you just set them [the thermostats] all at 20˚. So that if your house is at 20 ˚ then your heating will go off and it will stay off; if it goes lower than that the heating will come on. I said “Well you show me where **** 20 ˚ is then and I will”, Then he looked at [the thermostat] and went “Ooh well I think it’s about there.” So I‘ve got it just set, but it could be 30 ˚; I don’t know.”*

Figure 122 – Heating System Controls

202 Crucially, the heating and hot water system was complex enough without seemingly simple technology such as a thermostat being difficult to understand and therefore to adjust. It also raises a more fundamental point about why such controls are used more generally in the construction industry when they are so clearly inappropriate for guiding residents on the internal temperatures of their dwellings. In the case of the room thermostats at Elm Tree Mews, the housing team at JRHT provided a description of the temperature scale of thermostats in the household information pack given to the residents (JRHT 2008).[12]

Figure 123 – Room Thermostat Dial at Elm Tree Mews

---

[12] The scale on the room thermostats ranges from a minimum of 5°C to a maximum of 30°C (Uponor, 2007)

Knowledge and Confidence

203 Being in control is important to people and their sense of wellbeing. 'Home' is the site where people can feel in control of their space (Seamon, 1979; Cresswell, 2004) and when this control is disrupted it is likely to have an impact on how rooted and content they feel with the property. Having the knowledge and confidence to make use of the dwelling in terms of heating, energy and ventilation affects your control over the internal comfort of the dwellings. With rented properties this confidence is not only in your own understanding of the heat and energy systems, but in the capability of the landlord and their maintenance services to deal with this new technology correctly.

204 Mention has already been made about the variation in the heat and ventilation of the different dwellings, but to what extent does this relate to resident needs and desires and how much is it to do with lack of knowledge and confidence of using the systems? Clearly, to tease out such relationships requires purposive testing of this on a micro scale, and beyond the scope even of this detailed study. However, there are things that can be said broadly about this relationship that suggest that such a micro study might be worthwhile.

205 For example, knowledge and understanding of the heating system appears to affect how confidently residents use the systems and, as might be expected, how effectively they use them. An example of this is the thermostatic controls in the dwellings. In a couple of cases the thermostats were left by residents or were only changed in response to the research team or the maintenance people suggesting a change be made.

"It's been okay,… because I didn't know how far to turn them, up without it costing me a fortune…. so I left them. It was warm, but it could've been warmer, but I didn't know what to do so I just left them and we found that we marched through. I'm sure I could've turned them up, but I daren't because I didn't know how high I was turning them." (Female resident with family)

206 Whilst in another case this lack of knowledge and understanding has led a resident to have his downstairs heating extremely high:

"What I tend to do is I tend to change the thermostat on the unit itself the main one saying what temperature I want it at, …If I change these thermostats downstairs …I feel it's like it helps turn the heating off quicker. Although that's not a problem downstairs, there's still times when downstairs is nice and warm, we still want the heating on up stairs. So I tend to keep the thermostats on the walls as they are quite high, trying to help, especially during the winter to get it nice and warm up stairs. …I have it set at 27, …I have it set at that to try a get it to get hot quicker." (Male resident with family)

207 Similarly in terms of ventilation, several residents were unaware of the trickle vents and how they worked, as a result they had not been used: "*I didn't know what they were so I thought, I'm not touching them."* (Male resident with a family) Instead windows were opened when the dwellings got too hot, rather than a more measured ventilation of the properties which the trickle vents were designed to provide.

208 Finally, the complexity of this relationship between knowledge and understanding is brought home when the need to incorporate housing association service and maintenance staff is required. Such involvement means that not only is the control of ones property passed onto a third party to resolve an issue, but lack of knowledge and understanding among the maintenance staff mean that this 'intrusion' into the private space of the home is increased as the problem reoccurs. This can affect how residents feel about their 'home' and how they subsequently report problems.

209 A good example of how this intrusion has an effect on the way residents feel about the properties is the showers on the second floor. The doors to the shower cubicle in the en-suite bathrooms in the houses and duplex flat were a source of bewilderment and frustration to the residents. The showers were designed to be accessible for those with a disability and consequently the shower doors were of half height (see Figure 124).

210 However, the householders all noted that the showers leaked and asked for the doors to be replaced. However, it took a number of visits across a long period of time for the problem to be resolved because the type of shower unit being used was innovative but not functioning properly. The effect on residents was one of frustration as one resident noted,

*"Four months it took them to get that [fixed]. We couldn't use that shower for four months. Now I don't care who you are. Now that is ridiculous. And in the end after four months, they suddenly decided, that they would put a normal shower cubicle in. So we said to them, why didn't you just do that in the *** first place?" (Male resident with a family).*

Figure 124 – Shower in En-suite Bathroom

Affordability

211 Linked very closely to this idea of knowledge and confidence is that of affordability. If low carbon housing is to provide dwellings that offer low income households an affordable roof over their heads then it has to be clear what energy savings can be made and how systems can be run to maximise this efficiency. Otherwise, lack of understanding of how expensive these hot water and heating systems are can lead to uncertainties, which in turn will affect how residents use the systems. As noted previously, how people use a property relates both to their personal circumstances and their understanding of the property.

212 Residents on the whole have been really pleased with the low heating bills that they have been charged with and, as noted earlier the low energy bills are a really positive outcome for this set of dwellings, as one happy tenant observed: *"When we first moved, we got a payment card for them to help keep track of payments and stuff and I'd go down and I say "Can I have £1.26 on this?" and the guy looks at me as if he hasn't heard me right."* (Female resident with a family).

213 Although there were concerns about the electricity bills in some cases *"So £60 to their [her parents] £110, or however much, seems a bit steep because they're using a lot of things every day. And especially when theirs isn't a house built as such as this."* (Single female resident) Indeed, low income households have to keep a tight reign on their finances particularly if they are on benefits and this can mean that even with the potentially low bills they still feel they cannot maintain their property at a comfortable level: *"There's no heating on in here and that's because I can get away with out it being on. But realistically it should be on but I daren't put it on because I don't want to have to pay for it. I'm sorry, that's just how it is."* (Male resident on benefits)

214 Several residents also showed concern about the problems of insufficient hot water and how this can lead to a lot of unnecessary energy and water wastage:

"I've had quite a few cold baths. Well nearly-cold baths. And I suppose even though they've put an immersion heater on, and there's a timer apparently on it, I keep switching it off cause I kind of feel it's the complete opposite to what they [the dwellings] were originally built for." (Single female resident)

*"… it's meant to be eco and save water; but it can take a *** gallon to get the hot water to come through. So you've wasted all that water in the shower just waiting for it to come through. Where as an electric shower heats it {snap of fingers} there and then and only there and then the immersion heater, if you leave it on, will heat the water to a certain point, then leave stop and then heat it up again. So there's things in the house that have defeated the object."* (Male resident)

215 Overall, the affordability of these properties is critical since this is the tangible outcome for residents; it is the one area that they can see measurable differences between this type of housing and traditional structures. This needs to work for all income levels, but particularly for those on low incomes and benefits, if it is to provide a viable option for social housing providers in the future.

Understanding the Relationship

216 The relationship that residents have with their properties is highly complex, and understanding this relationship is critical if we are to design and produce low carbon housing that really works for a range of households now and over their lifetime in the properties.

217 It seems appropriate to end this section on the resident experience with a useful quotation from one of the residents about where all this should be taking us:

"It's not just that I've cut down on the amount of energy that I use; I try to plan ways of making do with less. And I think that's what we need to do. We don't just need to cut down a little bit, turn down our heating by one degree, recycle a bit more. We need to reassess how we are living our lives and create a plan." (Female Resident)

218 What is being suggested here is not simply people occupying better housing, but actually a qualitative shift in their attitudes and behaviour. As the chapter has shown, people use their homes in a variety of ways and this in turn affects the overall performance of the dwellings. Yet, understanding this complex relationship is of paramount importance since as one resident clearly put it:

"I think you can soon be made to feel disenchanted with the whole thing. You don't think what's the point but you do feel that it can easily become a façade where it looks good but you're not actually putting things into practice and they're not working so is it doing any good. And I think then you become a bit, …I suppose you just feel disillusioned a bit." (Female resident)

219 The findings from the social survey suggest that, if we are to tackle the issues of living in low carbon housing, then there are two key concerns that need to be addressed. The first of these is the need to understand the complex relationship between property performance (in terms of heating, ventilation and energy) and the people who live in the properties through careful systematic longitudinal monitoring at a micro scale to see whether designs stand up in the face of resident use and need. Second, we need a corresponding understanding of the extent to which information and advice affect the way people use their properties and make informed decisions about their energy consumption. The Elm Tree Mews study ahas indicated that the level of information that is given about how to best ventilate, heat or manage energy within a home affects how people understand how properties function and what behaviours are likely to be most effective for reducing their carbon footprint.

Specific Performance Issues

220 As would be expected, a range of specific performance issues were raised by the residents during the final interviews. These concerned not just the performance of the heating and hot water systems but also other aspects of dwelling performance such as noise, space, storage and general amenity. These issues were fed back by the research team directly to the housing team at JRHT. The main issues can be summarised as follows:

221 **Hot Water** – All residents highlighted at least some concerns about the availability and temperature of the hot water. Although some residents said they are generally satisfied, most were not. The residents said that most of the main problems occurred during the winter months. This would be expected due to the reduced solar input to the cylinders and would depend upon the hot water consumption and usage patterns. Those households with higher usage seemed to be reporting the most problems. It is clear that the residents have had to adapt their behaviour to make best use of what they have got – e.g. having showers rather than baths. Examples of this adaptive behaviour quoted by the residents are as follows:

a) One house mentioned having to use the kettle to provide hot water for washing up as there was insufficient available from the cylinder

b) One house mentioned not allowing the children to have showers in the morning as there was not enough water in the morning for more than one shower – the kids had to shower in the evening only.

c) One house mentioned timing their baths to match the availability from solar input on sunny days and in particular after the weekly pasteurisation cycle.

222 **Heating** – In general, space heating was not perceived as a major problem. However, there were some concerns about control of heat and the usability of the control systems.

a) All the occupants of the terraced houses complained about the downstairs toilet and hall landing being cold. This was confirmed by the temperature measurements taken during the monitoring programme which show that the toilet can be 4 or 5 degrees colder than the rest of the ground floor. When asked how they set the thermostat for the toilet, the residents all responded with "what thermostat?" Physical checks by the research team confirmed that there was no thermostat in the toilet or ground floor hallway. The closest thermostat was in the living room next to the main heating controller. Heat loss calculations showed that the underfloor heating would be capable of heating the toilet and hall, even allowing for the extra heat loss from the party wall bypass. Further discussions with the developer revealed that the thermostat in the living room should have been fitted in the hallway. This has since been rectified.

b) The residents of two houses complained that it was sometimes difficult to heat the upstairs rooms. One of the residents said that, even with the thermostats upstairs on full (set at 30°C) and the main heating controller set at 27°C, it was still not possible to achieve the desired level of comfort in the bedrooms. In this particular case, the temperature difference between living room and the upstairs was confirmed by the mean monitored data (living room ~22°C and first floor bedroom ~17°C). It is likely that this problem is related the designed control strategy and the way that the main heating controller and room thermostats work. The main controller has its own thermostat setting, and if this temperature is satisfied then the two-valve to the communal heating main will close. The room thermostats are linked to the thermostatic valve controlling the manifolds to each zone. Therefore, even though the room thermostat may be calling for heat, if the thermostat on the main controller is at temperature, then heat will not be supplied to any of the heating zones.

c) All residents complained about the lack of numbers on the thermostat dials. The lack of any direct feedback on the temperature set point in each room does not allow them to make informed decisions about how they set the heating in the house other than the maximum temperature on the main controller and "low" "medium" or "high" on the thermostats.

d) One resident stated that they were still very cautious about using the heating due to concerns about cost. This is likely to stem from how different Elm Tree Mews is from a "normal" gas heated dwelling and a lack of confidence and familiarity with the system and its controls. Other factors that will be relevant would include the past experience of the resident in terms of energy costs combined with their current financial situation. Perhaps what are needed in this sort of situation is better feedback of how the system is performing and the relative cost of the heating and hot water provided.

e) One resident report uncontrollably high temperatures in the front 1st floor north facing bedroom but this room was not one of the ones being monitored so it was not possible to check this.

223 **Ventilation** – In general, the residents said they were happy with the air quality in the houses. There were a few ventilation issues raised by the residents that are worth noting.

a) All but one of the households said they were not aware of the window trickle vents and what they were used for, and had not touched them or altered their position since they had moved in. The one resident who did change the position of the trickle vents said they preferred them closed as they tended to be draughty.

b) One resident turned off the Ventaxia fans on the wet rooms at the isolator switch rather than let the fans turn on/off with the humidistat controllers. The reason given was the noise of the fans.

c) One resident mentioned mould issues in the en-suite bathroom. This was mostly a result of a leaking shower which was rectified during snagging. However, the same resident reported black mould on the window frames which may be an early indication of a lack of ventilation from the bathroom.

224 **Noise**

a) The biggest concern with regard to noise was the heat pump. The resident from one of the flats reported that the noise from the heat pump in the plant room adjacent was very audible, especially in the bedroom closest to the plant room. The resident said that this noise would sometimes affect sleeping patterns. It may be possible to alleviate this problem with better acoustic insulation of both the heat pump and the plant room.

b) Some residents complained about the noise from the circulation pump used for the pasteurisation cycle. This would be related to the fact that most residents have it timed to come on early in the morning and those sleeping in the bedroom(s) adjacent to the cylinder cupboard could potentially be affected if they were noise sensitive. It would of course be possible to change the timing of the pump if this was thought to be a significant problem.

c) The residents report very good internal sound insulation (i.e. from room to room, floor to floor).

d) No issues were reported about external noise.

225 **General Amenity and Other Issues**

a) All residents remarked about the lack of storage facilities. This is a common complaint in new housing in the UK.

b) The one household with specific disability/access requirements said there several problems relating to the layout of the house that made using the house difficult.

c) Several households complained about the lack of space to put a dining table in the downstairs living room area. The winter garden was found to be unsuitable for this purpose as it is unheated in the winter and it would be difficult to put a table in there anyway due to the space needed for the doors to open outwards.

d) The winter garden was generally used as a storage area or drying area for clothes. Several residents said that it was too cold in winter to be of use as a living space. Most residents would have preferred the winter garden to be have been heated and to be part of the living area.

e) One resident in one of the terraced houses said that they did not like their young children playing in the back garden due to the fact that they tried to swallow the gravel. They would have preferred a grassed surface.

f) One householder in one of the houses was concerned about the safety of the low sill on the window in the north facing first bedroom, saying that they thought it presented a potential risk of falling out if the window was left open.

g) One resident complained that the heated towel rails were ineffective. This is perhaps no surprise given that the flow temperature of the heating system varies between around 38 to 42°C. This could be resolved by installing electric towel rails instead but this would of course have an impact on both energy costs and carbon emissions.

h) There were no significant complaints about issues of summer overheating; although this should be considered along with the fact the external temperatures over the summer of 2009 were not exceptionally high. One resident did say that on some days they had to open the balcony doors in the bedroom in order to provide enough through ventilation in the evening to keep the temperatures down to an acceptable level.

i) All residents complained about the shower cubicles with the half-height shower doors saying that they leaked and that the showers were difficult to use with the shower curtains. They would rather have had a full height shower screen. As far as the research team is aware the original shower doors have since been replaced with a full height screen and door.

j) There are numerous unsightly black heat marks on the west facing windows in the ground floor flat. These are apparently inside the glazing cavity (probably on the low-E soft coating) and as such cannot be cleaned off. It is believed that these marks were caused by welding sparks landing on the window when the external fencing was installed adjacent to the windows.

Discussion and Recommendations

226 The fabric performance testing and site observations made at Elm Tree Mews give rise to a range of conclusions and recommendations with respect to the various design and construction processes that were used. To a large degree these conclusions correspond closely with those made by the Stamford Brook project (Wingfield, Bell, Miles-Shenton, South & Lowe, 2008) and highlight that many of these issues are systemic and deeply embedded in the culture and practices of the UK house building industry. These issues need to be addressed at a fundamental level if the housing industry in the UK is to deliver its intended energy, carbon and environmental performance targets over the next 10 years.

Airtightness

227 The results from airtightness testing at Elm Tree Mews were disappointing, but perhaps unsurprising given the low priority that airtightness measures have apparently been given in both the design and construction processes. The assessment of design data and documentation showed that there was no defined airtightness strategy, and that the target for air permeability was confused. The initial design airtightness target was 3 $m^3/h.m^2$, and this figure was used in the low carbon heating options report. However, in the later SAP calculations for the dwellings the air

permeability target was given as the building regulations maximum default value of 10 $m^3/h.m^2$. There was no clearly defined air barrier on any of the design drawings, no mention of any specific construction detailing for airtightness in any of the detailed specifications and no record of any training in the processes and techniques that would be required to achieve low levels of air permeability.

***Recommendation**: Dwellings design must have a clearly defined strategy for airtightness and a formal and transparent target for air permeability. This strategy must include a clearly designated and resolved air barrier in the design of all dwelling types, including all variations in detailing and elevational treatment. All drawings should show the location of the air barrier and were appropriate be annotated with additional information on specific airtightness measures such as sealing and taping. There should be a clear understanding of the airtightness strategy by the client, design and construction teams and subcontractors, and where necessary suitable training will need to be developed to disseminate the procedures needed to achieve the desired levels of airtightness. Routine pressure testing of dwellings should be undertaken throughout the period of construction in order to provide feedback on performance and to identify any issues that may arise. It is of particular importance that production control processes for each dwelling include pressurisation testing at the point at which the air barrier is complete and exposed. In this way defects can be readily identified and dealt with. This approach would carry considerable training benefits also.*

Ventilation

228 The ventilation strategy used at Elm Tree Mews was for a naturally ventilated system supported with trickle vents in the windows, extract ventilation fans in the bathrooms and toilets and an extract hood over the hob in the kitchen. The extract vents in the toilet and bathroom are fitted with humidistat controllers with a manual override. The concept design in the original competition submission was shown with a passive stack ventilation system but this did not make it to the final design as-built due to cost saving measures. The final designed ventilation system was appropriate for the actual airtightness of the dwellings as constructed, but this appears to be fortuitous rather that as part of any deliberate airtightness-ventilation design strategy. Indeed, the timber framing system used should be capable of airtightness levels of less than 3 $m^3/h.m^2$ and this level could have been achieved purely by chance. If this had been the case, then there would have likely been problems with internal air quality, internal humidity levels and condensation issues without a whole house mechanical ventilation system.

***Recommendation**: The design of the ventilation system needs to be considered in conjunction with the airtightness strategy at an early stage in the design process. The energy requirements at for dwellings that comply with level 4 of the code for sustainable homes or better will require very low levels of air permeability, perhaps as low as $1m^3/h.m^2$. If this is the case then the ventilation strategy will almost certainly be one based on mechanical ventilation with heat recovery. Any ventilation strategy should also consider the possible requirements to reduce the risk of summer overheating. This might for example include an option for overnight purge ventilation combined with exposed thermal mass. The possible requirement for a mechanical ventilation system would place additional requirements for dwelling design to ensure that duct runs and space provision for fans and vents are an integral part of the building design.*

Fabric Design and Performance

229 The design of the thermal envelope at Elm Tree Mews was complex, both geometrically and structurally. Geometric complexity presents considerable difficulties for detailed design, particularly with respect to maintaining air barrier continuity, minimising thermal bridging and avoiding thermal bypasses. Geometric complexity also increases the amount of attention and design rigour required to ensure robust on-site construction (buildability). The structural issues in I-beam wall design, particularly over three or more storeys require very careful thought and there needs to be a good understanding between the structural engineer and the fabric designer of the interrelationships involved. The structural design at Elm Tree Mews could in theory have been optimised to reduce the amount of solid timber within the panels, but the key problem with the wall design was the failure of the design team to appreciate the impact of additional timber on heat loss from the fabric (U-values and Ψ values). Any type of design in which structural elements penetrate the insulation layer will always be prone to the sort of problems observed. As a guiding principle such penetrations should be minimised and fully accounted for. One way of tackling the problem could have been to use a design with a continuous insulation layer that was external (fully or partially) to the main structure. Such an approach can also reduce thermal bridging at junctions. It is possible that a U-value of 0.18 W/m^2K for the wall could have been achieved more reliably with some element of external insulation, potentially with no increase in overall wall thickness.

***Recommendation**: The issues relating to the design of the thermal envelope must be addressed very early in the design process with realistic estimates of U-value and thermal bridging effects. This is crucial since there are compromises that may have to be made between thermal performance and aesthetic performance. Design culture is wont to minimise the problems of detailed design at concept and master planning stage. It is crucial that this does not happen since, in the end, the only compromise that is likely is in detailed design and thermal performance. Such compromises in detailed design may go unnoticed until occupation, by which time it is too late.*

Process, Production and Quality Control

230 It is always tempting to dismiss construction problems such as those experienced at Elm Tree Mews as a one-off and of particular contractual interest only. Although this may be reasonable to some extent, it is important to identify the underlying issues that are raised. The story of Elm Tree Mews, as discernable from the limited design and construction retrospective work that was carried out, would suggest that the issues relate to a generally low level of understanding of thermal design and performance principles at all levels and at all stages in the process. The wall design is an interesting example of design quality control. The panel manufacturer quotes a nominal U-value; the designer believes it and passes it onto the services designer; who then calculates the dwelling emissions rate using a SAP worksheet which is based on the initial unchecked and unverified value. The result is underperformance. Site construction problems resulted from a culture in which the detailed planning of the sequence of timber panel erection put the integrity of the panels at risk of damage from the weather, and an erection team inexperienced in the particular roofing system further compounded some of the problems.

231 In common with the conclusions from the Stamford Brook field trial (Wingfield et al. 2008), these findings are largely indicative of a set of underlying systems issues relating to process management and control, all of which impact on thermal performance. Many of the issues are cultural and relate to such things as education and training, team communications, design and construction planning and sequencing. To a large extent the story at Elm Tree Mews is one in which a largely unfamiliar construction method has been parachuted in as a “solution” to low carbon housing, but applied in an existing cultural and organisational environment that is not capable of delivering the required level of performance in a robust way. It amounts to new technology applied in old ways. Such an approach is not likely to succeed reliably, especially when applied to mass housing.

***Recommendation**: The issues referred to here are deep seated and difficult to address in a single development. Improvements to both culture and process are required across the industry in both design and construction. Designers and constructors also need to develop methods and techniques to enable them to measure and verify performance at all stages in the process.*

Cost Engineering and Product Substitution

232 The substitution of components and materials during the cost engineering process can have a significant detrimental effect on realised performance if the potential impact of such changes are either not fully understood or not properly considered. The best example of this occurring at Elm Tree Mews is with the windows. The windows originally specified by the architect were Danish Rationel timber frame double glazed units (which were also the windows specified and used at Stamford Brook – see Wingfield et al. 2008). With argon fill and very low emissivity coating, these windows have a whole window U-value of 1.5 W/m^{2}K. With insulated edge spacers the whole window U-value for these Rationel double glazed windows can be as low as 1.3 W/m^{2}K. Due to cost considerations the specification was changed to locally sourced timber framed windows with ostensibly the same low-E coating and argon fill specification as the Rationel windows. However, due to confusion between the definition of whole window U-value and centre pane U-value, the windows actually installed did not meet the required specification. The windows used actually had a whole window U-value of around 2.0 W/m^{2}K and a centre pane U-value of 1.5 W/m^{2}K. This change would increase carbon emissions for the end terrace house by around 0.8 kgCO$_2$/m^2 compared to one with windows with a whole window U-value of 1.5 W/m^{2}K. However, there are also other effects that need to be considered. There will be a greater risk of condensation on the alternative windows, especially at the window edges due to the aluminium edge spacer, and there will be more leakage around the frame seals as these appeared to be leakier than the Rationel window units observed by the Leeds Met research team at Stamford Brook (Wingfield et al. 2008). We also know that typical UK-manufactured trickle vents are leaky, even when in the closed position, when compared to Scandinavian trickle vents such as those used by Rationel. Again this was found to be the case at Elm Tree Mews where the trickle vents were shown to be a significant source of leakage during pressure testing. In comparison, pressure testing at Stamford Brook has shown the

Rationel trickle vents to be well sealed. There are also considerations of thermal comfort. Windows with higher U-values have colder surface temperatures with associated radiant temperature effects and also an increased risk of cold downdraughts which may be noticed by occupants in that certain positions in a room will feel cold and draughty. Such effects may be more noticeable at Elm Tree Mews which has an underfloor heating system and therefore there are no radiators located under the windows.

***Recommendation**: The cost engineering process should be designed to fully consider the effects and risks of any proposed changes in products, materials or processes on thermal performance, airtightness, ventilation, buildability, maintainability, condensation risk, thermal comfort and any other performance factors.*

Training

233 Training of the design and construction teams needs to take place throughout the development process so that problems can be minimised and any that do occur identified early and permanently resolved. The general lessons learned and the levels of performance actually achieved should be extracted and disseminated both at an organisational level and nationally and internationally so as to ensure that schemes such as Elm Tree Mews are able to influence the production of low carbon housing in general.

***Recommendation**: Initial training should be planned now and built into budgets. This should involve a review of existing proposals so that they can be used as training materials as well as using material from other sources such as Stamford Brook and the Passivhaus programme. Training should be continually reinforced, refreshed and updated to ensure that messages are not forgotten and that all teams are able to learn from each other as work progresses.*

Control of Design Changes

234 Several design changes were made at Elm Tree Mews during the course of the construction programme. The consequential impacts of some of these changes were not always fully understood by the design and construction teams. The best examples of this were the changes made to the bay windows in the ground floor flat and duplex flat. This design change was driven by the need to increase the amount of kitchen workspace and cupboard space. The chosen solution was to install a worktop and floor cupboards in the bay window area. This also required changes to the bottom half of the bay windows in order to fix the cupboards. It was decided to paint the inside of the windows black and to cover the inside of the window with a layer of chipboard, with a gap between the chipboard and inside window surface. This was observed by the research team after the changes had been implemented. It was realised by the research team that the design as used could potentially give rise to problems of interstitial condensation between the chipboard and window, which if left unresolved would have increased the risk of mould growth. These concerns were confirmed by a condensation risk analysis calculation undertaken by the research team. The design and construction teams were made aware of the issue and the decision was made to remove the bottom windows and replace them with an insulated panel which would mitigate the risk.

***Recommendation**: The design change process must be set up to fully consider the effects and risks of any proposed changes in design, products, materials or processes on thermal performance, airtightness, ventilation, buildability, maintainability, condensation risk, thermal comfort and any other important performance variables. Training of construction teams and sub-contractors should highlight the potential problems of uncontrolled ad-hoc design changes.*

Inspectability, Measurement and Compliance Checking

235 The issues at Elm Tree Mews with hidden timber in the external wall panels, slumped insulation in the wall and ceiling panels and misaligned structural members in the party wall panels were exacerbated because the closed panels did not make it possible to inspect or check compliance. One of the conclusions from the Stamford Brook project was that the various stages of the construction process should be designed to allow inspection and, for example, suggested that building in insulation batts during the construction of a masonry cavity wall was preferable to post-filling with blown insulation as it was much easier to check compliance. Similarly, where testing is feasible (particularly pressurisation testing), this should be programmed at appropriate stages so that any potential for underperformance can be identified and dealt with before it is too late. In addition, there is considerable benefit to be had from an off-line testing programme for those details that are crucial to performance and are expected to be repeated many times. The construction of prototype details and testing them would provide a very useful design and training tool.

***Recommendation**: Construction processes and detailing should be chosen on the basis of ease of inspection. The development of the required inspection methods and compliance checking protocols should be an integral part of the overall design process. A similar approach to measurement and testing should also be taken. As with training, the budget for the scheme should take into account the need for an enhanced inspection and testing process.*

Modelling of Energy Performance

236 The analysis of the final as-built worksheets for the SAP submissions for Elm Tree Mews showed that there were some errors and discrepancies in some of the input variables. These included such variables as the hot water cylinder volume (too large), the heat pump COP (did not take account of communal system losses), the roof surface area for the end terrace (too small) and the efficiency of the hot water energy input (different assumptions for different dwellings). Such variability in SAP calculations is not unusual and it would be expected that software with such a large number of inputs will always be prone to input errors. However, this does suggest that there needs to be a more rigorous process of checking both at the design stage and as part of the regulatory compliance regime. It may also be possible to develop SAP software that has some level of intelligent self checking and feedback built-in, although this would require significant development of the software. The sorts of errors observed in SAP would suggest that more complex energy models such as the Passive House Planning Package (PHPP, PHI 2007) would be prone to an even higher number of errors due to the higher number of inputs and variables in the model.

237 The lack of suitable design tools to model the system performance of the relatively complex heating system at Elm Tree Mews indicates that this is an area in the design process that could be improved. Such a model would need to take account of factors such as system interactions, variability in the timing of heat inputs and storage/distribution losses.

238 It should be noted that some of the weaknesses in SAP2005 model as related to thermal bypassing and thermal bridging have been addressed in the latest version SAP2009 (BRE 2010). The inputs into SAP2009 now include a requirement to account for potential heat losses from the thermal bypass caused by party wall cavities. The requirement for the calculation of losses from thermal bridging is also more rigorous in SAP2009 than was the case in SAP2005.

Feedback and Continuous Process Development

239 Low carbon housing developments such as Elm Tree Mews frequently involve a range of new materials & products, novel construction techniques and a range of processes that unfamiliar to most house designers, construction professionals and site tradesman. It is therefore inevitable that some mistakes will be made, especially during the early phases of the development. It is crucial that those lessons are captured and fed back into the design and construction process. It is also essential that data from performance measurements such as pressure tests, monitoring data, acoustic tests, ventilation tests, commissioning results and other site measurements are used to inform a process of continuous improvement in design, construction and in conjunction with the supply chain.

***Recommendation**: A formal procedure of continuous process development should be developed to ensure that the process and product improvement become an integral part of the overall design and construction process. A range of tools are available around which to form a framework for continuous process development, most of which are based on some form of PDCA cycle (**P**lan, **D**o, **C**heck, **A**ct). Our recommendations for inspection, measurement and testing will be crucial to the development of an effective feedback process.*

System Commissioning

240 The outcomes of the system commissioning procedures used at Elm Tree Mews were very variable. For example, the heat pump was commissioned in isolation from the rest of the communal system which had not been completed at the time. The commissioning of the solar hot water systems was not able to spot the problems with pipe kinks and control issues that were identified later during the monitoring programme. A range of problems and issues were also identified with various aspects of the communal heating and hot water systems both during and following installation. This suggests that the procedures used to commission the various systems were not sufficiently robust and that there were potential communication problems or training issues. Part of the problem will lie with the relative complexity of the heating system at Elm Tree Mews and the fact that several different subcontractors and heating engineers were working on different parts of the system requiring careful coordination of activities. The heating system at Elm Tree Mews is perhaps more akin to that in a non-domestic building. It may therefore have been more appropriate

to use some formal bedding-in and commissioning process along the lines of the "soft landings" approach developed by the team that led the PROBE studies (BSRIA 2009). The procedures for such an approach in a domestic environment would of course have to be different. The costs and time required to carry out this type of approach would also have to be factored in and planned for during the initial design stages of any project.

***Recommendation**: Formal procedures and methodologies are needed for commissioning of all building services including heating, hot water and ventilation systems. These must be well documented and communicated to all relevant members of the design and construction teams. Where systems are complex and interdependent, such as in the case of communal heating or where there are multiple heat sources, the commissioning process may require some form of initial bedding in period during which the system controls and settings can be monitored and adjusted to maximise performance and optimise efficiency.*

Construction Sequencing

241 The problems caused by the delay to the installation of the communal heat main pipe work until after the structure of the building had been completed illustrate the importance of getting the sequencing of the various construction activities correct. This requires careful and detailed planning at the design stage to identify the most efficient order for the different construction processes and to make sure that the appropriate materials and labour are available at the right time. The sequence and timing of the various individual sub-processes that form the whole construction process are critical to the final performance of the structure in terms of optimising airtightness, ensuring continuity of the insulation layer and minimising the potential for thermal bypasses. Problems with sequencing can occur as a result of poor planning of the construction process, lack of detailed design drawings or design advice, a lack of material or component supplies at the required times, a lack of appropriate trades people at required times, faults arising from the rectification of construction errors requiring rework or simply a lack of understanding by designers and site management teams of the optimum construction sequence for the different construction forms. This lack of understanding is reinforced by a failure to prototype complex and potentially tricky details.

***Recommendation**: The planning and design of construction processes should include well documented and sufficiently detailed guidance on the correct sequencing for the various construction tasks. Where possible, details and methods should be prototyped at a relevant scale to identity potential sequencing problems so that they can be resolved before actual construction begins.*

Learning the Lessons from Elm Tree Mews and Stamford Brook

242 The results and conclusions from the fabric testing and monitoring at Elm Tree Mews show clear similarities with those of the Stamford Brook field trial, including factors that relate to design and construction processes. In both cases, the dwellings have been shown to underperform with respect to the original design intent. The underlying reasons for this are deeply embedded in the culture and practices of the UK house building industry. However, there is a real opportunity for the industry to learn from both the Elm Tree Mews and Stamford Brook experiences and to use this information to inform and improve design and construction processes so that low carbon housing can become a reality. The implications for policy, regulation and the house building industry are discussed in more detail in the Elm Tree Mews final policy report (Bell et al. 2010).

References

ANDERSON, B. R., CHAPMAN, P.F., CUTLAND, N.G., DICKSON, C.M., HENDERSON, G., HENDERSON, J.H., ILES, P.J., KOSMINA, L. & SHORROCK, L.D. (2002) *BREDEM-12 Model Description – 2001 Update*, BRE 438, Building Research Establishment, Garston

BELL, M., WINGFIELD, J., MILES-SHENTON, D. & SEAVERS, J. (2010) *Low Carbon Housing – Lessons from Elm Tree Mews*, Joseph Rowntree Foundation, York, http://www.jrf.org.uk/sites/files/jrf/low-carbon-housing-full.pdf, Accessed on 5/11/10

BORDASS, W., LEAMAN, A. & RUYSSEVELT, P. (1999) *Probe Strategic Review 1999 – Final Report 4 Strategic Conclusions*, http://www.usablebuildings.co.uk/Probe/ProbePDFs/SR4.pdf, Accessed on 3/7/08

BRE (2005) *The Government's Standard Assessment Procedure for Energy Rating of Dwellings – 2005 Edition – v9.8*, Building Research Establishment, Garston

BRE (2010) *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*, 2009 Edition, version 9.90, 23rd March 2010, modified 28 May 2010, Building Research Establishment, Garston http://www.bre.co.uk/filelibrary/SAP/2009/SAP-2009_9-90.pdf accessed on 3/8/2010

BRECSU (2000) *General Information Report No 72, Heat Pumps in the UK – A Monitoring Report*, Building Research Establishment, Garston

BSRIA (2009) *The Soft Landings Framework: For Better Briefing, Design, Handover and Building Performance In-use*, BSRIA Report BG4/2009, BSRIA, Bracknell

CALPEX (2006) *Calpex – Technical Information Sheets Pre-insulated Pipes*, downloaded from http://www.pipe2000.co.uk/downloads/pipe/CPXFull%20Data_V11006.pdf on 3/7/08

CHAN (2009) *Distribution Analysis of Domestic Electricity and Gas Consumption in Great Britain*, Department for Energy and Climate Change, http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file50672.pdf accessed on 2/11/10

CRESSWELL, T. (2004) *Place: A Short Introduction*. London: Blackwell.

DTI (2006) *Energy – Its Impact on the Environment and Society, Annex 3B - Regional and Local Use of Energy in the Domestic Sector*, Department of Trade and Industry, downloaded from http://www.berr.gov.uk/files/file20328.pdf on 27/6/08

EST (2010) *Getting Warmer: A Field Trial of Heat Pumps*, Energy Saving Trust, London

HABINTEG (2010) *Lifetime Home: Revised Criteria*. London: Habinteg. www.lifetimehomes.org.uk

HSE (2000) *Legionnaires' Disease: The Control of Legionella Bacteria in Water Systems, Approved Code of Practice and Guidance L8 (2nd Edition)*, Health and Safety Executive, TSO, London

HSE (2003) *Legionnaires' Disease: Essential Information for Providers of Residential Accommodation,* Health and Safety Executive, TSO, London

JRF (2005a*) Background to the Design and Build Competition*, Joseph Rowntree Foundation, York, http://www.jrf.org.uk/housingandcare/suburbanhousing/background.asp, accessed on 2/6/08

JRF (2005b) *Centenary Competition for 21st Century Suburban Housing, New Earswick, York, North Yorkshire for Joseph Rowntree Foundation*, July 2005, Joseph Rowntree Foundation, York

JRHT (2006a) *Design Statement to Support Planning Application for 21st Century Housing - Elm Tree Garage Site. New Earswick, York*, Joseph Rowntree Housing Trust, York

JRHT (2006b) *Elm Tree Garage Site - New Earswick, Outline Specification – Preliminary (Dated 26/4/06)*, Joseph Rowntree Housing Trust, York

JRHT (2006c) *Elm Tree Garage Site - New Earswick, Energy Efficiency and Sustainability Targets (Dated 23/5/06)*, Joseph Rowntree Housing Trust, York

JRHT (2006d) *Specification – New Earswick, Sustainable Housing for Joseph Rowntree Foundation, 25th July 2006*, Joseph Rowntree Housing Trust, York

JRHT (2006e) *Former Garage Site New Earswick: Specification for Mechanical & Electrical Services, Rev A, Sept 06*, Joseph Rowntree Housing Trust, York

JRHT (2008) *Elm Tree Mews Residents' Home User Manual and Information Guide*, Joseph Rowntree Housing Trust, York

KENSA (2006) *Operation, Installation and Maintenance Manual, Twin Compressor Compact Heat Pump Manufactured in the UK by Kensa Engineering Ltd, Version 4.1*, Kensa Engineering Ltd, Falmouth

KENSA (2008a) *Kensa Heat Pumps Fact Sheet – Heat Pump Operating Temperatures*, Kensa Engineering Ltd, Falmouth, http://www.kensaengineering.com/Fact-sheets/FactSheet-HeatPumpOperatingTemperatures.pdf, accessed on 2/7/08

KENSA (2008b) *Kensa Heat Pumps Fact Sheet – Buffer Tanks and Kensa Compact Heat Pumps,* Kensa Engineering Ltd, Falmouth, http://www.kensaengineering.com/Fact-sheets/FactSheet-BufferTanksandKensaCompactHeatPumps.pdf, accessed on 2/7/08

LEEDS METROPOLITAN UNIVERSITY (2010) *Carbon, Control and Comfort Project Web Page*, Leeds Metropolitan University, Leeds, http://www.lmu.ac.uk/as/cebe/projects/ccc/index.htm, Accessed on 4/11/10

LOWE, R.J., WINGFIELD, J., BELL, M. & ROBERTS, D. (2008) *Parametric Domestic Energy Model – Version 15.5*, Leeds Metropolitan University, Leeds & UCL, London

NHBC (2008) *Air Leakage Testing and EPCs*, Standards Extra, No 41, p 4, May 2008, National Home Building Council, Milton Keynes http://www.nhbc.co.uk/NHBCPublications/LiteratureLibrary/Technical/StandardsExtra/filedownload,33628,en.pdf accessed on 25/6/10

ODPM (2006) *The Building Regulations 2000 - Approved Document Part F1: Mean of Ventilation (2006 Edition),* Office of the Deputy Prime Minister, London, TSO

OFGEM (2010) *Revision of Typical Domestic Consumption Values*, Report Ref 106/10, Office of Gas and Electricity Markets, London

PHI (2007) *Passive House Planning Package 2007,* Passivhaus Institut, Darmstadt, Germany, http://www.passiv.de/index.html?07_eng/phpp/PHPP2004_F.htm, Accessed on 21/11/10

POUT, C. (2009a) *Methodology for the Generation of UK Emission Factors for Use in the National Calculation Methodologies*. Building Research Establishment, Garston. http://www.bre.co.uk/filelibrary/SAP/2009/STP09-CO202_Methodology_for_generation_of_UK_emission_factors.pdf Accessed on 3/08/10

POUT, C. (2009b) *CO_2 Revised emission factors for the National Calculation Methodologies. Technical Papers Supporting SAP 2009*, Building Research Establishment, Garston. http://www.bre.co.uk/filelibrary/SAP/2009/STP09-CO201_Revised_emission_factors.pdf Accessed on 3/08/10

ROBERTS, D., BELL, M. & LOWE, R.J. (2004) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 2 – Design Process*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del2design.pdf

ROULET, C-A. & FORADINI, F. (2002) *Simple and Cheap Air Change Rate Measurements Using CO_2 Concentration Decay*, International Journal of Ventilation, Volume 1, No.2, pp 39-44

RUSS.C. (2009) *Monitoring - Wärmepumpen im Gebäudebestand*, Fraunhofer-Institut für Solare Energiesysteme ISE, http://www.wp-im-gebaeudebestand.de/download/Monitoring.wp-im-bestand-090327.ppt, Accessed on 2/10/10

SEAMON, D. (1979) *A Geography of the Lifeworld*. New York: St. Martin's.

SANTON (2007) *Unvented Mains Pressure Solar Water Heater: 190, 210, 250 and 300 Litre Direct and Indirect Models – Installation and Servicing Instructions*, Santon Ltd, Norwich

SCHOTT (2008) *Schott Evaluated Tube Collector ETC 16 Data Sheet*, Schott, Germany

SONTEX (2007) *Superstatic 440 – Static Heat Meter, Static Cooling Meter* (http://sontex.com/download-pdf/Data%20Sheet%20Superstatic%20440%20EN%2009-06-2010.pdf accessed on 1/11/10

TRINICK, J., ELLIOTT, E., GREEN, M., SHEPHERD, J. A. & ORME, M. (2009) *Research into Compliance with Part L of the Building Regulations for New Homes – Phase 2 Main Report*. London: Energy Efficiency Partnership for Homes

TYFOROP CHEMIE (1999) *Tyfocor LS Technical Information – Ready-to-use reversibly evaporisable special heat-transfer fluid based on 1,2-propylene glycol for utilisation in solar heating installations*, Tyforop Chemie GmbH, Hamburg, Germany

UPONOR (2007) *Uponor RF 230/(RF24) Room Sensor Mounting Instructions*, Uponor GmbH, Norderstedt, Germany

WARD, S. (2008) *Heat Losses from Closed Panel Timber Systems*, BSc Dissertation, School of the Built Environment, Leeds Metropolitan University, Leeds

WATSON, J. & HILL, M. (2006) *Elm Tree Garage, New Earswick: Low Carbon Heating Options,* Report for Joseph Rowntree Foundation - Report 060530, Joseph Rowntree Foundation, York

WINGFIELD, J., BELL, M., MILES-SHENTON, D., SOUTH, T & LOWE, R.J. (2008) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Final Report: Lessons From Stamford Brook - Understanding the Gap between Designed and Real Performance*, PII Project CI39/3/663, Leeds Metropolitan University, Leeds

WINGFIELD, J., JOHNSTON, D, MILES-SHENTON, D. & BELL, M. (2010) *Whole House Heat Loss Test Method (Coheating),* Leeds Metropolitan University, Leeds, http://www.leedsmet.ac.uk/as/cebe/projects/coheating_test_protocol.pdf

Appendix 1 – Interview Protocol for Design & Construction Retrospective

Elm Tree Mews Project

Design and construction retrospective

Interview protocol for design and construction team members

Preamble

As you know we are seeking to build up a picture of the design and construction process on the Elm Tree Mews development. This will help us to put the physical testing and monitoring results into context and to understand design and construction decisions made from the point of view of those who made them and the circumstances prevailing at the time they were made. The main function of the interview is to understand your views in relation to your direct involvement in the project. None of the responses you give will be attributed directly to you personally. However reports and other publications will describe and discuss the interview responses in general terms. Anyone who knows you and your involvement may be able to recognise your view so you need to be aware of this when agreeing to take part and in making your responses. We hope, with your permission, to record the interview. This will either be transcribed or used as an aid to making a full note. Any transcription or note will be sent to you for confirmation and at that stage you will be at liberty to change anything you wish. Following this verification process the voice recording will be destroyed/deleted from all media. If at any stage up to the writing of any project report you feel that you would like to withdraw your contribution you are at liberty to do so by contacting the research team.

General information.

First of all I would like to establish some background information about you (your experience and qualifications and your general role in your company:

1. Please outline your qualifications and general experience
2. How would you describe your general role in your organisation?

Elm Tree Mews involvement – Role and responsibilities.

I would now like to be clear about what stage you began work on the Elm Tree Mews project and your role within it:

1. At what point in the project did you become involved?
2. What do you see as your role and responsibilities on the project?
3. How would you describe the way this role relates to other roles and responsibilities you have?
    i. Other projects?
    ii. Other general roles?
    iii. The same as the role taken at Elm Tree Mews?

Interactions with other team members and their roles

The next area I would like to cover relates to the way you see your role within the whole design and construction team:

1. How would you describe the different roles within the team?
    i. What about the way the team works having a number of different organisations involved?
2. In relation to the team please describe the systems of communication.
    i. Between the various organisations in the project
    ii. How well do you think they have worked/are working?
    iii. Any aspects that you think worked particularly well
    iv. Any aspects that could be improved?

Design and construction issues

I would now like to explore a number of design and construction issues:

1. From the point of view of your role what do you see as the key attributes of the Elm Tree Mews design?
    i. Overall adherence to the brief?
    ii. Energy and environmental performance?
    iii. Issues of detailed design?

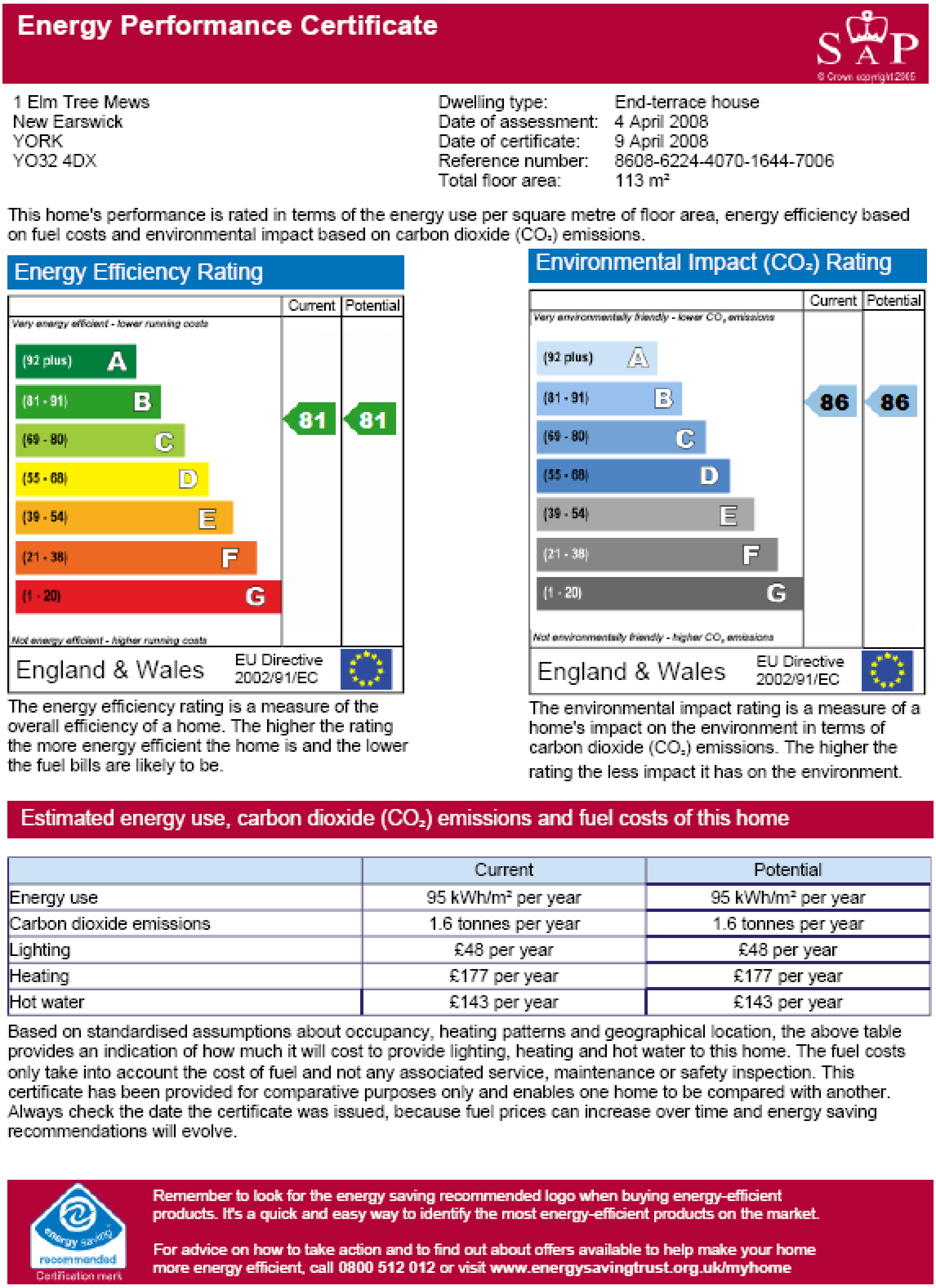
        iv. Any general concerns as to performance?
2. As part of the design team please describe what approaches were taken to predict performance in general and energy performance in particular?
    i. Specific tools and models?
    ii. What is your view on the usefulness of the tool used?
    iii. What improvements, if any, would you consider?
    iv. Are there any areas where you feel that more support in the way of modelling tools or guidance is needed for the design of schemes like Elm Tree Mews?
3. With respect to your involvement can you give any examples of aspects of design and construction that you feel have exceeded expectations?
    i. In design?
    ii. In construction?
4. Please describe and give examples of aspects of the project that you feel have not gone as well as you would have liked?
    i. In design?
    ii. In construction?

Project management issues
The last area I would like to explore relates to the project management of the scheme:

1. I would be grateful if you would outline the principle types of documentation that have been used in the project.
    i. Drawings – general view on usefulness?
    ii. Project plans?
    iii. Specifications?
2. How would you describe the effectiveness of project management during the construction process?
    i. How were project management issues communicated through the project teams?
    ii. What metrics, process measurements or other criteria does your organisation use to monitor progress of the project and whether the project is achieving its aims and objectives?
    iii. Have you identified any training issues or requirements as a direct result of the requirements of the project? Are then any areas that you want to comment on relating to regulatory issues, compliance matters, performance criteria or performance measurement?

Appendix 2 – Energy Performance Certificates

House F (end terrace)



Energy Performance Certificate

1 Elm Tree Mews
New Earswick
YORK
YO32 4DX

Dwelling type:	End-terrace house
Date of assessment:	4 April 2008
Date of certificate:	9 April 2008
Reference number:	8608-6224-4070-1644-7006
Total floor area:	113 m²

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

Energy Efficiency Rating

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills are likely to be.

Environmental Impact (CO_2) Rating

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

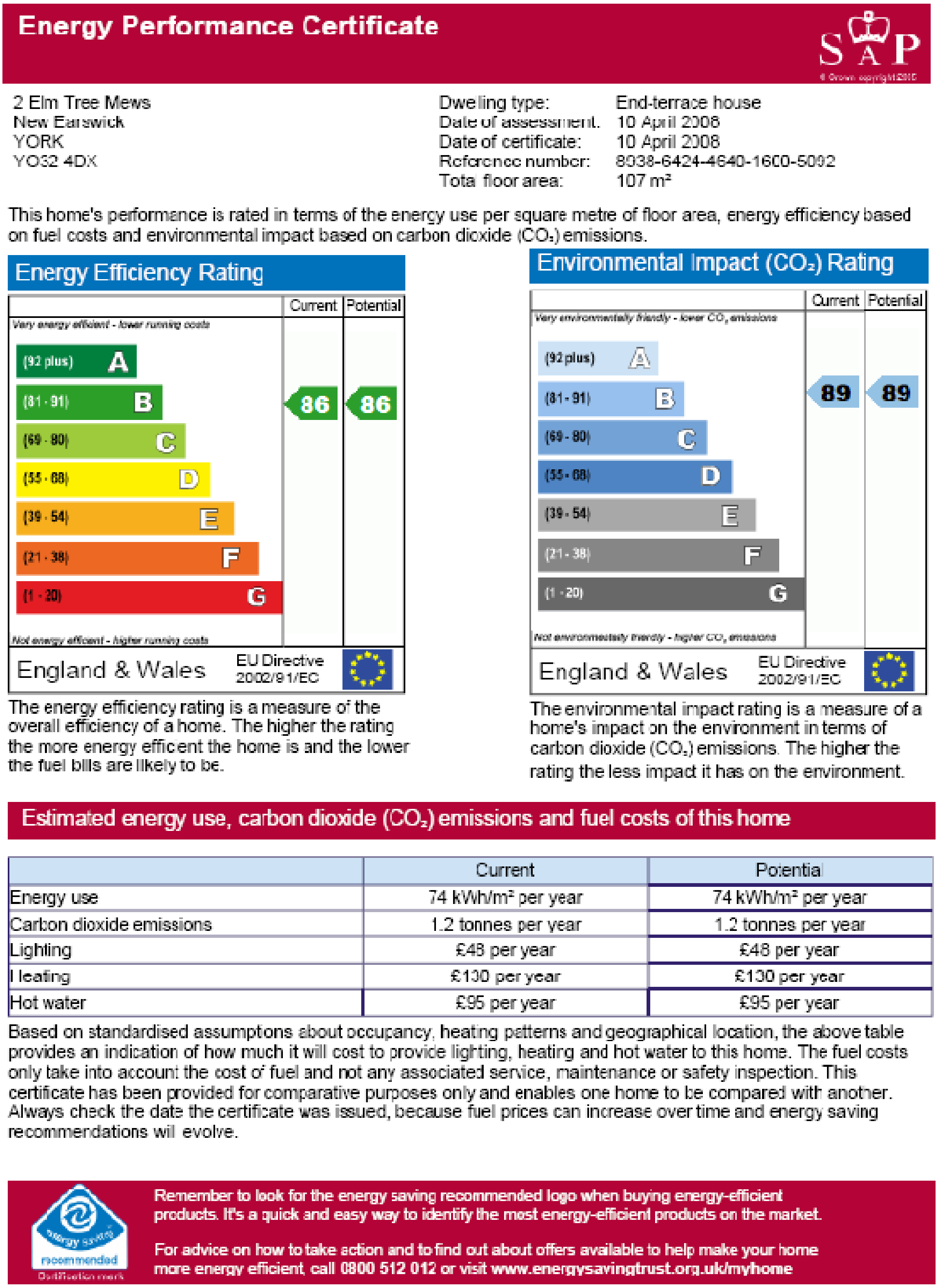
	Current	Potential
Energy use	95 kWh/m² per year	95 kWh/m² per year
Carbon dioxide emissions	1.6 tonnes per year	1.6 tonnes per year
Lighting	£48 per year	£48 per year
Heating	£177 per year	£177 per year
Hot water	£143 per year	£143 per year

Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

Remember to look for the energy saving recommended logo when buying energy-efficient products. It's a quick and easy way to identify the most energy-efficient products on the market.

For advice on how to take action and to find out about offers available to help your home more energy efficient, call 0800 512 012 or visit www.energysavingtrust.org.uk/myhome

Houses A, B and D (mid terrace)



Energy Performance Certificate

SAP

2 Elm Tree Mews
New Earswick
YORK
YO32 4DX

Dwelling type:	End-terrace house
Date of assessment:	10 April 2008
Date of certificate:	10 April 2008
Reference number:	8038-6424-4640-1600-5092
Total floor area:	107 m²

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

Energy Efficiency Rating

	Current	Potential
Very energy efficient - lower running costs		
(92 plus) A		
(81 - 91) B	86	86
(69 - 80) C		
(55 - 68) D		
(39 - 54) E		
(21 - 38) F		
(1 - 20) G		
Not energy efficient - higher running costs		
England & Wales	EU Directive 2002/91/EC	

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills are likely to be.

Environmental Impact (CO_2) Rating

	Current	Potential
Very environmentally friendly - lower CO_2 emissions		
(92 plus) A		
(81 - 91) B	89	89
(69 - 80) C		
(55 - 68) D		
(39 - 54) E		
(21 - 38) F		
(1 - 20) G		
Not environmentally friendly - higher CO_2 emissions		
England & Wales	EU Directive 2002/91/EC	

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy use	74 kWh/m² per year	74 kWh/m² per year
Carbon dioxide emissions	1.2 tonnes per year	1.2 tonnes per year
Lighting	£48 per year	£48 per year
Heating	£130 per year	£130 per year
Hot water	£95 per year	£95 per year

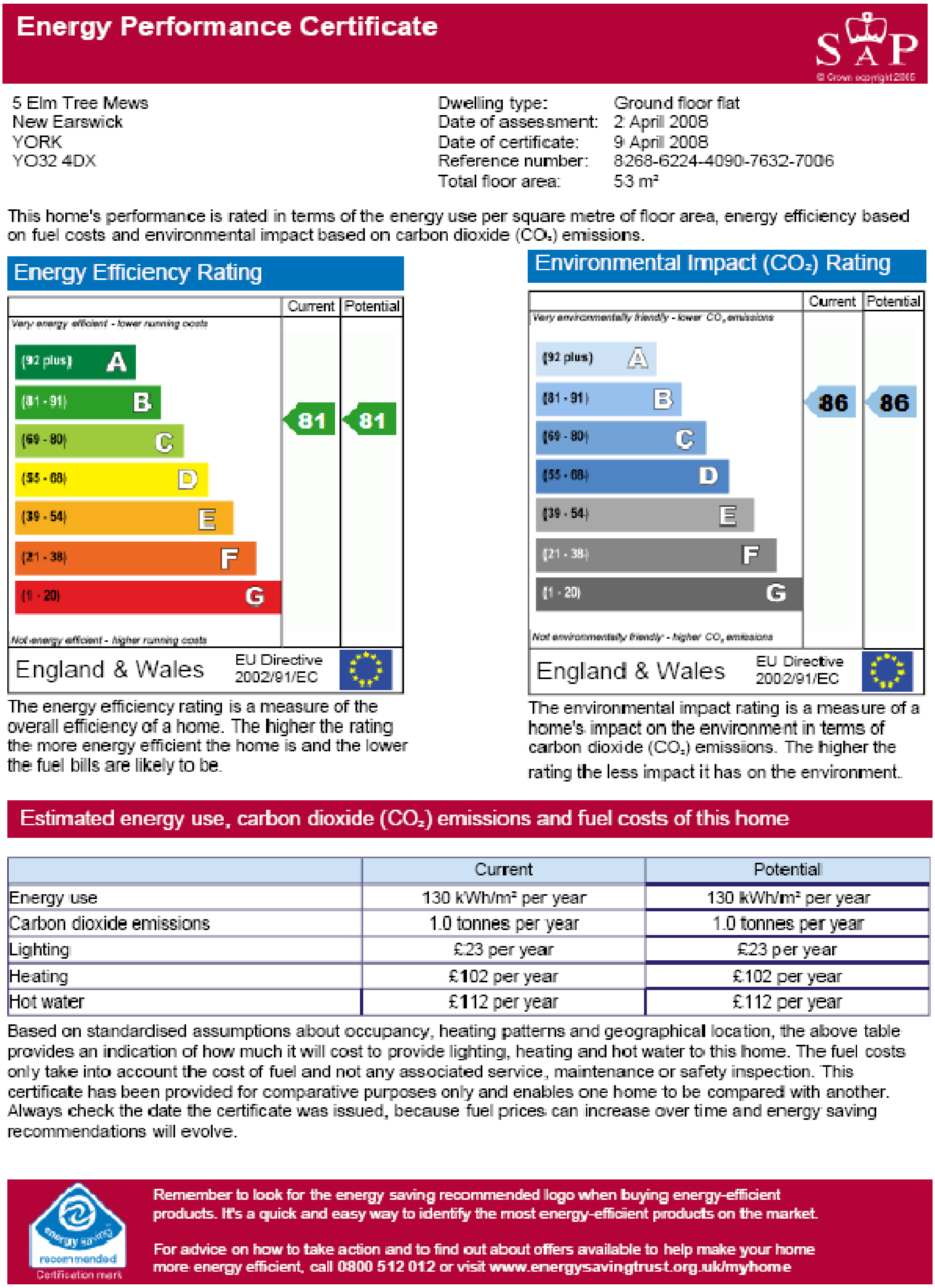
Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

energy saving recommended
Certification mark

Remember to look for the energy saving recommended logo when buying energy-efficient products. It's a quick and easy way to identify the most energy-efficient products on the market.

For advice on how to take action and to find out about offers available to help make your home more energy efficient, call 0800 512 012 or visit www.energysavingtrust.org.uk/myhome

House C (ground floor flat)



Energy Performance Certificate

5 Elm Tree Mews
New Earswick
YORK
YO32 4DX

Dwelling type:	Ground floor flat
Date of assessment:	2 April 2008
Date of certificate:	9 April 2008
Reference number:	8268-6224-4090-7632-7006
Total floor area:	53 m²

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

Energy Efficiency Rating

Very energy efficient - lower running costs

	Current	Potential
(92 plus) A		
(81 - 91) B	81	81
(69 - 80) C		
(55 - 68) D		
(39 - 54) E		
(21 - 38) F		
(1 - 20) G		

Not energy efficient - higher running costs

England & Wales EU Directive 2002/91/EC

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills are likely to be.

Environmental Impact (CO_2) Rating

Very environmentally friendly - lower CO_2 emissions

	Current	Potential
(92 plus) A		
(81 - 91) B	86	86
(69 - 80) C		
(55 - 68) D		
(39 - 54) E		
(21 - 38) F		
(1 - 20) G		

Not environmentally friendly - higher CO_2 emissions

England & Wales EU Directive 2002/91/EC

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy use	130 kWh/m² per year	130 kWh/m² per year
Carbon dioxide emissions	1.0 tonnes per year	1.0 tonnes per year
Lighting	£23 per year	£23 per year
Heating	£102 per year	£102 per year
Hot water	£112 per year	£112 per year

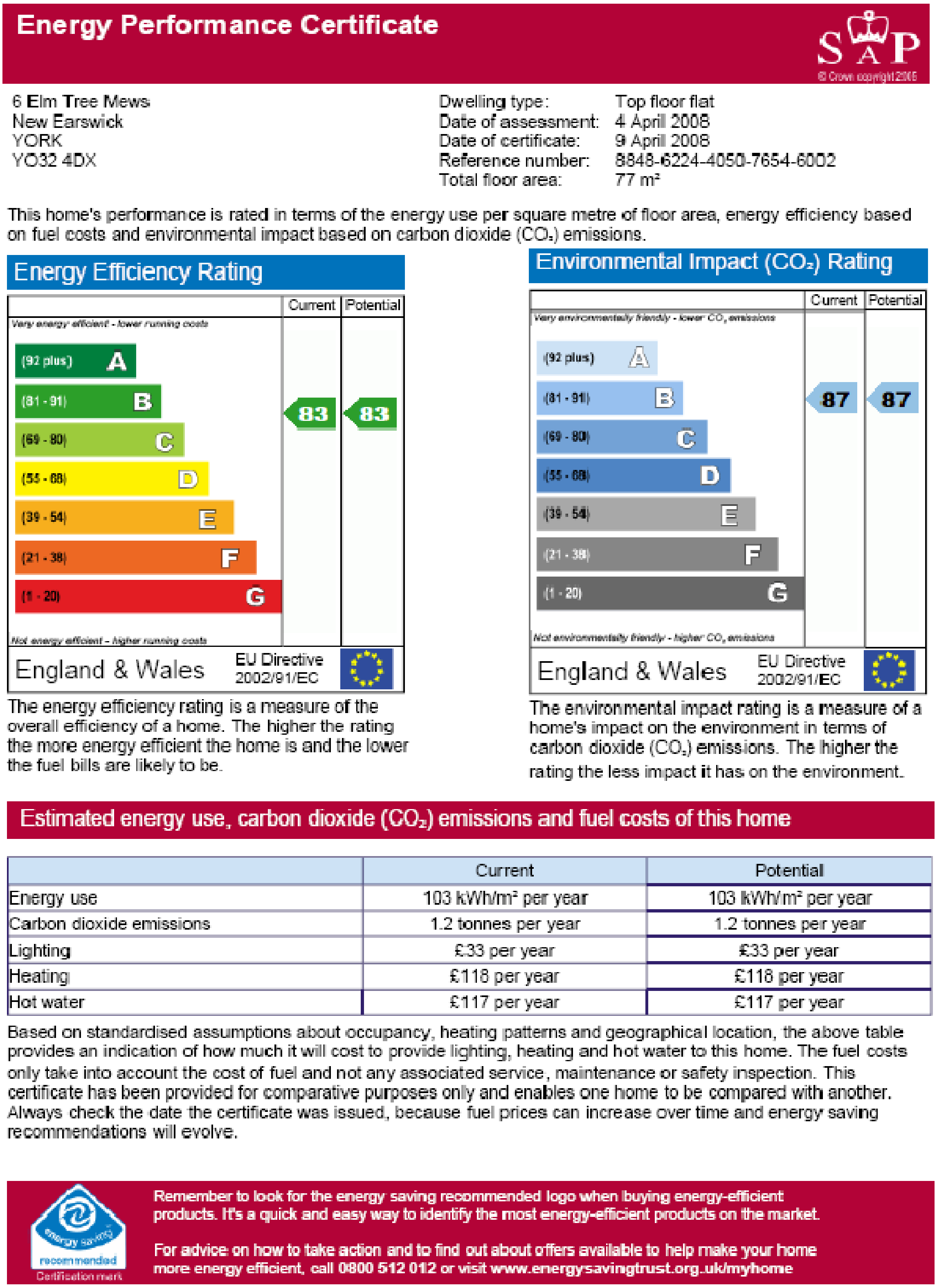
Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

energy saving recommended
Certification mark

Remember to look for the energy saving recommended logo when buying energy-efficient products. It's a quick and easy way to identify the most energy-efficient products on the market.

For advice on how to take action and to find out about offers available to help make your home more energy efficient, call 0800 512 012 or visit www.energysavingtrust.org.uk/myhome

House E (upper floor duplex flat)



Energy Performance Certificate

© Crown copyright 2005

6 Elm Tree Mews
New Earswick
YORK
YO32 4DX

Dwelling type:	Top floor flat
Date of assessment:	4 April 2008
Date of certificate:	9 April 2008
Reference number:	8848-6224-4050-7654-6002
Total floor area:	77 m²

This home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO_2) emissions.

Energy Efficiency Rating

Very energy efficient - lower running costs

	Current	Potential
(92 plus) A		
(81 - 91) B	83	83
(69 - 80) C		
(55 - 68) D		
(39 - 54) E		
(21 - 38) F		
(1 - 20) G		

Not energy efficient - higher running costs

England & Wales EU Directive 2002/91/EC

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills are likely to be.

Environmental Impact (CO_2) Rating

Very environmentally friendly - lower CO_2 emissions

	Current	Potential
(92 plus) A		
(81 - 91) B	87	87
(69 - 80) C		
(55 - 68) D		
(39 - 54) E		
(21 - 38) F		
(1 - 20) G		

Not environmentally friendly - higher CO_2 emissions

England & Wales EU Directive 2002/91/EC

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home

	Current	Potential
Energy use	103 kWh/m² per year	103 kWh/m² per year
Carbon dioxide emissions	1.2 tonnes per year	1.2 tonnes per year
Lighting	£33 per year	£33 per year
Heating	£118 per year	£118 per year
Hot water	£117 per year	£117 per year

Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

energy saving recommended
Certification mark

Remember to look for the energy saving recommended logo when buying energy-efficient products. It's a quick and easy way to identify the most energy-efficient products on the market.

For advice on how to take action and to find out about offers available to help make your home more energy efficient, call 0800 512 012 or visit www.energysavingtrust.org.uk/myhome

Appendix 3 – Interview Protocol for Social Survey

Social Survey: Protocol

Introduction

Thank you for giving up the time to take part in this discussion today. I would like to begin by giving you a brief description of how the interview will work and the part it will play in our research.

As you know we are working with the Joseph Rowntree Foundation and the Housing Trust to look at the energy efficiency of the properties here at Elm Tree Mews. We are doing this by monitoring homes such as your own, and recording factors such as temperature and humidity for approximately 12 months.

In addition to this monitoring, we would value your views and opinions of this type of housing, in particular how you use the property and what it is like to live in. This will provide us with a much clearer picture of the effectiveness of this type of development. It is this that we hope to discuss with you today.

We are grateful for any thoughts or views you give, however you do not have to answer any of the questions and may decline to do so at any time. Also, any information you give us will be kept entirely anonymously and your names will only be known to members of the immediate research team at Leeds Metropolitan University. With your agreement, we would like to record the discussion and produce an anonymised transcript of the recording. Once transcribed the recording itself will be destroyed.

Finally, the interview will take the form of a short questionnaire detailing some of the bare facts about the property and your routine. This will be followed by a series of more open questions through which we can discuss your views on the property and Elm Tree Mews in general. During this section we will aim to enable you to talk as freely as you wish on the issues you feel are relevant.

Interview Topic Guide

I want to tackle a number of aspects in this discussion ranging from your housing experiences here and prior to moving to Elm Tree Mews, your expectations of the property, your use of the heating and other appliances, and your experiences of living in these properties.

1. The Household Characteristics

1.1. First of all, can you tell me when you first moved into Elm Tree Mews?

1.2. How many people live in this property?

1.3. It would be useful to find out a bit about each member of the household.

	Male/ Female	Age	Working Full-time	Working Part-time	Unemployed	Main carer	School or College	Other (incl. preschool, retired, maternity etc.)
Person 1								
Person 2								
Person 3								
Person 4								
Person 5								
Person 6								

2. Housing Histories

2.1. Can you tell me about your previous home?
- *its location*
- *tenure*
- *type of property*
- *age of property*

2.2. What were your reasons for moving to Elm Tree Mews?

(Location, cost, the area, the property, etc)

2.3. At the time of searching for a property to move to, what were the other areas and types of property that you considered?

2.4. To what extent did the location influence your choice of an Elm Tree Mews property?

- What were the deciding factors?

2.5. When you were considering the properties available to you, how important were the environmental aspects of the property?

2.6. To what extent did the fact that it was an 'eco-home' influence your decision at all?

2.7. Have you ever lived in an eco-home before?

3. Attitudes and Expectations

3.1. Thinking back to the decision you made to move to Elm Tree Mews, what did you expect the property would be like to live in?

3.2. Can you recall what your first impressions of this property were?

3.3. How do you feel about it now after you have been living here for a year or so?

- Compared, say to previous properties you have lived in?
- What do you think about the level of comfort? (Temp, air quality, ventilation, draughts.)
- Is it a healthy house?
- Is it cheap to live in?
- Is it easy to use?

3.4. We know there have been some issues with the property – are there any that have affected you in particular?

3.5. Are you concerned about fuel costs??????

4. Living in Elm Tree Mews

We are interested in how you use the property and movements in and out of the property since this affects its energy efficiency.

4.1. In a typical working day, when would each person expect to leave for work, and school, and when would they be expected to return home?

	Person 1	**Person 2**	**Person 3**	**Person 4**	**Person 5**	**Person 6**
Leave						
Return						

4.2. Do any members of the household regularly work from home?
(Including unpaid work/carer role)

4.3. Could you indicate how regularly the following appliances are in use?

- *Washing Machine*
- *Tumble Drier:*
- *Dish Washer*
- *Shower*
- *Bath (i.e. Fill the bath)*
- *Do you mind if we a quick audit of the household appliances*

4.4. When you go away for any length of time do you change the house settings (e.g. heating timers, lights etc) - Do you change the settings between autumn to winter and in spring – or at any other time?

4.5. Moving on to more specific aspects of the property, how have you found the heating/hot water system to use?

4.6. What information or guidance were you given to help you with the heating system? Enough/too much/too technical? (e.g. was the household info pack useful?)

4.7. Do you have a routine for dealing with the heating of the property? Reason for this?

- was this base on previous experience, only one that works, etc.

4.8. Do you know roughly what temperature you set your thermostat? If so what?

- Does it vary from room to room? Which rooms and why.
- Do you change it at all during the day? Why?
- Can you tell me the timing for your hot water and heating?

4.9. How do you control the temperature in the property?

- Do you change the thermostat, open windows etc…. compared to your previous homes?
- Do you understand how the system works (we are trying to understand if the system is too complex to use)

4.10. How do you ensure that you have enough fresh air in your property?

(Windows, doors, trickle vents etc) opening pattern?

Has anyone explained what the trickle vents are – and what they are used for.
Do you usually have your trickle vents open or shut?
Do you regularly open the windows?
How do you feel about ventilation in the Kitchen when you cook?
What about steam in the bathroom?
How did the house feel over the summer?

4.11. How does this property compare in terms of draughts to your previous home?

4.12. How satisfied are you with your hot water system?

- How is the temperature?
- Do you have enough hot water? – at the time when you need it?
- How does it compare with your previous property?

4.13. In addition to the energy used for heating and hot water, we are also interested in how much energy you use when cooking. How often do you use the hob, oven and microwave? For example

- How much time do you spend cooking?
- Which appliances do you normally use…. Does this vary?

4.14. Is there anything else about your property that you feel it would be useful to discuss?

- I'm thinking of factors such as noise, or dust, anything really that effects the way you use the property.

4.15. When you consider our discussion, how would you say your experience of this property compares to your experiences of previous homes?

- Controlling temperature, hot water, draughts, cost, aesthetic
- What type of property was that?

4.16. How did you feel your energy bills?

- Better than expected?
- Better than previous home?

4.17. Is there anything else you would like to mention about the property itself before we move on?

5. General Questions

Finally, as you know Elm Tree Mews is designed with environmental sustainability in mind. Before you came to live here, what were your views on environmental issues? Do you have any concerns?

What part do you feel the individual has to play?
How important do you think this is on a global scale?
What do you think most people in the UK feel about this?

I have now reached the end of my questions, but is there anything else you would like to ask, or mention that you think we would find important?

Appendix 4 – List of Measurement and Monitoring Equipment

Coheating Test Equipment

Component	Equipment Used	Specification/Comment
Datalogger	Eltek RX250 Receiver Logger	250 channel radio receiver logger Set at 10 minute logging interval
GSM Modem	Wavecom Fastrak GSM Modem	
Temperature and Relative Humidity Sensor & Transmitter	Eltek GC-10 Temp/RH Transmitter	5 per dwelling
kWh Meter	Elster A100C	1 Wh pulse output
Pulse Transmitter	Eltek GS-62 Pulse Transmitter	1 per kWh meter
Thermostat	Honeywell T4360B Thermostat or Sunvic TLM 2253 Thermostat	16A load capacity Mounted on a tripod at 1m above floor level 1 per kWh meter
Fan Heater	Delonghi THE332-3 3kW Fan Heater or Dimplex DLB503 3kW Fan Heater	3 kW max heat output 1 per heating zone
Circulation Fan	Prem-I-Air HPF-4500 Air Circulator	18" fan blade 1 to 2 per floor
Thermocouple	Type K Thermocouple (5m long) – mixture of 150mm long air sensor probe and surface sensors	150mm probes thermocouples placed in party wall cavity
Thermocouple Transmitter	Eltek GS-24 Type K/T Thermocouple Radio Transmitter	4 thermocouples per transmitter
Hot bulb anemometer	Airflow TA35 anemometer	Instantaneous air flow readings taken by inserting anemometer into holes drilled into party wall cavity
CO_2 Sensor	Vaisala GWM25 CO_2 sensor	0-2000 ppm CO_2 concentration range 4-20 mA current output 2 per test dwelling
CO_2 Transmitter	Eltek GS-42 DC Current/Voltage Radio Transmitter	4-20 mA current input

Pressure Test Equipment

Component	Equipment Used	Specification/Comment
Blower Door	Energy Conservatory Minneapolis Model 3 Blower Door	Pressure tests carried out in both pressurisation and depressurisation modes
Differential Pressure and Flow Gauge	Energy Conservatory DG700 Digital Pressure/Flow Gauge	-
Anemometer	Air Flow Instruments LCA501 Vane Anemometer	Used to measure instantaneous wind speed
Barometer	Testo 511 absolute pressure meter	Used to measure internal and external barometric pressure
Temperature/Humidity Gauge	Vaisala Temperature & Humidity Probe	Used to measure internal and external temperature and humidity

Weather Station Equipment

Component	Equipment Used	Specification/Comment
Datalogger	Eltek RX250 Receiver Logger	250 channel radio receiver logger Set at 10 minute logging interval
GSM Modem	Wavecom Fastrak GSM Modem	
Temperature/Humidity Sensor	Rotronic Hygroclip S3 temperature/humidity sensor	In Stevenson screen and positioned at ~6m on mast attached to gable end of building
Temperature/Humidity Transmitter	Eltek GenII GS13 Rotronic transmitter	Attached to Rotronic sensor and located in weatherproof sensor box
Mean Wind Speed Sensor	Vector Instruments A100R anemometer with pulse output	Positioned at ~6m on mast attached to gable end of building
Mean Wind Speed Transmitter	Eltek GS62 pulse transmitter	Attached to Vector Instruments anemometer and located in weatherproof sensor box
Instantaneous Wind Speed/Direction Sensor	Schiltknecht Meteo Anemometer & Wind Vane	Positioned at ~6m on mast attached to gable end of building
Instantaneous Wind Speed/Direction Transmitter	Eltek GenII GS42 current transmitter	Attached to Schiltknecht Meteo Anemometer and located in weatherproof sensor box
Pyranometer	Kipp & Sonnen CM3 pyranometer	Vertical Orientation South Facing Positioned at ~6m on mast attached to gable end
Pyranometer Transmitter	Eltek GenII GS42 voltage transmitter	Attached to pyranometer and located in weatherproof sensor box

Heat Flux Measurement Equipment

Component	Equipment Used	Specification/Comment
Datalogger	Datataker DT500	10 channel wired logger Set at 10 minute logging interval
Heat Flux Sensors	Hukseflux HFP01 Flux Sensor	Attached to wall using thermal paste and masking tape
Thermal Paste	Corning 340 silicone heat sink compound	Used to improve thermal contact between sensor and wall

Thermal Camera

Component	Equipment Used	Specification/Comment
Infra-red Thermal Camera	FLIR Thermacam B4	Used with 23° standard lens or 41° wide angle lens Camera calibrated for typical temperatures observed in building energy assessments

In-use Monitoring Equipment

Component	Equipment Used	Specification/Comment
Datalogger	Eltek RX250 Receiver Logger	250 channel radio receiver logger Set at 10 minute logging interval
GSM Modem	Wavecom Fastrak GSM Modem	
Temperature/Humidity Sensor & Transmitter	Eltek GC-10 Temp/RH Transmitter	5 per dwelling
3 Phase kWh Meter 3 (On supply to heat pump)	Iskrameco MT171 Polyphase kWh Meter with Pulse Output	Meter in plant room 100 pulses/kWh
Single Phase kWh meter (on supply to immersion heaters, secondary meter on main supply, and buffer tank immersion heaters)	Iskrameco ME160 Single Phase kWh Meter with Pulse Output	3200 pulses/kWh
Heat Meter on Output from Heat Pump and Input to Houses	Landis and Gyr 2WR5 Ultrasonic Heat Meter with combined Pulse and M-Bus Outputs	1 pulse/kWh
Heat Meters on Input to Hot Water Cylinder	Landis and Gyr 2WR6 Ultrasonic Heat Meter with Pulse Output	1 pulse/kWh
Water Meter in Cold Water Supply to Hot Water Cylinder	GWF Unico 2 single jet water meter with pulse output (Qn = 2.5 m^3/h)	1 pulse/litre
Pulse Transmitter	Eltek GS62 pulse transmitter	Connected to all kWh meters, water meters and heat meters.
Thermocouples	Type K Thermocouple (5m long) – mixture of 150mm sensor probes and surface sensors	Sensor probes inserted into temperature pockets in flow/return pipes and cylinder/buffer tank. Surface sensors attached to surface of flow and return pipes using Velcro and thermal paste
Thermocouple Transmitter	Eltek GS-24 Type K/T Thermocouple Radio Transmitter	4 thermocouples per transmitter
CO_2 Sensor	Vaisala GWM25 CO_2 sensor	0-2000 ppm CO_2 concentration range 4-20 mA current output Calibrated at start of monitoring using pure nitrogen and 2000 ppm CO_2 in nitrogen. 1 per dwelling
CO_2 Transmitter	Eltek GS-42 DC Current/Voltage Radio Transmitter	4-20 mA current input
Current Clamp	Pace SC100 100 A current clamp (0-5v output)	Used with Datataker DT500 datalogger during monitoring of the solar pumps.