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Evaluating the impact of an enhanced energy performance standard on load-bearing masonry domestic construction

Understanding the gap between designed and real performance: lessons from Stamford Brook

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Understanding the gap between designed and real performance: lessons from Stamford Brook

Dr Jez Wingfield, Prof Malcolm Bell, Dominic Miles-Shenton

Centre for the Built Environment, Leeds Metropolitan University

Tim South, School of Health & Human Sciences, Leeds Metropolitan University

Prof Bob Lowe, Bartlett School of Graduate Studies, University College London

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Department for Communities and Local Government
Eland House
Bressenden Place
London
SW1E 5DU
Telephone: 030 3444 0000
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Abstract

This report is aimed at those with interests in the procurement, design and construction of new dwellings both now and in the coming years as the Government's increasingly stringent targets for low and zero carbon housing approach. It conveys the results of a research project, carried out between 2001 and 2008, that was designed to evaluate the extent to which low carbon housing standards can be achieved in the context of a large commercial housing development. The research was led by Leeds Metropolitan University in collaboration with University College London and was based on the Stamford Brook development in Altrincham, Cheshire. The project partners were the National Trust, Redrow and Taylor Wimpey and some 60 percent of the planned 700 dwelling development has been completed up to June 2008. As the UK house building industry and its suppliers grapple with the challenges of achieving zero carbon housing by 2016, the lessons arising from this project are timely and of considerable value.

Stamford Brook has demonstrated that designing masonry dwellings to achieve an enhanced energy standard is feasible and that a number of innovative approaches, particularly in the area of airtightness, can be successful. The dwellings, as built, exceed the Building Regulations requirements in force at the time but tests on the completed dwellings and longer term monitoring of performance has shown that, overall, energy consumption and carbon emissions, under standard occupancy, are around 20 to 25 percent higher than design predictions. In the case of heat loss, the discrepancy can be much higher.

The report contains much evidence of considerable potential but points out that realising the design potential requires a fundamental reappraisal of processes within the industry from design and construction to the relationship with its supply chain and the development of the workforce. The researchers conclude that, even when builders try hard, current mainstream technical and organisational practices together with industry cultures present barriers to consistent delivery of low and zero carbon performance. They suggest that the underlying reasons for this are deeply embedded at all levels of the house building industry. They point out also that without fundamental change in processes and cultures, technological innovations, whether they be based on traditional construction or modern methods are unlikely to reach their full potential.

The report sets out a series of wide ranging implications for new housing in the UK, which are given in Chapter 14 and concludes by firmly declaring that cooperation between government, developers, supply chains, educators and researchers will be crucial to improvement. The recommendations in this report are already being put into practice by the researchers at Leeds Metropolitan University and University College London in their teaching and in further research projects. The implications of the work have been discussed across the industry at a series of workshops undertaken in 2008 as part of the LowCarb4Real project (see <http://www.leedsmet.ac.uk/as/cebe/projects/lowcarb4real/index.htm>). In addition, the learning is having an impact on the work of the developers (Redrow and Taylor Wimpey) who, with remarkable foresight and enthusiasm, hosted the project. This report seeks to make the findings more widely available and is offered for consideration by everyone who has a part to play in making low and zero carbon housing a reality.

Acknowledgements

The Stamford Brook project was funded by the Department for Communities and Local Government and its predecessors (Partners In Innovation project - CI 39/3/663), the National Trust (land owners), the developers, Redrow Homes and Bryant Homes, the National House-Building Council, the Concrete Block Association, and Vent-Axia. The funding from partners together with their unstinting in-kind support is gratefully acknowledged. We acknowledge also the in-kind support provided by Construction Skills and Pilkington.

The research was led by the Buildings and Sustainability Group in the Centre for the Built Environment at Leeds Metropolitan University in collaboration with the Bartlett School of Graduate Studies at University College London.

The project was carried out over some 6 years and in that time we have been fortunate to have the help and advice of a very large number of committed individuals who deserve our special thanks and acknowledgement.

At the Department for Communities and Local Government we have had outstanding support and encouragement throughout from the Building Regulations Part L policy officer, Ted King, backed up by a number of very able and dedicated project officers from AEA Technology. We are very grateful for the project management support from Tony Wilson, Julian Wilczek, Susan Batt-Rawden and Kate Dapr e, all of whom have made an important contribution to the project.

Support from National Trust staff has been invaluable. In particular we would thank Rob Jarman and Sara Braune whose vision and tenacity in the early days and throughout the project was vital. As the National Trust's project manager, Catherine Prasad has made an enormous contribution for which we will be forever grateful. In a general support capacity we would thank David Houston, Steve McGlade, John Shaw, Kirsten Proctor, Nick Grant and James Rothwell for their encouragement and their enthusiasm. At different times over the life of the project, contributions were made by a large number of consultants to the National Trust and the developers. We acknowledge the contributions of all those who have contributed in this way, but in particular we would like to acknowledge the contributions of David Kendall, Maria Andersson, Peter Fauset and Peter Warm.

Without the constant and unstinting support of the developers there would have been no project. Their encouragement and support as well as their willingness to engage with the research process as contributors and partners for over 6 years have been remarkable.

At Bryant Homes a considerable contribution was made by Joe Isle and David Poole from the inception of the project to its completion and along the way the contributions of Gavin Charlton (design), Cathy Partington & Allen MacInnes (project managers), Dave Finnegan and Steve Birch (site managers) have been considerable. Crucial support at a senior level in Bryant has always been enthusiastic and we would thank Joe Isle for steering the project in the early days and Mark Mainwaring for his unstinting support through the construction phases.

The contribution from staff within Redrow has been of the same calibre with considerable support from Paul Brickles (project manager), Jon Moss (design), Allen Bradshaw (site project manager) and John Bennett. As in the case of Bryant, support from senior management in Redrow has been vitally important and in this respect

thanks are due to John Grime and David Lee who have seen the project grow from an idea to development on the ground.

There are many people working on site who have helped to make the project the success that it is. Unfortunately we cannot name them all but we would acknowledge the contribution of all subcontractors and their staff. They accepted our presence and were always very helpful and cooperative. In particular we would like to thank Phil from Loftus Construction for his help both during the development of the cavity wall details and also during the coheating tests and Harry from MB Heating for his help in the installation and removal of the heat meters.

The sales teams, Sue and her team from the Redrow and Linda and her team from Bryant, were especially helpful in obtaining consents from householders and accessing completed dwellings for testing. They have our gratitude.

Monitoring of energy in use requires the enthusiasm and cooperation of occupants. It is they who have sensors dotted about their homes and who provide the data without which the research could not take place. We are very grateful for their forbearance and considerable contribution. In particular we would like to thank Pete and Jayne for helping us with the additional experiments on their heating systems.

In a project of the length of Stamford Brook changes in research personnel are almost inevitable. The project was fortunate to have the contribution of David Roberts as the project's first research fellow. David shepherded the project through the first 4 years and co-authored project deliverables 1 to 4. He brought to the project a remarkable combination of experience as a housing site manager and academic researcher. We are very grateful for David's contribution and wish him well in his academic career. We would acknowledge also the contribution of Jonathan Bell who spent some 6 months as a research assistant on occupant interviews, the first round of coheating tests and some pressurisation testing. Throughout the research Laifong Chiu made an invaluable contribution on action research issues as well as leading a number of important focus group sessions.

All projects of this nature are guided by an advisory group. In addition to the staff from the National Trust and the developers who we have already acknowledged we would like to pay tribute to the support and advice from Neil Smith from the National House-Building Council, Ben Cartwright of Construction Skills, Gerry Pettit of the Concrete Block Association, Brian Walton, Paul Davis, Andy Cowell, and Mike Massey of Vent-Axia and Rick Wilberforce from Pilkington Glass. A particular word of thanks is due to Chris Palmer who as a director of Baxi Air Management was very supportive in establishing the project and providing considerable advice on ventilation systems through the early phases of the project. He also ensured a smooth transition to Vent-Axia during the merger with Baxi.

In a project of the scale and complexity as Stamford Brook 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 such individuals and express our general gratitude to all who have supported the project.

The views expressed and the statements made in this report, together with any errors or omissions, lie with the authors. The report does not purport to represent the views or policies of the Government, the National Trust, Bryant, Redrow or any other partner organisation.

Disclaimer

This report does not provide any specific guidance on the design or construction of any particular scheme or development and the authors can take no responsibility for the use of the material in any specific context.

TABLE OF CONTENTS

Abstract.....	3
Disclaimer	6
Executive summary	9
Background.....	9
Methodology	11
Findings on energy performance	11
Implications for new housing development.....	14
Introduction.....	27
Background to the Stamford Brook development	28
The partnership.....	29
Project objectives.....	30
The EPS08 energy standard	30
Stamford Brook design specification	31
Methodology	33
Action research.....	33
Reflections on the action research approach at Stamford Brook.....	35
Learning at Stamford Brook	35
Time and Money.....	36
Trust and Tensions.....	37
Stamford Brook and the Development of Energy Performance Standards	39
Context	40
Summary of results.....	42
Design process observations.....	42
Construction observations	43
Inherent Design problems	44
Workmanship	49
Buildability	50
Ad-hoc Design Changes	55
Adherence to Design Drawings.....	59
Construction Tolerances	60
Construction Sequencing	62
Inappropriate Material and Component Selection.....	66
Product Substitution	67
Airtightness	70
Pressure Test Results.....	70
Discussion of Stamford Brook Airtightness Data	76
Coheating tests	79
Acoustic tests.....	87
Inter-Dwelling Sound Transmission	87

Intra-Dwelling Sound Transmission	88
Thermal imaging	90
Thermal modelling	92
Monitoring of occupied dwellings.....	94
Energy Consumption.....	96
Temperature and Humidity.....	106
Summer Overheating	110
Predicted versus measured energy use	111
Comparison of energy performance with other low energy housing developments.....	117
Ventilation and air quality.....	119
Ventilation System Performance.....	119
Carbon Dioxide Concentration	121
Nitrogen Dioxide Concentration	123
Construction costs	123
Implications for domestic construction in the UK: Key findings.....	125
The gap between designed performance and realised performance	125
Getting the fabric right first.....	126
Rethinking the construction process.....	126
Building regulations.....	129
Code for Sustainable Homes.....	131
Dwelling design process	134
Construction process	138
Supply chain	142
Training and education	145
Communication	146
Process improvement.....	147
Energy models.....	149
Design tools	150
Performance monitoring protocols and performance testing.....	151
Occupant behaviour and usage patterns.....	152
Existing housing stock	152
A research vision for Zero Carbon Homes	153
Concluding statement.....	155
References	157
Appendix 1 – Bibliography of Stamford Brook Interim Project Reports	164
Appendix 2 – Key Individual Contributors	167
Appendix 3 – Household Monitoring Test Equipment.....	169
Appendix 4 – Procedure for Correcting Parametric SAP Calculation for Non-standard Variables	170
Appendix 5 – Energy Star Qualified Homes Thermal Bypass Inspection Checklist	171
Appendix 6 – Research Outline for Low and Zero Carbon Housing	172

Executive summary

Background

1. Stamford Brook is a development of over 700 cavity masonry dwellings that are being constructed on part of the National Trust's Dunham Massey Estate near Altrincham in Cheshire. The development is being carried out under a partnership agreement between the National Trust (land owner) and the two developers, Redrow and Bryant (now part of Taylor Wimpey). The development was planned and designed from the outset to an Environmental Performance Standard (developed by the National Trust with the two developers) that included land use, building density, plot orientation, and a wide range of sustainable development measures. The energy and carbon performance of the dwellings formed an important element of the environmental standard and it is this aspect that is the focus of the research project reported here. Construction on the site began in 2004 and is expected to continue until 2009 or 2010.
2. This report is the final output from the Stamford Brook research project, which has run in parallel with the Stamford Brook development since its inception in 2001. The project was funded through the UK government's Partners in Innovation Programme, a programme operated jointly by the Department for Trade and Industry, now the Department for Business, Innovation and Skills) and the Department for the Environment, Transport and the Regions (now the Department for Communities and Local Government (DCLG)), and by the project partners. The research team are based in the Centre for the Built Environment at Leeds Metropolitan University and have had additional support from a colleague currently at the Bartlett School of Graduate Studies at University College London. The objectives of the project were to:
 - comprehensively evaluate the impact of an enhanced energy performance standard designed for possible incorporation into an amendment to Part L of the Building Regulations in the context of a large development, using load-bearing masonry construction and
 - communicate and disseminate the results of this evaluation effectively to all stakeholders
3. The enhanced energy performance standard, referred to in this report as the "EPS08 energy standard", is some 25% to 35% in advance of the 2002 building regulations for England and Wales and is 10% to 15% in advance of the 2006 regulations. An important principle for the design and construction of the dwellings was to achieve the EPS08 energy standard through durable, passive, construction measures concentrating on the thermal envelope as the longest lived and most difficult to modify element of a dwelling.
4. While it draws upon and summarises the results and conclusions of a number of interim project reports, the main function of this report is to review and discuss the implications of observations, measurements and analysis undertaken in the period between 2004 and June 2007. These cover the construction process, air leakage, envelope thermal performance and the in-use performance of four occupied dwellings. In addition, the report discusses the implications of the findings for issues such as future regulation, energy standards, the nature of the design and construction process, training, quality control procedures and occupant behaviour

patterns. The final report also contains a reflection on the methodological questions raised by the project.

5. The focus of the Stamford Brook project has been on near-term innovation and its deployment at large scale, in a fully commercial context. The development has been broadly typical of the volume house building industry in the UK in terms of commercial and contractual arrangements, and management. The real construction context within which the enhanced energy performance standard has been implemented is central to the relevance of the project for the development of energy performance standards in the UK and to the construction industry as a whole. Therefore, within the limitations of any case study, we believe that many of the insights from the project can be generalised to the house building industry at large.
6. In interpreting the results of the study (as presented in this report and earlier project outputs) it is important to recognise that the observations made and conclusions drawn are focused primarily on the energy and carbon performance of the dwellings and the implications for the achievement of government targets for low and zero carbon new housing. The comments made should not be interpreted as having a direct bearing on other aspects of dwelling performance or quality, such as structural integrity, weather tightness, standard of finish and the like. In these other respects we consider the overall performance and the quality achieved to be almost certainly commensurate with and, in all likelihood, better than that achieved on any other housing development being constructed by the UK house building industry.
7. The function of the PII project was to support future reviews of Part L of the Building Regulations by evaluating the various impacts on a large scale masonry housing development of a range of improvement measures that could be used to meet the requirements of an advanced energy performance standard. Crucially the project sought to improve our understanding of the design and production process and the issues that would need to be addressed by the house building industry at large if it is to achieve consistently high levels of energy performance “on the ground”. The recent dramatic shift in the UK Government’s regulatory targets, designed to achieve zero carbon new homes within 10 years, has made it even more important that the lessons from the project are absorbed and acted upon by government, the industry, its supply chain, educators and others who are part of the industry’s supporting infrastructure.
8. Although the focus of the work was exclusively on house building, some of the findings may have application in renovation of existing dwellings. We highlight the relevance of our findings to heating system design whenever heating systems are being replaced or modified, the possibility of reducing thermal bypasses through such measures as injecting cavity wall insulation to existing party wall cavities and the use of a number of the measurement and testing techniques used at Stamford Brook in the forensic examination of existing dwellings so as to optimise improvement measures.

Methodology

9. The Stamford Brook project has been conducted using an action research approach, in which the research team simultaneously participated in (largely in a consultative capacity) and observed the various aspects of the development process. A combination of qualitative and quantitative tools was used to observe, assess and evaluate the design, construction and occupation phases of the development. This is probably one of the first major housing field trials in the UK to have explicitly adopted this approach and represents a significant step forward in terms of the range of methodologies available for housing field trials.
10. The action research approach, with its focus on change and process, with its treatment of those involved in the project as research partners rather than objects of research, and with its ability to address the “why” as well as the “what” of energy performance, is particularly well suited to the demands of such a field trial. At Stamford Brook, the approach provided an overarching framework for a wide variety of activities, and a range of different investigations using qualitative and quantitative methods. These activities and investigations have facilitated developments in house design and construction such as working with the supply chain on the sourcing of windows to meet a demanding U value target of 1.3 W/m²K, securing approvals for the use of plastic wall ties and developing the parging approach for improving the airtightness of masonry. Also, the partnership has enabled important findings of strategic importance and has provided an unprecedented insight into the determinants of energy performance in mass housing. The continued involvement of the developers in the project up to and including the writing of this report has contributed to its potential impact and credibility within the house building industry and in Government.
11. It is clear that the action research approach has worked well given the constraints imposed by the project such as the fluid nature of employment on the site, the tight initial budget for the research project, the unexpectedly long duration of the project (now approaching seven years) and the difficulties of keeping the whole project team together over this period. However, we acknowledge that there was limited previous experience of action research within the research team and that in future projects a greater emphasis will be needed on the action research aspects so that even greater benefit can be achieved. While this would increase the cost of studies like Stamford Brook, we believe it would enhance considerably their value.

Findings on energy performance

12. In a highly detailed study of construction and energy performance, such as that reported here, it is inevitable that the focus will be on those aspects that need to be addressed. However, as indicated above, it would be quite wrong to conclude, from the results of performance testing and the catalogue of construction observations, that, overall, the dwellings did not meet specification requirements or that the developers involved produced housing that did not meet the quality standards expected from the house building industry. In fact, given the limited experience within the industry of low energy construction, what has been achieved at Stamford Brook represents a significant step forward and demonstrates a considerable achievement within a relatively short time scale. A number of the construction features adopted at Stamford Brook some six years ago, such as using separate lintels to minimise thermal bridging and the introduction of parging

as a means of improving airtightness, are only now beginning to be identified as good practice within the industry at large. Even allowing for the observed gap in performance when measured against the enhanced energy standard, the energy performance of the dwellings remained significantly in advance of the 2002 building regulations standard in force at the time they were constructed.

13. We have shown at Stamford Brook that there can be a significant discrepancy between the performance of a dwelling, as designed and that realised, as constructed and in use. We have been able to quantify the size of the performance gap for a range of conditions and have also determined the key issues that have contributed to the observed discrepancies, both in terms of the design and construction of the dwellings and in the operation of the heating and ventilation systems.
14. Some of the reasons for the discrepancies in thermal performance relate to specific design and construction issues such as hitherto unrecognised heat loss mechanisms via party wall and other construction cavities, unnecessary air leakage and thermal bridging. Other factors are more strategic and include the nature of industry wide design and construction processes, the need to revise theoretical models and modelling tools, the nature of the supply chain and its relationship with the rest of the industry, the availability of skills and knowledge at all levels, the focus of education and training provisions, the need for more extensive and “real world” research and development programmes and the need for effective government interventions through improved regulation and other policy instruments.
15. The mean air permeability of the 44 dwellings pressure tested at Stamford Brook was $4.5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ which is below the target of $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ required by the EPS08 energy standard. Although some 14 (37%) out of the 44 dwellings did not achieve the target, the mean of $4.5 \text{ m}^3/(\text{h.m}^2)$ represents a remarkable improvement on existing UK practice as represented by the mean of $9.2 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ obtained for a sample of 99 dwellings constructed on a number of developments built to 2002 regulatory standards. Analysis of the test results from Stamford Brook, along with detailed observations of the construction process, indicated that relatively low levels of air leakage are possible with cavity masonry construction as long as sufficient consideration is given to the design and construction of the air barrier. Furthermore, in order to maintain the desired levels of airtightness, we have shown that a formal pressure testing regime is likely to be necessary, linked with a robust process control system and a culture of continuous improvement. Performance feedback is vital to improve detailed design of the air barrier and to optimise the construction process so that the air barrier is constructed as designed. Optimisation of construction processes for improved airtightness is also likely to lead, in the long term, to other benefits such as improved productivity.
16. Coheating tests¹ were carried out on six attached dwellings at Stamford Brook. The results of these tests showed that the measured whole house heat loss

¹ A coheating test is a way of measuring the specific whole house heat loss coefficient and includes a fabric heat loss component and a background ventilation loss component. The test is carried out by electrically heating a test dwelling to a set temperature and measuring the daily total electrical energy input and the daily mean internal and external temperatures. The heat loss coefficient in W/K is the slope of the least square fit line through a plot of daily power input (Watts) versus the mean daily inside-outside temperature difference (K).

coefficients were higher (in some cases by more than 100%) than the heat loss coefficients predicted using nominal fabric U -values, modelled thermal bridging factors and measured air permeabilities. Analysis of temperature data, air flow patterns and thermal imaging showed that a large part of the discrepancy was due to a thermal bypass operating via the party wall cavity between the attached dwellings. This is one of the most significant technical findings from the project since current design and regulatory practice assumes that heat loss from party walls is insignificant and can be ignored in the calculation of dwelling carbon emission rates. However, the coheating test findings at Stamford Brook have demonstrated that the unaccounted for heat loss can be very large. This has far reaching implications for regulation, the design of dwellings and energy modelling protocols. The party wall bypass is also an example of the tensions and potential conflicts between the requirements of the various Building Regulation Approved Documents. The party wall at Stamford Brook was designed to comply with the acoustic performance requirements of Part E of the building regulations. The presence of the party wall bypass shows that there can be a conflict between acoustic performance and thermal performance.

17. The effective U -value of the party wall was found to be of the order $0.5 \text{ W/m}^2\text{K}$ to $0.6 \text{ W/m}^2\text{K}$. This is more than twice the notional U -value of the external wall ($0.23 \text{ W/m}^2\text{K}$) and around three times the notional U -values of the floor ($0.17 \text{ W/m}^2\text{K}$) and ceiling ($0.14 \text{ W/m}^2\text{K}$). A mineral wool-filled cavity sock positioned horizontally in the party wall cavity at the level of the ceiling insulation was found to partially mitigate the effect of the thermal bypass and reduced the size of the effective party wall U -value to around $0.2 \text{ W/m}^2\text{K}$. It is likely that fully filling the party wall cavity in conjunction with edge sealing of the type used would eliminate this bypass but this would require further measurements to be certain and to ensure that sound attenuation requirements are not compromised. There is potential for considerable carbon savings for both newly constructed and existing dwellings if measures such as this were implemented across the UK in order to reduce or eliminate the bypass. The potential carbon saving in all new terraced and semi-detached cavity masonry dwellings built in the UK each year, would be of the order 20,000 tonnes CO_2 per annum, and there are potential carbon savings of the order 850,000 tonnes CO_2 per annum in the existing stock built since the 1960's.²
18. The evidence from thermal imaging and construction observations suggests that the real U -values of the walls, floors and ceilings were higher (worse) than their notional equivalents and that heat losses due to linear thermal bridging at junctions were higher, also, than those predicted using thermal modelling. This gap between the designed thermal performance of construction elements and junctions compared to that actually achieved in constructed dwellings is related to a range of complex issues. Many of the issues have their roots in the generally low level of understanding of thermal design and construction that exists within the industry including designers and other consultants, the supply chain and many of those providing education and training at every level. To a large extent this is to be

² The potential annual carbon savings for new dwellings are based on the assumption that all party cavity walls in new mid-terraced and semi-detached cavity masonry houses have an effective U -value of $0.5 \text{ W/m}^2\text{K}$, and that the current annual construction rate of mid-terraced and semi-detached cavity masonry dwellings in the UK is 38,000 and 27,000 units respectively. In the case of the existing stock it is assumed that all semi-detached and mid-terrace cavity masonry dwellings built since 1965 have a cavity party wall with an effective U -value of $0.5 \text{ W/m}^2\text{K}$, and that the stock of mid-terraced and semi-detached houses built between 1965 and 2006 is 1.76 million and 1.32 million respectively.

expected since, hitherto, thermal design to the levels required at Stamford Brook has not played a large part in house building. As a consequence many of our observations of design and construction identified issues relating to the adequacy of thermal design information available to construction teams, the buildability of details for thermal performance, the thermal complexity of designs, build sequencing and detailed programming to ensure continuity of insulation and air barrier, understanding of the impact of construction tolerances, very little thermal performance measurement and underdeveloped process and change control systems. Although the observations in this report are drawn from Stamford Brook, it is clear from other work undertaken by the research team that the issues are not site or developer specific but are rooted in common processes and practices throughout the house building industry.

19. It was found that the measured system efficiencies of the gas-fired heating systems in occupied dwellings were less than expected and that measured boiler efficiencies fell below the declared SEDBUK ratings. Measured boiler efficiencies ranged from 85% to 89% compared to the boiler SEDBUK efficiency rating of 91.3%, and system efficiencies (boiler plus pipework and other system components) were found to be as low as 50% during the summer. This low level performance was partly related to heating system design that resulted in overly long and uninsulated primary pipework in some dwelling types, and partly due to user programming.
20. The overall annual space heating energy consumption of monitored occupied dwellings was found to exceed that predicted by modelling. It was possible to account for the difference between measured and predicted performance by taking into account factors such as the party wall thermal bypass, heating system inefficiencies, higher linear thermal bridging, higher fabric losses and unusual occupant behaviour patterns. However, the root causes of the measured gaps in energy performance are much more complex than a simple list of design and construction characteristics and system inefficiencies would suggest. They relate much more to the interrelationship of the various parts of the construction process from design conception all the way through to completion and occupation. The potential size of the energy performance gap has considerable implications both for the housing industry and the regulatory environment that supports it and it is clear that a high level of investment in research, development and testing will be required in order to close the gap. Closing the gap will become increasingly important if low carbon homes are to become a reality. This in turn will require close cooperation between the house building industry and its supply chain, and also with regulatory bodies and the supporting research infrastructure.

Implications for new housing development

21. The main aim of the Stamford Brook project was to demonstrate that an advanced energy standard could be successfully introduced by volume house builders on a large scale development in the UK. In large part this aim has been achieved and we have been able to demonstrate that significant in-use energy savings are possible compared to existing dwellings and new dwellings built to current building regulation standards. However, the actual level of performance achieved fell short of design expectations and performance targets. In normal circumstances, the discrepancies in performance would not have been identified at all since almost no routine thermal performance testing is carried out and occupants would be unlikely

to notice because, typically, heating systems are over sized to allow for variability in heat loss. Even if performance in use had been measured but not scrutinised to the level of detail as at Stamford Brook, then, in all probability, discrepancies would have been attributed to uncertainties in construction or occupant behaviour patterns (mainly occupant behaviour). In fact, the underlying reasons for underperformance are likely to be much more complicated and relate not just to the specific construction issues identified in this report but, more importantly, to general system performance issues within the whole process, from regulation, planning & specification through to design, research & development, procurement & supply, training, construction, testing & inspection and finally to occupation of the completed dwellings

22. As we move towards low and zero carbon housing standards, many small things will become increasingly important. In our view, existing processes and practices, that may have served the industry well in the past, will need to change in a fundamental way. The learning that has been achieved through the efforts of all the partners at Stamford Brook has enabled many of the issues to be exposed so that they can be highlighted within the industry at large and addressed in time so that by 2016 house builders will produce dwellings that deliver real zero carbon performance in practice as well as in theory. By way of conclusion we have identified the following set of implications for new house construction in the UK as the industry grapples with the requirements of low and zero carbon housing development:
- a) **Rethinking the construction process** - We have identified issues within the system of regulatory advice, a need for more integration between different aspects of building regulation, problems with levels of understanding within the design process, inadequacies in design tools and modelling protocols, failures in the training of designers and building physicists, a lack of comprehensive energy performance testing and prototyping of dwelling designs and details, a lack of feedback of performance data into the design process and the need for significant changes in planning and executing construction processes. These are all symptomatic of problems with the system as a whole. The organisational challenges in the construction industry have been identified on a number of occasions with Government review reports going back to the 1960's, and more recent reports in the late 90's and the early part of this decade. However, if it is to achieve the target of zero carbon homes by 2016, the UK housing industry (in its widest sense) and regulators can no longer ignore these deep seated issues, many of which are embedded within industry cultures. It is crucial that the UK housing industry rethink the whole construction process and embrace modern process improvement tools and systems thinking methodologies. This sort of change is much more important and difficult than simply looking for a panacea, such as off site construction technologies. Although it is recognised that so called, modern methods of construction (MMC) may well play an important part in delivering low carbon dwellings, we see no evidence that the adopters of such systems are addressing the fundamental culture and processes changes that are likely to be required.
 - b) **Building regulations** - The findings at Stamford Brook have significant implications for regulatory change, particularly in terms of supporting research, design guidance and advice on construction practice. Based on the experience of Stamford Brook, we have some confidence that the expected energy performance levels that will be required in the 2010 review of Part L could be

achievable by the UK housing industry now, using existing technologies and relatively standard construction techniques. However, this assumes that actions are taken to tackle the issues that we have highlighted in this report such as thermal bypassing, heating system design and the revision of construction details, and also to address the underlying system and process weaknesses we have identified. It is also critical to future regulatory changes that we understand the level of compliance of dwellings with respect to the current ADL1a 2006 carbon emission targets and also with respect to expected future changes to the regulations. From our experience on this project we would expect that, in most cases, there will be a significant gap between the designed Dwelling Carbon Emission Rates for new dwellings built to Part L-2006 and the actual realised performance, both in terms of fabric performance and energy in use. In this respect, the dwellings at Stamford Brook would be expected to represent a best case scenario for typical mass housing in the UK, and it is very likely that other new dwellings across the UK will under perform to a greater extent. However this cannot be said for certain since, to our knowledge, there have been no significant studies that have attempted to measure the performance of typical 2006 compliant dwellings and the existence or otherwise of a performance gap and if present, its size. This feedback loop providing real performance data back into the regulatory process is however essential if the industry is to realise the targets for reduction in carbon emissions for housing. It is critical that a compliance testing programme is put in place as soon as possible in order to provide the necessary data for the next proposed review of the building regulations in 2010.

- c) **Code for Sustainable Homes** - An exploration of different compliance packages for the different standards in the Code for Sustainable Homes would suggest that for gas heated dwellings to meet the requirements of Code Level 3, a typical combination of fabric measures and system efficiencies would be similar to the design values for Stamford Brook, albeit with an enhanced wall U -value of around 0.15 W/m^2 . This indicates that Stamford Brook could act as a template for Code 3 compliant dwellings. The actual carbon emissions achieved by such dwellings would of course depend upon how well the design, construction and process issues identified at Stamford Brook are addressed. For Code Level 4 compliant dwellings, in the absence of abundant carbon free generation, the dwelling fabric will have to achieve passive house standards. This would require U -values of around $0.1 \text{ W/m}^2\text{K}$ for opaque elements, air permeability somewhere around $1 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ and thermal bridge free construction. With air permeabilities at $1 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, it would be difficult to show compliance with the ventilation requirements of Approved Document Part F using natural ventilation alone, and adequate ventilation would therefore require the use of some form of whole house mechanical ventilation system, preferably a balanced system with heat recovery. Achieving Code Level 4 will therefore require a step change in performance compared with that achieved at Stamford Brook. However it is worth noting that achieving passive house standards need not preclude the use of masonry or any other traditional form of construction. For example, the lowest air leakage achieved ($1.75 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$) suggests that passive house air leakage levels could be within reach, given design and construction improvements.

d) **Dwelling design process** - House design is a process that seeks to balance the sometimes conflicting and contradictory requirements of cost, planning constraints, aesthetics, building regulation and buildability with the requirements of performance. The design requirements for volume house builders are complicated further by the need to ensure replicability and adaptability of standard house designs and the availability of materials and components. The Stamford Brook project has identified a range of issues for typical house design processes and the consequent impacts that any shortcomings can have on the thermal performance and airtightness of dwellings when constructed. It was apparent from an analysis of the designs of the dwellings at Stamford Brook that, although a significant attempt was made to follow general thermal design rules and principles, this intention did not always result in robust thermal design and construction. We have also observed that links between the design process and the construction process or between the design process and the final occupation of the constructed dwellings were not sufficiently strong to ensure the achievement of intended performance. The lessons from Stamford Brook in terms of house design can therefore be summarised as follows:

- ***Thermal design principles*** - House designers should strive to maintain the principles of effective thermal design in terms of thermal insulation and the air barrier, and these should become embedded in the organisational culture. This applies to design at every level. There is much that can be done at the level of house type and elevation design as well as detailed design.
- ***Improvements in detailed design*** - Detailed design needs to consider to a greater extent the requirements of thermal performance in terms of buildability, sequencing, minimisation of complexity and robustness. This requires designs to be tolerant of construction variation or to be designed in such a way as to minimise the potential for variations to occur through the use of appropriate materials, components and build sequences.
- ***Pattern book approaches*** - The use of standard detailing may help the process of detailed design but should not be seen as a substitute for a solid understanding of thermal design principles and the use of appropriate modelling tools. Although there may be merit in accredited details within the regulatory process and as part of a design culture that has the necessary understandings backed up by robust modelling tools, a reliance on an accredited pattern book, on its own, is unlikely to deliver low carbon housing on a reliable and robust basis. In our view there is a need to change the culture of housing design to reflect a more holistic and integrated approach and this will require a greater level of thermal design expertise within the house building industry and the consultants that support them.
- ***Inspectability*** - In order to achieve the desired final thermal performance characteristics, designs need to take account of inspection requirements and performance checking during the construction phase to ensure that the various elements have been built in accordance with the original design specifications.

- **Continuous improvement** - A culture of continuous improvement in design should be adopted that actively seeks feedback on realised energy performance data from completed buildings and also information of the performance of the construction process such as buildability and sequencing issues. This will require a higher level of integration and cooperation between design and construction departments within companies and also between developers and their sub-contractors, suppliers and design consultants.
 - **Communication issues** - Communication between design departments and the construction teams should be improved especially in terms of the actual design information that is provided to site. Design drawings need to be more comprehensive and should be supported by detailed construction and sequencing information that fully detail the construction sequence and that identify appropriate control measures, quality issues and measurable performance indicators.
 - **Change control procedures** - The design process requires some form of change control procedure that can monitor and evaluate any modifications in design or any material or product substitutions to ensure that such changes do not negatively impact on buildability or any performance criteria such as energy use or ventilation. This change control procedure will have to link with both the construction process and also to the procedures used by the supply chain.
- e) **Construction process** - At a high level, the construction process at Stamford Brook was ordered and followed a logical sequence. However, at lower levels of detail, it was apparent that there was considerable variation in the way that many detailed tasks were organised and sequenced, and that monitoring or checking of compliance with design details was not always easy to do. The approach, in which build sequences were allowed to vary within some overall build programme may provide flexibility but can lead also to processes that make it almost impossible to ensure continuity of the air barrier or insulation layers. Construction observations illustrate that very often site teams have to cope with insufficient detailed design and sequencing information and this often results in the need to work round problems as they arise and to engage in on-site detail design without access to the necessary knowledge, understanding or modelling tools. Such an approach may be adequate to deal with other aspects of performance but, as we have observed, is not conducive to increasingly high levels of thermal performance. Quality is often seen primarily in terms of finish and the level of service provided by installed equipment and systems. However, many construction problems relating to such things as airtightness, continuity of insulation, unsealed service penetrations or installation of pipe insulation remain hidden in completed dwellings and the associated performance reduction remains unresolved. There is therefore a need to introduce systems and procedures for the continuous monitoring and inspection of the whole construction process that would ensure dwellings are constructed as designed and that the necessary thermal performance requirements are fully built-in. The lessons from Stamford Brook in terms of the house construction process can therefore be summarised as follows:

- **Buildability** - Improved buildability of designs is needed to ensure that details can actually be built as intended in order to achieve the desired level of thermal performance. This will require close cooperation between design and construction teams and with the supply chain, and will also necessitate some form of testing and prototyping of designs and construction processes. It will be critical that any issues of buildability or any problems arising during construction that are a result of the complexity of details and junctions are fed back to the design teams so that designs can be adapted and improved.
- **Continuous improvement** - A culture of continuous improvement is needed to ensure that process problems are identified and fixed during construction and that there are procedures to record and capture this information to feedback into the design and construction processes.
- **Change control procedures** - Robust procedures are needed for the control of changes to the construction process and for product and material substitutions. This will ensure that any changes are identified and that the potential effects of such changes on energy and carbon performance are assessed before being implemented.
- **Build sequencing** - Improved sequencing of construction tasks and more comprehensive documentation of preferred construction sequences would be expected to result in closer correlation between details as designed and as constructed. There is also a need for developers to analyse existing and new construction processes in order to identify opportunities for improvement in terms of performance characteristics such as airtightness and thermal bridging.
- **Construction variability** - It is clear that robustness of thermal design is an important characteristic and further research is needed to find ways of quantifying robustness and repeatability of the designs of junctions and details and how variability can influence thermal performance and airtightness. In the shorter term, an empirical approach to the problem based on observations such as those carried out at Stamford Brook may suggest design solutions, construction products and processes that could be considered more robust than existing techniques.
- **Process documentation** - Improvements to the level of detail of process documentation allied with comprehensive process flow charts and detailed construction planning will make it more likely that junctions and details are constructed as designed and that the correct build sequences and materials are used. This in turn will make it more likely that the desired thermal performance targets will be achieved.
- **Performance measurement** - Measurement of the performance of completed dwellings will become a crucial aspect of the feedback of realised performance back into the design and construction processes and as an indicator of the efficiency and effectiveness of the construction process itself. Existing testing regimes such as airtightness pressure tests will have to become routine and more comprehensive than that required merely for regulatory compliance checks and systems commissioning.

Additional tests will have to be developed that are capable of determining thermal performance in a resource efficient manner.

- f) **Supply chain** - To a large extent house design in the UK is driven by the type and availability of components and materials from construction product manufacturers and the materials supply chain. It is our belief that the introduction of new materials and components is dominated by perceptions of need within in-house research and new product development programmes of the companies within the supply chain rather than in response to the demand for new products from housing developers. Although this may be seen as inevitable, it suffers from problems of narrow vested interests and does not engage sufficiently strongly with developers and the need to extend and improve their design portfolios or to re-engineer their construction processes. What is needed are closer and more effective working relationships between house builders and their supply chain, working together to design products suitable for low energy houses, a process that starts with the whole dwelling working down to the particular components that are required to achieve the desired performance. This more integrated approach would go a long way to solving some of the construction process and performance issues that we have highlighted in this report such as buildability, robustness, sequencing and build tolerances. There will be many opportunities for materials suppliers and component manufacturers to develop new products and improve existing ones in response to the performance requirements of low carbon homes and the imperative for house builders to re-engineer their processes.
- g) **Training and education** - The knowledge transfer process at Stamford Brook took several forms and included formal training sessions, focus groups, review meetings and on-site discussions and demonstrations. However, the process of diffusion of this training and awareness within the different organisations remains unclear and we do not know how well the lessons from Stamford Brook have been retained and applied or how internal processes and procedures have changed. We have concluded from our observations that, if the focus on training and feedback is weakened, as in the case of the airtightness results, then this can result in a resumption of previous patterns of working with a consequent degradation in performance. It was also evident from the design of later details at Stamford Brook that some of the key design principles and tools developed in the earlier phases of the project had not taken hold within the design teams and that the problem of embedding the necessary knowledge and understanding was much more difficult than was at first envisaged. Given the experience within this project and others it is almost certain that UK house builders currently lack the capacity, in depth knowledge and training infrastructure that will be required to implement and sustain the changes that will be needed to meet the design and performance requirements of low and zero carbon energy standards. There is a need for improvements in training and awareness of the issues at all levels for designers, on-site professionals, trades people, the construction supply chain and regulatory authorities. The information and learning from Stamford Brook could be developed further as a comprehensive case study for the industry in order to reinforce the key messages highlighted by this report.
- h) The responsibilities for ensuring that the necessary training and re-education takes place will rest with several organisations. At the level of professional designers, site-based management and trades, it will be the professional and trade institutions that will have to take this on board as part of their CPD

requirements and the supporting educational institutes will have to make available the resources to help this take place. There will also be an onus on universities and colleges to continually refresh and update their own staff so that course content reflects the demands of low carbon design and construction. Above all, courses need to ensure that the next generation of built environment professionals are ready for the challenges of low carbon buildings.

- i) **Communication** - The findings from Stamford Brook have highlighted the critical nature of communication. It is clear that there is considerable scope for improvement in the flow of information affecting thermal performance both upwards and downwards throughout the organisations involved whether developer, designer, subcontractor or individual trade. Very often, design information affecting thermal performance was not available, not at the right level of detail, confusing or just not referred to by operatives. This led to a rather diffuse process as operatives followed their own judgement based on their trade skills and knowledge rather than using detailed design information. In the better understood areas of structure, weather tightness and the like, this may not result in performance degradation but it is not conducive to robust thermal performance. At a more general level, there did not appear to be any particularly well developed mechanism for feeding back information on performance, nor was it clear how the design and construction lessons were being absorbed for use in making improvements to processes or actual designs. To a large extent this is links with our conclusions on the need for a more detailed and clearly defined process control system, for without such a system there can be no definition of problems, identification of their causes or framing of solutions. If the industry is to improve energy and carbon performance, improve its control of construction processes and better integrate design with construction, then an important task will be to look at the way information is communicated within developer and other organisations and between themselves, their partners and subcontractors in the supply chain. Perhaps the most critical aspect of communication in terms of energy performance relates to the availability and precision of design drawings and associated process information and procedural documentation. The experience at Stamford Brook is that this is often not at the right level of detail and that this lack of detailed information can have a significant impact on the measured energy performance of completed dwellings.
- j) **Process improvement and control** – The observations and analysis of the design and construction processes indicate that the control of processes was not always clear, with a number of personnel playing similar but different roles and with very little feedback on thermal performance. An analysis of the control systems being used indicated a very strong reliance on inspection with problems being dealt with informally and on the spot, but with less clarity when it came to the collection, collating and interpreting of process control data and the provision of feedback on performance. Similarly, the roles played by independent site agents and building professionals, such as NHBC inspectors, building control officers, National Trust staff and the Leeds Met research team, were not clear. In general there was no obvious formal framework to provide consistent quality control feedback on particular thermal performance characteristics such as airtightness. It was also apparent that as construction progressed, the original construction specification was increasingly being overtaken by changes in construction. Various changes in techniques,

k) **Energy models and design tools** - There are no specific requirements in Part L1A 2006 of the Building Regulations to take account of heat loss by thermal bypasses. Current conventions and advice documents do not include any guidance for calculating heat losses via party wall cavities between adjacent heated dwellings, as it is assumed, incorrectly, that these losses would always be negligible. This flawed assumption is maintained in SAP 2005, where it states that “Losses or gains through party walls to spaces in other dwellings or premises that are normally expected to be heated are assumed to be zero”. It will therefore be necessary to update SAP 2005 and all accompanying documentation to take account of the potential for the party wall cavity thermal bypass and other similar thermal bypass mechanisms. It is also apparent that both the Part L Accredited Details and Part E Robust Details contain several classes of junction that include some form of thermal bypass. It will therefore be necessary to examine these catalogues to identify any details that have the potential to give rise to a thermal bypass. It is also recommended that a desk study is undertaken to identify other classes of bypass mechanism that may be present in the design of common UK house types or that may be related to specific construction methods and technologies used in the UK. The observed variability in construction quality and the potential effect that this can have on thermal performance raises the question as to whether such variability should

be accounted for in models. One approach could be to apply a general correction factor such as a percentage increase on *U*-values and linear thermal bridging values in order to account for typical variability. However, such an approach would have to be supported by data on real fabric performance of dwellings, for example by coheating tests and/or heat flux measurements.

- l) **Performance monitoring protocols and performance testing** - The research findings from Stamford Brook emphasise the importance of a detailed and comprehensive testing and monitoring programme in order to fully understand the complex nature of the underlying system and process issues that can affect the construction process and realised performance. It is clear that the assessment of performance, both during the construction phases and from post completion testing, is a crucial factor in understanding the construction and design processes. The monitoring and feedback of such test data will also be important as part of any quality control system and continuous improvement process. We have used a range of performance monitoring techniques at Stamford Brook such as detailed photographic records, thermal imaging, pressure tests, coheating tests and monitoring of energy in-use. It is crucial that further methods and techniques are developed in order to provide developers with the required level of data to feedback into the design and construction processes. The use of coheating tests is, we believe, likely to be one of the main tools for the assessment of the fabric performance of different dwelling designs and construction techniques. However, recently published data on the use of coheating tests to measure the real fabric performance of dwellings are very sparse and limited. Further research will be required to develop the coheating test methodology and data correction protocols.
- m) **Occupant behaviour and usage patterns** - Real dwelling performance in use is a function of fabric and system performance and the interaction of these factors with occupant behaviour. We have shown at Stamford Brook that some occupant effects can be significant. For example, over-ventilation of dwellings in winter can give rise to large increases in energy consumption and even small changes to the timer settings of heating systems can significantly improve system efficiencies. Improvements in advice and information provided to householders could be very powerful, providing opportunities to influence behaviour patterns for the better and lead to improvements in in-use energy performance. However, it is notoriously difficult to effect such changes in human behaviour and we do not really know the true extent or impact that such advice is likely to have. It may also be possible to achieve reductions in in-use energy consumption through the use of smart technology and intelligent system controls including prominent energy consumption displays.
- n) **Implications for research to support Zero Carbon Homes by 2016** - A large part of the success of the Stamford Brook research project lies in the action research approach taken and the high level of trust between the research team and the site teams. This trust was built up gradually over the seven years that the Leeds Met worked with the National Trust, the two developers, sub-contractors and other partners. This created a non-adversarial relationship and no-blame culture in which the research team has been able to observe and record construction activities and design outcomes that might have been hidden or otherwise distorted. We have also shown the benefit of detailed observation of the design and construction processes combined with a comprehensive performance testing programme. This has resulted in a much clearer

understanding of heat loss mechanisms, system inefficiencies and the underlying system causes. It must be remembered, however, that Stamford Brook represents a single case study and that achieving very low and zero carbon housing will require an ambitious research programme, involving research into methods approaches, technologies and, most important of all, the way all these aspects come together to produce the product “on the ground”. In our view the research methodologies and analysis techniques employed at Stamford Brook could act as a blueprint for future field studies of low carbon housing. In supporting the production of low and zero carbon homes we recommend that the following types of research studies should be undertaken in a ten year coordinated research and development programme:

- **Design process studies** – This type of study is primarily a qualitative study that seeks to understand the low carbon design process in general and, in particular, the means by which carbon performance is integrated into design. It should identify the issues involved and the barriers to the development of acceptable solutions.
- **Construction studies** – The process by which designs are translated into completed dwellings is crucial to achieving robust carbon performance. Studies of construction are likely to have two complementary objectives depending on how the study fits into an overall research project or programme. In the first place it will be important to understand the processes by which design material is translated into construction, including the approach to quality control and on site performance assessment as construction proceeds and, in the second observations of realised construction will provide important contextual material to support post construction performance monitoring.
- **As-built studies** – Such studies should be designed to verify, as far as is possible through the measurement of fabric and systems in unoccupied dwellings, the extent to which designed performance is achieved. Where in-use performance monitoring of occupied dwellings is to be undertaken, the measurement of as-built performance provides a very important base line against which to set the results of the longer term in-use studies. With some exceptions, such as where new technologies are being evaluated, as-built performance should involve real commercial schemes developed at a scale that is representative of the industry as a whole.
- **Intensive energy in-use studies** – The purpose of this type of study is to generate as clear a picture as possible of performance in use at a detailed, disaggregated, level. This type of study is able to provide data on the different energy flows (space and water heating, cooking and electricity consumption etc.), the performance of services (efficiencies, air flows/air quality etc.) and internal temperatures as well as overall energy consumption. However, use is extremely variable and it is often very difficult to disentangle the impact of different household structures and use patterns on energy consumption. For this reason such monitoring projects require a particular blend of physical and social science so as to understand what performance may be use related and what relates more directly to the design and construction of the dwellings.

- **Extensive energy in-use studies** – This type of study should be designed to provide a statistically robust measure of actual energy consumption within a particular development or a number of developments designed to achieve the same performance standard. Unlike intensive studies, this type of approach concentrates on gathering a small amount of data from a large number of dwellings and its value lies in being able to determine just what level of energy performance is being achieved across a particular cohort. Results from such studies would have considerable benefit in providing timely feedback on energy performance and highlighting areas of underperformance (or, indeed, over-performance) that should be investigated in more detail.

In shaping a long term research programme the overriding objective will be to enable the industry to learn how to produce low carbon housing in a robust and reliable way, the early phases of any programme should be biased towards intensive studies of processes and detailed performance so that studies have considerable explanatory power. Such work would have to be designed so that results can be disseminated in a phased way, as they are obtained and analysed, rather than waiting for the end of what can be quite long projects. As the programme matures and as regulations change, more extensive studies of impact and general performance will be necessary so as to measure overall progress within the industry at large.

Achieving low and zero carbon standards in all new housing will require a coordinated effort in which data is shared and compatible, and where researchers collaborate with each other, the industry and government. Clear leadership will be necessary at all levels and adequate funding will be required to support the programme. All this will be possible only if there is a strong coalition of government, industry and the research community that is committed to long term and fundamental change.

23. We have concluded from our work that, even when one tries hard, current mainstream housing processes are unlikely to deliver, on a consistent basis, housing that meets the demands of the proposed low and zero carbon performance standards for 2016 and beyond and that the underlying reasons for this are deeply embedded in the culture, processes and practice at all levels of the house building industry. Further, we have concluded that change at the level of construction technology and techniques or design tools and the like, are unlikely to effect significant change since they would remain embedded in the same cultures and processes as the old technology and would be just as prone to underperformance. The UK is not alone in experiencing the sort of systems problems that we have identified. Evidence from the United States suggests that similar problems exist within at least some parts of the house building industry on the other side of the Atlantic Ocean. In a study of code compliance in Fort Collins, Colorado during the late 1990s and early 2000s, the authors concluded that designers rarely understood or took serious notice of energy performance issues, particularly when it came to detail design, constructors followed previous, usually flawed, experience and rules of thumb and failed to notice many of the problems that degrade thermal performance. Although the remit of the work at Fort Collins is much broader and less focused on the detail of design and construction than the work at Stamford Brook, the similarities in conclusion are uncanny.

24. The task that is before us in the UK and, so it would seem, others elsewhere, is to bring about fundamental change in the way houses (and other buildings for that matter) are built. House building is a manufacturing system, like any other, and if the required change is to take place we need to re-engineer the whole system based on sound principles. Old tools and processes may have served us reasonably well in a past characterised by undemanding environmental imperatives but in a low and zero carbon future they are redundant and to continue to adopt them would be foolish indeed. We believe that the industry and its supporting infrastructure have reached a critical point in the development of new housing, a point that will demand a fundamentally different way of building our homes.

Introduction

- 1 Stamford Brook is a development of around 700 cavity masonry dwellings being constructed on part of the National Trust's Dunham Massey Estate near Altrincham in Cheshire. The development was designed to an energy efficiency standard some 25% to 35% in advance of the 2002 building regulations for England and Wales (10% to 15% of the 2006 regulations) and the associated research project sought to evaluate the standard and the extent to which it could be achieved in the context of a large scale commercial housing development. Construction on the site commenced in 2004 and is expected to continue until around 2009-2010. The development is being carried out under a partnership agreement between the land owner, the National Trust, and the two developers Redrow and Bryant. The development partners are also participating in the Stamford Brook Field Trial which is a "Partners in Innovation" (PII) research project led by Leeds Metropolitan University (Leeds Met) that is investigating various aspects of the design and construction processes. This report is the final output from the PII project and summarises the results and conclusions of the interim project reports. Also discussed are the results of intensive in-use energy monitoring of four occupied dwellings at Stamford Brook. The implications of the data obtained during the project are discussed in the context of issues such as building regulation, future energy standards, dwelling design, construction processes, training, quality control procedures and occupant behaviour patterns. This report should be read in conjunction with the interim project reports listed in Appendix 1.
- 2 This report, together with its supporting interim reports provide a unique record of the achievements, successes, failures, problems and solutions that occurred during the project and, as such provides considerable insight into the issues that are likely to arise during the implementation of advanced energy standards on a large scale housing developments. The research project team has followed the progress of the development from initial discussions on the energy standard and environmental standard, through the detailed design process, observation of construction of the dwellings, performance testing of completed buildings and monitoring of occupied houses. The project has been a collaborative effort between land owner, housing developers, sub-contractors, supply chain, regulatory bodies, householders and the research team. The data gathered during the project will help to inform the UK housing industry as it rises to meet the challenges resulting from climate change and the proposed new energy targets due in 2010, 2013 and 2016. It is expected that the results from the project will directly influence the development of new standards, test methods, dwelling design process and construction practice.

Background to the Stamford Brook development

- 3 Stamford Brook is located on land which once formed part of the National Trust's Dunham Massey estate. The Dunham Massey estate was left to The National Trust in 1976 by Lord Stamford and is now run by the Trust as a 'Special Trust in Credit'. This means that the estate has to find all the income for its upkeep from its own resources such as from visitor entrance fees and rents from its farm tenants. It receives no external funding. When Lord Stamford left Dunham Massey to the Trust, he was concerned that it should continue to be run as a 'traditional country estate'. With some foresight, Lord Stamford identified certain areas of land on the estate as investment land, which if necessary, could be sold to raise funds for the future upkeep of the Dunham Massey Estate. One of these was the 25 hectare parcel of land at Brookside Farm which now forms the Stamford Brook development.
- 4 The National Trust took the decision to maintain a degree of control over the scope of the development and to work in partnership with the two chosen developers. The Trust wanted to ensure that the development was carried out in a way that was environmentally sustainable, was designed to reflect the quality and character of traditional homes in the local area, that would create an attractive urban fringe environment for the benefit of residents, wildlife and the existing local community and that could also serve as an exemplar of a sustainable development that would be within the compass of all commercial and social housing developers. The development was planned and designed from the outset to an Environmental Performance Standard developed by the National Trust with the two developers that included land use, building density, plot orientation, and a wide range of sustainable construction measures. The underlying principle for the houses was to achieve high thermal performance through passive durable construction measures. As part of the partnership agreement a comprehensive environmental performance standard was developed (National Trust 2003) that set performance targets and requirements for energy use, water conservation, waste minimisation, recycling and material selection for the first phase of the Stamford Brook development that were in addition to those required under building regulation. The additional costs to the developers of meeting the environmental performance standard criteria were funded by the National Trust from the payments made by the developers to purchase the land at Brookside Farm. The National Trust retains ownership and responsibility for the upkeep of the green spaces in and around the Stamford Brook development and all homeowners pay an annual maintenance charge towards the cost of maintaining the common areas.
- 5 Photographs of the development showing completed houses and apartments at Stamford Brook are shown in Figure 1. These photographs illustrate the wide range of dwelling types that have been constructed and the overall aesthetic which, driven by the National Trust, became an important goal of the partnership.



Figure 1 – Photographs of completed dwellings at Stamford Brook

The partnership

- 6 The National Trust decided to work in partnership with the developers Bryant and Redrow for the duration of the Stamford Brook programme. The Trust also recognised the importance of the opportunities that the development provided to generate a better understanding of the development and construction processes for low energy mass housing and also the need to measure the real performance of the dwellings in use compared to expectations. In order to facilitate this effort the Trust worked with the Centre for the Built Environment at Leeds Metropolitan University and the Department for Communities and Local Government (DCLG) and its predecessors to develop a PII research programme to investigate the construction process and also to advise on regulatory, performance and construction issues. Other partners in the research project include the Bartlett School of Graduate Studies at University College London (UCL), the Concrete Block Association (CBA), Vent-Axia, the National Home Building Council (NHBC), Construction Skills and Pilkington. The names of all the key individuals who have contributed to the project are listed in Appendix 2.

Project objectives

- 7 The overall PII project objective was to support future reviews of Part L of the Building Regulations by evaluating the various impacts on a large scale masonry housing development of a range of improvement measures that could be used to meet the requirements of an advanced energy performance standard that would likely be introduced as part of such a review. The impacts and issues that the project was designed to be assessed are outlined in the project proposal (Lowe & Bell 2002) and included the following key issues:
 - a) Technical Impact
 - b) Economic Impact
 - c) Regulatory Issues
 - d) Design Process Issues
 - e) Site Project Management and Construction Process Issues
 - f) In-use Performance
- 8 The project objectives were modified in 2006 after taking into consideration data from the initial round of post construction tests and the difficulties encountered by the research team in recruiting the planned number of households to take part in the in-use monitoring programme. The decision was therefore taken in June 2006 to revise the project objectives and re-orientate resources in order to concentrate efforts on investigations of observed heat losses via the party wall and also to address problems of a trend towards deteriorating levels of airtightness in completed dwellings. This decision limited the number of intensively monitored households to the four who had already signed up at the time and also meant that the intended extensive energy surveys of a wider cohort of occupied houses was not carried out.
- 9 The focus of the Stamford Brook project has been on near-term innovation and its deployment at large scale, in a commercial context. The development has been broadly typical of the volume house building industry in the UK in terms of commercial and contractual arrangements, and management. The real construction context within which the enhanced energy performance standard has been implemented is central to the relevance of the project for the development of energy performance standards in the UK and to the construction industry as a whole. Within the limitations of any case study, we believe that many of the insights from the project can be generalised to the industry at large.

The EPS08 energy standard

- 10 The National Trust and partners decided to use the Leeds Met EPS08 enhanced energy performance standard (Lowe & Bell 2001) as the energy standard for Stamford Brook. With the qualification that the energy goals of EPS08 should be achieved through passive, durable construction measures, this standard was incorporated by the project partners into a broader Environmental Performance Standard, which covered all aspects of environmental performance at Stamford Brook. The EPS08 standard was originally developed as a prototype energy standard for the St Nicholas Court project (Lowe, Bell & Roberts 2003), with the intention that it would inform the revision of the Building Regulations that was

expected at the time to occur in 2008¹. The EPS08 standard defines elemental target *U*-values for the main construction elements, a maximum limit for air permeability and a limit on the carbon intensity of the heating system. In EPS08, calculated *U*-values include all contributions from both point and linear thermal bridges. A summary of the main requirements of the standard is given in Table 1. Compliance with the EPS08 standard is by one of three routes. This can be either the elemental standard as shown in Table 1, an equivalent mean *U*-Value or by a carbon index calculation. The equivalent carbon emission rate for an EPS08 compliant dwelling would be around 10% to 15% better than that required under Part L1a 2006, depending upon dwelling form and size and some 25% to 35% in advance of the 2002 building regulations for England and Wales. For example, an 80 m² semi-detached dwelling built to EPS08 would have a calculated annual Dwelling Carbon Emission Rate (DER) of 20.6 kgCO₂/m² compared to the ADL1a 2006 Target Emission Rate (TER) for an 80 m² semi-detached dwelling of 23.2 kgCO₂/m². EPS08 also stipulates minimum performance requirements for ventilation as shown in Table 2.

Table 1 – EPS08 prototype performance energy standard requirements

Element/Parameter	EPS08 Requirement
Exposed Walls	<i>U</i> -value: 0.25 W/m ² K
Roof	<i>U</i> -value: 0.16 W/m ² K
Floor	<i>U</i> -value: 0.22 W/m ² K
Windows, Doors & Roof-lights	<i>U</i> -value: 1.3 W/m ² K , Max Area: 25% of gross floor area (GFA)
Air Permeability	5 m ³ /(h.m ²) at 50Pa
Carbon Intensity of Heating System	70 kg CO ₂ /GJ Useful Heat – This equates to a minimum gas condensing boiler efficiency of 85%

Table 2 – EPS08 prototype ventilation standard requirements

Minimum Air Supply Requirements for Main Habitable Rooms (l/s)		Minimum Air Extract Requirements for Main Wet Rooms (l/s)	
Double Bedroom	10	Kitchen	20
Single Bedroom	5	Bathroom	10
Living Room	5	Separate WC	10
Dining Room	5		
Other Habitable Room	5		

Stamford Brook design specification

- 11 The target design specification for the main elements, systems and air permeability used by the developer at Stamford Brook in order to meet the EPS08 requirements are given in Table 3. The target elemental *U*-Values in Table 3 do not include any thermal bridging allowance.

¹ In order to maximise the impact on climate change, the Government announced in the 2003 Energy White Paper (DTI 2003) that it would aim to bring forward by three years the expected 2008 review of Part L of the Building Regulations to 2005. A small delay meant the revision was eventually implemented in 2006.

Table 3 – Stamford Brook target design specification

Element/Parameter	Stamford Brook Design Values
Exposed Walls	U -value: 0.23 W/m ² K
Roof	U -value: 0.15 W/m ² K
Floor	U -value: 0.19 W/m ² K
Windows, Doors & Rooflights	Window U -value: 1.3 W/m ² K Door U -value: 1.0 W/m ² K
Air Permeability	5 m ³ /(h.m ²) at 50Pa
Heating System	Potterton Promax 15HE gas condensing boiler with SEDBUK efficiency ranging from 90.8% to 91.3% Sealed system with indirect unvented cylinder
Ventilation System	Vent-Axia Multivent MVCD-MS Whole house mechanical extract system

- 12 A summary of the structural make up of the main construction elements and their nominal U -Values are given in Table 4. Calculated linear thermal bridging factors for all major junctions as initially designed are given in Table 5 and are compared to the default thermal bridging values for Part L accredited details given in SAP2005 (BRE 2005).

Table 4 – Construction elements and nominal thermal performance

Element	Nominal U -Value (W/m ² K)	Main Construction Details of Element
External Wall	0.230	103 mm Facing Brick 100 mm Medium Density Concrete Block (~1400 kg/m ³) 142 mm External Wall Cavity ² 250 mm Glass-filled Polyester Wall Ties (External Wall) Fully Filled Blown Mineral Fibre Insulation Parging Plaster Layer (2-4 mm) on Blockwork of External and Party Walls Plasterboard on Adhesive Dabs
Ground Floor	0.172	150 mm In-situ Cast Reinforced Concrete Suspended Floor 100 mm Rigid Polyurethane Insulation below Slab
Cold Roof	0.142	250 mm Blown Recycled Cellulose Insulation at Ceiling Level
Warm Roof	-	Attic Truss Room-in-roof Construction with 75mm Rigid Polyurethane Insulation between Rafters and 50mm Rigid Polyurethane Insulation above Rafters
Windows ³	1.30	Double Glazed Timber Frame Units

² For semi-detached and terraced dwellings, the party wall cavity thickness was maintained at the same depth as the external wall cavity at 142mm in the case of dwellings built by Bryant but reduced to 75mm in the case of dwellings built by Redrow. In both cases, the party wall was not filled with any insulation except for where the acoustic cavity mineral wool socks installed at the vertical junction between the party wall and external wall may have protruded sideways into the party wall cavity.

³ The windows were also required to have a BFRC domestic window energy rating (DWER) rating of 70 or better (Roberts, Bell & Lowe 2004). The windows used at Stamford Brook achieved a DWER rating of 71 (Chiltern Dynamics 2003).

		Glazing configuration: 4mm glass - 18mm cavity - 4mm glass Ultra Low Emissivity Soft Coating (e = 0.04) Centre Pane Glazing U-value 1.175 W/m ² K Solar Energy Transmittance (g-value) 0.63 Argon Filled (90% argon, 10% air) Low Conductivity Spacer Bar
Doors	1.00	Timber-Aluminium Faced Timber Frame with Polyurethane Core

Table 5 – Linear thermal bridging

Location of Thermal Bridge	Linear Thermal Transmittance Optimised Stamford Brook Details (W/mK)	SAP Table K1 Accredited Details Ψ Values (W/mK)
Cold Roof-External Wall – Gable	0.061	0.24
Cold Roof-External Wall – Eaves	Redrow: 0.023, Bryant: 0.033	0.06
External Wall-External Wall	0.070	0.09
External Wall-Party Wall	Redrow: 0.024, Bryant: 0.027	0.03
External Wall-Ground Floor	0.112	0.16
External Wall-Intermediate Floor	0.004	0.07
Party Wall-Ceiling	Redrow: 0.130, Bryant: 0.157	Not in Table
Window/Door Sill	0.022	0.04
Window/Door Jamb	0.018	0.05
Window/Door Lintel	0.016	0.30

Methodology

Action research

- 13 The Stamford Brook project has been conducted using an action research approach, in which the research team simultaneously participated in (largely in a consultative capacity) and observed the various aspects of the development process. A combination of qualitative and quantitative tools was used to observe, assess and evaluate the design, construction and occupation phases of the development. The decision by the Department for the Environment, Transport and the Regions (now DCLG) to fund this project represents a significant step forward in terms of the range of methodologies available for housing field trials. The Stamford Brook project has been the second major low energy housing project⁴ to have been conducted within an explicit action research framework, and the first that has attempted to track the construction process. It is therefore appropriate to reflect on and review this framework and what we have learnt through and about it.
- 14 The action research approach, with its focus on change and process, with its treatment of those involved in the project as research partners rather than objects of research, and with its ability to address the “why” as well as the “what” of energy performance, is particularly well suited to the demands of such a field trial. In the

⁴ The first was the St Nicholas Court Field Trial (Lowe, Bell & Roberts 2003).

final report of the St Nicholas Court Field Trial (Lowe, Bell and Roberts, 2003), we stated:

“The appeal of action research in the present context stemmed, to paraphrase Greenwood et al. (1993), from the fact:

- *that it addresses real-life problems;*
- *that it is change-oriented;*
- *that it emphasises a participatory approach in which participants and researchers generate knowledge and understanding through collaborative processes in which all participant’s contributions are valued;*
- *that it is an eclectic approach that embraces ideas, knowledge and theory from any source that is able to contribute to the goal of addressing the research problem;*
- *that it does not insist on classical experimental methods as the only way of establishing truth, particularly in the social domain;*
- *that it maintains the validity of meanings negotiated by free agents in the course of undertaking and reflecting upon a shared task.*

[...]

“Finally, the approach appeared to be the only possible way:

- *of enabling stakeholders in the procurement process to develop considered views on the impact of an enhanced energy performance standard, through the process of designing and building dwellings to that standard;*
- *of providing a framework and a process through which the development of those views could be documented and evaluated;*
- *of allowing the research team to participate in and provide technical support throughout the design (and, had it taken place, the construction phase) phase thus ensuring that the other members of the team would not simply be left to sink or swim as they came to terms with the enhanced energy performance standard.*

This last point in our view is crucial. The construction industry has to negotiate changes in the building regulations approximately every 5 years. Such changes are normally negotiated publicly over a period of 2 or 3 years, are presaged by consultation documents and draft approved documents and are underpinned by a wealth of supporting material provided by BRE, BRECSU, CITB, NHBC and others to ensure that, by and large, disasters are avoided. In the case of the 2002 revision to Part L, the industry has had a period of approaching 4 years to adjust to the new requirements. For the St Nicholas Court partners in the context of EPS08 [...], none of this has been true. To have attempted to implement a non-participatory research approach - insisting on clear distinctions between researchers and researched - would have led, in our view to any or all of:

- *unacceptably high risk of technical failure;*
- *unrealistically high costs;*
- *defensive and sub-optimal designs; and*
- *unremittingly negative views from many of those involved on the difficulties imposed by the proposed standard.” (Lowe et al. 2003:4-5)*

- 15 At Stamford Brook, the approach provided an overarching framework for a wide variety of activities, and a range of different investigations using qualitative and quantitative methods. These activities and investigations have facilitated significant innovation in house design and construction, have produced findings of strategic importance and have provided an unprecedented insight into the determinants of energy performance in mass housing. The continued involvement of the developers in the project up to and including the writing of this report is likely to be a key determinant of its impact and credibility within the house building industry and in Government. The success of the project in these respects appears to justify fully the original decision to frame the project in this way, and of the assessors for the PII programme to support the proposal. Nevertheless the implementation of the approach was less than perfect and there is much to be learnt from a reflection on it.

Reflections on the action research approach at Stamford Brook

LEARNING AT STAMFORD BROOK

- 16 Learning from the Stamford Brook project can be divided into level 1 and level 2⁵. Level 1 refers to learning that is specific, context bound and concrete. Specific examples include the partial solution to the party wall bypass, the details of the wide, fully filled cavity wall, the securing of NHBC approval for the use of plastic wall ties, the sourcing of windows to meet a U value target of 1.3 W/m²K, and the development of the parping process to achieve airtightness.
- 17 It is critical to note that the useful life of a significant proportion of level 1 learning is likely to be measured in years rather than decades. The importance of convective bypasses is likely to be a permanent contribution, with relevance to all forms of construction, but lessons relating to the specifics of construction detailing are likely to be overtaken quite quickly by changes in construction technology and practice. A major factor in the short shelf life of much of the level 1 learning from Stamford Brook is the Government's zero carbon target for new housing (DCLG 2006b). If even partially successful, this will result in a period of unprecedented change in the house building industry – change that is likely rapidly to overtake a number of the specific lessons from Stamford Brook.
- 18 Ultimately for the house building industry, it is the fruits of level 1 learning that are built into houses and determine their performance. For academia, the fruits of level 1 learning would include specifications and protocols for various types of investigation. The purpose of level 2 learning is to increase the ability of individuals, systems, research groups and companies to learn and to apply learning at level 1. What was established at Stamford Brook was an environment and a process within which learning could and did take place. The key questions at level 2 are, how did we achieve this, how might we repeat it, and how might we improve upon it?
- 19 With the benefit of hindsight, it is clear that the action research approach, whilst successful, has been implemented only partially at Stamford Brook. The reasons for this include the fluid nature of employment on the site, the tight initial budget for

⁵ These learning levels are based on Bateson (1973). Bateson summarised level 1 as “learning” and level 2 as “learning to learn”.

the research project, the unexpectedly long duration of the project (now approaching 7 years) and the difficulties of keeping the whole project team together over this period. But they also include the lack of AR experience within the research team, dominated as it was by the disciplines of building physics, surveying and engineering. This latter deficiency, at least, should be addressed in future projects. While this would substantially increase their cost, we believe it would also significantly increase their value.

Specific weaknesses of the research effort at Stamford Brook include:

- a) Much of the data from the contract negotiation and early design phases of the project remain unanalysed and unreported. The development of the environmental performance standard was a truly participatory process, which lasted until early 2003. We began to document this process in Deliverables 2 and 4, but there is more material in the form of meeting notes, minutes, spreadsheets that has not yet been analysed. After the passage of so much time, there must be doubt about the value of now doing so.
- b) One of the most important vehicles for collective reflection over the life of the project was the Advisory Group Meeting. The Advisory Group met roughly quarterly throughout the project. Minutes were taken, and from 2005 onward, meetings were recorded. As with records from the design process, this material has not been reviewed or analysed. None of the documentation from the project really captures the sense of involvement and excitement that was present at various stages through the project, or of the tensions between partners that became apparent from time to time.
- c) The training programmes undertaken by Roberts shortly after the start of construction were reported only briefly in Deliverable 4, but not evaluated.
- d) Too little time was available, during the final evaluation phase of the project, for engagement with the partners and although there were a number of useful iterations in which the partners commented on and contributed to the evaluation, the final report remains dominated by the voice of the research team. This reflection was written at the very end of the process as a partial attempt to address this final weakness, and in the hope of prompting and focusing further reflections from all partners in the project, while these are still reasonably fresh.

TIME AND MONEY

- 20 Comparison of Stamford Brook with its predecessor, St Nicholas Court, suggests that at Stamford Brook, the participatory process was placed under strain by two specific factors – the length of the project, and the inclusion within it of the construction phase. The demands placed on both the research team and the developer partners by the construction phase of the project were intense.
- 21 One of the factors that was insufficiently appreciated at the start of the project was the time needed to establish a participatory action research project in construction of this magnitude, length and complexity. From the viewpoint of the research team, planning began in mid 1999 with a search for a partner for a project designed to explore the impact of the enhanced energy performance standard that had been developed for the St Nicholas Court Project in the context of load bearing masonry construction. An outline bid for Partners in Innovation funding was submitted in autumn 1999, and a full bid early in 2000. There followed more than a year of negotiation before contracts were signed with the main partners in the research project following a meeting in April 2001. Negotiation between the Trust and the

developers for the sale of the land took a further two years – the contract for the sale went unconditional in June 2003. The following year was taken up with the construction of infrastructure: the construction of an access road into the site from the A56, a bridge over the railway that runs along the southern edge of the site, and the first estate roads. House construction began in July 2004, and the first houses were completed mid 2005.

- 22 The Stamford Brook Partners in Innovation Project (PII), which was originally conceived of as a 33 month project, has therefore dominated the lives of the research team from the beginning of 2000 to the end of 2007 and the lives of our partners for almost as long. While the cost of some of this overrun was covered by some project extension funding from project partners, most of it was borne by the University. It has been customary, for at least a quarter of a century, for researchers involved in housing field trials to conclude that such trials are almost always under funded and subject to delays because of factors over which research teams have little or no control. This project and this research team are no different in this respect, though it is ironic that the authors of this report have themselves made such statements on several previous occasions. It is perhaps time for this research team, the wider research community and research funders to absorb and act on the lessons from this history, and to establish more flexible methods of funding, with provision for contingencies on a scale more appropriate to the evident risks and uncertainties.
- 23 Two final observations need to be made here. The duration of the Stamford Brook Project is longer than the nominal 5 yearly cycle of building regulation revision, almost as long as the period remaining before the Government's proposed zero carbon standard for new housing comes into force (DCLG 2006b), and more than half as long as the period remaining before the European Union's CO₂ emission reduction target for 2020 (CEC 2006). This long timescale is a further argument in favour of an approach to research that is able not just to discover what happens, but to shed light on why – the rate of change that needs to be supported over the coming decade allows too few iterations for such fundamental questions not to be addressed in some detail. This issue is addressed later in the discussion section of this report. It also provides an ethical justification for foregoing any approach to research that stifles rather than harnesses the imaginative and innovative capacities of partners – to interfere so deeply in the lives of others over such a period without providing scope for personal and professional growth and development should be out of the question.

TRUST AND TENSIONS

- 24 There is a need in projects such as this, for time to build up trust. One of the most important tasks of the period from 2000 through to the conclusion of the contract between the Trust and the developers, was to build up trust within the triad formed by National Trust, the developers and the research team. At the beginning of 2000, none of the actors in this three-way relationship had any particular reason to trust the others. The developers and National Trust were brought together by an accident of land ownership – the former owned land that governed access to Brookside Farm on the Dunham Massey Estate which the Trust wished to develop. Neither the Trust nor the developers had had any contact with the Leeds Metropolitan University team before the autumn of 1999, and had no reason to assume that we were in a position to make a positive contribution to the project.
- 25 The fact that the development has achieved as much as it has in terms of energy performance is due in large part to the Trust's insistence that Stamford Brook

make a significant contribution in this respect. This insistence stemmed from the commitment of key individuals within the Trust, particularly of Rob Jarman and Sara Braune, from Trust policy in support of sustainable development, and from the Trust's requirement to demonstrate to its membership that the sale of a portion of the Dunham Massey estate would achieve objectives that went beyond maximising the sale price.

- 26 We believe that a further contribution to the Project's achievements was a perception on the part of the developers that the context for house building was changing, and that with or without the Stamford Brook project, they would have, within a few years, to raise the energy performance of their product. This perception arose from a combination of increasing certainty around the issue of climate change, a sense that the Government was preparing to raise regulatory standards for new homes significantly, and the increasing weight attached by the developers themselves to the issue of Corporate Social Responsibility.
- 27 Throughout the contract negotiation and design phase of the project, Lowe and Bell, supported by Roberts, acted as advisors to both of the other parties, as well as (imperfect) documenters of the process. At the same time they attempted to use the opportunity to advance their own agenda for energy efficient housing⁶. The fact that this agenda was more closely aligned with that of the Trust than of the developers, meant that the role of the Leeds Metropolitan University team was delicate. The Leeds Metropolitan University team is of the view that the survival of relationships between all three partners through the contract negotiation phase (and indeed to the end of the project) was due to:
- a) the fact that each understood the position of the other two
 - b) the fact that the tensions between the partners were discussed between the partners on a number of occasions
- 28 Specific sources of tension during this phase of the Project were the cost of energy efficiency and other environmental measures that were required by the Trust and, specifically, the developers' concern that the airtightness standard proposed in the energy performance standard (Lowe and Bell, 2001) and required by the Trust and would not be achievable⁷. The former was overcome through the process of negotiation between the Trust and the developers, assisted (we believe) by specific contributions from the research team and from the developers working in collaboration. Such contributions included:
- a) the sourcing of high performance double glazed windows from Rationel at a price significantly below the cost of equivalent windows sourced in the UK – the financial saving that resulted was of the order of £600,000 (£3,000 per dwelling) over the first 200 dwellings
 - b) the demonstration, in an exercise led by Joe Isle of Bryant Homes, that the airtightness standard required by the Trust could be achieved by extending the parging process, already used by a number of developers to achieve compliance with Part E (acoustics) of the Building Regulations, to all internal walls within the dwelling

⁶ This had been set out in 1998 by Lowe and Bell, in *Towards Sustainable Housing: Building Regulation for the 21st Century*.

⁷ This standard had originally been set at 3 ac/h @ 50 Pa in EPS08, and was relaxed to 5 m³/h.m² @ 50 Pa during the contract negotiation and design phase of the project. The change was prompted by discussions with the building regulations division and was based on the suggested future standards contained in the consultation on the 2002 revision to part L (ODPM, 2000, part 5).

- 29 The latter, reported by Roberts, Johnston & Isle (2005), demonstrates probably better than anything else, the advantage of the AR approach over alternatives. Such a development would have been unlikely within a classic controlled field trial and were it to have taken place, the conduct of the trial would be called into question.
- 30 A final source of tension that will be mentioned here was between the aesthetic and functional aspects of the design. In one case at design stage, the detailing of window reveals presented a conflict between thermal performance and aesthetics, which was resolved quickly and satisfactorily through a discussion, in a meeting devoted to passive solar layout and detailed design, between members of the research team and Peter Fauset and David Kendal of JDDK Architects, who were responsible for the overall design of the scheme. In another case from the construction phase, a detrimental change in roof vents specification for the mechanical ventilation systems was identified following performance testing by the research team, and the problem was resolved retrospectively with further changes to the specification of the roof vents. (See paragraph 160 and Wingfield et. al., 2006).

STAMFORD BROOK AND THE DEVELOPMENT OF ENERGY PERFORMANCE STANDARDS

- 31 There are grounds for believing that Stamford Brook helped to shape the climate of opinion in which the 2006 revision of Part L was undertaken. The relationship was not simple or mechanical, and the evidence for it remains anecdotal and based in the main on the perceptions of Lowe and Bell, the members of the Leeds Metropolitan University team who participated in the Part L review. We believe in particular that the early results from the Stamford Brook project provided the Department (now DCLG) with some confidence that the construction industry would be able to accept and deliver two key features of the energy performance standard that emerged from the review process – an upper limit to air permeability of 10 m/h @ 50 Pa and the wider walls needed to achieve U values of 0.3 or below. The demonstration by the project of high performance double-glazed windows and of a variety of techniques for reducing thermal bridging showed that the new standard left the industry with room to manoeuvre, and justified the incorporation into it of a fuller treatment of thermal bridging.
- Key factors in this were:*
- a) the independence of the research team from the Department
 - b) the collaborative nature of the project, and the presence within it of developers who acted as guarantors of the relevance and validity of the results of the project in the context of large scale house building
 - c) the fact that the goals of the project were defined as supporting near-term rather than blue sky innovation
- 32 Undertaking near-term research imposes its own risks. The most obvious is that the goals of the project will be overtaken by general advances in energy performance standards and construction practice. The man who chooses to walk in front of the bus to show it the way is likely to come to grief. In the end, practice, regulation and the Stamford Brook Project managed to stay more or less in step: of the three, practice within the industry as a whole advanced the slowest, while the change in regulation that had originally been expected in 2005 was in the end delayed to 2006, matching the delays in contract negotiation and design phase of the project.

- 33 The appropriateness and effectiveness of using research in this way to support regulatory change is one that should be discussed with our partners and funders at DCLG. It is perhaps worth noting that the Stamford Brook Project was initiated four years before the review of Part L that (we believe) it supported. We are unaware of any analogous project now under way that could support the 2010 review. Given the timescales and uncertainties involved, getting the timing and goals of such research projects right is not a trivial matter. This problem will be made more difficult by the much greater rate of change expected over the next decade.

CONTEXT

- 34 One of the fundamental issues not addressed in depth in the rest of this report is the impact of contextual and industry organisational and structural factors on the project and its conclusions.
- 35 An example of the importance of context and structure is raised by the extent of the use of sub-contracting in the modern house building industry and its impact on dwelling performance and the ability of the industry as a whole to innovate. This question surfaces briefly in this report in connection with the rise in air permeability that took place around the middle of the period of construction described here, and the measures that were taken by the developers to correct it. The issue appears to be important, but it is not one that has been addressed or discussed at length by the partners. It appears that action research can sometimes help to illuminate the problems of structure, and suggest potential solutions, but developing and implementing solutions is likely to require further rounds of action research using other tools and approaches and to be beyond any single project.
- 36 A second example of the importance of context is provided by the task of deciding what general lessons to draw from the discovery of the party wall bypass. It would be easy to conclude that the fact that this bypass has gone almost unnoticed until now is evidence of failure in quality assurance processes within the construction industry itself. Such a view overlooks other important contributory factors in the development of building science and in the wider context of construction in the UK.
- 37 The forensic investigation that first brought this heat loss mechanism to light at Stamford Brook has become significantly easier and cheaper to do over the last 20 years. In the early 1980's, infra-red cameras were bulky and cooled by liquid nitrogen and their resolution was poor. It would have been difficult to have carried such a camera into an attic, and even if this had been done, the images that resulted may not have revealed the effect. There appears to be a tendency, even on the part of those who were involved in construction research at this time, to forget how difficult, expensive and in some cases ineffective were the investigatory and analytic techniques that were in use at the time. The improvements that have taken place in these respects make it possible to undertake more, more detailed and more effective investigations of energy performance in buildings than ever before⁸. The idea that techniques that were available through the 1980's and 1990s at only a handful of sites in the UK could or should have been applied by the construction industry to measure and control the performance of its product, is unrealistic.

⁸ Examples abound. The infra-red camera used in the final months of the project was a factor of 5 cheaper than the one used in the initial investigation of the party wall bypass that took place the previous year, and 60% lighter – but with essentially the same performance.

- 38 A significant contribution to the delays in uncovering and characterising the cavity wall bypass can be ascribed to a relatively underdeveloped UK building science community, compounded by loss of a large proportion of that community and its basic infrastructure as an indirect consequence of the privatisation of the energy industries following the 1989 Energy Act, coupled with systemic failures in the system of research funding. These are substantial claims, which are however supported by the history. Siviour, who through the 1980's and early 90's was based at the Electricity Council Research Centre (ECRC) at Capenhurst, published his technical note on empirical *U* values of house walls in 1994 and retired shortly afterwards. With the transfer of the laboratory first to ERDC in 1989, then to EA Technology in 1991, much of the capacity at Capenhurst was lost. With it went the most immediate possibility of confirming and extending Siviour's results. The decade that followed the publication of his paper saw the privatisation of the Building Research Establishment and the loss of much of its building science capacity. In overall terms, the period from 1997/8 to 2004/5 saw a 69% reduction in public funding for applied construction research (House of Lords European Union Committee⁹ 2004, House of Lords Science and Technology Committee 2005).
- 39 Much the same is true with respect to the problems of plasterboard-on-dabs construction. The earliest hint that this form of construction was poorly understood and that its use might result in significant additional heat loss was present in the Pennyland Project, which was funded in the late 1970's under the Passive Solar Programme and subsequently through the Science Research Council's Specially Promoted Programme on Energy. This hint came in the form of anomalously high energy consumption for a group of houses, Neath Hill, which alone among the field trial dwellings, had been constructed using plasterboard-on-dabs construction. The finding was not well understood, and the possibility of a link to the use of plasterboard was not recognised until some years afterwards.
- 40 The main findings of the Pennyland Project and the parallel Linford Project were that passive solar could, at best, make a marginal contribution to space heating in housing, and that insulation and airtightness were the keys to reducing demand for space heating. The negative finding with respect to passive solar resulted in the transfer of the Passive Solar Programme from ETSU to BRECSU and a shift in priorities from empirical investigation to modelling. The potentially much more interesting findings with respect to insulation, airtightness and the unexplained Neath Hill result did not, however, result in the establishment of an alternative programme to explore them further. The first technical paper on the energy performance of dwellings built with dry lining was published in 1995, more than 15 years after the introduction of the technique on site, by Rayment, who was based at the BRE. As with Siviour's paper, Rayment's coincided with the privatisation of the BRE and the ensuing decline in funding for applied construction research.

⁹ In his evidence to this committee, Sir David King, the Chief Scientist until 2007, stated: "*When I first got this job, I set up an Energy Research Review team to look at the current state of energy research in the UK. We found, my Lords, something very unnerving, which is that, faced with the climate change issues, the UK's investment in energy research had dropped very sharply. The reason for that is very simple. The Central Electricity Generating Board had been privatised and the utilities, as they took it over, shut down the research laboratory that they had inherited. The net result is that our major repository of energy research, which was within the Central Electricity Generating Board, has closed down.*" As noted above, these comments apply not only to the capacity for research into energy generation and transmission that was undertaken at CERL, but also to the UK's capacity for applied construction research.

- 41 The systemic failure in the system of research funding referred to above, relates to the mismatch between the approach of the EPSRC and the nature and requirements of applied research in construction. The main test applied by EPSRC to a funding proposal is whether it is scientifically innovative. The authors are uncertain as to whether a proposal to EPSRC to fund work to investigate thermal bypasses would have passed this test – such work would have used existing measurement techniques to investigate a phenomenon that had been identified and documented in the late 1970's, and that involved no new physics. The main funding body for engineering and physical science operates under a conception of engineering and physical science research that makes it difficult if not quite impossible for it to engage with the detailed, context- and process-bound problems that arise from the deployment, as opposed to the initial development of technology.
- 42 In principle, for many years, BRE, ECRC and the Watson House laboratory operated by British Gas, provided a focus and funding mechanism that complemented that of EPSRC, but a large part of this was lost or dispersed on their privatisation and closure. These laboratories operated in partnership with the construction industry as more narrowly defined. One of the functions of the laboratories was to support an industry-wide quality assurance process. The mechanism was complex and slow acting but broadly appropriate to an era when technological change was slow, performance requirements modest, and the craft cultures within the industry relatively stable. To conclude without this qualification that the industry lacks such a mechanism is over simple. It is more correct to conclude that from the end of the Second World War to the early 1990's, the industry had such a mechanism, albeit neither perfect nor in a form that conforms to current models of how such systems should be implemented, but that from the early 1990's onward, key components of this system were dismantled. One of the many consequences of this was to leave research funding mechanism operated by the EPSRC looking isolated and unbalanced.
- 43 The recent establishment of the Technology Strategy Board, which is intended to operate in parallel with EPSRC and other organisations within an overarching Energy Research Partnership, and which is designed among other things to support the deployment process, may or may not address this structural weakness.

Summary of results

Design process observations

- 44 The involvement of the Leeds Met research team during the design process is detailed in project Deliverable 2 (Roberts, Bell & Lowe 2004). During this process, the research team advised the design teams on various aspects of detailing that would be needed to meet the thermal insulation, thermal bridging and airtightness requirements of the EPS08 standard.
- 45 It was apparent from an analysis of the designs of the dwellings at Stamford Brook that, although a significant attempt was made to follow general thermal design rules and principles, this intention did not always result in robust thermal design and construction. It has also become increasingly apparent during the later phases of the project that many of the critical decision making processes needed to ensure energy efficient dwelling design have not yet been embedded within the developers' design culture. This has been highlighted by observations of thermal

deficiencies in the design of some details in new dwelling types currently being constructed at Stamford Brook. The research team were not involved during the design of these new types and the flawed details were not present in the original portfolio of dwelling designs. This suggests that the designers have not yet fully understood some of the sometimes complex design concepts relating to such aspects as thermal bridging and the primary air barrier. That some of the key design principles and tools developed in the earlier phases of the project had not taken hold within the design teams is a clear indication that the task of embedding the necessary knowledge and understanding was much more difficult than was at first envisaged, and this will have significant implications for training and development for the housing industry as whole. Given the experience within this project and others it is almost certain that UK house builders currently lack the capacity, in depth knowledge and training infrastructure that will be required to implement and sustain the changes that will be needed to meet the design and performance requirements of low and zero carbon energy standards. There is therefore a need for improvements in training and awareness of the issues at all levels for designers, on-site professionals, trades people, the construction supply chain and regulatory authorities.

- 46 Other potentially important changes to design that were identified during the course of the research project have yet to be implemented in dwellings now being constructed. This illustrates that it can take some time for new information to filter through to designs and perhaps that developers are understandably reluctant to make major changes to designs on existing developments.
- 47 To a large extent the research team – design team relationship during the initial design phase of the project tended to reinforce existing cultures within the developer's organisation. Although the developers took responsibility for undertaking detailed design, they relied heavily on the research team to do thermal bridging calculations and advise on their design implications. In general this was seen as a "specialist activity" beyond the compass of the detailed designer, as is typically the case when structural calculations are required. At no point did the developers take over thermal bridging calculations, preferring, instead to follow the general rules gleaned from the initial calculations. Had greater emphasis been placed on developing capacity within the developers' designers, some of the detailing problems observed later in the process may have been reduced. However, given our conclusions (see paragraphs 218 to 221) on the general lack of a process control culture within housing development, it is likely that attempting to address specific deficiencies such as thermal bridging calculation would have little impact unless the deeper systems problems are addressed.

Construction observations

- 48 Observations by the Leeds Met team of the construction of dwellings at Stamford Brook commenced in September 2004 when the initial infrastructure works were already under way and continued up until the final stages of the construction of Phase 1 of the development in June 2007. The early stages of observation concentrated on checking how the designs were actually being constructed on-site and identifying and rectifying any initial problems with either materials, components or sequencing. These initial observations are reported in project Deliverable 4 (Roberts, Anderson, Lowe, Bell & Wingfield 2005). The later stages

of observation concentrated on the identification of possible design flaws, buildability problems, workmanship issues, product substitution and other process factors that could affect the as-built performance of the dwellings. It is not possible within the scope of this report to describe all of the site observations in detail. Instead, selected observations have been used to illustrate some of the critical factors and how they might influence energy usage in terms of the continuity of insulation, thermal bridging and airtightness, as well as other performance criteria such as acoustics.

INHERENT DESIGN PROBLEMS

- 49 Some of the dwelling types at Stamford Brook incorporated some quite complex detailing in features such as recessed doors and bay windows. Observations of the construction of these details on site showed that they often contained inherent design difficulties that have high potential for problems with continuity of thermal insulation, thermal bridging or airtightness. Perhaps the best example of such complexity is exhibited by the recessed front door porch detail. Examples of this detail in completed dwellings are illustrated in Figure 2.
- 50 Photographs of the recessed door in various stages of construction are shown in Figure 3. It can be seen that, in order to accommodate the recess, the detail requires the use of 3 single leaf lintels to support the recessed inner blockwork (2 lintels) and the inner leaf of the main external wall, together with a single leaf arched lintel to support the external brick leaf to the main wall. It is apparent from these pictures that there are multiple changes of plane to resolve both in terms of airtightness and continuity of insulation. Clearly, this detail would require quite careful setting out and a high level of workmanship in order to ensure the desired standard of finish. This detail was not one of those that was analysed by the research team in the early stages of the project, either using thermal modelling or as part of the initial review of the airtightness strategy during the design phase. However, it is apparent from observation of this detail, as constructed, that it contains significant problems, both in terms of thermal bridging and discontinuities in the air barrier.



Figure 2 – Recessed doors in completed dwellings



Figure 3 – Construction of recessed front door

- 51 In relation to thermal bridging, it can be seen that the lintel supporting the main internal blockwork wall (see A in Figure 3) bypasses the cavity wall insulation and would form a significant thermal bridge as shown by the red arrow in the sectional drawing in Figure 4. The soffit of the recess was finished off with a piece of plain cement board attached to the underside of the lintel, with no attempt being made to minimise the thermal bridge by for example using an insulated board. Heat loss via this thermal bridge can be seen using an infra-red thermal camera as shown in Figure 48 in the later section on thermal bridging. It can also be seen that there is a significant discontinuity in the primary air barrier at the head of the door as there is no designed airtight connection between the parging layer on the upper blockwork wall (A in Figure 4) with the parged layer on the lower section on blockwork (B in Figure 4). This would likely give rise to air leakage at this point, especially when taking into account the many service penetrations into the intermediate floor, which are not always effectively sealed.

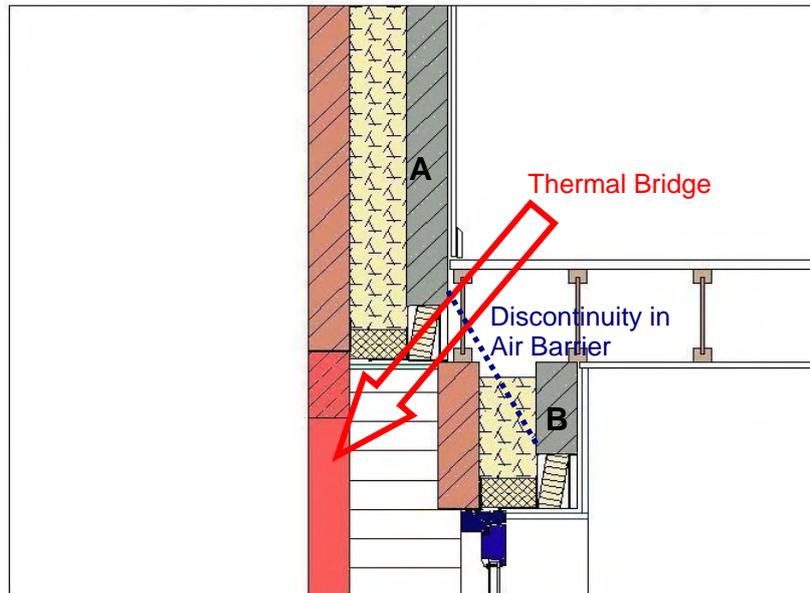


Figure 4 – Section through recessed door detail as built

52 A more detailed analysis of the air leakage around the recessed front porch detail is given in project Deliverable 6 (Miles-Shenton, Wingfield & Bell 2007). The research team have only been able to find one general arrangement (GA) drawing that shows the recessed door arrangement and have found no specific detail drawing. The GA drawing does not match the detail as constructed, which indicates that the site team have, in part, developed the detail on site without consulting the design team. Clearly, this detail needs significantly more attention at the design stage to resolve the issues we have identified and suggests that the technical processes and management culture needed to achieve this standard of design are not yet fully embedded within the organisations. It is likely that this inertia to change will exist across the UK housing industry which clearly has implications for training but also for the development of management systems and design cultures. Given the exacting requirements for zero carbon housing, it is difficult to see how the goal can be achieved in mass house building without changes in the way that design and construction processes are set up so that there are robust procedures in place that will capture, resolve and feedback issues such as buildability and thermal performance. Reductions in complexity could also be achieved with an architectural "self-denying ordinance" by which designers would forego the use of features and details that were too complex to be worked out satisfactorily.



Figure 5 – Bay windows in completed dwellings

53 Other examples of complex detailing at Stamford Brook that have yet to be effectively designed both thermally and for airtightness are the various ground floor bay window designs, as illustrated by the completed examples in Figure 5. These are generally constructed with a combination of short sections of low height cavity walls, timber windows and a timber roof with lead covering. External thermal imaging of dwellings with bay windows showed significant heat loss around the bay window head (see Figure 49 in thermal imaging section). This heat loss is associated with the thermal bridge created by the outer lintel supporting the brick leaf (A in Figure 7). The detail drawing of the bay (Figure 6) shows that the ceiling of the bay should have been constructed with insulated plasterboard, which would have reduced the heat loss to some degree. However, observations of construction showed that plain plasterboard was used. Thermal images from inside during a coheating test on a dwelling with a bay window also showed both the thermal bridge and an air leakage path into the plasterboard plenum at the junction between the timber roof and external wall, which had not been sealed during construction and also via the cavity (see Figure 8). Again, this detail needs more attention both at the design stage and also in interpretation of the design during construction. This, incidentally, is an example of a detail that could probably be made simultaneously better and cheaper: in this case by omitting the lower three courses of external brickwork and running the cavity insulation directly into the bay window roof.

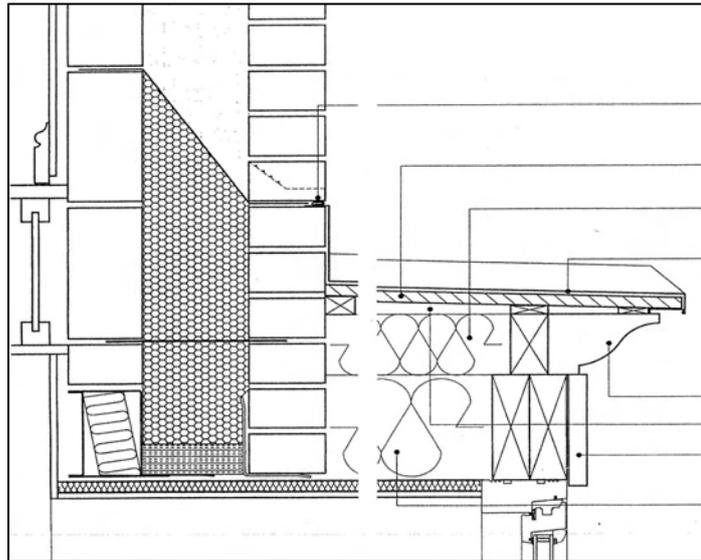


Figure 6 – Bay window detail drawing

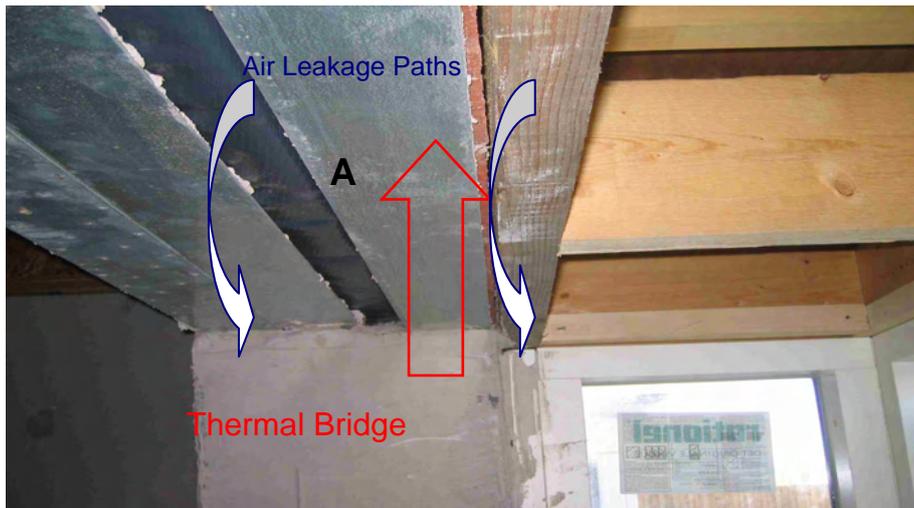


Figure 7 – Bay window under construction

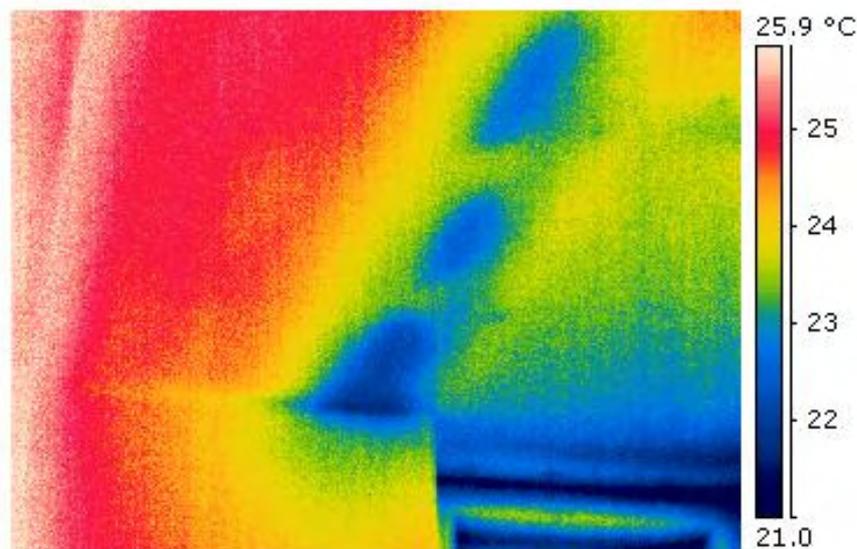


Figure 8 – Infra-red thermal image of bay window head taken from inside during coheating test

WORKMANSHIP

54 One of main areas of concern relating to general workmanship was with the variability in quality of the brickwork and blockwork. In some cases the quality was excellent, with clean cavities and well filled mortar beds and perpend. However, the research team observed several instances of debris in the cavity, poorly filled joints and significant mortar snots bridging the cavity, especially at cavity trays. Some examples are illustrated in Figure 9.

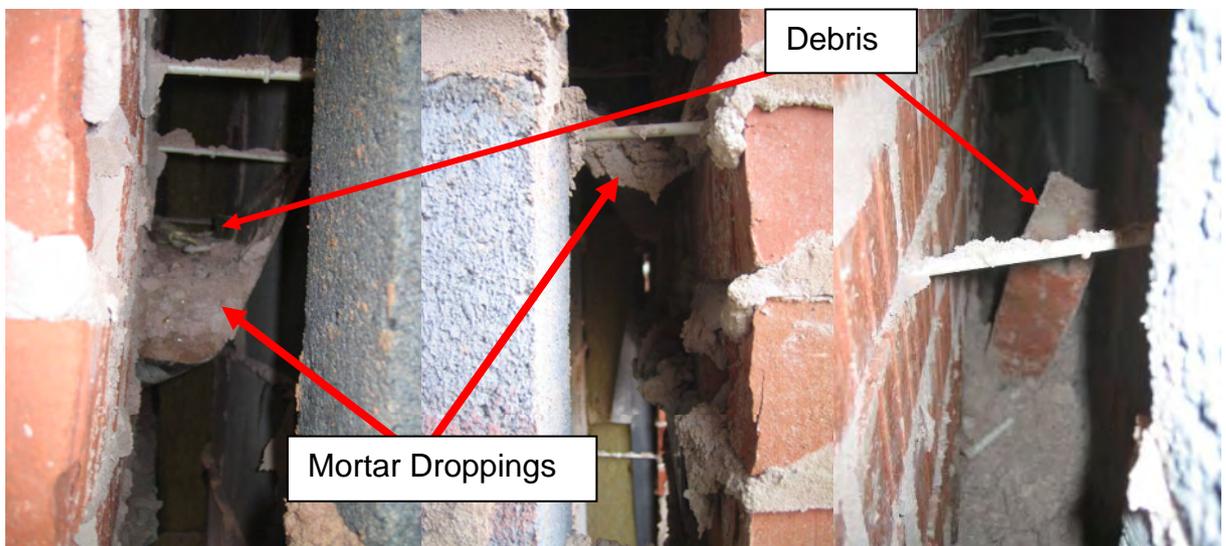


Figure 9 – Excessive mortar snots and debris in Cavity

55 Other workmanship problems related to the proper fit of components. For example, the fitting of the mineral wool insulation batts between the lintels above door and window head was often observed to be poorly executed, resulting in multiple air gaps as shown in Figure 10. These air gaps would have the effect of increasing thermal bridging across the junction, as illustrated by the thermal image of the door head shown in Figure 51. Part of the problem here is that the design of

the detail does not take into account the difficulties of construction, requiring adherence to tolerances that are unrealistic and, in some cases, almost impossible to achieve. There are clearly opportunities for better component design that would reduce or remove completely these problems. For example, in the case of the window head it is possible to envisage a specially shaped section of insulation that would completely fill the gap between the lintels and the cavity above. This approach would necessitate much closer cooperation between developers and their supply chains in order to develop appropriate solutions for a range of details.

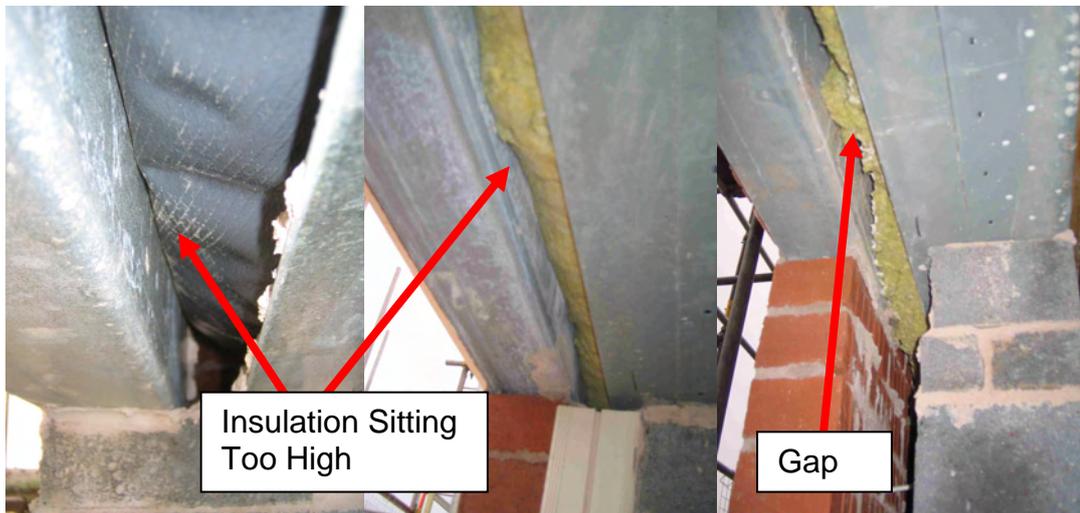


Figure 10 – Workmanship faults at window and door heads

BUILDABILITY

- 56 Perhaps the best example of a detail that has intrinsic problems with buildability is the use of plasterboard on adhesive dabs with perimeter sealing. The experience, not only from Stamford Brook, but also from other work carried out by Leeds Met on a range of construction sites across the UK (Johnston, Miles-Shenton & Bell 2006) is that it is extremely difficult, if not impossible, to achieve completely airtight perimeter seals around the edges of the plasterboard. Observations of the plasterboard installation teams at Stamford Brook show they are actually making considerable efforts to try and achieve continuous ribbons of adhesive, and from conversations between the research team and individual plasterers, they were all aware what was expected of them and the need for a high quality approach in order to achieve the desired levels of airtightness. The photographs in Figure 11 show typical application of adhesive ribbons prior to fitting the plasterboard. It can be seen that the ribbon of adhesive is formed by a line of adjacent dabs that are trowelled on by the plasterer. It can also be seen that there is a gap between the adhesive ribbon and the edge of the wall which is necessary to allow for the smearing of the adhesive and escape of air when the board is applied on to the wall.



Figure 11 – Application of perimeter ribbons of plasterboard adhesive

- 57 Observation of exposed edges of the board at reveals and junctions shows that, after the board is applied, gaps in the adhesive ribbon will always remain where the dabs that form the ribbon meet as illustrated in Figure 12. There will also be a small gap running around the edges of the board where the adhesive ribbon has not quite smeared out right to the edge. These gaps will allow the free movement of air in the plenum formed between the plasterboard and blockwork wall. The multiple plenums across the house will all be linked up due to the unavoidable gaps that we have observed and, in effect, create a continuous leakage path that will serve to link up all the other leakage paths and voids within the dwelling. This air movement can be demonstrated by thermal images taken of the ceiling-wall junction when a dwelling was being depressurised during an airtightness pressure test as shown in Figure 13. It can be seen in Figure 13 (A) that cold air from the loft (coloured blue) is being pulled down due to the pressure difference through the gaps in the adhesive perimeter ribbon and into the plasterboard plenum. In Figure 13 (B) cold air can also be seen being pulled into the framed partition wall. It is apparent that it is virtually impossible to build this detail as intended which will obviously have a significant detrimental effect on airtightness. It is worth noting that continuous ribbons of adhesive would have been unnecessary if the houses had a separate continuous air barrier at this junction where the parging layer was explicitly linked with the ceiling. In practice, the air barrier at Stamford Brook consisted of a complex and poorly defined combination of plasterboard and parging.

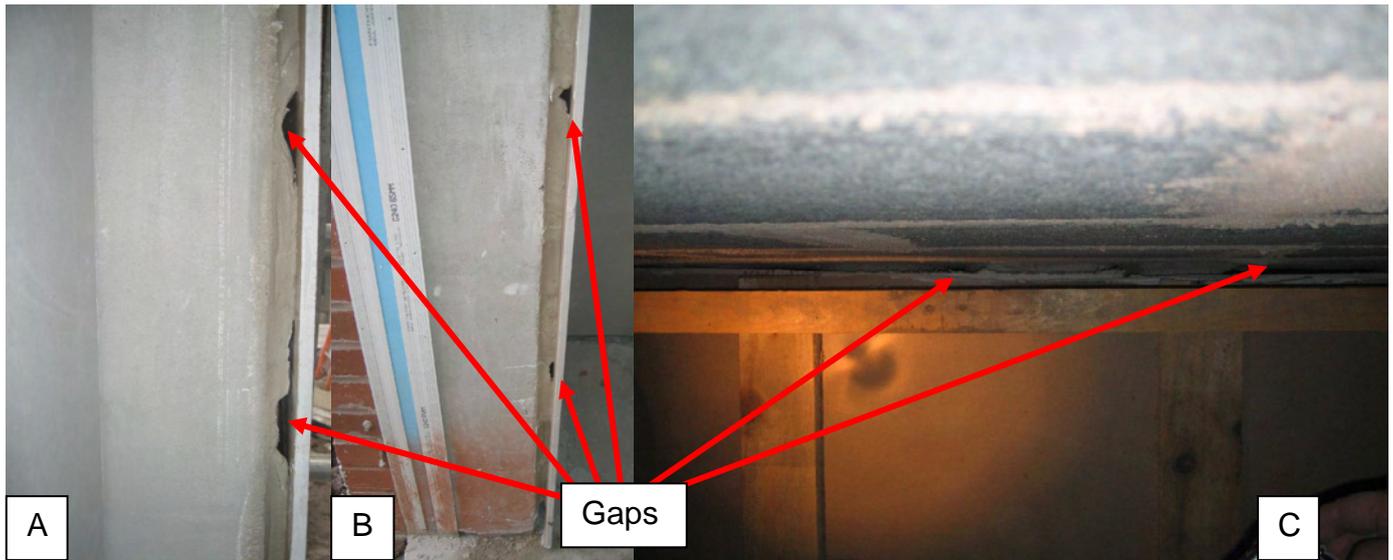


Figure 12 – Gaps in plasterboard perimeter ribbon at reveals (A, B) and loft-ceiling junction (C)

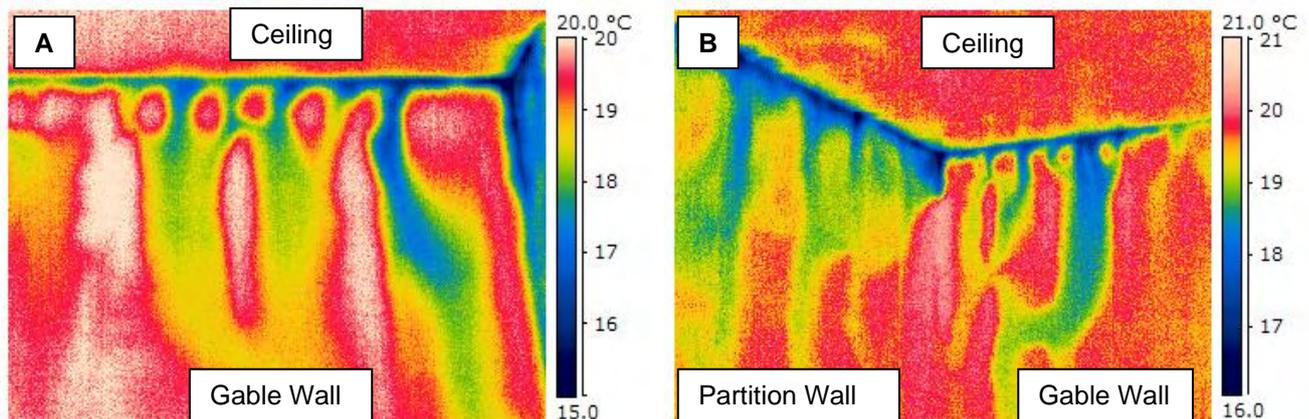


Figure 13 – Thermal images of ceiling-wall junctions during depressurisation test

58 There is compelling evidence to support the belief that the relatively high levels of air leakage observed in modern UK mass housing compared to European best practice standards is, in large part, related to the continued reliance of UK house builders on the use of plasterboard on dabs as an internal finish and air barrier, coupled with timber intermediate floors and cavity masonry walls¹⁰. It may be possible to reduce the level of leakage around the edges of the plasterboard by improved installation of perimeter adhesive ribbons by, for example, the use of a mechanical sealant gun that could apply consistently sized and repeatable beads of adhesive at the extreme edges of the board, together with a method of equalising pressure during mounting of the board. It will also be necessary to

¹⁰ The idea that the plasterboard provides the wall air barrier is implicit in all official advice relating to the fitting of the lining (continuous ribbons of adhesive, sealing behind skirting boards etc.) yet there remains very little understanding of the nature of air barrier design, its identification and continuity. The practical impossibility of achieving the required sealing using adhesive ribbons has been known about for almost 20 years yet its use is still advocated. In the context of low and zero carbon housing this position is no longer tenable.

improve the sealing of the gap in the primary air barrier at the junction between the ceiling plasterboard and the external and party walls. This could be achieved by the use of a membrane or angled component that could link up the ceiling air barrier to the wall air barrier. However, perhaps a more robust approach would be the consideration of alternative methods to wall finishing such as traditional wet plastering that would remove the plasterboard plenum completely. Housebuilders and developers in the UK are generally reluctant to use wet plastering methods due to issues of extended drying times and a perceived lack of skilled plasterers in the UK. These issues could be overcome by the use of modern mechanical plastering techniques such as spray-on plastering methods, which are faster than manual application and also quick drying. For example, a 3 man team can plaster 150 m² of wall per day using the projection plastering method (Knauf 2007). A transition to wet plaster would require comprehensive revision of electrical and plumbing distribution routes and practices. House designers should also consider other approaches and technologies for wall finishing that do not involve plastering or plasterboard.

- 59 Another common example of a buildability problem related to situations where several joists and beams were designed to be built very close to each other as shown by the examples in Figure 14. At Stamford Brook beams and joists were built into the blockwork wall rather than being supported on joist hangers. The design of the primary air barrier required that all joists and beams are carefully mortared in at both the inside and outside interfaces at the junction with the blockwork. There is also a requirement that the internal interface between the joist and wall is chased out and sealed using an appropriate sealant. However, in the cases of the multiple joists in Figure 14 the difficulties with accessing these interfaces at the restricted positions between the joists makes this task virtually impossible to complete.



Figure 14 – Multiple adjacent built-in joists and beams

- 60 One of the clearest opportunities to improve buildability of the dwellings at Stamford Brook relates to the construction and insulation of the cavity wall. There were some issues with the use of the plastic wall ties which were stiff compared to steel wall ties and also relatively easy to break. However, these were relatively minor problems that would most likely be solved with the use of a different plastic material or tie design. The main issue relates to the use of the method of blowing-in loose fill mineral wool insulation for the external wall at Stamford Brook instead of building the insulation in with mineral wool batts or rolls. The retro filling method of construction means that the cavities remain clear until the walls are complete. We have observed large accumulations of mortar snots at the bottom of cavities, on top of cavity trays, on top of cavity socks and on top of wall ties. The level of mortar build-up in the cavity could have been reduced by the use of cavity boards but these were not employed at Stamford Brook. We have identified several areas

of missing insulation where the filling process has not completely filled the cavity. We have also observed that sometimes the insulation does not always fill right up to the top of a cavity, as for example in the case of the threshold of Juliet balconies and at the tops of walls. All these factors would have reduced the effective U -value of the external walls. One advantage often stated for retro-filling is that it is more likely to stop air flow in the cavity and thus avoid any potential problems with bypassing caused by air circulation via gaps around improperly installed mineral wool batts. However, we have shown with our experimental work on the party wall thermal bypass that there can still be significant air flows in retro-filled cavities. Using built-in mineral wool batts would have reduced the occurrence of mortar snot accumulations. It would also be easier to visually inspect, monitor and control the installation of built-in insulation during the construction process compared to retro-filling where it is much more difficult to check whether the installation has been carried out properly, as the entire process is hidden from view. This can be seen by the example of the construction of a 150mm wide cavity in a masonry wall using mineral wool insulation rolls on a site in Lincolnshire as shown in Figure 15. This illustrates that this form of construction is easier to inspect visually and that any mortar dropped on top of the insulation can easily be seen and removed¹¹. More fundamentally, the approach to construction of cavity trays in cavity masonry walls makes such walls almost impossible to insulate the area above and between windows in such walls properly by retro-filling. The design of cavity trays and lintels has developed over the decades incrementally, with little empirical feedback on the aspects of performance that these elements of construction are supposed to ensure, and with none on aspects of performance that may be compromised by them. It is hard to resist the conclusion that a fundamental reassessment of the detailing of masonry cavity walls is needed to address issues of buildability and complexity. It is perhaps interesting to note that Bryant have acknowledged the various problems associated with blown-in insulation and have made the decision to switch to insulation batts for the remaining construction phases at Stamford Brook (Poole 2007).

¹¹ The example shown in Figure 15 is not without its problems however since the batts are not fitting a snugly to the inner leaf as one would like. However the most important point is that this can be observed and corrected much more readily that if it were blown in after the wall was constructed.



Figure 15 – Construction of masonry cavity wall using built-in insulation (site in Lincolnshire)

AD-HOC DESIGN CHANGES

61 It became apparent from comparisons of observations of details as constructed on site with the detailed design drawings that many ad-hoc changes were being made to designs of certain junctions on site. Many of these were undocumented and unapproved, and the changes being made had implications both for thermal performance and airtightness. Perhaps the best example of such a change was for the intermediate floor “Juliet” balcony door detail used by both Redrow and Bryant. Examples of Juliet balconies in completed dwellings at Stamford Brook are shown in Figure 16. Observation of the construction of these balconies, in all dwellings where they were used, showed that the threshold detail did not match the designed detail, as shown in Figure 17. The threshold detail as designed (Figure 17 A) is similar to a typical window sill detail and has a short insulated upstand at the threshold formed by a reveal block over which is positioned a sill board. The cavity between the sill block and external brickwork is shown with an insulated closer in the original design drawing, in order to minimise thermal bridging at this point. By comparison, the threshold as built (Figure 17 B) had no insulation to the upstand and the flooring continued over the cavity to meet the external brickwork.



Figure 16 – Juliet balconies in completed dwellings

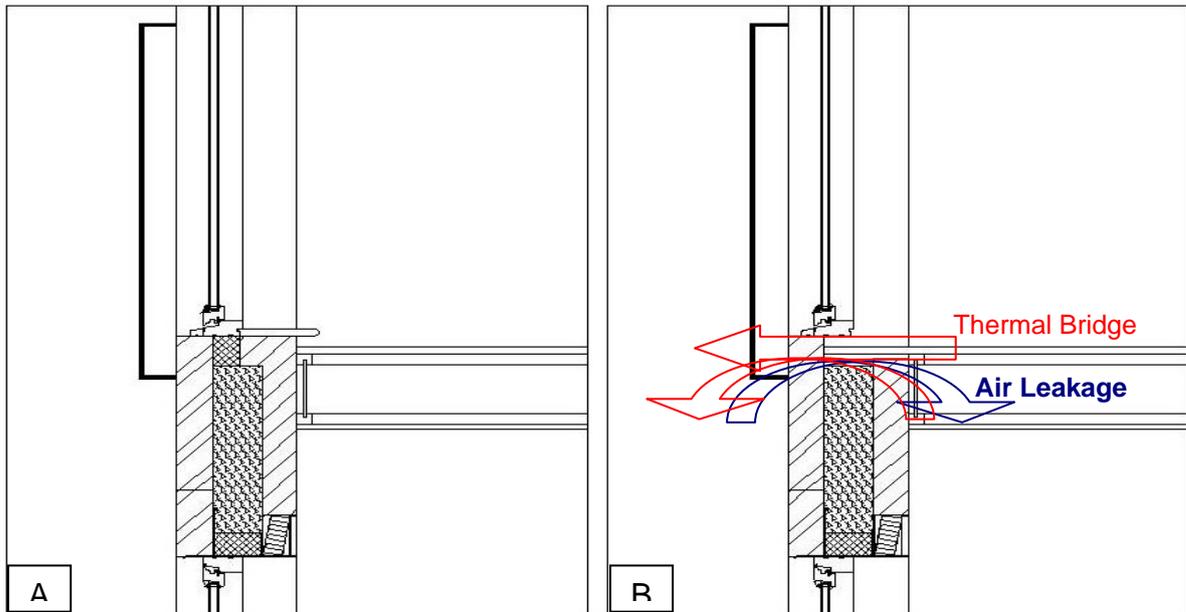


Figure 17 – Juliet balcony detail as designed (A) and as built (B)

62 Various stages of construction of the Juliet balcony threshold are shown in Figure 18. It can be seen in Figure 18 A that there is no cavity closer in the sill and that at this stage the flooring stops just before the blockwork. It should also be noted that the floor I-beam joists protrude above the top of the blocks which would result in a large gap between the flooring and blocks. In Figure 18 B, with the door now fitted, the cavity is still exposed and debris can easily fall down into the cavity. With the cavity insulation in place in Figure 18 C, it can be seen that the level of the blown in mineral fibre insulation falls short of the top of the blockwork. The final stage of construction as shown in Figure 18 D is to fill the gap in the flooring with a short section of board which is cantilevered across the cavity. A timber filler piece is inserted into the gap at the threshold between the door frame and flooring board with no insulation being placed in the gap behind. It is clear that the way this detail

has been constructed has severe problems both with a lack of thermal insulation at the threshold and the presence of direct air leakage paths. Thermal images of external walls of facades with Juliet balconies all showed severe heat loss at the threshold as shown by the example in Figure 50 in the thermal imaging section of this report. Leakage detection during airtightness pressure testing confirmed that there was significant air leakage at the Juliet balcony threshold as shown by the thermal image under depressurisation in Figure 19 A and the flow of smoke into the floor cavity under pressurisation as shown in Figure 19 B. This is a clear demonstration as to why detailed design should not be undertaken at a site level as, in general, site based staff do not have the necessary knowledge of the concepts, time to think through the issues, nor access to the modelling tools that would be required to design a thermally efficient detail. It is also an indication that the existing quality control systems are not set up to capture complex issues of thermal design and illustrates that existing feedback loops and communication mechanisms between the off-site design process and the on-site construction process will need to be changed and improved.



Figure 18 – Juliet balcony threshold in various stages of construction

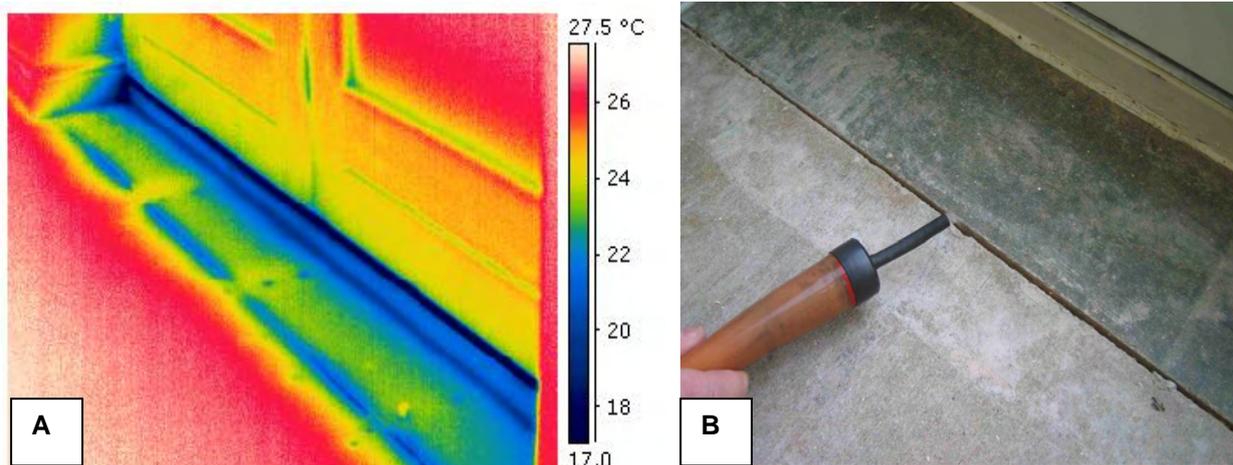


Figure 19 – Testing of Juliet balcony threshold: Depressurisation (A) and pressurisation (B)

63 Some on-site changes were made for purely aesthetic reasons, without apparent regard for the consequences that such changes might have on thermal performance or airtightness. An example of this was the substitution of insulated plasterboard at window and door reveals with plain uninsulated board as shown by the installation in Figure 20 A. The use of insulated board as per the detailed design drawing (Figure 20 B) was critical to minimising thermal bridging at window and door heads, and at window and door jambs. The use of uninsulated board at these positions would significantly increase the level of linear thermal bridging above that calculated by thermal modelling of these junctions at the design stage. Discussions with the developers' site teams identified that this was a site-based decision. The change was apparently made as there was concern that insulated boards would have covered over a large part of the window frame that would normally be visible from inside the dwelling, and that the expectation was that potential home owners would prefer to see more of the frame. We have no evidence to back up this supposition but it was clear that this decision had been made without consultation with either the research team or with the developers' design teams. If a sufficiently detailed change control process had been in operation, then it is likely that this change would have been picked up. It is probable that the site-based teams do not fully understand the performance implications of apparently minor changes or tweaks to the dwelling design, many of which can be critical to the performance of low energy house designs. As is noted in paragraph 65, the horizontal separation between the two lintels is a critical factor in the performance of this detail. Heat loss would also be reduced if the window was moved further in and the horizontal section of the inner lintel shortened. The insulated plasterboard would then be made unnecessary.

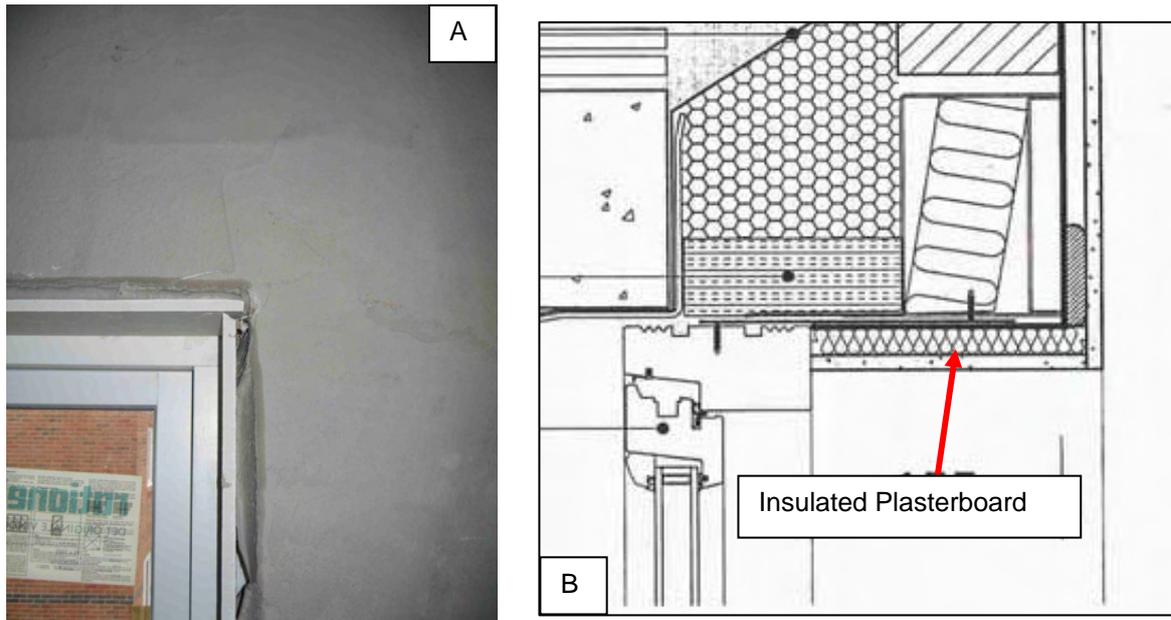


Figure 20 – Plasterboard reveals at window jamb and head (A) and head design drawing (B)

ADHERENCE TO DESIGN DRAWINGS

64 A common occurrence in housing construction in the UK is the failure to build exactly according to the detailed design drawings. There is generally no intent to deviate from the design; rather it is typically a simple matter of insufficient training, time pressures and a lack of effective communication between the site management and construction teams. These training and knowledge issues may be exacerbated by an expectation on site that designs are not always thoroughly worked out in the office. A good example of this is the recessed doorway referred to in paragraph 50. There is a strong case for prototyping such details during the design process, rather than on site. Construction at Stamford Brook was no different in this regard and several instances were observed where design drawings had not been properly adhered to. Perhaps the best example of this at Stamford Brook was during the construction of the floor slabs of the very first dwellings built. Observations of the first pair of semi-detached houses built at Stamford Brook at the end of 2004 showed that the concrete slab had been incorrectly laid all the way across the external cavity around the whole perimeter of the ground floor as shown in Figure 21 A. The actual design required the slab to terminate at the inner edge of the cavity, with the cavity then extending below floor level in order provide the required level of edge insulation (Figure 21 B). The consequence of filling the cavity with concrete would be to significantly increase thermal bridging at the ground floor-wall junction. This was confirmed by infra-red thermal imaging of the ground floor-wall junction of these dwellings when completed (Figure 53), which shows a significant level of heat loss at this point. In this case, changes to the foundation design for these particular dwellings were required due to ground conditions. However, the additional thermal performance standards at Stamford Brook were not fully communicated to the design consultant who designed the foundation and slab to meet normal thermal requirements. Fortunately, this error was picked up in the early stages of the development (Roberts, Andersson, Lowe, Bell & Wingfield 2005), construction was immediately

halted whilst the design fault was corrected, and all subsequent dwellings were constructed with the floor slab laid correctly. This incident highlights the importance of a robust quality control system that is able to identify such mistakes early on in the construction process so that any necessary rectification measures and improved training procedures can be put in place to avoid any recurrence, which in this case they were, quite successfully. It also illustrates the importance of communication throughout the design and construction process.

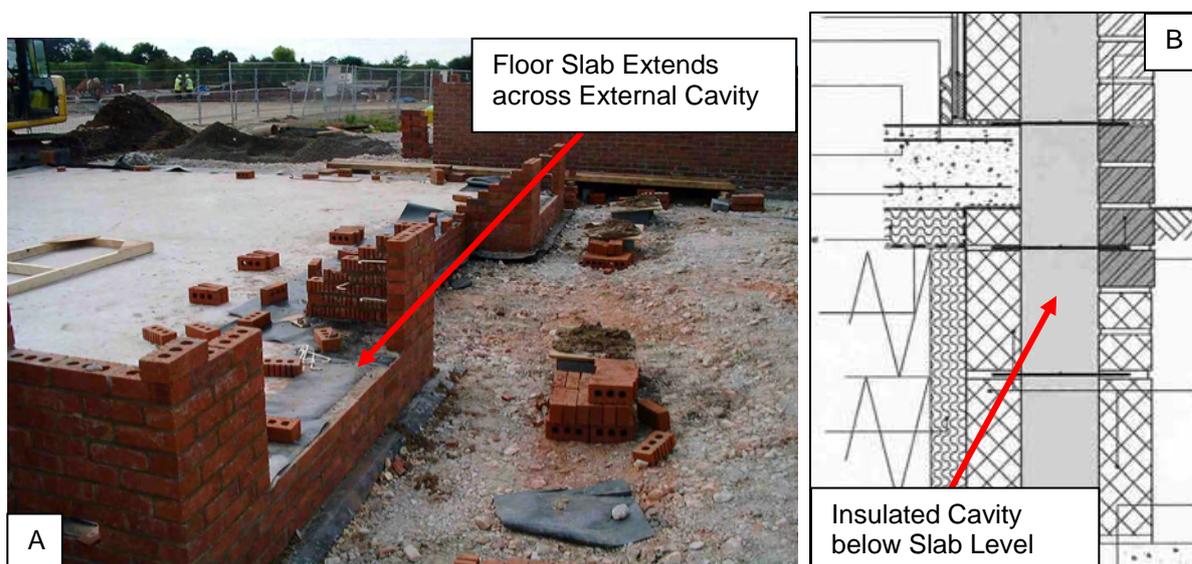


Figure 21 – Incorrectly constructed floor slab (A) and floor-wall junction design drawing (B)

CONSTRUCTION TOLERANCES

65 It would be expected that the construction techniques used at Stamford Brook will give rise to a range of construction tolerances in the distances between components, cavity/wall widths, mortar bed depths and other areas of construction that are reliant on manual placement of material and components. An example of the effect that the expected variability in these construction tolerances can have on performance is illustrated by the window head detail used at Stamford Brook. The design of the window head detail underwent several iterations during the initial design phase of the project (Roberts et al 2004) which reduced the thermal performance of the detail. In particular, the purity of the original design concept of separate steel lintels for inner and outer leaves instead of the more normal combined steel lintel was compromised due to the use of a lintel with a protruding toe on the bottom flange for the inner leaf (see Figure 22). The intended purpose of the flange was to provide support for the plasterboard lining in the window reveal. However, the flange reduced the designed gap between the steel lintels to only 42mm as shown in Figure 22A. Observations and measurements taken by the research team of the distance of this gap as constructed showed that the actual gap could be as low as 20mm (Figure 22B), which would have increased thermal bridging at this point. In addition, the poor placement of insulation between the lintels (Figure 10) would have degraded thermal performance even further.

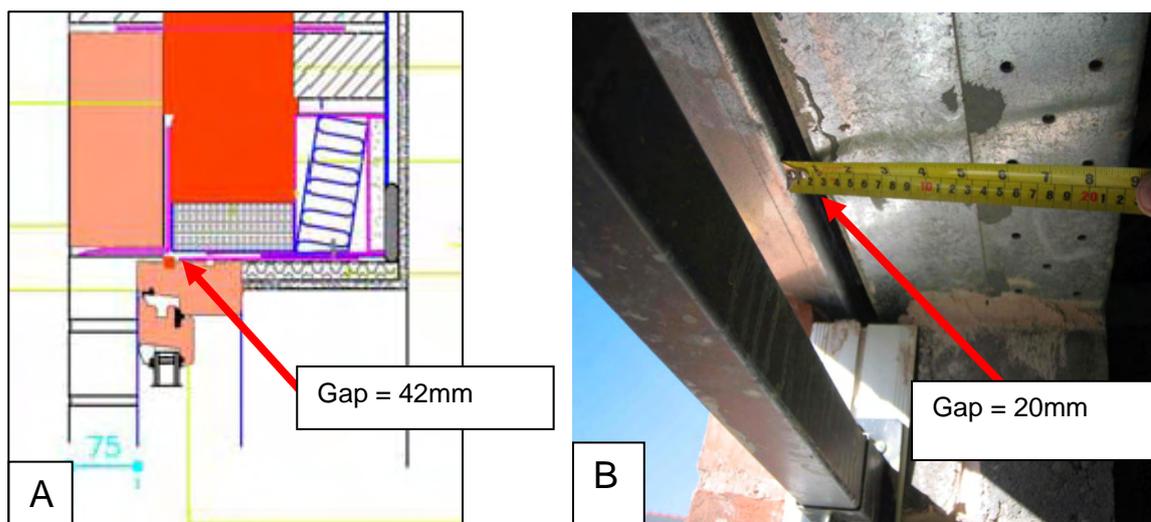


Figure 22 – Gap between window head lintels as designed (A) and as built (B)

- 66 Thermal analysis of the window head detail taking into account all the observed design compromises and construction faults gives a value for linear thermal bridging of this detail as constructed (worst case) of 0.203 W/mK (Wingfield, Bell, Miles-Shenton, Lowe & South 2007 – see also paragraph 121). This compares to the thermal bridging for the detail constructed as designed (fig. 22A) of 0.068 W/mK.¹² This is a 200% increase in actual thermal bridging compared to the as designed value and some 12 times the optimal value (see paragraph 121). The as constructed value also approaches that for a window head with typical combined steel lintel of 0.3 W/mK given in Appendix K of SAP 2005 (BRE 2005). The increase in thermal bridging at the window head over the design value would have the effect of increasing the predicted carbon emissions from a 73m² semi-detached dwelling by 0.3 kgCO₂/m².
- 67 Another example of the way that construction tolerances can affect thermal performance is illustrated by the roof truss overhang at the wall plate in the Bryant dwellings. According to the design drawings (Figure 23A) the truss overhang should be 50mm. Observations of actual construction showed that the overhang, as built, was normally much smaller than this, and was typically around 10mm (Figure 23B). The effect of this would be to reduce the amount of insulation at the eaves junction and therefore increase the level of thermal bridging at this point. This effect would be further exacerbated by the fact that in some dwellings the loft insulation was not properly installed. This meant that the cellulose insulation material did not properly fill the eaves gap right up to the timber baffle on the underside of the roof as shown by the example in Figure 24.
- 68 When the effects of the variability in construction tolerances across the range of details in a typical house are combined, they would be expected to have a significant detrimental effect on thermal performance. However, it is not believed that issues of tolerance and construction variability are properly considered in

¹² This compares with a Ψ value of 0.016 W/mK (Table 5) for the initial, unmodified, window head design - window in line with the insulation and no extended toe. The compromise of the toe and a shift in window position made only a small difference to the Ψ value but was, clearly, susceptible to tolerance and buildability degradation.

design. Indeed, it is rare in the UK for new house designs or variations in design to be prototyped and fully tested before construction of houses for sale.

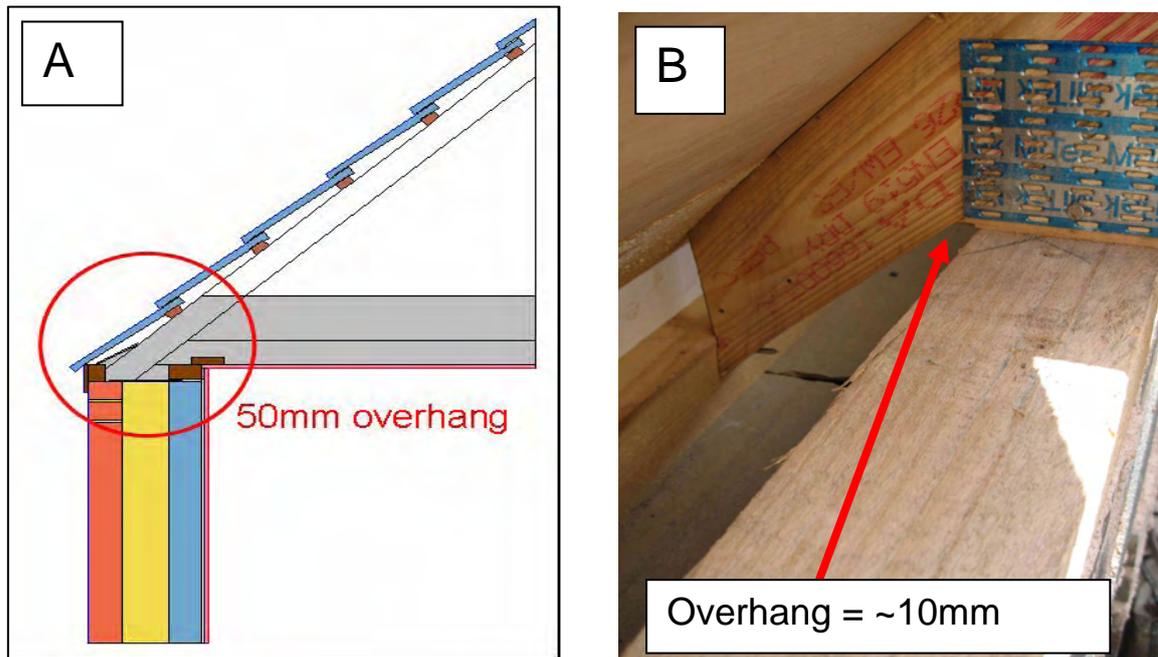


Figure 23 – Roof truss overhang at wall plate as designed (A) and as built (B)

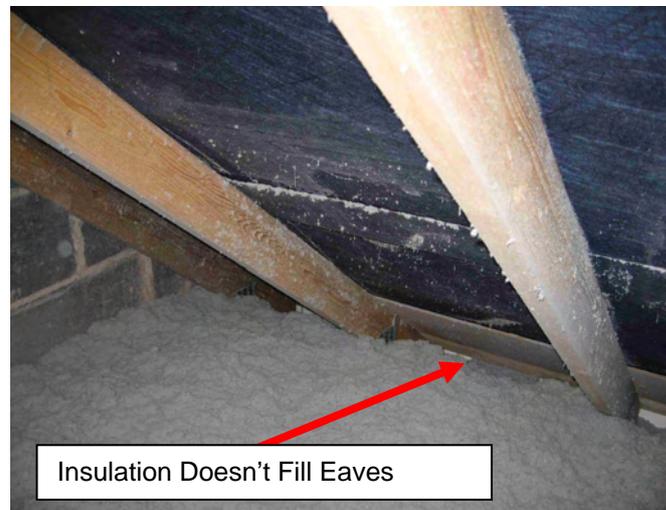


Figure 24 – Lack of cellulose insulation in loft at eaves junction

CONSTRUCTION SEQUENCING

69 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, and lack of feedback on experience on site.

- 70 An example at Stamford Brook of the impact of sequencing issues caused by a combination of poor planning and the need for remedial work is the routing of ducting and pipework through the insulated sections of a pitched roof in room-in-the-roof dwelling designs. Observations by the research team showed that ducting for the mechanical ventilation system and soil vent pipes were routed through the insulation layer of the pitched roof as shown in Figure 25 A, B and C rather than via a separate boxed in duct run inside the insulation layer. The consequence of this decision would be to reduce the effectiveness of the insulation layer at this point. There would also be other effects such as the potential for condensation of water within the MEV ducting as the duct is in on the outside of the insulation layer. Gaps will also be formed between the insulation and air barrier which would give rise to thermal bypassing and potential air leakage paths. It can also be seen that in order to get the MEV duct into the ceiling, several sharp bends in the duct run have been made which would cause a significant air flow restriction.
- 71 Discussions with the site team revealed that the decision to route the ducts through the insulation layer was taken on site in the absence of detailed design guidance on the drawings. The problem was exacerbated further when, after the roof had been boarded over, it was realised that the installation team had forgotten to install one of the soil vent pipes. The decision was then taken to remove the boarding and insulation in order to install the soil vent pipe as shown in Figure 25 D and E. This remedial work has damaged the membrane and it is doubtful whether the insulation could be effectively reinserted through the hole shown. All these faults are of course hidden in the final finished construction as shown in Figure 25 F. However, thermal imaging of the affected area from the inside of the completed dwelling when heated, highlights the detrimental effect of this process on thermal performance. The infra-red image of the ceiling shown in Figure 25 G shows that the surface temperature of the section of ceiling with the duct work (left hand side of picture) is at around 18°C to 19°C whereas the rest of the ceiling (right hand side of picture) is at around 21°C to 22°C showing that the *U*-Value of the section of roof with the ductwork has been seriously degraded.
- 72 It is clear that this situation could have been avoided if better design information had been available to the site team and also with better control of the sequencing of the various construction tasks. The experience of the Leeds Met team across a range of construction sites in the UK is that, generally speaking, information on optimum sequencing is not given on design drawings and other general design documentation. It is also apparent that requirements for pipe runs and other services and the consequences of poor placement are not always fully considered during the design process. This could become a critical factor in design as mechanical extract systems and whole house balanced ventilation systems become more common as is likely in low carbon house designs. Poor sequencing also illustrates the discontinuity between the design process and the construction process.

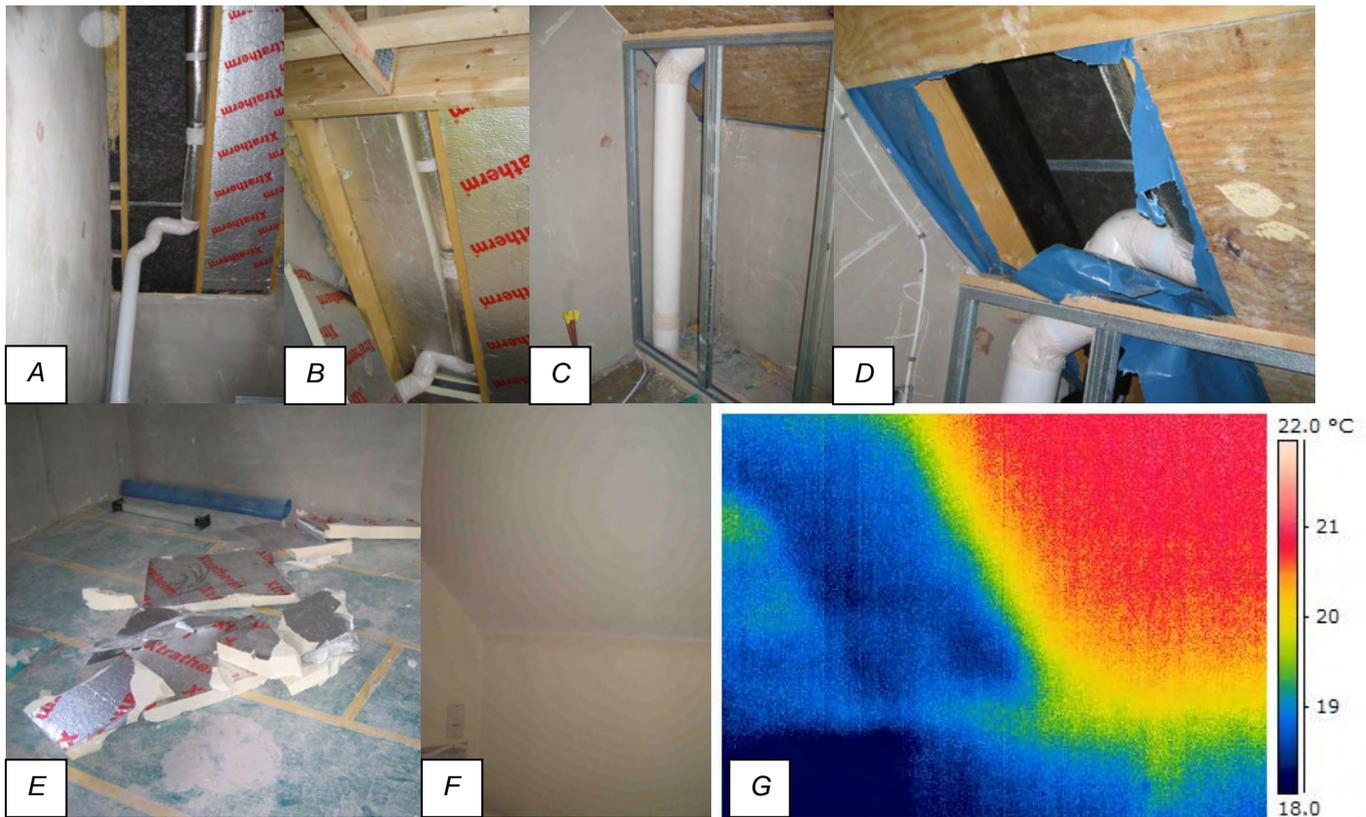


Figure 25 – Routing of MEV ducting and soil vent pipe via insulated sloping roof section

73 One of the most compelling demonstrations at Stamford Brook of the potential influence that a relatively small change in sequencing can have on performance is the effect of the construction of the top floor ceiling on levels of airtightness. Common construction practice in the UK is to erect the room partitions on the top floor prior to installation of the plasterboard ceiling¹³. This leaves numerous potential air leakage paths into the loft space at the junctions between the partition walls and ceiling which would need to be carefully sealed in order to achieve good levels of airtightness. The alternative construction sequence of erecting the ceilings before the partitions is an effective way of avoiding this problem (Figure 26 A). Both developers at Stamford Brook were reluctant to adopt the strategy of ceilings up first as they were concerned with potential hazards to electricians and plumbers working in the loft once the ceiling had been boarded out. Instead the developers chose to minimise the potential for leakage by using timber headers at the top of the partitions as shown in Figure 26 B. However, following a run of poor pressure test results Bryant decided to switch to the ceiling-first approach. Since implementing this change, the airtightness of Bryant built dwellings at Stamford Brook improved dramatically and they now regularly achieve air permeability levels of $4 \text{ m}^3/(\text{h} \cdot \text{m}^2) @ 50\text{Pa}$ and below at Stamford Brook. Leakage path testing using smoke detectors has shown that in Bryant dwellings there is now no leakage via

¹³ One is tempted to refer to this practice as “standard construction practice” however this would misrepresent what is done. From observations on this project and others it would appear that there is no “standard practice”, rather there is only what happens to be the policy of each developer and even that may vary from site to site depending of the view of the site team.

the top floor partitions whereas in the case of Redrow, who still use the timber-header approach, there is still significant leakage via partitions into the loft space. Indeed, such has been the perceived benefit of the ceilings-first approach that Bryant has now adopted this strategy nationwide. There are added benefits to the ceilings-first method such as reduced construction complexity as well as quicker and easier installation of the ceiling boards with associated reduced materials wastage due to less board cutting. It is also a highly visual process that makes it easier to check compliance. It should also be borne in mind that using the ceiling-first approach will not on its own solve all the problems of air leakage into the loft via the ceiling. There will remain issues of leakage via the soil stack, leakage around the ceiling-wall junction, leakage via penetrations for lighting and ventilation and leakage associated with the loft hatch.



Figure 26 – Top floor ceiling construction – plasterboard ceiling first (A) and partitions first (B)

- 74 Another illustration of the problems that can be caused by poor sequencing is related to the order of construction of the inner blockwork leaf relative to the outer brickwork leaf. In cases where a substantial height of outer brickwork is constructed before the inner blockwork above the position of the intermediate floor (see examples in Figure 27) difficulties arise in accessing the outer face of blockwork as the construction of the inner blockwork has to be carried out from the intermediate floor, which is being used as a working platform. This in turn causes problems of mortaring the joints in the external face of the blockwork and also mortaring around the built-in joists, both of which are critical to the construction of the air barrier. This problem illustrates the lack of guidance and documentation available to the site trades and sub-contractors as to what are normal procedures and methods for common tasks such as wall construction. One solution would be to provide sufficiently detailed documentation for common procedures. However, this would not necessarily prevent bricklayers constructing walls in this way. An alternative approach would be to view the problem as a system failure and to reassess the whole sub-process of wall construction and its relationship with other sub-processes within the whole construction process. This would open up a range of potential solutions. For example, by choosing to support the intermediate floor joists on joist hangers rather than building them into the wall, this would eliminate the need to mortar around the joist ends and would also mean, for safety reasons, that it would not be possible to use the intermediate floor as a working platform until a sufficient number of courses of block had been laid over the top of the joist hangers. Designers might also consider other options for construction of the intermediate floor such as in-situ concrete floors which not only improve airtightness but also potentially remove the need for wall ties in the party wall. If insulation batts were used in preference to blown-in insulation, then this would

have required that the inner blockwork wall lifts were constructed before the brickwork.



**Figure 27 - Intermediate floor construction – external leaf built before inner leaf
INAPPROPRIATE MATERIAL AND COMPONENT SELECTION**

- 75 Observations have shown that some construction processes were made more difficult or thermal performance/airtightness degraded by the use of inappropriate materials or components. In many cases these issues are common to masonry construction across the UK. For example, there is a mismatch in dimensions between the height of a standard concrete block and mortar course (215mm + 10mm = 225mm) and the height of the most commonly used engineered I-beam joists which are typically 241mm. This results in a gap in the construction of the intermediate floor of around 16mm that has to be filled with mortar (as shown in Figure 28). The consequence of this is to cause a further mismatch in the alignment of the coursing of the blockwork wall with the coursing of the brickwork wall. This means that wall ties do not align properly and the bricklayer has to compensate for this by adjusting the thickness of mortar beds higher up the wall. This was a particular problem at Stamford Brook as the plastic wall ties are relatively stiff compared to normal steel wall ties and can break if bent too far. The simple solution here is to use joists and blocks that match in size. Engineered I-beam joists are readily available in heights of 225mm from a range of manufacturers so this issue is not the result of a lack of suitable components. We are unsure as to the exact reason why 241 mm joists were selected at Stamford Brook, but suspect that it is probably a combination of cost and acoustic performance. We know that the guidance in Part E of the building regulations (ODPM 2004) requires that internal floors meet a minimum airborne sound insulation value of 40dB when tested in the laboratory. Typically this would require that timber intermediate floors contain a 100mm thick layer of sound absorbent mineral wool. However, laboratory tests of 241mm I-beam joists have shown that they can just meet the 40dB criteria (BRE 2003), so using these in preference to shallower joists would save the cost of the mineral wool layer.
- 76 It is possible to think of other design changes that would further simplify the construction of the intermediate floor such as using joist centres appropriate for standard block widths so that blocks do not have to be cut to fit. It is doubtful that the implications of the selection of joist size on buildability were fully appreciated by the developers' design and costing teams. We have concluded from these findings and other similar observations that house design is probably dominated by simplistic cost considerations and that the design processes do not properly

cost in the advantages of designing for construction and design simplification. This suggests a lack of appropriate design and costing tools, poor process mapping and a lack of understanding by designers of the system complexities and interactions of the construction process. A systematic reassessment of the sub-process of intermediate floor construction might suggest different approaches such as the use of solid concrete floors or other construction methods that could have other process and performance synergies. For example, the use of concrete intermediate floors could have added benefits in terms of additional thermal mass, better acoustics, and improved airtightness, structural stability and fire performance. Depending on how services were routed horizontally, concrete floors might also reduce the overall building height.



Figure 28 – Mismatch between joist height and block height for built-in joists

PRODUCT SUBSTITUTION

77 Several instances of product substitution were observed which gave rise to issues of buildability or performance. For example, in one dwelling the research team observed that an intermediate floor had been built on one supporting wall with a combination of both built-in joists and joists supported on joist hangers as shown in Figure 29. The construction specification required the use of joist hangers only for connections to other joists or beams. The reason given by the site operatives for the apparent confusion in this dwelling was that there were an insufficient number of floor joists in stock on site that were long enough to be built in to the wall, but there were some shorter ones available that were just long enough if used with hangers. The consequence of this was that there was a mismatch of around 10mm between the height of the floor supported on the joists on hangers and the height of the floor on the built-in joists. There were further complications when it was realised that the bricklaying team had begun to load the floor with blocks for the construction of the next wall lift but that an insufficient number of block courses had been laid over the joist hangers which could have led to a collapse if the floor had been overloaded. The bricklaying team had to quickly remove the blocks from the intermediate floor. It is probable that the use of the two types of support system would have also degraded the acoustic performance of the floor.



Figure 29 – Intermediate floor built with combination of built-in joists and joists on hangers

- 78 As part of their continual assessment of costs, the developers identified a UK source of front doors that would meet the required Stamford Brook performance specification at a lower cost than the existing doors supplied from Denmark. When the research team checked the first installations of these new doors it was observed that, in some cases, the doors came as a set with a sidelight window as shown in Figure 30. However, it was realised that, although the door would match the desired performance specification, the sidelight would likely not meet the maximum window U -Value requirement of $1.3 \text{ W/m}^2\text{K}$. In fact, when the thermal performance of the sidelight was checked with the door manufacturer it was discovered that the U -Value of the sidelight was only $1.7 \text{ W/m}^2\text{K}$. This demonstrates that care is required when sourcing materials and components in order to ensure that all parts of the specification are met and that suppliers need to be given sufficiently detailed information on required performance.
- 79 The windows at Stamford Brook were constructed with proprietary insulated window former cavity closers to minimise the thermal bridge at the window jamb and sill (see Figure 31 A). However, it was observed in several instances that the cavity closers had been replaced with plain mineral wool closers as shown in Figure 31 B and the specified closers had been removed and used on another plot. In many cases the mineral wool closers were pushed up to 50mm into the cavity, which would have created an air gap around the edge of the window frame, thus increasing the size of the thermal bridge at this point. The proprietary closers were supplied as complete window sets specifically marked for each plot. Further observations showed that the window closer sets were being used in the wrong plots and in the wrong windows, sometimes giving rise to a mismatch between the height of the window and the height of the closer.



Figure 30 – New door and sidelight window



Figure 31 – Window openings with specified cavity closers (A) and non-standard closer (B)

80 One of the developers used foam end caps to help provide an effective air seal between the I-beam joists and blockwork when the joists are built into the wall (Figure 32 A). The foam end caps were supplied in a range a sizes to suit the various flange widths and web heights in use on site. However, it was clear that the construction teams were not all aware of this fact and the wrong sized end caps were frequently used as shown in Figure 32 B. This would have the

consequence of making it more difficult to seal the joists to the wall which could potentially affect levels of airtightness.

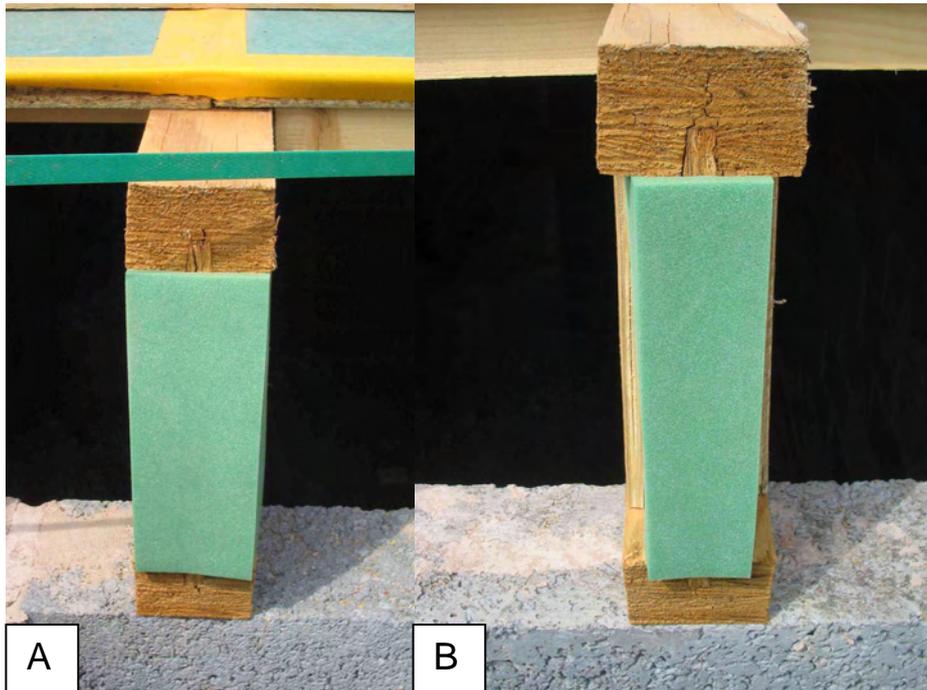


Figure 32 – Foam end caps for I-beam joists

Airtightness

PRESSURE TEST RESULTS

- 81 The basic strategy for achieving the EPS08 airtightness target of $5 \text{ m}^3/(\text{h.m}^2) @ 50 \text{ Pa}$ at Stamford Brook is outlined in project Deliverable 2 (Roberts et al 2004). The main airtightness specific design measure that was adopted by the developers was the use of a 2mm to 4mm paring layer of render that was applied to the internal blockwork of all external walls and party walls, the function of which was to seal the walls and mortar joints. This was proposed as an alternative to fully wet plastered walls due to concerns about drying times. In addition to the physical design measures, comprehensive training on the requirements and procedures for ensuring airtightness was provided by the Leeds Met team for management teams, site operatives and sub-contractors (Roberts et al 2004). The training covered the airtightness design measures for each of the different on-site trades to ensure that all operatives were aware of the construction requirements and the consequences of poor workmanship. As well as this formal training, informal feedback was provided to the developers after each individual pressure test.
- 82 The uncertainties of the developers' build programmes, and the expected short window of opportunity for testing between completion of a dwelling and handover to the client, meant that it was not possible to develop a statistically randomised sample for pressure tests. Instead, an ad hoc strategy for airtightness testing was adopted. Thirteen initial tests were conducted between February 2005 and May 2005. These first tests were focused on dwellings constructed during the very first phase of construction. This first series of pressure tests were intended to establish whether the design strategy and training regime had resulted in dwellings with air permeabilities within the target of $5 \text{ m}^3/(\text{h.m}^2) @ 50 \text{ Pa}$ and to provide feedback to the developer on their initial performance. Following these initial tests

83 A total of 44 individual dwellings were pressure tested at Stamford between February 2005 and June 2007. The results are summarised in Table 6 and Figure 33 and are discussed in more detail in project Deliverables 5 and 6 (Wingfield, Bell, Bell and Lowe 2006, Miles-Shenton, Wingfield & Bell 2007). The mean air permeability was $4.5 \text{ m}^3/(\text{h.m}^2) @ 50 \text{ Pa}$. This is within the EPS08 target of $5 \text{ m}^3/(\text{h.m}^2) @ 50 \text{ Pa}$. However, it should be pointed out that 32% of the 44 dwellings tested exceeded the design target. It can be seen that the best results were obtained with the simpler 2-storey dwelling types with the worst results coming from the more complex 2-½ storey room-in-roof designs where they are specific design issues to overcome that are related to the continuity of the air barrier around the junction between the wall and sloping section of ceiling.

Table 6 – Summary of pressure test results

Building Form	Sample Number	% of sample meeting target of 5	Air Permeability		Volumetric Leakage	
			$\text{m}^3/(\text{h.m}^2) @ 50\text{Pa}$	Standard Deviation	ach @ 50Pa	Standard Deviation
1-Storey Apartment	3	67%	4	2.5	5.7	3.5
2-Storey Detached	6	83%	3.5	1.4	3.2	1.4
2-Storey Terrace/Semi-detached	12	100%	3.7	0.9	3.9	0.9
2½-Storey Terrace/Semi-detached/Detached	14	43%	5.4	2.2	4.7	1.9
3-Storey Terrace/Semi-detached/Detached	9	56%	4.9	1.1	4.4	1.1
All Building Forms	44	62%	4.5	1.7	4.3	1.7

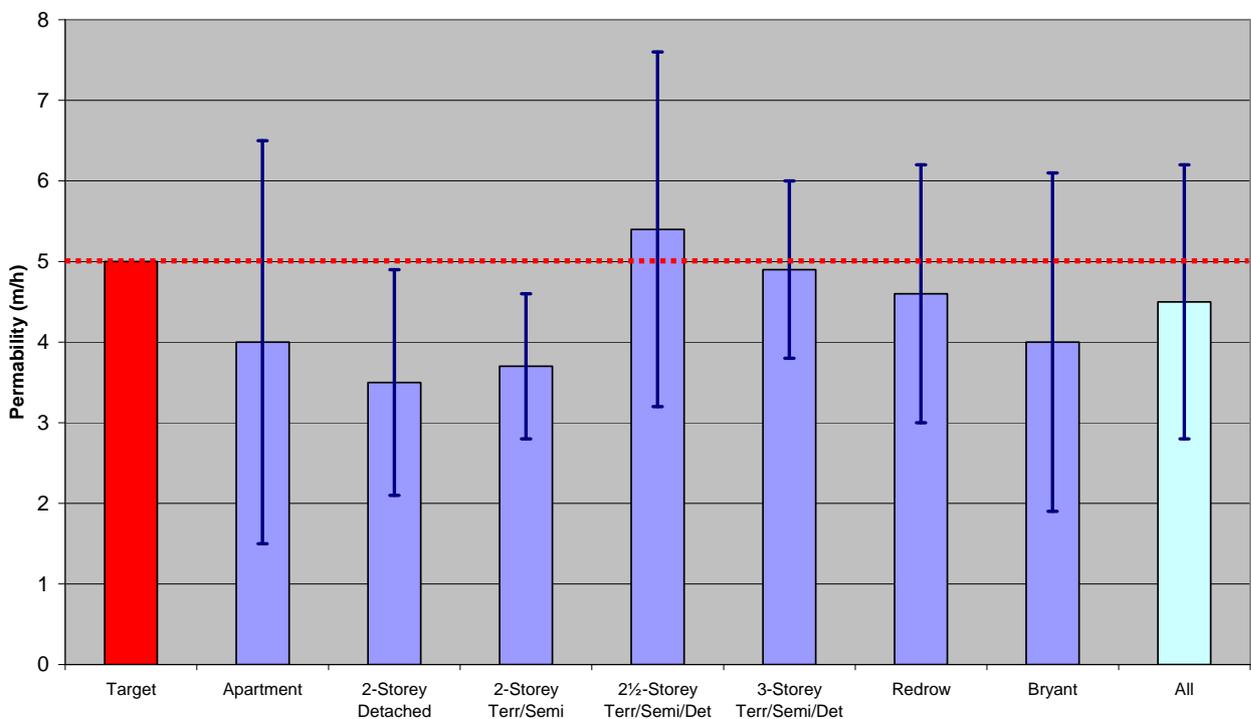


Figure 33 – Bar chart of air permeability results

84 The airtightness of the dwellings at Stamford Brook is significantly better than the typical performance of UK dwellings. For example, a comparison of the air permeability probability distribution for Stamford Brook with that of the Energy Saving Trust’s 99 dwelling ADL1 2002 compliant dataset (Grigg 2004) is shown in Figure 34. The mean air permeability of the EST dataset was 9.2 m³/(h.m²) @ 50 Pa compared to the 4.5 m³/(h.m²) @ 50 Pa achieved at Stamford Brook. These data illustrate that the Stamford Brook dwellings are significantly more airtight than typical modern UK dwellings with a much narrower distribution. The Stamford Brook results are also better than those recorded in a Leeds Met study of the airtightness of UK dwellings constructed to meet the requirements of ADL1 2002 (Johnston, Miles-Shenton & Bell 2006) which ranged from 4.0 to 16.5 m³/(h.m²) @ 50 Pa, with a mean of 11.1 m³/(h.m²) @ 50 Pa. The Stamford Brook results also compare well to the mean air permeability of 6.34 m³/(h.m²) @ 50 Pa for five 2-storey maisonettes tested on the BedZed development where the air permeability target of 2 m³/(h.m²) @ 50 Pa was much lower than that at Stamford Brook (ARUP 2003).

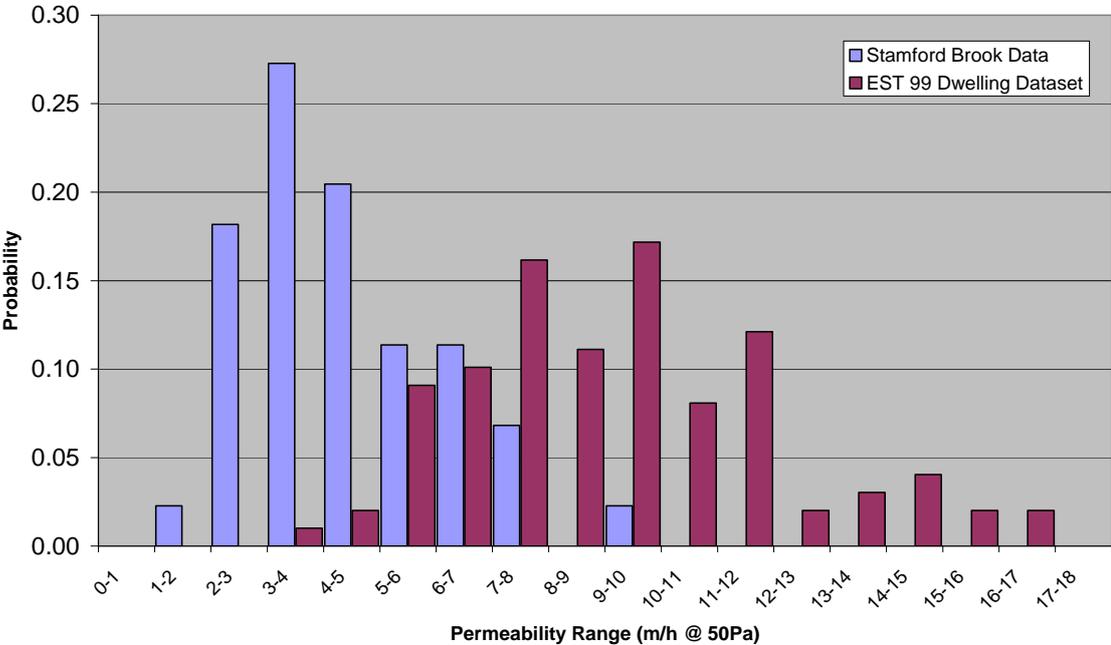


Figure 34 – Air permeability probability distribution: Stamford Brook and EST datasets

85 It is interesting to compare the airtightness of the 2-½ storey dwellings from Stamford Brook with the available data on similar 2-½ storey dwellings constructed at BedZed and St Nicholas Court in York. A bar chart comparison of the results from the five 2-½ storey houses in the Stamford Brook detailed airtightness study with the published results from BedZed (ARUP 2003) and St Nicholas Court (Johnston, Wingfield & Miles-Shenton 2004) is shown in Figure 35. Given that the air permeability target at both Stamford Brook and St Nicholas Court was 5 m³/(h.m²) @ 50 Pa and at BedZed was 2 m³/(h.m²) @ 50 Pa, it can be seen that the dwellings at Stamford Brook outperformed those on both the other developments

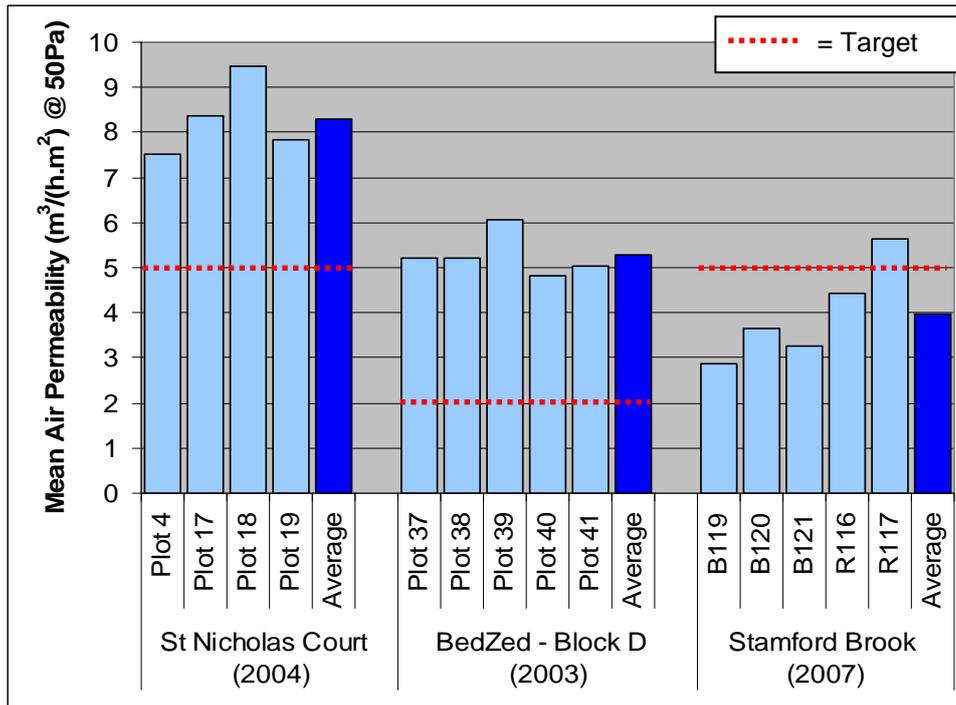


Figure 35 - Comparison of the airtightness of 2-1/2 storey dwellings

86 The very first pressure test results recorded at Stamford Brook between February 2005 and May 2005 were very promising ranging from around 2 to 3 m³/(h.m²) @ 50 Pa. However, test results showed that there was a gradual deterioration in performance over time and by April 2006 the mean air permeability of houses¹⁴ had risen to over 5 m³/(h.m²) @ 50 Pa. This general upward trend in results can be seen in Figure 36.

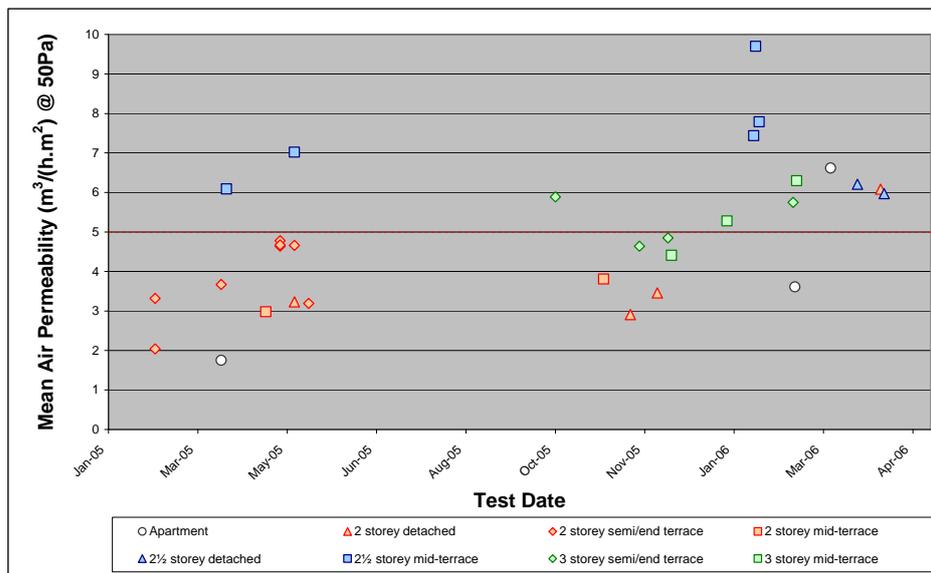


Figure 36 – Trend in pressure test results: February 2005 to April 2006

¹⁴ Not including flats, by 7th April 2006 28 houses had been pressure tested at Stamford Brook by the Leeds Met research team with an average mean air permeability of 5.02 m³/(h.m²) @ 50 Pa.

- 87 Possible reasons for this deterioration in performance over time are discussed in project Deliverables 5 & 6 (Wingfield et al 2006, Miles-Shenton et al 2007) and included factors such as a shift in focus away from airtightness, inadequate quality control procedures, training issues and changes in personnel. This shift in performance raised concerns and the PII project aims were revised to allow the research team to work more closely with the design and construction teams to resolve airtightness issues and to study the improvement process in some detail based on a series of detailed case studies of problematic dwelling types. Five 2½ storey dwellings were specially selected for the study as they contained a greater degree of design complexity. In addition, four dwellings that were undergoing coheating tests during the winter of 2006-2007 were also included for comparison in the study as they were all of comparatively simple rectilinear design with only a limited number of complex details such as recessed front doors and bay windows. The airtightness study involved close observation of the construction process with a photographic record taken of all the critical stages before being pressure tested on completion. Detailed leakage detection was undertaken using smoke guns under pressurisation and infra-red thermal imaging under depressurisation.
- 88 When the timeline plot of pressure tests is extended to include the data from the airtightness study along with other later results supplied by the developers (Figure 37), it can be seen that there has been a significant improvement in performance compared to that obtained during October 2005 to April 2006. It is also apparent that there has been a dramatic improvement in performance of the more complex 2- ½ storey dwelling types. It can be seen from Figure 37 that there are effectively three different phases with three different levels of performance. These phases are the initial testing period from February 2005 to May 2005, the middle testing phase from October 2005 to April 2006, and the final testing phase from September 2006 to June 2007.

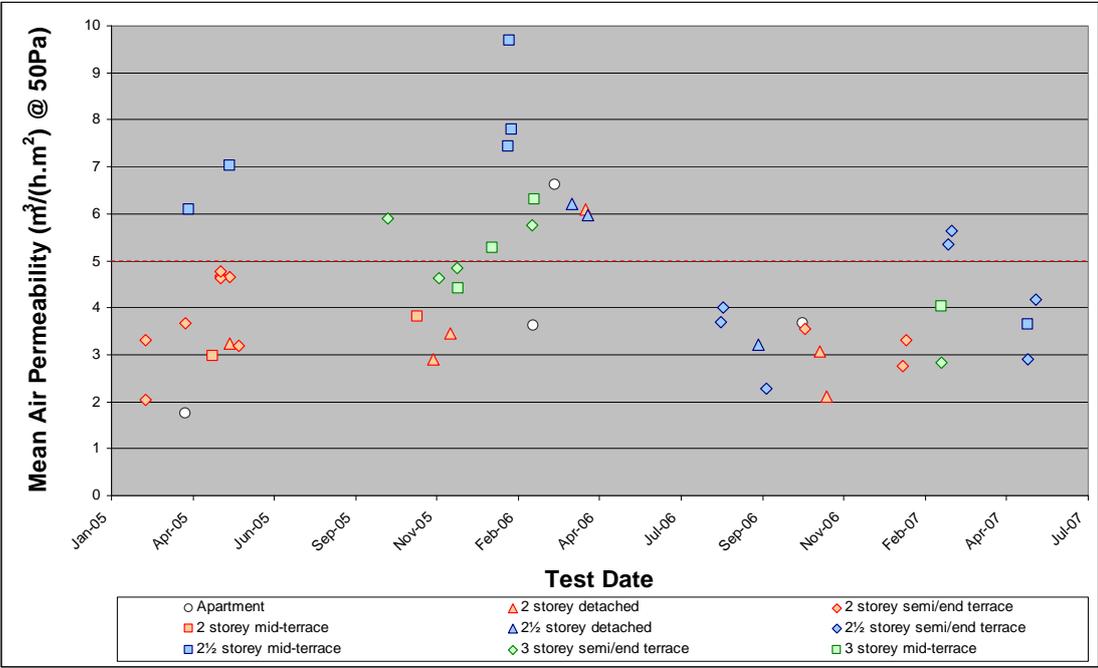


Figure 37 – Trend in pressure test results: February 2005 to May 2007

- 89 Five of the dwellings from the airtightness study were retested, which offered an opportunity to investigate the impact of secondary sealing on airtightness. The initial test results and re-test results for these 5 dwellings are given in Table 7. In

the case of plots B116, R110 and R111 the retest followed observations of partial degradation of secondary sealing over the period of the coheating tests. It is likely that these failures were caused either by the inability of the sealant used to withstand the size of the shrinkage movements or adhesive failure at one of the surfaces, probably associated with inadequate surface preparation. The consequence of these failures was an average increase in permeability of over $0.64 \text{ m}^3/(\text{h.m}^2)$ per dwelling and a percentage change ranging from +13% to +30%. In plot R116 additional secondary sealing was applied in order to improve airtightness following a disappointing test, whereas plot B121 was initially tested prior to any secondary sealing purposefully to observe its effect on the overall airtightness of the dwelling. This resulted in an average reduction in the mean air permeability of $0.90 \text{ m}^3/(\text{h.m}^2)$ ¹⁵ with percentage change ranging from -17% to -22%.

Table 7 - Comparison of mean air permeability for initial pressurisation tests and re-tests

Plot	Mean Air Permeability ($\text{m}^3/(\text{h.m}^2)$ @ 50Pa)		Difference ($\text{m}^3/(\text{h.m}^2)$)	Percentage Change
	Initial test	Re-test		
B116	2.75	3.57	+ 0.82	+30%
R110	4.03	4.78	+ 0.75	+19%
R111	2.84	3.20	+ 0.36	+13%
R116	5.34	4.45	- 0.89	-17%
B121	4.17	3.27	- 0.90	-22%

- 90 Given the small number of retests and the fact that the results are largely anecdotal it is not possible to draw any firm conclusions from these data. However two tentative points emerge:
- Although not the major component, the impact of secondary sealing, at the level of airtightness achieved in the dwellings tested, can be reasonably significant at between 30% and 13% of the initial test result.
 - Secondary sealing is prone to degradation over a relatively short time period.
- 91 The degradation of secondary sealing observed in the co-heating dwellings (B116, R110 and R111) will have been affected, to some extent, by the relatively high internal temperatures (between 25 and 29°C) maintained during the 4 week test period. However this is more likely to have simply accelerated effects that would have happened during the first year, particularly as temperatures rise and drying takes place over the summer months. Visual observations during the tests indicated drying, shrinkage and settlement at the intermediate floor perimeters causing the floor to skirting gap to open in all properties. In a number of cases this gap expansion appeared to be beyond the elastic and adhesive capabilities of the sealant used. This is not altogether surprising as the type of flexible silicone sealants suitable for this purpose tend to have a movement tolerance of around 30~50% and the gap between skirting and floor can be expected to increase by double that over time (NHBC 2006) and even greater on timber floors with larger

¹⁵ For the pressurisation re-test plot B121 the blower door was positioned in the rear entrance door, for the initial test it was located in the front door. However this is not thought to have affected the results significantly.

spans where deflection and deformation can take place caused by heavy furniture and usage. Similarly, large gaps and cracks appeared around other wooden elements where less flexible sealants had been utilised, most noticeably around stairs, window sills and loft hatches where a water-based decorators' caulk had been applied. Also observed was the adhesive failure of the sealant, which is likely to have been a result of inadequate surface preparation. Examination of failed sealant often revealed that the surface was dusty prior to application or the sealant had been applied over debris. Figure 38 illustrates some of the observed failures in the secondary seals.

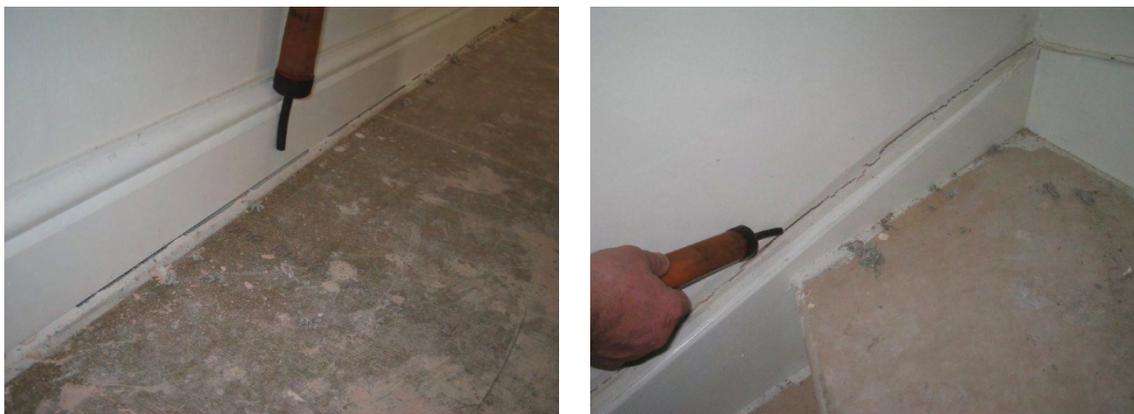


Figure 38 – Shrinkage and cracking of secondary sealing following coheating test

- 92 Historically, much of the guidance on building airtight dwellings has placed an unduly high priority on the use of secondary sealing, creating a misconception amongst many within the industry that it is the boundaries visible from inside the completed dwellings that form the primary air barrier. To some extent this has continued and features in some of the generic details in the accredited detail set, which often show sealing in secondary areas such as skirting board and floor junctions (DEFRA 2001, BSI 2007). Without a clear and precise definition of where and what constitutes the primary air barrier in design and other guidance documentation, misunderstandings will continue to occur. With so many of the internal voids connected, a point of air leakage detected in one place may be far removed from the eventual point of air leakage from the dwelling and, unless all the points of entry into all the connected voids are sealed, this method of reducing air permeability will never be completely successful and is unlikely to be robust in the long term. In our view, the time, effort and money spent on sealing many of these secondary areas would be much better spent by concentrating on the primary air barrier where the actual air leakage from the dwelling is occurring. The utilisation of secondary sealants to provide a secondary air barrier may have some benefit in the short-term in reducing the air permeability of dwellings for the purpose of passing a pressurisation test but it is not a robust long-term solution.

DISCUSSION OF STAMFORD BROOK AIRTIGHTNESS DATA

- 93 The analysis of the qualitative and quantitative results from the detailed airtightness study demonstrate that the technology adopted (cavity masonry construction) is perfectly capable of delivering the specified target air permeability of $5 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50 \text{ Pa}$, even in dwellings with complex roof forms. Only one of the 9 dwellings was above the target. The group had a mean permeability of 3.8 and a range between 2.67 to $5.45 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50 \text{ Pa}$. The results from the 44 dwellings tested over the whole project suggest also that a level of 2 and below is achievable on a reasonably consistent basis. However, it is clear that if a target of

5 and below is to be achieved consistently, considerable improvement in the processes through which the technology is applied will be required. As the industry strives to meet ever tighter carbon standards to 2016 and beyond, improvements in design and construction processes will become unavoidable.

94 A full discussion of the airtightness test results obtained at Stamford Brook is given in the Project Interim Reports No 5 (Wingfield, Bell, Bell & Lowe 2006) and No 6 (Miles-Shenton, Wingfield & Bell 2007) and includes an analysis of the data in the context of the detailed construction observations and leakage path assessments by smoke detection and infra-red thermal imaging. From this analysis of airtightness performance at Stamford Brook we have reached the following broad conclusions:

- a) **Design:** Contrary to advice given by, among others the BRE, between 2004 and 2006, design is crucial and there is an urgent need to re-engineer fundamental airtightness design processes. In the first instance the design process should ensure that the primary air barrier is identified, specified and located at an early stage. As design progresses detail design should ensure the continuity of the air barrier at all junctions and provide information on such issues as construction sequence, so as to ensure the effective construction of what has been designed. We have observed a tendency for design effort to shy away from complex problems and leave these to be resolved on site. The opposite is needed and designers need to focus more effort on complex 3 dimensional junctions, service penetrations and so on.
- b) **Quality control:** The overwhelming conclusion from the observations and analysis of construction in this study, and from a more general study of the construction phase of the project as a whole, is that quality control processes are extremely diffuse with a number of actors playing similar but different roles which are almost always carried out in isolation. It is perhaps not surprising that with no clear airtightness quality control process in place, sequencing was often out of phase and known errors were repeated time and time again. The other key conclusion to emerge is that testing and the presence of a team of individuals dedicated to monitoring construction and providing feedback is essential to any quality control process.
- c) **Workmanship:** Workmanship is often cited as being the main reason why airtightness standards are not achieved in house building in the UK. At Stamford Brook a focus on workmanship, rather than making design changes was the approach chosen by the developers for the dwellings included in this study. Despite that fact that all but one of the test dwellings achieved an air permeability of less than $5 \text{ m}^3/(\text{h.m}^2) @ 50 \text{ Pa}$, we remain unconvinced that focusing on workmanship per se will lead to a consistently high (over 95%) "pass" rate at anything much below 5 or $6 \text{ m}^3/(\text{h.m}^2) @ 50 \text{ Pa}$. Of course, workmanship is important but, very often, it is the context in which trades have to work, the lack of specific training, the buildability of designs, the lack of detailed design and the lack of a general quality control process that underlie many workmanship problems. If such issues are not addressed, workmanship will always appear to be poor.
- d) **Training:** The action research approach included the provision of additional site and trade specific training regarding airtightness. However, with staff turnover and an increase in site staff numbers, there was a tendency for training to be relaxed. Towards the end of the airtightness study this began to be tackled by holding an air tightness awareness day, but more needs to be done to keep

these issues to the fore. In general, training should be seen as a constant requirement with day-to-day programmes in place for ensuring that existing teams are refreshed, new teams receive appropriate induction and all teams receive clear instructions about the design they are responsible for constructing.

- e) **Materials and components:** The most striking observation about the application of materials and components were the number of occasions on which materials intended for one location were used in another. This resulted in the use of under or oversized components and/or inappropriate materials coupled with significant modifications to construction details as operatives sought to “work round” the problems created. Scavenging materials from one dwelling to finish another (not always of the same type) seemed to be an acceptable way of meeting dwelling completion dates but often at the cost of reduced airtightness. In addition, there was a general lack of component and material testing and evaluation as part of a formal quality control process. At its most basic level a number of specified components, particularly roof lights and loft hatches, did not perform as expected. Similarly, changes in specification with the intention of improving performance (for example, joist end caps) or reducing cost were not routinely evaluated, sometimes leading to no improvement or reduced performance.
- f) **Sequencing:** The build sequence adopted often presented problems of accessibility when constructing the air barrier and maintaining its continuity. In addition to hindering the construction of an effective air barrier, the lack of detailed planning of work sequences often led to an approach that appeared to be one in which a completed detail was constructed then damaged or dismantled for a subsequent installation before being repaired or reconstructed. Very often damage to the air barrier was involved, damage that could not be adequately repaired. This “build – damage – install – repair” approach is an inefficient and unnecessary process. We believe that a more explicit consideration of construction sequence both as a design criterion and in detailed construction planning would bring long term resource benefits as well as improving airtightness.
- g) **Communication:** This and other studies at Stamford Brook have highlighted the critical nature of communication. It is clear that there is considerable scope for improvement in flows of information both upwards and downwards throughout the organisations involved whether developer, designer, subcontractor or individual trade. Very often, design information was not available, not at the right level of detail, confusing or just not referred to by operatives. This led to a rather diffuse process as operatives followed their instincts rather than using detailed design information. At a more general level there did not appear to be any particularly well developed mechanism for feeding back information on airtightness performance, nor was it clear how the design and construction lessons were being absorbed for use in making improvements to processes or actual designs. To a large extent this is linked with our conclusions on the need for a clearly defined quality control process, for without such a process there can be no definition of problems, identification of their causes or framing of solutions.

95 At Stamford Brook we developed a technology for airtightness that, at least in principle, worked but we identified various parts of the process that tolerated incomplete design information, that gave insufficient attention to detailed sequencing of operations, that were not systematic in their control of quality and

- 96 To the extent that all on-site processes tend to have similar characteristics, irrespective of the construction technology employed, the problems and issues identified have resonance beyond the realms of masonry construction in general and the Stamford Brook project in particular. Whatever the technology, exacting carbon emission standards will require exacting design and construction processes and this is something that the mass house building industry has not had to face in the past. Inevitably, a retooling of construction processes must be undertaken. A close partnership between government and the industry will be crucial because retooling will require significant investment in research and development if the goal of low and zero carbon is to be achieved in mainstream house building.

Coheating tests

- 97 Coheating tests were carried out on six dwellings at Stamford Brook. Two separate dwellings were tested during the winter of 2005-2006 and a further two pairs of adjacent properties during the winter of 2006-2007. The results of these tests are described in interim project reports 5 and 7 (Wingfield et al 2006, Wingfield, Bell, Miles-Shenton, Lowe & South 2007). A summary of the dwelling types and size of the six test houses is given in Table 8.
- 98 The results of the first set of coheating tests on plots 13 and 402 showed a significant discrepancy ranging from 75% to 103% between the measured whole house heat loss coefficient and that predicted from the fabric *U*-values and measured air permeability as shown in Table 9. Investigations of temperatures in the loft space and party wall cavity, together with thermal imaging of the party wall in the loft space indicated that a large part of the discrepancy could be due to a stack-driven thermal bypass operating via the party wall cavity.

Table 8 – Summary of coheating test dwellings

Plot No.	Developer	House Form	GFA (m ²)	Test Date	Comment
13	Bryant	2-storey Semi-detached	73	Dec 2005	Bryant show house
402	Redrow	3-storey Mid-Terrace	106	Jan 2006-Feb 2006	-
116	Bryant	2-storey Semi-detached	73	Jan 2007-Feb 2007	Same type as plot 13, Adjacent to 117
117	Bryant	2-storey Semi-detached	73	Jan 2007-Feb 2007	Same type as plot 13, Adjacent to 116
110	Redrow	3-storey Mid-Terrace	137	Feb 2007-Mar 2007	Adjacent to 111
111	Redrow	3-storey End-Terrace	141	Feb 2007-Mar 2007	Adjacent to 110

Table 9 – Coheating test heat loss coefficients - Plots 13 and 402

Plot No.	Predicted Heat Loss Coefficient (W/K)	Mean Heat Loss Coefficient from Solar Corrected Data (W/K)	Difference between Predicted and Corrected Heat Loss (W/K)
13	63.8	111.7 ± 5.9	47.9 (75%)
402	75.2	153.4 ± 3.3	78.2 (103%)

99 The four coheating experiments conducted during the winter of 2006-2007 were designed specifically to explore the party wall bypass mechanism. Pairs of adjacent attached dwellings were chosen in order to maintain temperature control on both sides of the party wall and additional temperature sensors were placed within the party wall cavity. A photographic record of the construction of the four dwelling was taken at critical stages. In addition, a mineral wool-filled cavity sock was installed horizontally in the party wall cavity between each pair of dwellings at the level of the ceiling. This cavity sock was removed halfway through each test to determine its effect on the thermal bypass. A series of photographs showing the cavity sock being inserted into the party wall cavity during construction and then removed during the coheating test is shown in Figure 39.



Figure 39 – Horizontal cavity sock being inserted into party wall cavity during construction (A,B) and then being removed again halfway through the coheating test (C,D)

100 Graphs of daily mean heat flux from the dwellings into the party wall cavity are shown in Figure 40 for plots 116-117 and in Figure 41 for plots 110-111. It can be seen that immediately after removal of the cavity sock from the party wall cavity there was a sudden increase in heat flux into the party wall cavity indicating that the horizontal sock had been cutting off the thermal bypass to some extent. Even with the sock in position there remained some heat loss via the party wall. The heat loss coefficient attributable to each side of the party wall was around 10 W/K with the sock in position and when the cavity sock removed was 19 W/K for plots 116-117 and 38 W/K for plots 110-111 (Table 10). The effective U -values ascribed to each side of the party wall with the sock in position ranged from 0.18 to 0.26 W/m²K and with the sock removed 0.5 to 0.63 W/m²K. These U -values are higher than that of the external wall (U -Value = 0.23 W/m²K), ground floor (U -Value = 0.172 W/m²K) and ceiling (U -Value = 0.142 W/m²K).

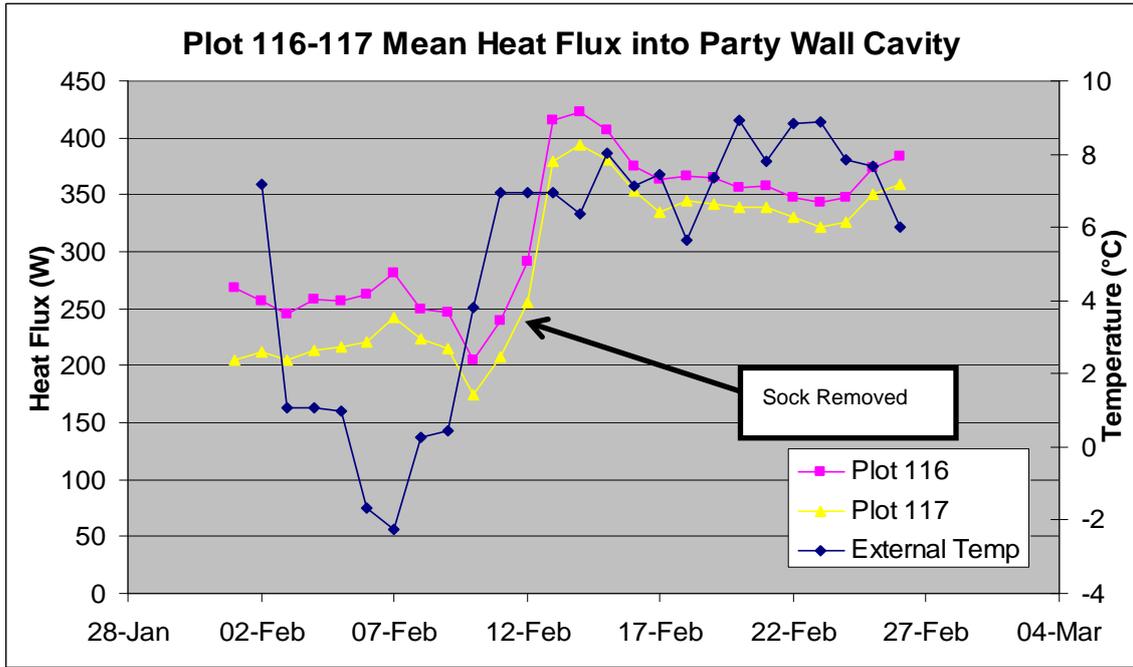


Figure 40 – Daily mean heat flux into party wall for coheating test on plots 116-117

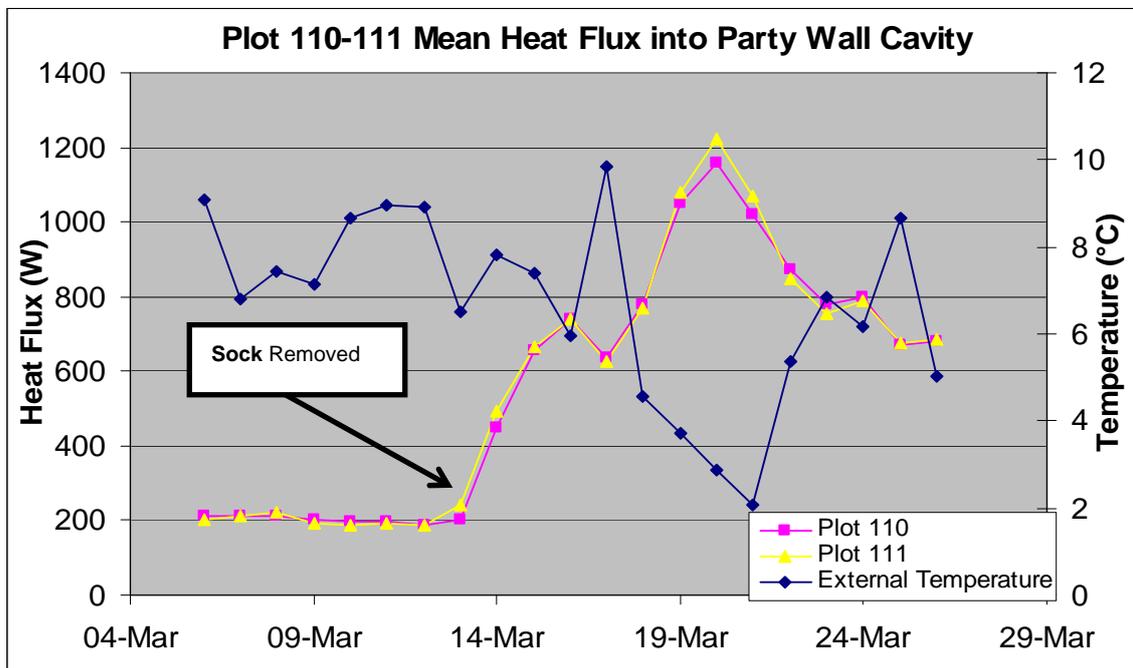


Figure 41 - Daily mean heat flux into party wall for coheating test on plots 110-111

Table 10 – Coheating test results – Bryant 116-117 and Redrow 110-111

Test Dwellings	Mean Party Wall Heat Loss Coefficient (W/K)		Effective Single-Sided Party Wall U-value (W/m ² K)	
	Before Sock Removal	After Sock Removal	Before Sock Removal	After Sock Removal
Bryant 116-117	10.1	19.2	0.26	0.50
Redrow 110-111	10.7	37.9	0.18	0.63

101 An infra-red image of the block work of the party wall in the loft of plot 117 with the horizontal cavity sock in position is shown in Figure 42 and after the horizontal cavity sock had been removed is shown in Figure 43. Both pictures were taken at around midday, with the external temperature at around 10°C in both cases. With the sock in position, the temperature of the party wall was around 10°C with little variation with height. In comparison, the infra-red image of the party wall taken when the sock had been removed shows the block work at the apex at a temperature of around 16°C, with the rest of the wall ranging from 14 to 15°C. These pictures are compelling evidence of vertical flow of warm air up the party wall cavity when the sock had been removed and are probably the clearest qualitative demonstration of the bypass mechanism.

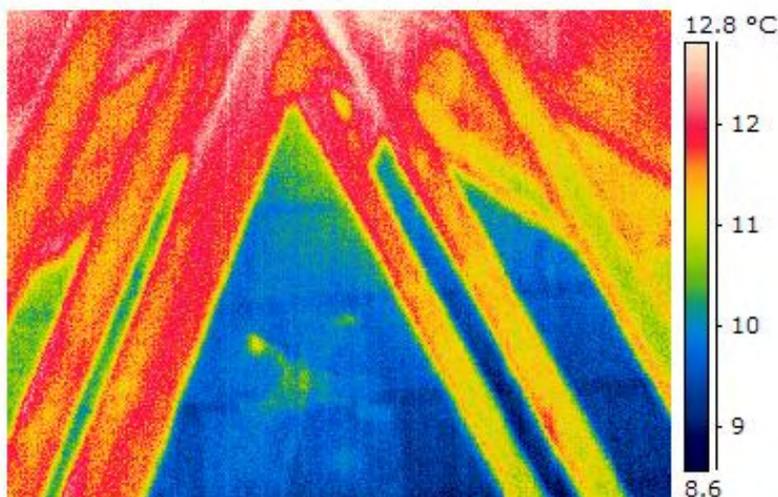


Figure 42 – Infra-red image of loft party wall in Bryant plot 117 – sock in position

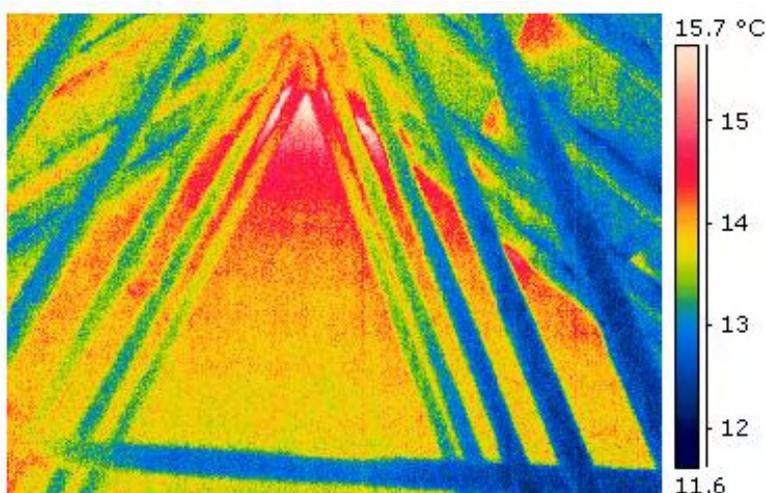


Figure 43 – Infra-red image of loft party wall in plot 117 – sock removed

102 Analysis of the heat loss data, cavity temperatures and air flow measurements within the cavity have shown that the mechanism for heat loss via the party wall is driven by upwards air movement in the cavity. This air movement is generated by thermal stack effects and by pressure differences caused by the action of wind moving across the dwelling. Heat transfer from the internal conditioned spaces occurs by conduction through the single leaves of the party wall into the party wall cavity. A schematic of the proposed mechanism is illustrated in Figure 44.

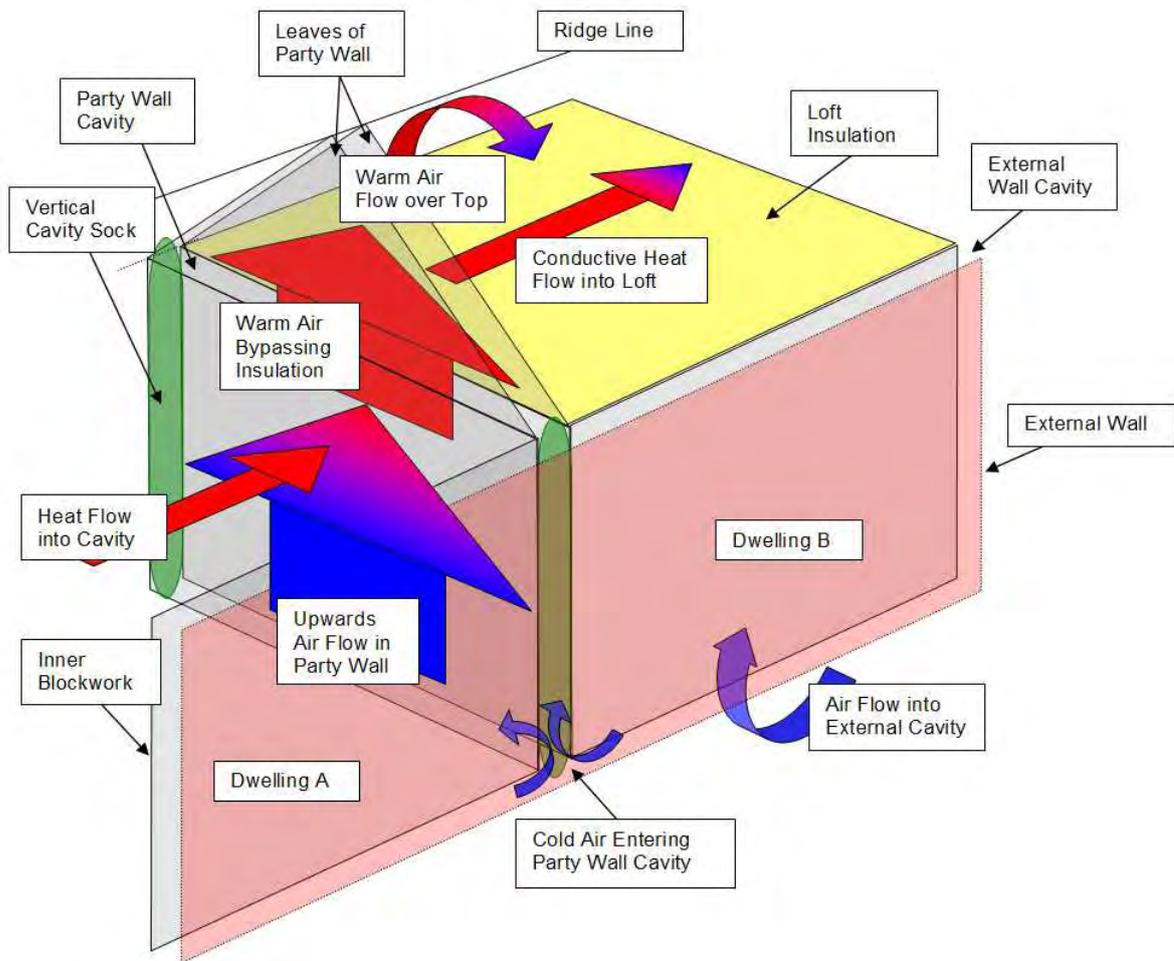


Figure 44 – Schematic of party wall bypass mechanism

103 There is potential for considerable carbon savings for both newly constructed and existing dwellings built with unfilled cavity masonry party walls if measures were implemented to reduce or eliminate the party wall thermal bypass. Such measures might include the use of horizontal cavity socks as tested at Stamford Brook, but other methods such as fully filling the party wall cavity with insulation, solid party wall construction or the use of spandrel panels to seal to top of the cavity are likely to be more effective in minimising the effect of the bypass. Of course any change must also ensure that the requirements for acoustic performance are not compromised. If it is assumed that a typical cavity party wall has an effective U -value of $0.5 \text{ W/m}^2\text{K}$, then the potential carbon saving if the party wall bypass were eliminated in all new terraced and semi-detached cavity masonry dwellings built in the UK each year would be of the order 20,000 tonnes CO_2 per annum. The possibilities for carbon dioxide savings in the existing stock could be even more significant than that in new dwellings. If the stock of terraced and semi-detached

dwellings built after 1965¹⁶ had improvement measures carried out to eliminate the party wall bypass then the potential carbon saving would be of the order 850,000 tonnes CO₂ per annum.

- 104 It is interesting to note that, contrary to normal expectations, one of the consequences of the party wall bypass is that terraced and semi-detached dwellings built to 2006 building regulation standards will have carbon emissions higher than that of a similarly sized detached dwelling based on the effect of the bypass alone without taking into consideration other defects in the fabric. For example, an 80m² 2006 compliant detached dwelling would have a fabric heat loss coefficient of 98.2 W/K and dwelling emission rate of 25 kgCO₂/m². In comparison, if we ignore the party wall bypass effect, an 80m² mid-terraced dwelling with an aspect ratio of 1.4 would have a fabric heat loss coefficient of 69.7 W/K and a dwelling carbon emission rate of 21 kgCO₂/m². However, if we include heat loss from the party wall with an estimated effective *U*-value of 0.5 W/m²K, then the fabric heat loss coefficient and dwelling emission rate for the mid-terraced dwelling increase to 107.2 W/K and 26.5 kgCO₂/m² respectively. As the detached dwelling has no party wall, we do not have to factor in any additional bypass loss. This means that an average sized mid-terrace dwelling will have a carbon emission rate around 1.5 kgCO₂/m² higher than that of an identically sized detached property and exceed its TER of 21 kgCO₂/m² by 5.5 kgCO₂/m².
- 105 The predicted whole house heat loss coefficients differ significantly from the heat loss coefficients measured during the coheating tests, but only some of the discrepancy can be accounted for by the party wall bypass. In the case of the two Bryant dwellings 116 and 117, the measured and uncorrected whole house heat loss coefficients for the coheating test period without the horizontal sock were of the order 105 W/K. This compares to the predicted value for these dwelling types of around 59 W/K (51 W/K fabric heat loss and 8 W/K ventilation heat loss). This therefore leaves a difference of around 46 W/K to account for. We have calculated from the party wall cavity temperatures that the size of the heat loss due to the party wall bypass for the Bryant test dwellings will be of the order 20 W/K. This means that a further heat loss of around 26 W/K has still to be accounted for. We know that some of this remaining 26 W/K heat loss will be due to the thermal bridging that we have observed at details such as window heads and bay window which will likely be over and above that calculated by theoretical modelling of the junctions as originally designed. If we assume a scenario whereby the actual thermal bridging for Bryant plots 116 and 117 is no better than that expected for accredited construction details by using the *y* value of 0.08 as outlined in SAP 2005 (BRE 2005), this would give a loss due to thermal bridging of 13 W/K rather than the 6 W/K predicted by modelling. This still leaves around 19 W/K to account for. We know that there will also be additional heat loss over and above the predictions due to other factors such as increased conductive heat loss via the walls that will result from the observed missing external wall insulation and mortar snots that bridge the external cavity. It is unlikely that such wall defects could account for all of the remaining 19 W/K discrepancy. It is therefore likely that we have underestimated the additional heat loss due to thermal bridging and there may still yet be other heat loss factors that have yet to be fully understood. These

¹⁶ Cavity party walls have been used for much of the 20th century, but until the 1960s many (we are unable to be more precise either as to the date or the proportions involved) reverted to solid construction in attics. Our conservative estimate is that only walls built after 1965 have cavities that are continuous into attics.

unknowns would include for example background ventilation losses and the effects of air movement in cavities.

- 106 The observed heat loss due to air movement in a party wall cavity is a classic example of a thermal bypass mechanism. These mechanisms are typically found in building designs which incorporate voids, cavities, chimneys, flues, ducts, enclosed service risers or other similar unobstructed passages that could provide potential routes for heat transfer involving the movement of air that can bypass the insulated external envelope. The possibility of significant heat loss from buildings via such thermal bypass mechanisms was first identified in the late 1970s and early 1980s by the Centre for Energy and Environmental Studies at Princeton University (Harrje, Dutt & Beyea 1979, Harrje, Dutt & Gadsby 1985). The Princeton research group identified several classes of heat loss mechanism involving air movement and convection in enclosed voids in combination with either air leakage or conductive losses. Examples of such mechanisms include air leakage into loft spaces via hidden paths in internal partitions, air movement in cavities formed by hollow block wall construction and convective loops in sealed but uninsulated soffits that allow air movement between the loft and the soffit cavity.
- 107 It is apparent from our party wall experiments at Stamford Brook and also our recent experience and analysis of the performance of other housing developments as part of the Building Operational Framework for the DCLG (Bell, Smith & Miles-Shenton 2005, Johnston, Miles-Shenton & Bell 2006) that, in general, the thermal design of new dwellings in the UK does not properly take account of the potential for either direct bypassing involving air leakage or indirect thermal bypassing involving a combination of conduction and air movement, such as in the case of the cavity party wall bypass. This is partly a regulatory issue, partly a knowledge issue and partly a training issue. The general principle of good thermal design requires a continuous layer of insulation and continuous air barrier around the conditioned space which are both in close contact with each and in the same plane through the dwelling. The potential for bypassing occurs where there are breaks in the air barrier and insulation layer or where the two layers become separated in the design. In design terms these faults are more likely to occur at critical junctions between elements, at connections between adjoining dwellings, at junctions between dwellings and unheated spaces such as integral garages and attics, and where there are complex construction details to resolve as are often found in complicated building forms. It is clear that a number of typical details in standard UK house designs break these basic principles. In addition, existing regulatory and design advice as thermal modelling protocols also do not properly address these issues. For example, the existing design guidance given in Accredited Details (DCLG 2007a) for separating party walls in masonry cavity wall construction (detail MCI-IW-02) would in fact give rise to the party wall thermal bypass as described in this report (see Figure 45), as well as (depending on the blocks used) an avoidable thermal bridge.

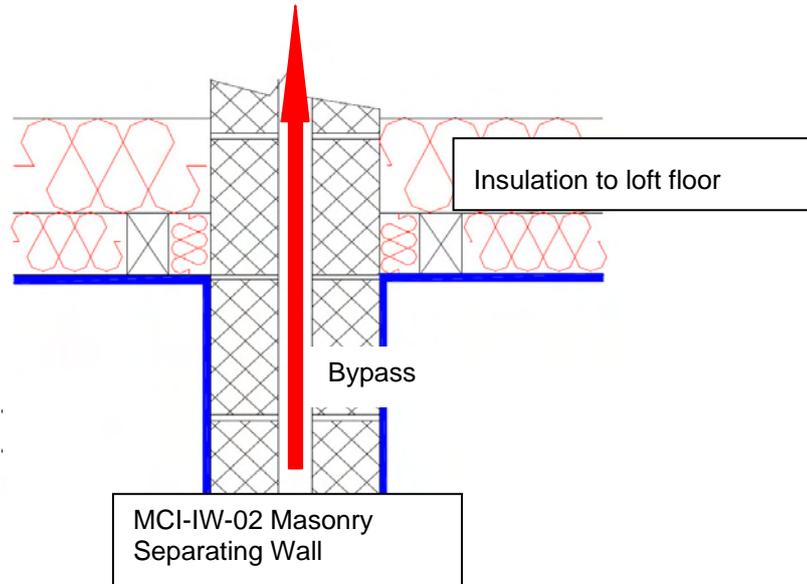


Figure 45 - Accredited detail drawings – masonry separating wall (DCLG 2007a)

108 There are other junctions described in the Accredited Details catalogue which would also give rise to thermal bypasses. For example, the pitched roof-eaves junction (detail MCI-RE-07) (DCLG 2007a) where the air barrier follows the line of the knee wall but the insulation follows the line of the rafters would give rise to a bypass as the air barrier and insulation are separated (see Figure 46).

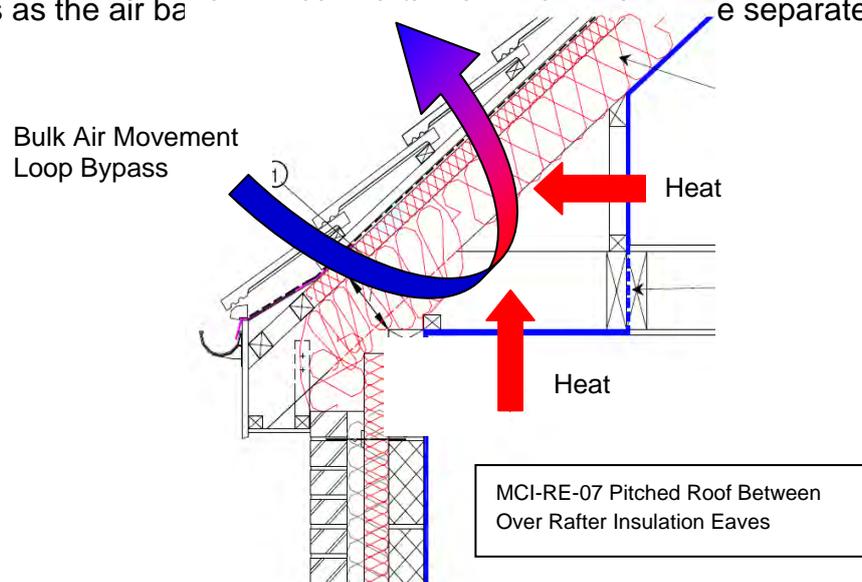


Figure 46 - Loop thermal bypass - accredited detail MCI-RE-07: pitched roof between over rafter insulation at eaves (DCLG 2007a)

109 It is likely that design advice supporting parts of building regulations other than Part L could give rise to the potential for thermal bypassing where the performance requirements are contradictory to those of good thermal design or where impacts on other performance criteria have not been fully explored. For example, the Part E robust detail for a separating wall in a steel frame construction (detail E-WS-1) (Robust Details Ltd 2005) contains two cavities that would form two separate

bypass routes into the attic space (see Figure 47). The documentation accompanying the Part E Robust Details catalogue does, of course, make it clear that its advice relates only to acoustic performance and Part E, and does not guarantee that the details will conform to other parts of the building regulations. It is therefore the responsibility of the house designer to ensure that there are no performance conflicts when using such design tools. However, it could be argued that more work needs to be done at a regulatory level to remove some of the inconsistencies in guidance and that there should more interaction between the different bodies responsible for the various parts of the building regulations.

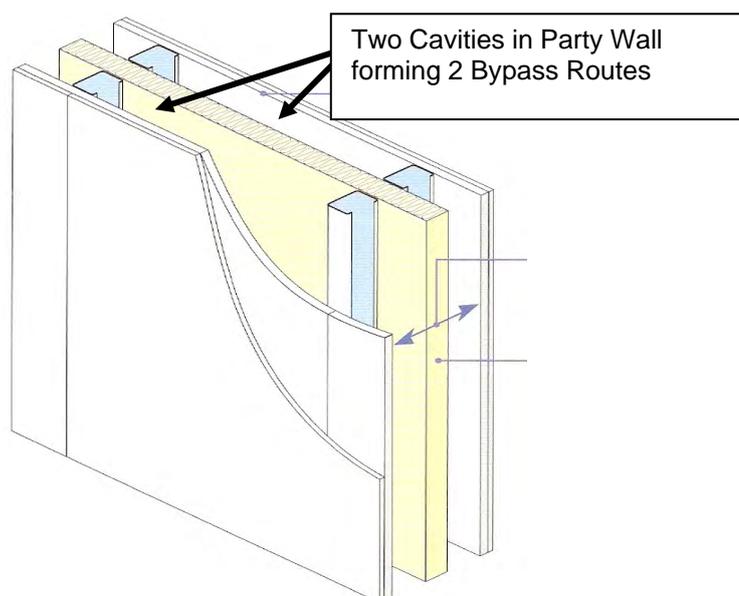


Figure 47 - Robust detail E-WS-1 steel frame separating wall (Robust Details Ltd 2005)

- 110 The coheating test has been shown to be a useful method for determining actual fabric heat loss from dwellings as constructed and for identifying poorly performing constructions qualitatively and, if resources allow, quantifying the additional heat loss. (It is not always necessary to quantify additional heat loss to identify and fix a problem). There would be significant benefits if the construction industry encouraged wider adoption of this technique for assessing the real performance of low carbon housing designs, especially if used in conjunction with long term monitoring of energy in use of occupied dwellings. The coheating test would be an invaluable tool to assess the impact of regulatory changes to energy legislation.

Acoustic tests

INTER-DWELLING SOUND TRANSMISSION

- 111 Acoustics tests of the airborne sound insulation of a party wall at Stamford Brook were conducted on coheating test plots 110-111. The acoustic tests were carried out on the completed dwellings immediately prior to commencement of the coheating tests when the horizontal cavity sock was in position in the party wall cavity. The acoustic tests were then repeated after completion of the coheating tests with the horizontal cavity sock removed. The acoustic tests were carried out according to the requirements of Appendix B2 of Approved Document E for field testing of the airborne sound insulation of separating walls (ODPM 2004). The

results are shown in Table 11. It can be seen that the change in acoustic performance before (sock in place) and after (sock removed) the coheating test was an increase in the sound insulation of 3 dB on the second floor. This improvement was probably associated with the removal of the bridging mortar layer lying on top of the sock, which was removed at the same time as the horizontal sock was taken out. Although it must be recognised that in a less well constructed party wall 3 dB could be significant, these results indicate that if attention is paid during construction to minimising mortar build up on top of the sock, a mineral wool filled sock is unlikely to create major difficulties. The mean sound insulation for the party wall before the coheating test was 55 dB, which easily exceeds the Part E requirement of 45 dB (ODPM 2004). A sound insulation value of 55 dB compares favourably with the average airborne sound insulation of 53.04 ± 4.06 dB from the 1066 sample national database for the identical EWM4 masonry cavity wall robust detail (Baker 2007). This indicates that the quality of construction of the party wall details at Stamford Brook, such as the parging layer and sealing of built-in joists, is of a standard that is towards the top end of UK construction practice.

Table 11 – Results of inter-dwelling acoustic tests – Redrow plots 110 and 111

Location of Test	Airborne Sound Insulation $D_{nT, w + Ctr}$ (dB)		
	Before Coheating Test	After Coheating Test	Change in Sound Insulation
Ground floor, Kitchen to Kitchen	57	57	0
First floor, Lounge to Lounge	55	55	0
Second Floor, Bedroom to Bedroom	53	56	+3

INTRA-DWELLING SOUND TRANSMISSION

- 112 Several complaints have been received by the developers at Stamford Brook regarding sound from various rooms, and particularly bathrooms and WCs, being readily audible in other rooms within the house. The sounds concerned seem to include both airborne and impact sources, and they are believed to transmit both horizontally and vertically within the building, not always to an immediately adjacent room. The householders who took part in the monitoring programme also mentioned their concerns about internal sound levels during their final interviews. In particular, the occupants of the two 3-storey terraced houses described being able to clearly hear in the ground floor kitchen conversations and noises originating from rooms on the second floor.
- 113 The 2003 revision of Approved Document Part E of the Building Regulations (ODPM 2004) imposed for the first time requirements for the airborne sound insulation performance of internal walls and floors. There are no requirements for impact sound insulation of internal walls and floors. The relevant regulation in Part E, E2, requires that;
- “Dwelling houses, flats and rooms for residential purposes shall be designed and constructed in such a way that; (a) internal walls between a bedroom or a room containing a water closet and other rooms; (b) internal floors; shall provide reasonable resistance to sound.”*
- 114 Approved Document E does not require post-construction testing of internal elements within dwellings. Instead, the method of compliance with Regulation E2

is to provide evidence to the building control authority demonstrating that, either the structures recommended in Approved Document E have been adopted, or that the structures specified have been tested and shown to meet or exceed the requirements of the standard. However, it is possible that post-construction tests could provide evidence that structures have not been built in accordance with the approved plans.

- 115 Approved Document E specifies an appropriate performance for airborne sound in terms of the weighted sound reduction index, abbreviated to R_w . This is a quantity widely used by the manufacturers and suppliers of building materials and systems to specify the performance of their products. It can only be measured in a specially constructed laboratory which minimises the influence of adjoining structures. Measurements in an actual building normally use different quantities (in the case of Regulation E1, measurements on separating floors and walls between dwellings are made using a quantity abbreviated to $D_{nT,w} + C_{tr}$). The airborne sound insulation quantity which can be measured in a real building and which can readily be compared with R_w is the weighted apparent sound reduction index, normally abbreviated to R'_w . Although R'_w can be measured within a completed building, it cannot directly be compared with R_w . R'_w will in practice always be lower than R_w because of the differences between a laboratory test facility and a real building¹⁷. The target minimum value of R_w stipulated in Approved Document E for internal floors and walls is 40 dB. The timber intermediate floor construction used at Stamford Brook (241mm TJI joists at 600mm centres, 15 mm plasterboard and 22 mm chipboard flooring) has been tested and shown to meet the 40 dB airborne sound insulation requirement (BRE 2003). As there are no requirements for impact performance of floors within dwellings, there is no target maximum value for the impact sound insulation value $L'_{nT,w}$.
- 116 Acoustic measurements were made of both the airborne sound insulation (R'_w) and impact sound insulation ($L'_{nT,w}$) of the structures separating two different pairs of rooms within Redrow plot 110. The procedures followed were based wherever possible on ISO 140 parts 4 and 7 (BSI 1998a, BSI 1998b) and on the additional guidance given within Approved Document E. The test results are given in Table 12.

Table 12 – Results of intra-dwelling acoustic tests – Redrow plot 110

Source & Receiving Rooms	Airborne Sound Insulation R'_w	Impact Sound Level $L'_{nT,w}$
First Floor Living Room to Ground Floor Kitchen	39 dB	78 dB
First Floor Bedroom to Ground Floor Dining Room	38 dB	80 dB

- 117 The measured airborne sound reduction R'_w was between 38 dB and 39 dB. The precise relationship between the apparent and actual airborne sound insulation indices R'_w and R_w will vary between buildings, but a difference of at least 3dB is to be expected. The results are therefore consistent with wall and floor structures

¹⁷ Laboratory acoustic tests assume perfect installation practices. On a real site, these practices are not always observed and indeed it may not be possible to follow instructions precisely. The junctions where different structures meet in a real structure – for example a wall and a ceiling – tend to be weaker acoustically than the uninterrupted structures used in laboratory tests. In a real building there can also be significant flanking sound transmission by indirect paths such as along side walls which will impair acoustic performance.

whose weighted sound reduction index R_w is 40 dB or higher, and therefore the evidence is that these structures comply with the airborne sound insulation requirements of Regulation E2. The measured impact sound level $L'_{nT,w}$ ranged from 78 dB to 80 dB. As there are no specific requirements in Part E for impact sound transmission within a dwelling, there are no performance targets against which to compare the impact sound results. However, laboratory tests conducted at Leeds Met on a typical timber intermediate floor gave an impact sound level $L'_{nT,w}$ of 72 dB (South 2007). This suggests that the impact sound level of the floor at Stamford Brook was around 6 to 8 dB worse than that indicated by laboratory testing.

Thermal imaging

118 Infra-red thermal imaging was carried out on various completed dwellings at Stamford Brook and also during airtightness pressure tests and the coheating tests. The camera used was a FLIR Systems Thermacam B4 infra-red camera. The camera was equipped with either a standard 27mm (23°) lens or a 15mm (45°) wide angle lens. Thermal images were taken from outside of dwellings when the external conditions were appropriate such as when the sky was overcast, or in the early morning. The coheating test dwellings provided particularly good opportunities for thermal imaging due to the consistent and large difference between inside and outside temperatures. Observations with the thermal camera identified several junctions with high levels of heat loss, and these generally related to known thermal bridges. Examples of these included the soffit of recessed front doors (Figure 48), bay window head (Figure 49), Juliet balcony threshold (Figure 50), front door head (Figure 51), window head (Figure 52) and the floor wall junction (Figure 53)



Figure 48 – Photograph and thermal image of recessed door soffit

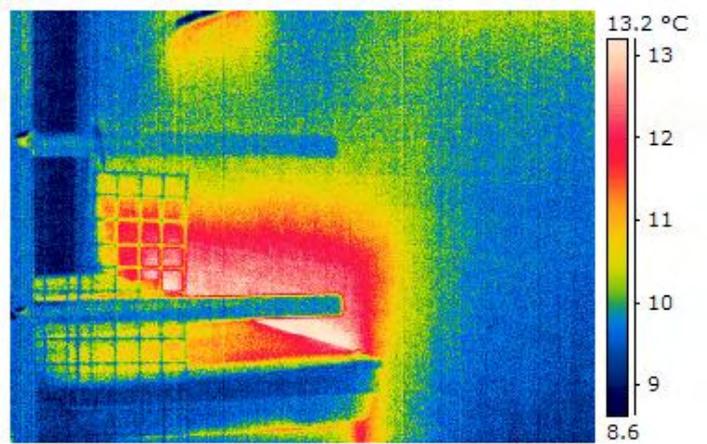


Figure 49 – Photograph and thermal image of bay window head

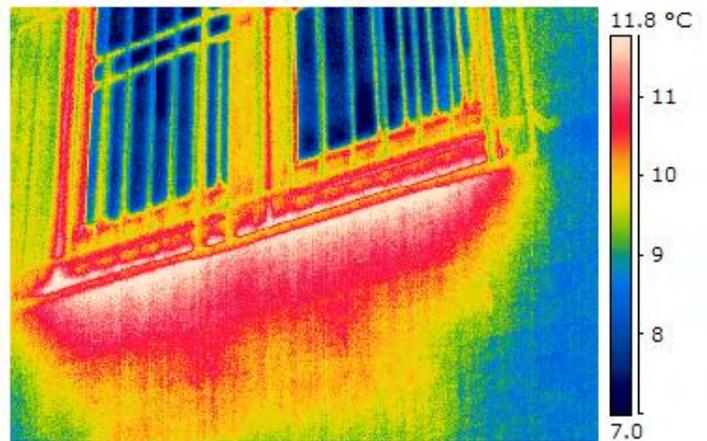


Figure 50 – Photograph and thermal image of Juliet balcony threshold

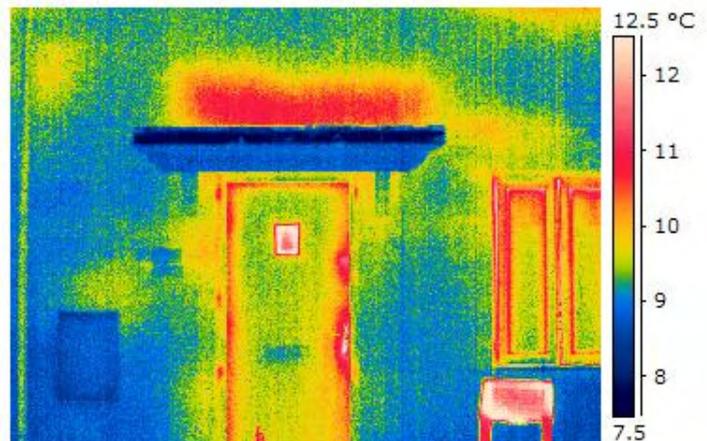


Figure 51 - Photograph and thermal image of door head

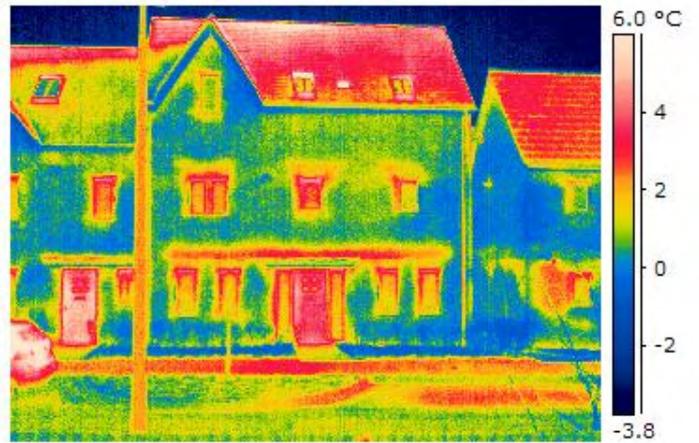


Figure 52 - Photograph and thermal image showing continuous line of thermal bridging across door and window heads in one dwelling

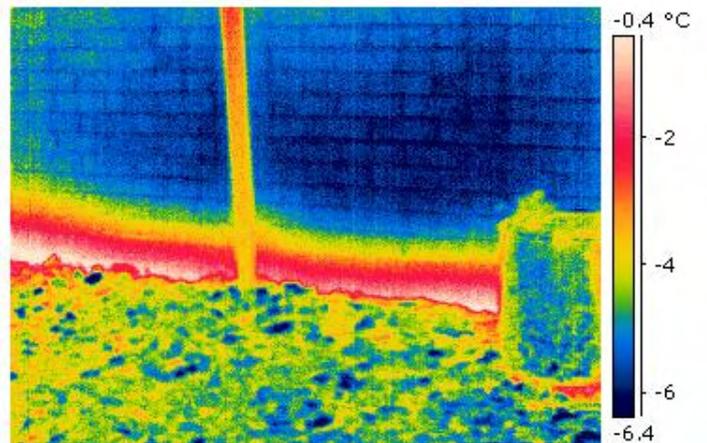


Figure 53 - Photograph and thermal image of external wall-ground junction (one of the first dwellings to be constructed showing thermal bridging at slab edge – see paragraph 64)

Thermal modelling

- 119 During the initial design stages at Stamford Brook, the Leeds Met team worked closely with the developers' in-house design teams in order to develop a set of optimised construction details for all the major junctions that minimised levels of thermal bridging taking into account design and cost constraints. The Therm two-dimensional finite element simulation tool (LBNL 2003) was used to thermally model the various design alternatives. The optimised design Ψ values for linear thermal bridging for junctions at Stamford Brook (see Table 5) give a significant improvement in the equivalent dwelling ΔU factor of $0.03 \text{ W/m}^2\text{K}$ compared to the allowance of $0.08 \text{ W/m}^2\text{K}$ used in SAP 2005 when accredited construction details are used (BRE 2005).
- 120 An example of this optimisation process is illustrated by the analysis of the effect of the window frame offset on the linear thermal transmittance of the window head junction (Roberts, Bell & Lowe 2004). Therm was used to model the window head

detail with the frame set at 8 different locations within the window reveal¹⁸. This analysis showed that, as expected, the lowest Ψ value was where the frame was in line with the cavity insulation as shown in Figure 54, although the minimum was fairly flat between in the region of 50mm around the centre line of the insulation. Based on this analysis the standard window frame offset was changed from 35mm in the original designs to 75mm in order to minimise thermal bridging around window frames.

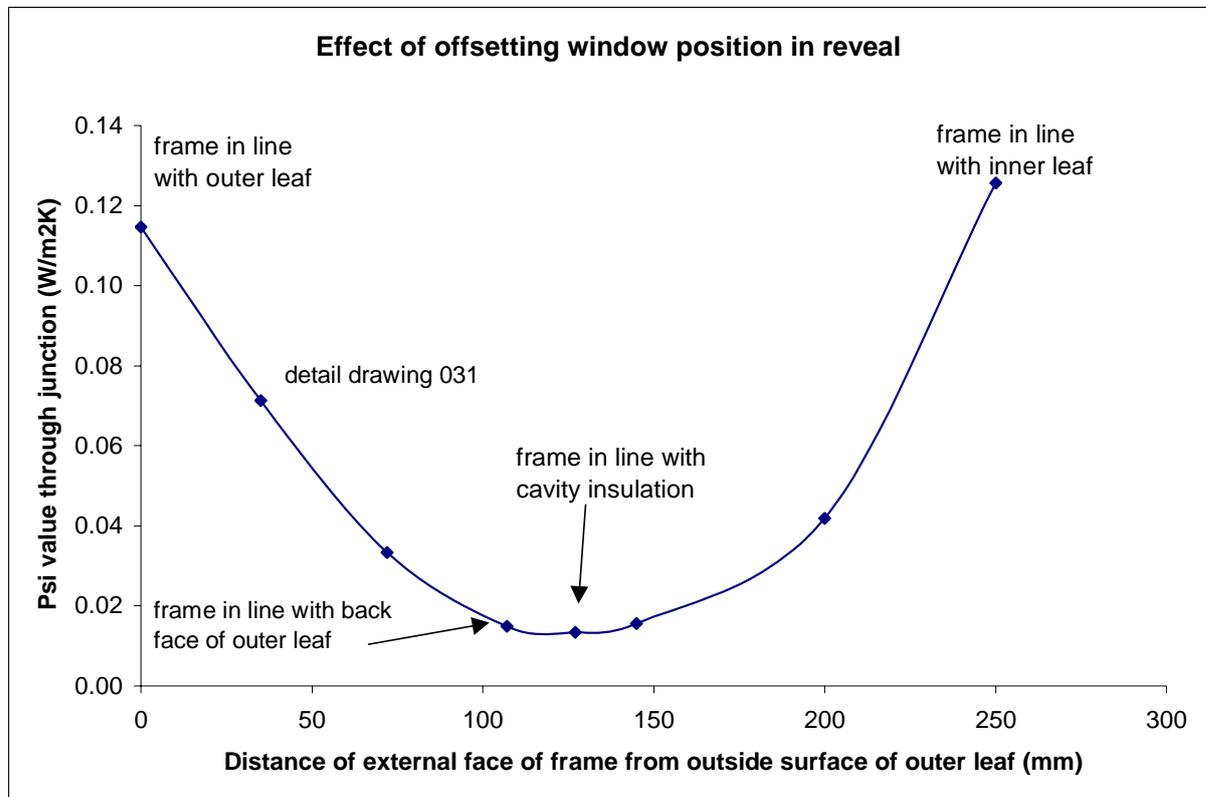


Figure 54 – Effect of window frame offset on linear thermal bridging

121 In order to illustrate the potential cumulative effect on thermal performance of the various design decisions that are constantly being made and also of the impact of construction variability, we have looked in more detail at the window head detail at Stamford Brook as it evolved from the design stage to actual construction on site. Changes in the window head design over time and other factors such as construction tolerances, quality control and workmanship all combine to change the real performance of the detail compared to the original design intention. Five different models were developed to take account of the various changes in window head design and also observed variability due to construction quality and build tolerances. Linear thermal transmittance values for each situation were calculated for these five models and are listed in Table 13. Also given in Table 13 is the standard Ψ value for a head detail built with a typical steel combined lintel of the type normally used in UK housing as opposed to the double lintels used at Stamford Brook. The starting point for the window head design is the optimum thermal solution with separate plain lintels, the window frame in line with the cavity

¹⁸ The 8 frame locations were with the front face of the frame relative to the external wall face at the following positions a) 0mm (in-line with the outer leaf), b) 35mm (the default offset in original drawings), c) 72mm, d) 107mm, e) 127mm (in-line with the cavity insulation), f) 145mm, g) 200mm, h) 250mm

insulation (125mm frame offset) and with insulated reveal boards. The Ψ value for this configuration is 0.016 W/mK with the heat flux from the inside of the window to the outside concentrated at the edge spacer around the window glass. There is a small increase in Ψ value to 0.019 W/mK with the change to a 75mm frame offset in order to allow for detailing of the sill. There is a larger increase in thermal bridging to 0.068 W/mK taking into account the inner lintel with 100mm protruding toe (see Figure 22 A) when the detail is built as designed. However, after taking into account actual construction tolerances and gaps in the window head insulation as observed this increases the Ψ value to 0.181 W/mK. Finally, if we then add in the effect of standard plasterboard, as the research team observed being used on site instead of the insulated board in the design (Figure 20), then the modelled Ψ value increases to 0.203 W/mK. There is clearly a big gap between the Ψ value of the optimal design concept (0.016 W/mK) and what is actually being built on-site (0.203 W/mK). The consequence of these increases in the thermal bridging at the window head would be to increase the predicted dwelling carbon emission rate for a typical semi-detached dwelling at Stamford Brook by around 2%. The final linear thermal bridging factor of 0.203 W/mK is getting close to that for a single combined lintel of around 0.3 W/mK showing that a large part of the benefit of the original design choice to use separate lintels has been lost. This demonstrates that, whilst the impact on performance of the various design decisions and site-based factors if taken in isolation may not seem too critical, the combined effect of all the factors taken together can be significant.

Table 13 - Window head linear thermal transmittance and effect on total thermal bridging

Description of Window Head Detail	Ψ value (W/mK)	Total Thermal Bridging (W/K)
Plain Twin Lintels – Optimum design with window frame position in line with insulation	0.016	5.98
Plain Twin Lintels – 75mm frame offset	0.019	6.00
Plain outer lintel & Inner Lintel with Toe – 75mm frame offset – modelled as drawing with 42mm lintel gap	0.068	6.44
Plain outer lintel & Inner Lintel with Toe – 75mm frame offset – modelled as observed with 20mm lintel gap & air spaces above lintel	0.181	7.43
Plain outer lintel & Inner Lintel with Toe – 75mm frame offset – modelled as observed with 20mm lintel gap & air spaces above lintel, no insulated reveal board	0.203	7.63
Combined Lintel – Table K1 value from SAP 2005 (BRE 2005)	0.300	8.48

Monitoring of occupied dwellings

122 Four occupied houses at Stamford Brook were monitored for energy consumption, internal temperature and humidity, and internal air quality for a period of at least one year. The original intention of the project had been to monitor the energy consumption and internal conditions of ten occupied dwellings over a period of one year. In order to simplify the monitoring process it was decided to only monitor houses and ignore apartments. The process for signing up householders to participate in the intensive monitoring programme is described in the Household Monitoring Protocol (Roberts, Andersson, Lowe, Bell & Wingfield 2005). The initial approach to the householders was made by the two developers during the house sales process. All new householders were invited to sign a contact form which

would then allow the developers to release their personal details to the Leeds Met research team. Of the more than one hundred houses that have so far been occupied at Stamford Brook, a total of seventeen signed the form allowing Leeds Met researchers to make initial contact and discuss the requirements of the project. Of these seventeen potential dwellings, only four households actually agreed to take part in the monitoring program. Details of these four monitored households are given in Table 14. The four dwellings were given a code number (A, B, C or K) in order to preserve the anonymity of the householders. All four houses were from the Redrow part of the development. This was not intentional but was merely due to the fact that only occupants from Redrow houses were prepared to take part in the project. Photographs of the house types being monitored are shown in Figure 55. Monitoring of the first house commenced in October 2005 and monitoring of the last house was completed in May 2007. A summary of the sensor types used and the datalogging equipment is given in Appendix 3.

Table 14 – Details of intensively monitored dwellings

Dwelling Code Number	Developer	Dwelling Form	Gross Floor Area (m ²)	No. of Bedrooms	No. of Occupants	Date of Sensor Installation	Date of Sensor Removal
A	Redrow	3-Storey End Terrace	105	3	3	Oct 2005	April 2007
B	Redrow	2-Storey Mid Terrace	84	3	2 to 3	Nov 2005	Nov 2006
C	Redrow	3-Storey End Terrace	105	3	2	Nov 2005	April 2007
K	Redrow	2-Storey Detached	129	4	2	Apr 2006	May 2007



Figure 55 – Monitored house types (1=dwelling A & C, 2=dwelling B, 3=dwelling K)

ENERGY CONSUMPTION

- 123 Gas and electricity consumption was monitored by taking readings from the supply meters at the start of each month during the monitoring period. The research team would have preferred to use the datalogger to take energy readings at five minute intervals, either from the supply meter or a secondary meter, but this was not possible due to space limitations for secondary meters and difficulties in gaining permissions from energy supply companies to attach sensors directly to the supply meters. The lack of this more detailed information makes it much more difficult to analyse heating system efficiencies. Annualised energy data for the monitored dwellings is shown in Table 15. The monthly gas and electricity readings for all four dwellings are given in Table 16. The influence of yearly changes in external conditions on heating energy demand is reflected in the gas consumption data for dwellings A and C which were monitored over a long enough period to cover both the winter of 2005-2006 and that of 2006-2007 as shown in Table 16. It can be seen that the annual gas consumption for both dwellings A and C was between 1000 and 1500 kWh higher for the period December 2005-November 2006 than for the period April 2006-March 2007.
- 124 In order to better understand any difference in energy consumption between dwellings, the monthly data were normalised for gross floor area and number of days between readings to give an average daily value in kWh/m²/day for each month. A bar chart showing the average gas consumption data for the four test houses is given in Figure 56. It can be seen that the biggest user of gas during the winter by a significant margin is dwelling A. This difference is most likely due to higher demand on central heating by A during the winter compared to B, C and K as the summer demand for all four dwellings is very similar indicating that the difference is not due to excessive demand for domestic hot water. Total annual gas consumption ranged from around 6500 kWh to 13000 kWh/annum compared to the UK average consumption of 20,111 kWh/annum (DTI 2006).

Table 15 – Mean annual energy consumption for monitored dwellings from meter readings

	Dwelling A	Dwelling B	Dwelling C	Dwelling K
Annual Gas Use (kWh/a)	12835	6444	7938	8849
Annual Electricity Use (kWh/a)	3086	2506	3019	3020
Total Annual Energy Use (kWh/a)	15921	8950	10957	11869
Total Annual Energy Use per m ² (kWh/m ² /a)	151.6	106.5	104.4	92.0
Total Annual CO ₂ Emissions (kgCO ₂ /m ² /a)	36.1	27.5	26.8	23.2

Table 16 – Monitored dwelling monthly gas and electricity usage in kWh

Date	Dwelling A		Dwelling B		Dwelling C		Dwelling K	
	Gas (kWh)	Electricity (kWh)						
Nov-05	1835	241	822	201	-	-	-	-
Dec-05	1990	283	1118	250	1703	460	-	-
Jan-06	1405	231	821	174	1136	299	-	-
Feb-06	1850	298	911	190	1050	230	-	-
Mar-06	1810	285	879	185	1156	255	-	-
Apr-06	899	222	468	177	524	242	801	172
May-06	1011	248	286	263	392	264	573	253
Jun-06	393	226	204	208	319	218	431	220
Jul-06	301	237	190	209	231	189	308	231
Aug-06	337	244	204	215	288	215	335	239
Sep-06	338	253	206	227	246	226	343	231
Oct-06	971	252	335	207	461	272	486	228
Nov-06	1440	249	-	-	983	275	940	267
Dec-06	1906	320	-	-	1161	314	1204	336
Jan-07	1794	333	-	-	1112	291	1134	295
Feb-07	1600	248	-	-	874	203	1139	240
Mar-07	1627	287	-	-	997	288	1156	308

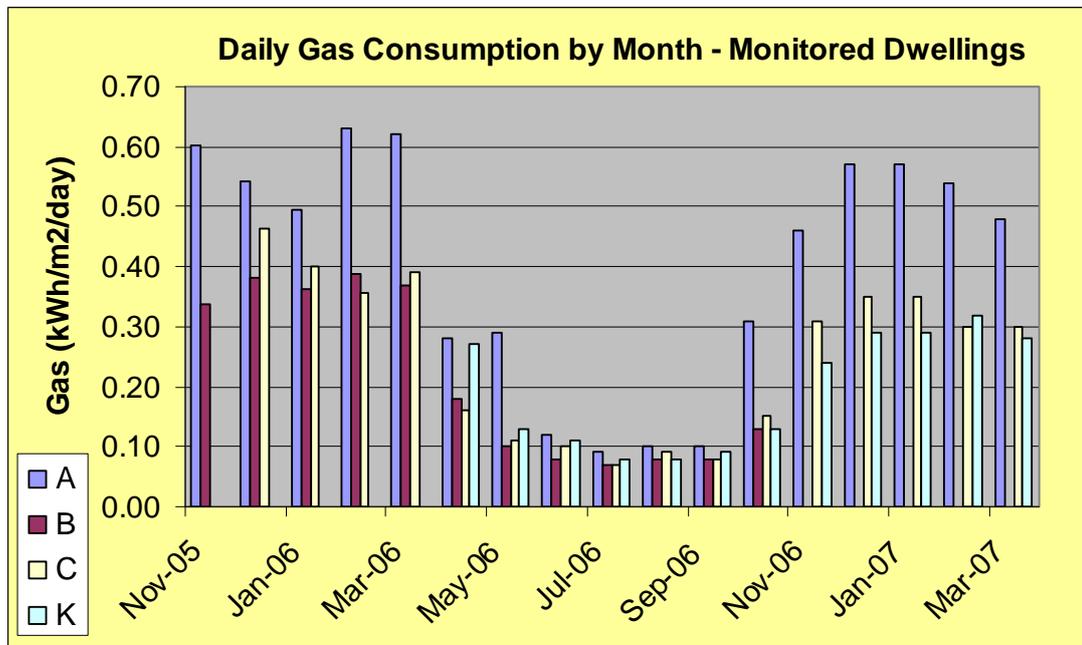


Figure 56 – Daily gas consumption by month in kWh/m²/day

125 A plot of the normalised average daily electricity consumption data for the four test houses is shown in Figure 57. There were no major differences in the electricity consumption of the four houses. Annual electricity consumption was in the range 2500 kWh to 3100 kWh. This is less than the average UK electricity consumption of 4300 kWh (DTI 2006).

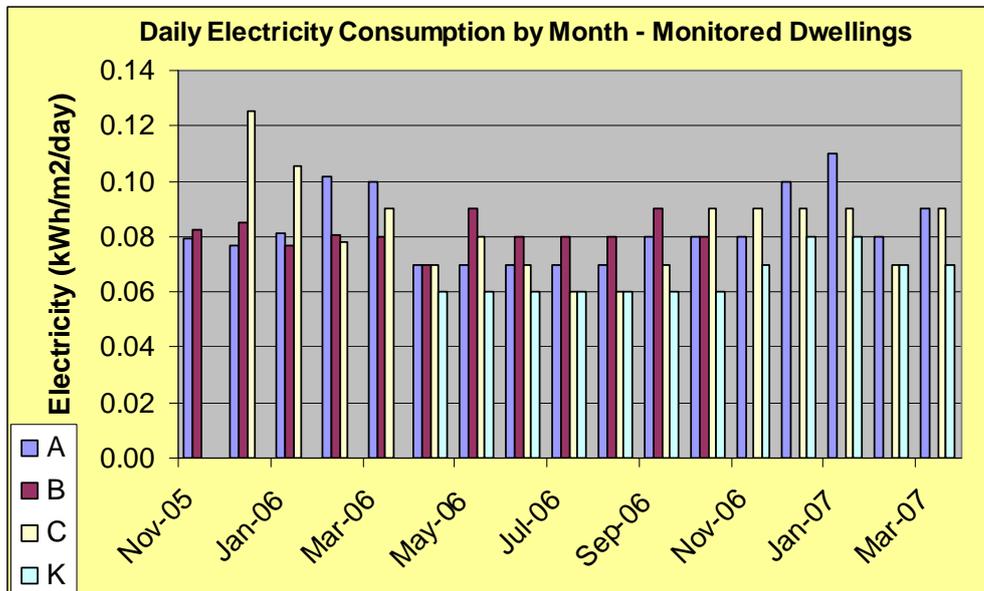


Figure 57 – Daily electricity consumption by month in kWh/m²/day

126 In addition to monthly gas meter readings, the energy use in dwellings C and K was monitored in more detail with heat meters fitted on the central heating (CH) and domestic hot water (DHW) systems. The meters were located in the cylinder cupboard immediately after the split in the primary pipe system as illustrated by the schematic diagram in Figure 58. It was not possible to position a heat meter immediately adjacent to the boilers in the kitchen due to the very limited space around the boilers. Photographs of the heat meters and sensors installed in the cylinder cupboard of one of the monitored dwellings are shown in Figure 59.

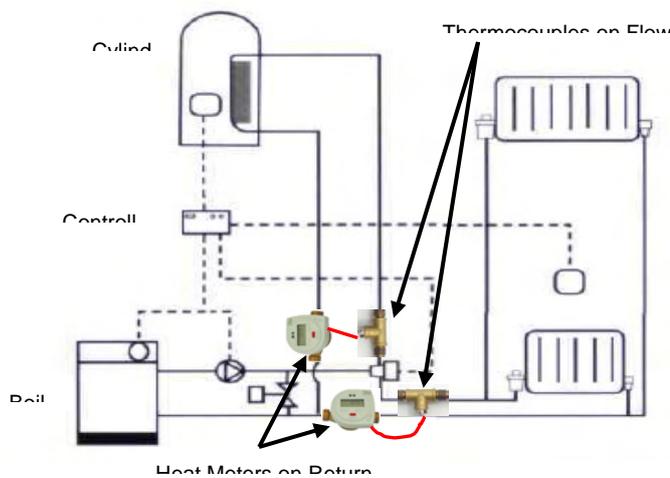


Figure 58 – Schematic diagram showing location of heat meters in heating system

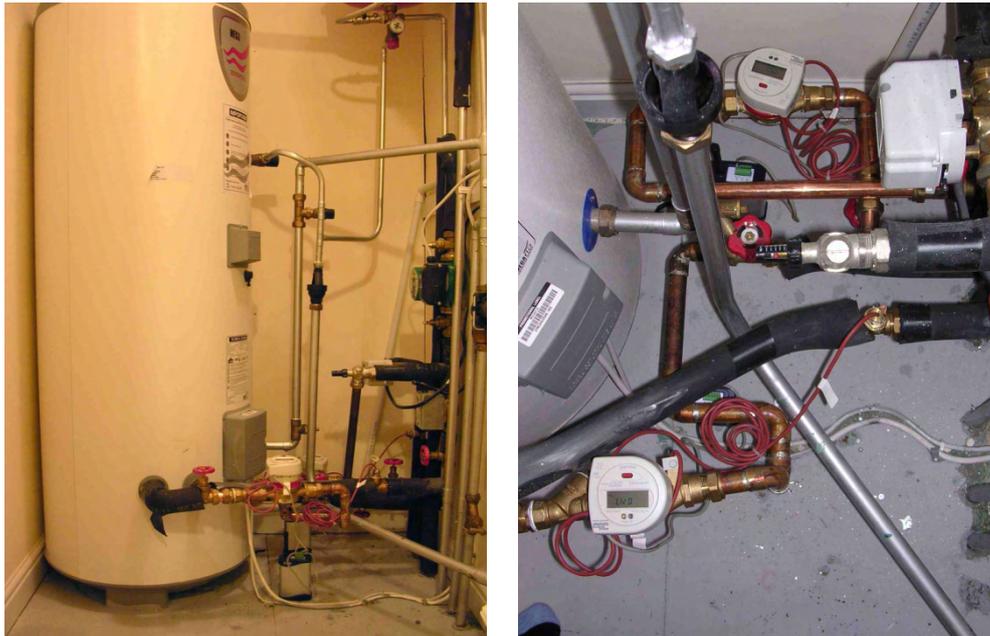


Figure 59 – Heat meter installation in cylinder cupboard

127 The monthly heat meter data for dwellings C and K are given in Table 17 along with the monthly gas consumption. The table also gives monthly heating system efficiencies for each dwelling after allowing for an estimated use of gas for cooking of 0.5 kWh/day. The data for two dwellings for the period April 2006 to March 2007 were used to calculate estimated seasonal boiler efficiencies after taking into account heat loss from the primary pipe work and gas energy used for cooking. The value for primary pipework loss of 610 kWh is the value used by SAP for uninsulated pipe (BRE 2005). It can be seen that the estimated seasonal efficiencies of C at 76% and K at 81% are much less than the expected SEDBUK boiler efficiency of 90.8 to 91.3 % for the Potterton Promax HE Plus modulating condensing gas boilers used at Stamford Brook (DEFRA 2007).

Table 17 – Monthly heat meter data – dwellings C and K

	Dwelling C				Dwelling K			
	Gas Used (kWh)	DHW Heat Meter (kWh)	CH Heat Meter (kWh)	System Efficiency* (%)	Gas Used (kWh)	DHW Heat Meter (kWh)	CH Heat Meter (kWh)	System Efficiency* (%)
Jan-06	1136	219	626	75.28	-	-	-	-
Feb-06	1050	189	545	70.85	-	-	-	-
Mar-06	1156	238	589	72.42	-	-	-	-
Apr-06	524	196	95	57.23	801	250	320	72.34
May-06	392	224	5	60.99	573	300	102	72.24
Jun-06	319	175	0	57.57	430	297	0	71.57
Jul-06	231	125	0	58.00	308	203	0	69.40
Aug-06	287	148	0	54.61	334	227	0	71.38
Sep-06	246	146	0	63.34	343	232	0	70.84
Oct-06	461	165	147	69.96	486	240	105	73.25

Nov-06	983	176	495	69.32	940	291	390	73.62
Dec-06	1161	196	640	73.01	1204	316	597	76.85
Jan-07	1112	190	582	70.37	1134	308	541	75.87
Feb-07	874	137	473	70.93	1139	278	553	73.87
Mar-07	997	211	455	67.89	1156	338	524	75.61

* System efficiency adjusted for estimated gas use for cooking = 0.5 kWh/day

Table 18 – Estimated annual boiler efficiency for dwelling C and K for year April 06 to March 07

Dwelling	Gas Used (kWh)	Heat Delivered to Cylinder (kWh)	SAP Heat Loss from Primary Pipe (kWh)	Estimated Gas for Cooking (kWh)	Estimated Boiler Efficiency
C	7587	4981	610	183	76 %
K	8848	6412	610	183	81 %

128 The trends in monthly system efficiencies for the two test dwelling are plotted on the graph shown in Figure 60. It can be seen that the system efficiency of the heating system of C is around 5% lower than that of K during the heating season and around 10 to 15% less than K when only the domestic hot water system is operating. This difference between the two dwellings is likely to be partly related to the different relative locations of boiler and cylinder in the two dwellings and the consequent difference in actual primary pipe heat loss from that predicted by SAP. The efficiencies will also be affected by the settings of the heater system timer and by the way the householders actually use the systems in summer and winter.

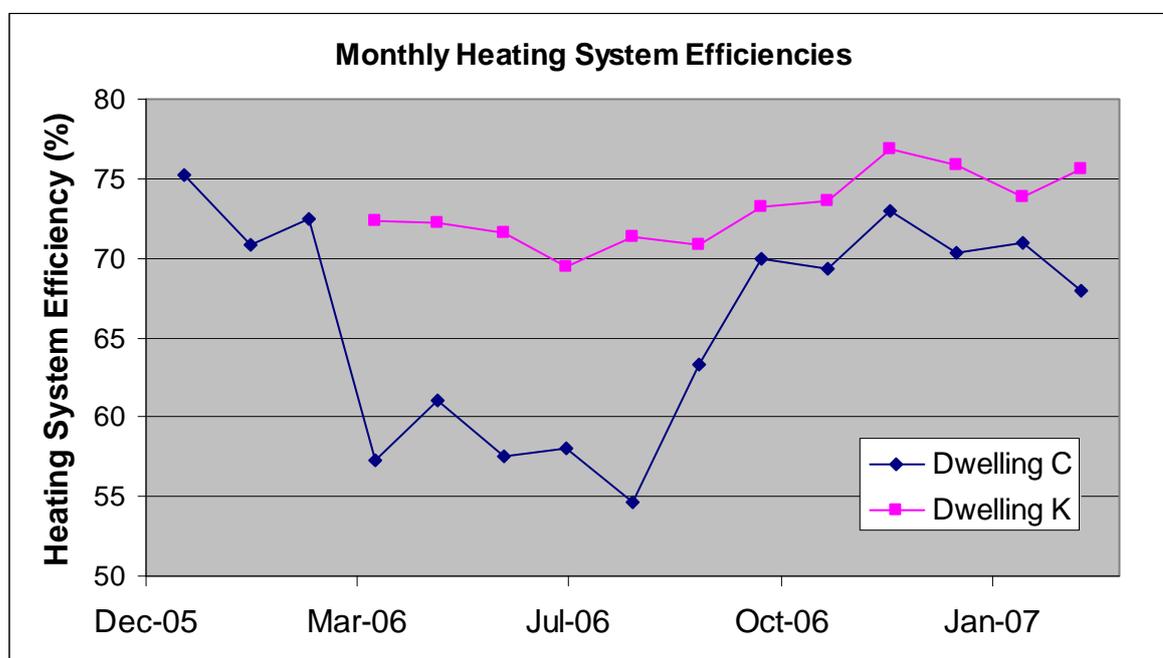


Figure 60 – Monthly heating system efficiency - dwellings C and K

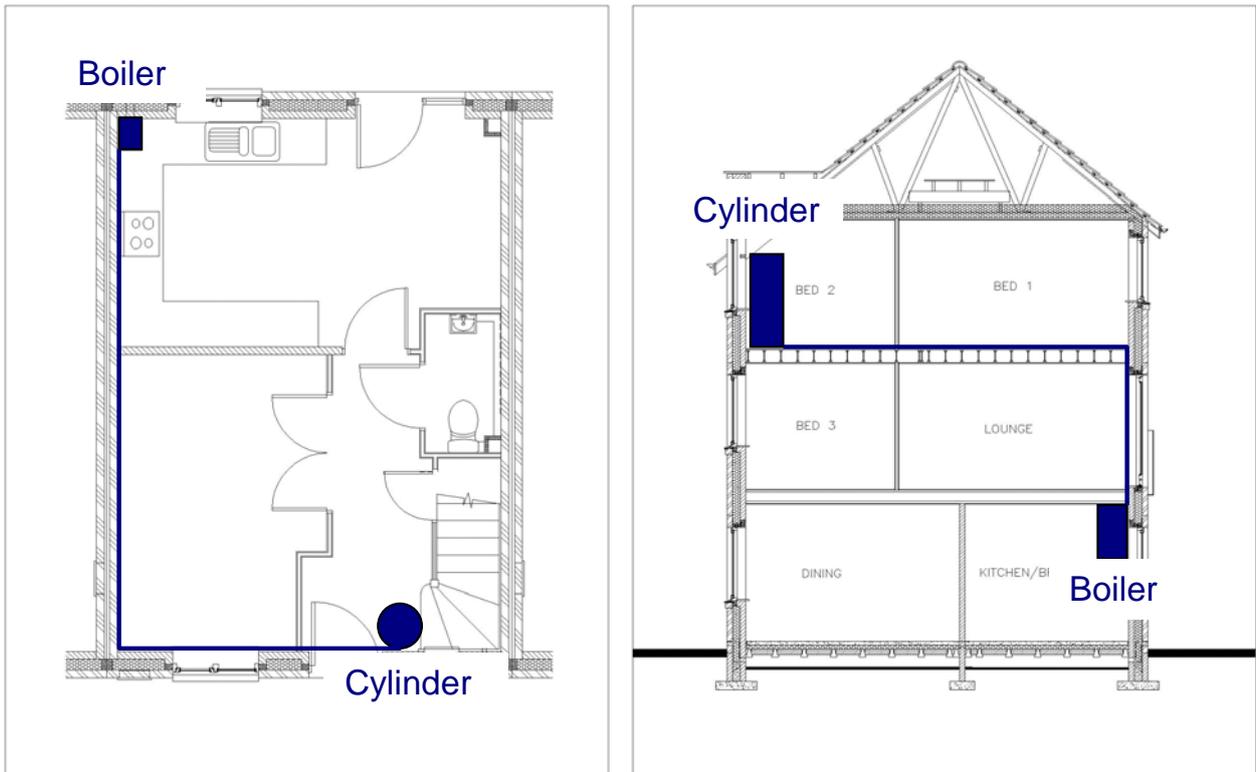


Figure 61 – Plan and elevation of plot C showing location of boiler and cylinder

129 If we look first at the potential effect of the heat loss from the primary pipework, we need to estimate the total length of pipe between the boiler and cylinder. In the two-storey dwelling K, the pipe run distance between the boiler situated in the ground floor kitchen and cylinder on the first floor is around 7 metres, giving a combined pipe length for the primary flow and return pipework of around 14 metres. By comparison, the pipe run distance in the three-storey dwelling C between the boiler situated in the ground floor kitchen and cylinder on the second floor is much longer at around 14 metres, giving a combined pipe length for the primary flow and return pipework of 28 metres. A schematic of the primary pipe run in dwelling C is illustrated in Figure 61. The heat loss from the primary pipework in dwelling C will therefore be approximately twice that of K. We know that the 22mm diameter primary pipework at Stamford Brook is not insulated. There will therefore be heat loss of around 60 W per metre of pipe length when the system is running, if we assume a temperature difference of around 55°C between the hot water in the pipe and internal air temperature (CIBSE 2007). This would give a primary pipe loss of 840 W for dwelling K and 1680 W for dwelling C. Using these heat loss factors together with typical daily system on times, we can estimate the boiler efficiencies for the heating season, the non-heating season and the whole year as shown in Table 19.

Table 19 – Estimated seasonal boiler efficiencies - dwellings C and K

Dwelling	Period	System Daily on Time (hours)	Gas Used (kWh)	Heat Delivered to Cylinder (kWh)	Primary Loss (kWh)	Estimated Gas for Cooking (kWh)	Estimated Boiler Efficiency %
C	Jun 06 – Sep 06	1	1083	594	202	61	78
K	Jun 06 – Sep 06	1.5	1415	959	151	61	82
C	Apr 06 – May 06 & Oct 06 – Mar 07	3.5	6504	4387	1210	122	91
K	Apr 06 – May 06 & Oct 06-Mar 07	4	7433	5453	605	122	86
C	Apr 06 – Mar 07	-	7587	4981	1613	183	89
K	Apr 06 – Mar 07	-	8848	6412	957	183	85

- 130 It can be seen in Table 19 that, now we have a more accurate estimate of primary pipe heat loss, the boiler efficiency of dwelling C in the heating season more closely matches the declared SEDBUK rating of ~91%. However, the efficiency of dwelling K in the heating season at 86% is still slightly below the SEDBUK rating. By contrast, the efficiency for both dwellings in the four months outside of the heating season from June to September is significantly less than the SEDBUK rating at 78% for dwelling C and 82% for dwelling K. It is believed that this reduction is related to the thermal inertia of the water in the primary pipework, which has to be heated up each time the heating system is turned on. This thermal inertia will begin to dominate efficiency in the summer due to the short heating cycles needed when the system is only being used to supply domestic hot water. The inefficiencies due to thermal inertia will be worse where the primary pipework is long, as this increases the volume of cold water in the pipe that needs to be heated up. This would explain why the boiler performance of C is worse than K in the summer, as the length of primary pipe in dwelling C is twice that of dwelling K.
- 131 It is clear that the lack of insulation around the primary pipework and the long lengths of primary pipe between boiler and cylinder have both contributed to a serious degradation of expected boiler efficiency. The situation could be improved by insulating the primary pipes. However, this would only reduce the heat loss by around 50%. The most effective solution would be to minimise the distance between the boiler and cylinder, which would reduce the required length of primary pipe and potentially reduce heat loss by 75% when combined with pipe insulation. There is no reason why, with a modern pressurised heating system, that the cylinder and boiler could not be positioned adjacent to each other, either in the utility room or in a larger combined boiler-cylinder cupboard. Alternatively, the house designer could ensure that, if it is still deemed necessary to have the boiler on the ground floor and the cylinder on an upper floor, that priority is given in the room layout design to have the cylinder cupboard located immediately above the position of the boiler. In the case of dwelling C, the position of boiler and cylinder were such that this created the maximum possible run of primary pipe. With more careful thought to requirements of the heating system as a whole, such a situation could have been avoided at the design stage.
- 132 The reason for the slightly lower efficiency in house K during the heating season compared to C is thought to be related to the way that the householder used the

heating system. We observed from the monitored internal temperature profiles and heat meter data that, either by turning down the thermostat or turning off the heating altogether, the occupant of dwelling K would allow the building to cool down to around 15 or 16°C over a period of several days. This would be followed by several days of boost heating to warm the house back up again to between 18 and 20°C. This temperature pattern can be seen for dwelling K during November 2006 in Figure 62. This pattern was repeated by the householder several times during the heating season. By contrast, it can be seen in Figure 62 that the temperature profile in dwelling C was relatively stable at between 18 and 20°C. It was confirmed during the final interview with the occupants of dwelling K that they did indeed operate an interventionist style of temperature management and would constantly adjust both the internal thermostat and heating timer over the course of the winter in the belief that this would save energy. The occupants of dwelling C on the other hand noted in their final interview that, once they had found a combination of time and temperature that suited them, they kept the central heating timer and thermostat settings fixed for most of the winter.

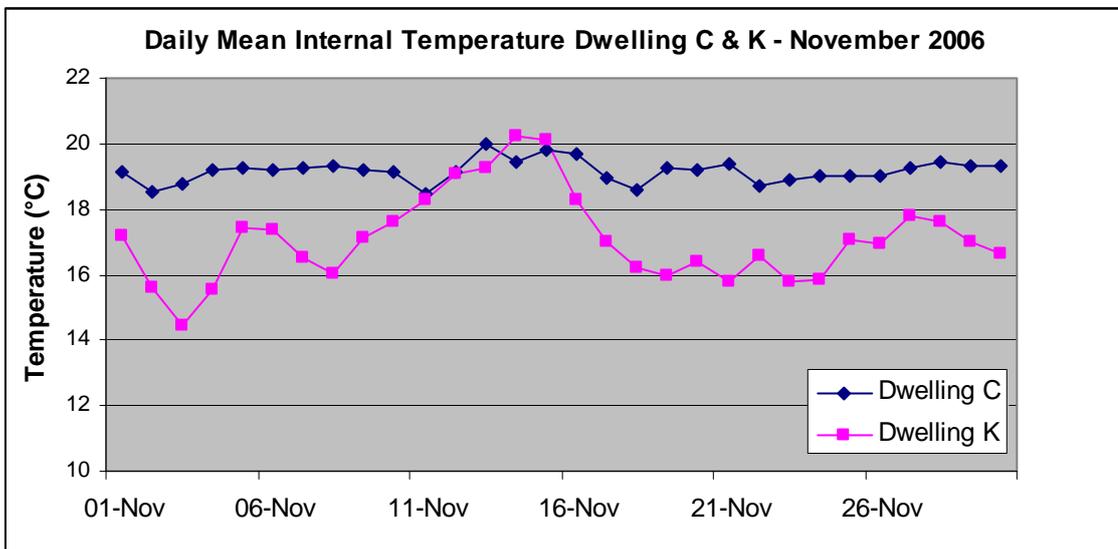


Figure 62 – Internal temperature trend – dwellings C & K – November 2006

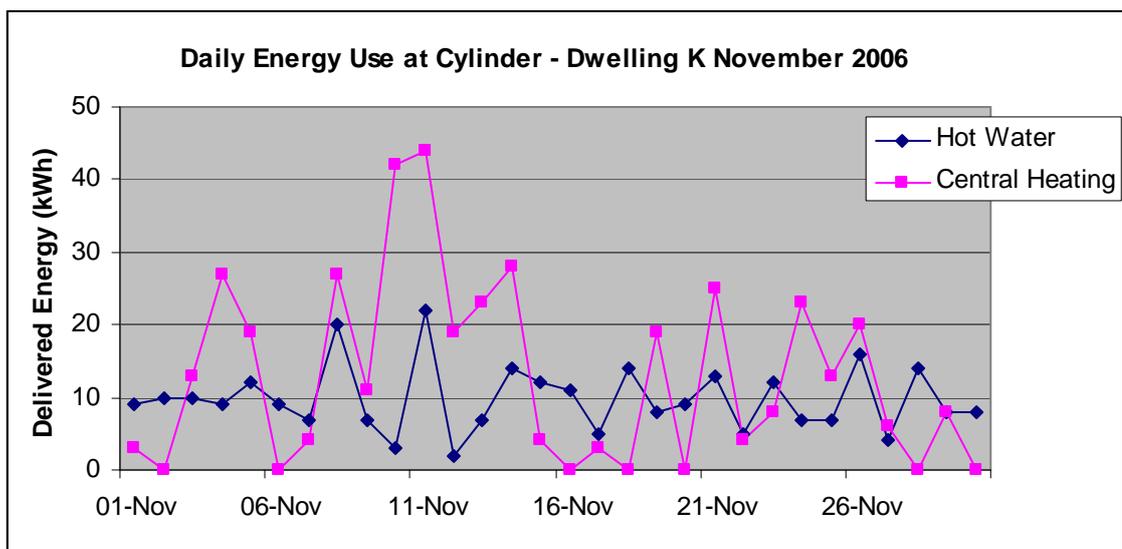


Figure 63 – Dwelling K central heating and hot water energy – November 2006

133 In addition to the day to day variation in central heating demand in dwelling K, it was also observed that the demand on the domestic hot water system would also vary from around 1 kWh/day to around 20 kWh/day. The combined effect of fluctuations in both hot water and central heating demand in K during the heating season meant that on some days the overall heating demand was very low at around 10 kWh/day, whereas total energy use on days of high demand could be up to 70 kWh/day, as can be seen in Figure 63. On those days where the demand was high, the boiler efficiency would be expected to also be high at around 90% or better. However, on those days where overall demand was low, the boiler efficiency would be expected to drop to that more typical of the summer period at around 80%. This would mean that the mean boiler efficiency for dwelling K during the heating season would be expected to lie somewhere between 80 and 90%. In the case of dwelling C, the daily fluctuations in demand were much smaller, and the trend in total daily energy use was much more stable at between 15 to 30 kWh/day as can be seen in Figure 64. This would mean that for most of the time during the heating season the boiler efficiency in dwelling C would be expected to be high at around 90%, as was indeed found to be the case.

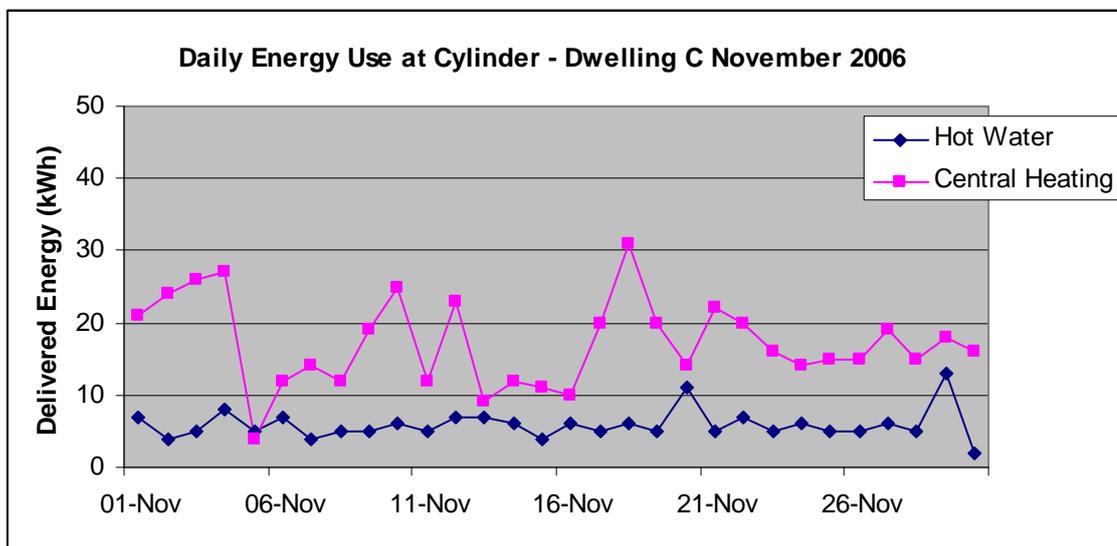


Figure 64 – Dwelling C central heating and hot water energy – November 2006

134 With the assistance of the householder in dwelling C, a short experiment was undertaken to further explore boiler efficiency during the summer period when the only demand would be from the domestic hot water system. Under the directions of the research team, the occupant gradually reduced the daily timed hot water period from a total of 4.5 hours per day to a minimum of 0.5 hours per day as shown in Table 20. Each setting was used for a period of between 8 and 13 days, during which time the householder took daily gas meter readings and also took meter readings before and after using any gas for cooking. The householder reported that, even at the minimum setting of half hour/day, there was normally sufficient hot water in the cylinder for the whole days use. It can be seen from Table 20 that the heating system efficiency (not including primary pipe losses) improved from 49.8% when the timer was on for 4.5 hours per day to 63.5% when the timer was on for only 0.5 hours/day. The overall daily gas usage also dropped from a maximum of 10.5 kWh/day to only 7.3 kWh/day, even though there was no apparent change in actual utilisation of hot water in the dwelling. The improvement in efficiency is thought to be due to the reduction in the cycling of the system in

response to demand from the cylinder thermostat. This would have the effect of minimising any inefficiency due to thermal inertia effects, as the system will only carry out one heating cycle during the whole day. Data obtained directly from the DHW heat meter at the start and end of a 20 minute hot water heating cycle in dwelling C showed that it took around 5 minutes to raise the temperature of the water in the primary flow pipe from 25°C to 62°C and a further 10 minutes to raise the temperature of the water in the primary flow pipe from 62°C to 77°C. (The flow temperature from the boiler was set at 82°C, the measured flow rate was 0.62 m³/h and the measured cylinder coil heat output was 11kW.) It is likely, therefore, that the thermal inertia inefficiency is partly associated with the first five minutes of the heat up period when the primary flow temperature is actually less than the cylinder temperature. During this initial time, the direction of heat flux will be from the cylinder to the water in the primary pipe rather than from the pipe to the cylinder.

- 135 The householder has decided to keep the hot water timer at 0.5 hour for the summer period. It is also interesting to note that during the heating season the occupant found that the system began to run short of domestic hot water at this setting and had to increase the timer period to one hour to ensure a sufficient supply of water for daily use. The householder expects to revert back to the half hour setting for the next summer.

Table 20 – Effect of daily hot water timing on system efficiency

DHW Timer Settings	Total Daily Timed DHW (hours)	No Test Days	System Efficiency %	Gas Usage (kWh/day)	DHW Heat (kWh/day)	Cooking (kWh/day)
06:00 to 07:00 & 15:30 to 19:00	4.5	10	49.8	10.5	5.2	0.10
06:00 to 07:00 & 15:30 to 16:30	2	11	55.5	10	5.6	0.08
06:30 to 07:00 & 15:30 to 16:00	1	13	56.3	9.3	5.2	0.11
06:30 to 07:00	0.5	8	63.5	7.3	4.6	0.44

- 136 With the continued cooperation of the householders in dwelling C, we were able to conduct another experiment, this time to investigate the energy consumption of the domestic hot water system and in particular the heat loss from the cylinder during those times when the occupants were on holiday. The experiment involved the householder leaving the hot water system turned on whilst they were away, and also recording the gas meter reading just before leaving on holiday and then again immediately on return from holiday. The results are given in Table 21. The measured cylinder standing heat loss was 2 kWh/day, which is in line with the value for standing energy loss of 2.2 kWh/day for this particular cylinder given in the BBA certificate (BBA 1995). It can also be seen in Table 21 that the system efficiency during the holiday had dropped dramatically from a typical level during normal use of around 55% to 40.5% during the holiday. This very low efficiency will be due to the very short cycle times that would be needed to keep topping up the hot water back to the cylinder set point of 60°C over the holiday period.

Table 21 – Cylinder heat loss factors and DHW system efficiency in summer

Normal daily DHW cylinder output during summer (at timer setting 2 x ½ hour per day)	~ 5 kWh/day
Normal daily DHW gas use during summer (at timer setting 2 x ½ hour per day)	~ 9 kWh/day
Normal DHW system efficiency during summer(at timer setting 2 x ½ hour per day)	~ 55%
Measured cylinder energy use during holiday when DHW left ON	2.0 kWh/day
Manufacturers quoted cylinder heat loss factor	2.2 kWh/day
Gas used for DHW during holiday when DHW left ON (at timer setting 2 x ½ hour per day)	4.9 kWh/day
System efficiency during holiday when DHW left ON (at timer setting 2 x ½ hour per day)	40.5%

137 The analysis of energy consumption trends in the four intensively monitored dwellings has identified several factors that contribute to overall heating system efficiency. These include:

- a) The potential benefits of optimisation of heating system timings.
- b) The influence of occupant behaviour in relation to their interaction with system controls.
- c) The importance of careful heating system design and its integration into the overall house design.

TEMPERATURE AND HUMIDITY

138 Internal temperature and relative humidity measurements in the four monitored households were taken at 5 minute intervals at five different locations within each dwelling. Temperature and humidity sensors were located in the entrance hall, kitchen, living room, master bedroom and bathroom. Monthly mean internal temperatures were calculated for each test dwelling by averaging the data from the five different internal locations. A plot of the monthly mean internal temperatures is shown in Figure 65. It can be seen from Figure 65 that there was a significant variation in internal temperatures between the four dwellings. In particular, it can be seen that the dwelling A was generally around 1 to 2°C higher than the other properties during the heating season at around 20°C. The exception to this was in November/December 2005 when the occupants were on holiday for several weeks and had turned the heating down while they were away. By contrast, the occupants of dwelling K kept their house cooler than the average at around 17°C. The occupants of dwellings B and C typically maintained the internal temperatures of their houses during winter close to the UK norm of around 18 to 19°C. The standard heating season internal temperature used by the algorithms in SAP is around 18.8°C. It is known that there is a trend for occupants to set higher internal temperatures in more highly insulated and energy efficient houses. For example, the final report on the CEPHEUS passive house project reported mean heating season internal temperatures on 11 passive house demonstration developments of around 21.5°C (Feist Peper & Görg 2001). A low energy house scheme in Denmark (Tommerup, Rose & Svendsen 2007) and a passive house scheme in Gothenburg, Sweden (Wall 2006) have reported internal temperatures during the heating season as high as 23°C. With the exception of dwelling A, this trend towards higher internal winter temperatures is not yet apparent at Stamford Brook, although it should be noted that the sample size is very small.

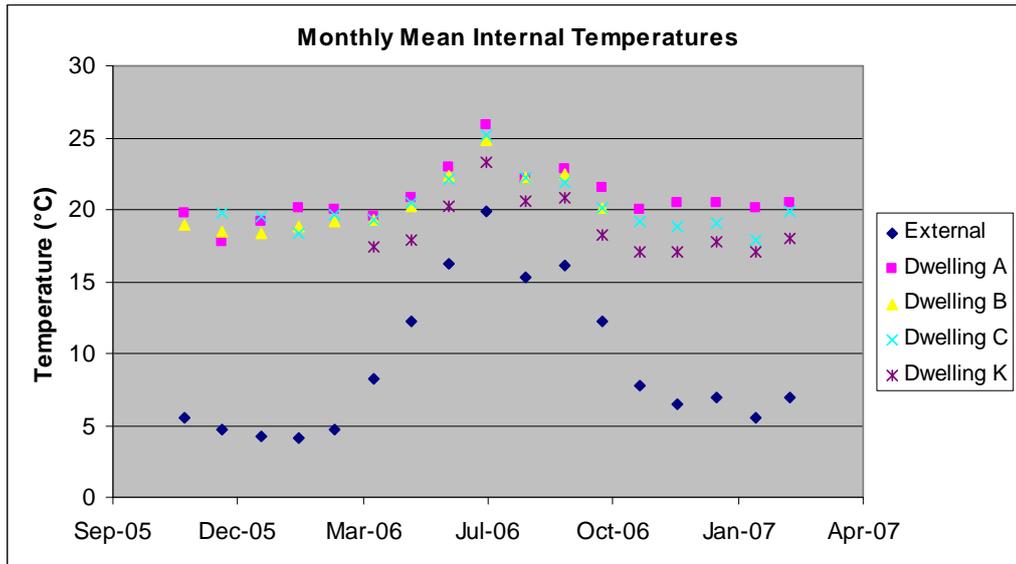


Figure 65 – Monthly mean temperatures

139 A plot of monthly mean relative humidity is given in Figure 66. It can be seen that, during the winter heating season the relative humidity in dwelling A was generally lower than the other three houses. This will be in part due to the higher internal temperatures in dwelling A. To allow for this temperature difference the relative humidity values were converted to absolute humidity in g/m^3 of water in air. The monthly absolute humidity data are shown in the graph in Figure 67. It can be seen that during the heating season, the moisture levels in dwelling A were around 1.5 g/m^3 higher than the external moisture level and around 1.5 g/m^3 less than in dwelling C, which is the same house type. This is despite the fact that C is only occupied by 2 persons compared to the 3 in dwelling A and would be normally be expected to have a lower moisture level than A due to the lower expected rate of household moisture generation. This indicates that the background ventilation rate in A is high, probably due to additional window opening by the occupants in A during winter.

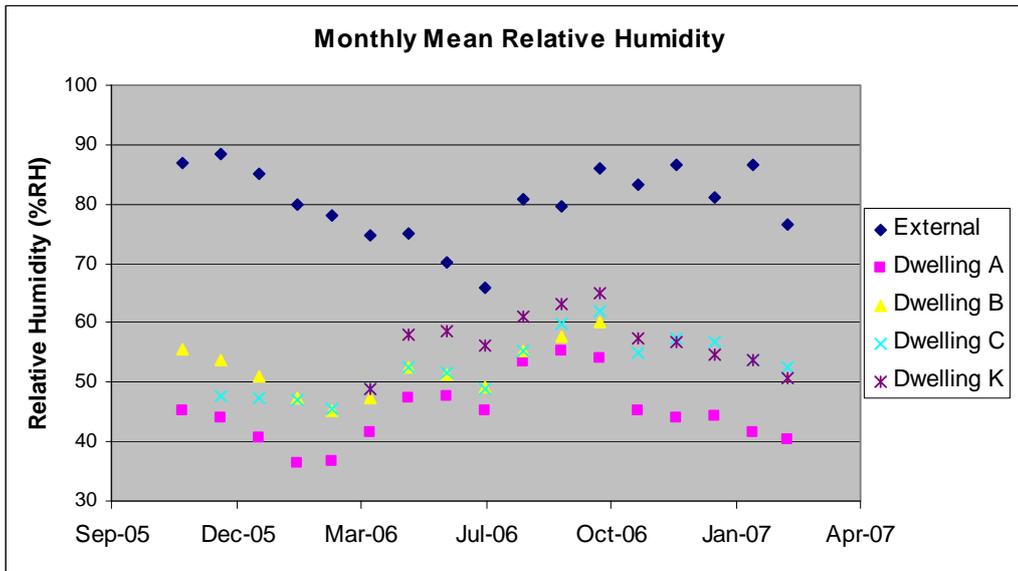


Figure 66 – Monthly mean relative humidity

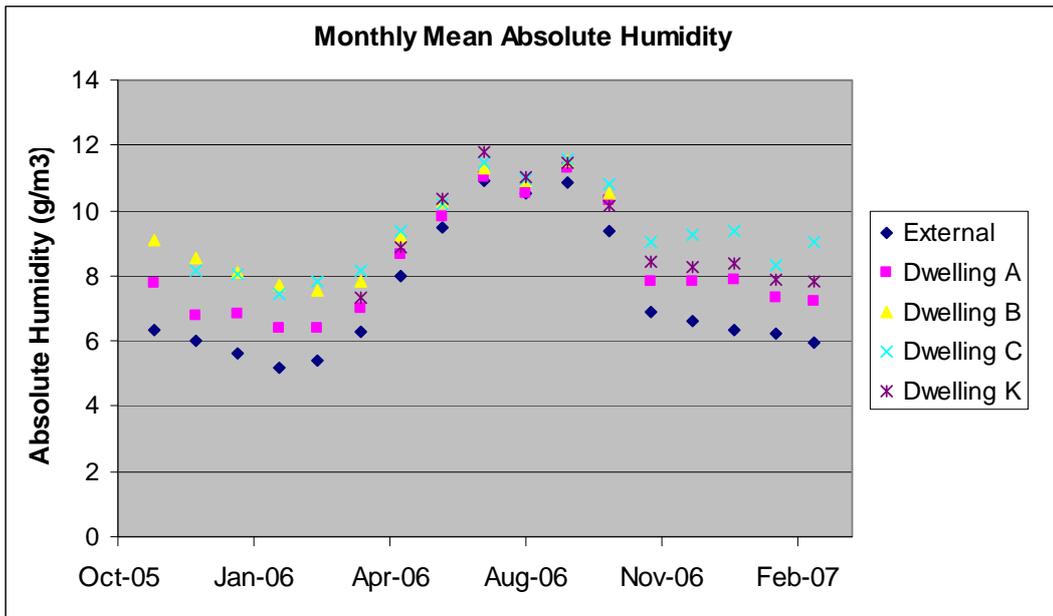


Figure 67 – Monthly mean absolute humidity

140 In order to determine an approximate value for the actual heating season background ventilation rates in dwellings A and C, a series of curves were developed using the methodologies in BS5250 (BSI 2002) to map the relationship between internal moisture generation in kg/day and additional internal moisture in g/kg at 5 different ventilation rates ranging from 0.25 ach to 2 ach as shown in Figure 68. The difference between the external specific humidity and internal specific humidity in grams per kilogram of air (the internal absolute humidity excess) was then calculated for plots A and C for the monitored heating seasons. In the case of dwelling A, the mean additional moisture inside relative to outside was found to be 1.3 g/kg and for dwelling C the difference was 2.3 g/kg. The expected internal moisture generation was calculated according to the moisture generation rates for the various internal moisture sources given in BS5250

141 (BSI 2002) and adjusted for the daytime and evening occupancy levels declared by the householders in their final interviews. In the case of dwelling A, the expected daily moisture generation rate ranged from 7.5 kg/day to 12 kg/day, depending upon the use of an unvented tumble drier. In the case of dwelling C, the expected daily moisture generation rate ranged from 5.5 kg/day to 8.5 kg/day, depending upon the use of an unvented tumble drier. These expected zones of operation for both dwellings were then plotted over the ventilation rate curves as shown by the coloured ellipses in Figure 68.

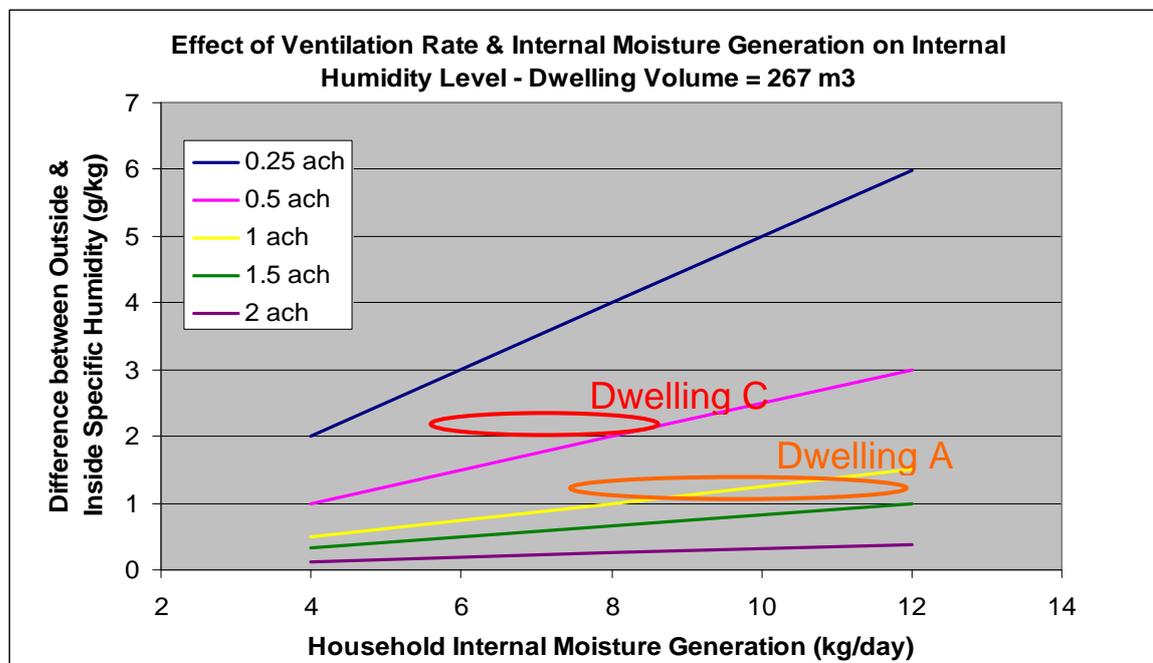


Figure 68 – Effect of ventilation rate on internal moisture content

142 Based on the location of these zones relative to the ventilation rate curves, we can estimate the true ventilation rates for the two dwellings. In the case of dwelling C, the ventilation rate would be of the order 0.4 to 0.5 ach and for dwelling A would be of the order 0.9 to 1.3 ach. The ventilation rate of around 0.5 ach in dwelling C is consistent with that expected by normal use of the whole house mechanical ventilation system with a small amount of window opening during the winter, and is in line with the value predicted by SAP for this dwelling type. However, the very high estimated ventilation rate of 1 ach (and possibly higher) for dwelling A indicates that the occupants of dwelling A are over ventilating the house. This would have serious implications for ventilation heat loss and would be expected to give rise to higher energy consumption in dwelling A than that predicted by SAP. During the final interview with the householders of dwelling A, it was discovered that the occupants of the house would often leave windows and the kitchen back door open for several hours a day during the winter time, especially when cooking in the kitchen. This would help explain the high ventilation rates in A.

143 The ventilation strategy adopted by householders during the heating season can clearly have a significant effect on the effective ventilation rate. Excessive winter time ventilation, such as that observed in dwelling A, would be expected to significantly increase ventilation heat loss and heating energy consumption. The final interview with the occupants of dwelling A suggests that the main reason why they opened doors and windows in the kitchen was to remove cooking odours that were not effectively removed by the carbon filter in the recirculating cooker extract

hood. Apart from this, the householder said that opening windows around the house was just a matter of personal preference, that they had always done it in previous houses and stated the belief that opening windows to get fresh air was important. There was no indication from any of the householders that the air in the houses at Stamford Brook was stuffy or stale when the windows weren't open. The reluctance of the householders of dwelling A to change their behaviour pattern to rely completely on fresh air provided via the trickle vents and background ventilation suggests that some of the issues that need to be addressed are cultural. For example, how do we educate and inform owners of well insulated airtight houses as to the most energy efficient ways to use their homes? Further work will be certainly be required to understand the cultural and historical reasons for user behaviour and to develop ways of persuading home owners to adopt appropriate heating and ventilation strategies for low energy houses that minimise energy use.

SUMMER OVERHEATING

144 It can be seen in Figure 65 that, during the summer of 2006, the mean internal temperatures in all four dwellings peaked at around 25°C during July. In their final interviews the occupants of the two 3-storey test dwellings A and C both complained about excessive and uncomfortable internal summer temperatures during this time. Indeed one occupant said that the situation had got so bad during July 2006 that they had even considering selling their house. More detail is given for the daily maximum internal room temperatures for dwelling A during this period in Figure 69.

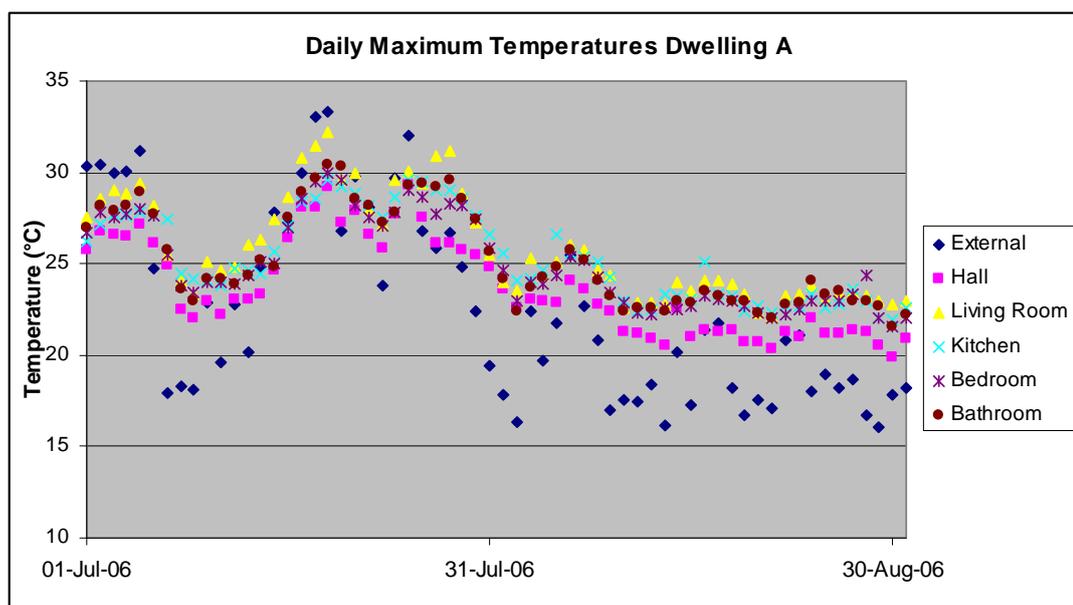


Figure 69 – Daily maximum internal room temperatures – dwelling A - July and August 2006

145 We can see in Figure 69 that the internal temperatures in the south west facing living room peaked at between 31 and 33°C on several days. This was only 1 degree less than the maximum external temperature at the time. It can also be seen that even when the external temperature had dropped, the internal temperatures remained high for several days afterwards. We specifically asked the occupants of dwelling A about their ventilation strategy during these hot periods. They said that, during this time, they opened all the windows and patio doors in

the main living areas and bedrooms but that their feeling was that this did not have a significant impact on internal temperatures. The indication from these results is that the dwellings at Stamford Brook will have a tendency to overheat when the external temperatures exceed around 30°C. The summer overheating in dwellings C and A will be exacerbated by excessive internal heat gains from the very long heating system primary pipework.

- 146 Problems of summer overheating may become more of an issue in the future as dwellings become more highly insulated and more airtight in response to regulatory requirements and also because average summertime temperatures are likely to increase as a result of climate change. The challenge for house designers is how to balance the thermal requirement to reduce winter heat loss with the requirement to keep houses cool in the summer. This problem can be more difficult to resolve when using construction technologies with low levels of thermal mass such as in the case of lightweight timber and steel framed structures. Issues can also occur in the some heavyweight structures where the main bulk of the thermal mass is isolated from the internal conditioned space such as in the case of internally insulated walls or where the mass is separated from the conditioned space by a dry-lined internal finish such as plasterboard-on-dabs instead of a solid finish such as traditional wet plastering. Part L 2006 (ODPM 2006b) introduced the requirement to consider overheating issues and the need to consider passive measures such as thermal mass, shading and ventilation strategies in order to control overheating. It is likely that these requirements will be reviewed and strengthened in future revisions of Part L in order to take account of climate change projections (DCLG 2007b).

Predicted versus measured energy use

- 147 The carbon emission rate for an 80m² semi detached dwelling built to the EPS08 elemental standard and predicted using SAP2005 is 20.6 kgCO₂/m² as shown in Table 22. In comparison, an 80 m² EPS08 compliant dwelling built using the design fabric standards, air permeability and boiler efficiencies adopted at Stamford Brook would be predicted to be slightly lower than this at 19.9 kgCO₂/m², mainly due to the much better SEDBUK rating of 91.3%. The actual performance of an 80 m² semi detached house dwelling constructed at Stamford Brook would be expected to be in excess of this due to factors such as the party wall bypass, wall *U*-values being higher than predicted, thermal bridging being higher than predicted and the true boiler efficiency being below the declared SEDBUK rating. We can estimate the potential impact of some of these factors by varying some of the inputs into the Leeds Met parametric SAP spreadsheet (Lowe, Wingfield, Bell & Roberts 2007) to allow for some of the observed and measured variability in performance. For example, by allowing for a party wall *U*-value of 0.5 W/m²K, a wall *U*-value of 0.25 W/m²K, air permeability at the mean of 4.5 m³/h.m², a thermal bridging ΔU of 0.06 W/m²K (allows for high Ψ value for window/door heads) and a seasonal boiler efficiency of 85%, the predicted emission rate for an 80 m² semi detached dwelling increases by 23% from 19.9 kgCO₂/m² to 24.4 kgCO₂/m². This would make the actual carbon emissions of this Stamford Brook type dwelling “as built” higher than the Target Emission Rate of 23.2 kgCO₂/m² under the requirements for ADL1a 2006.

Table 22 – Comparison of EPS08 requirements with Stamford Brook dwelling as designed and Stamford Brook as built for an 80m² semi-detached dwelling with aspect ratio of 1.4 & MEV

	EPS08 Elemental Standard	Stamford Brook – As Designed	Stamford Brook – As Built Estimated
Floor <i>U</i> -value (W/m ² K)	0.22	0.172	0.172
Wall <i>U</i> -value (W/m ² K)	0.25	0.23	0.25
Roof <i>U</i> -value (W/m ² K)	0.16	0.142	0.142
Window/Door <i>U</i> -value (W/m ² K)	1.3	1.3	1.3
Total Linear Thermal Bridging Δ <i>U</i> (W/m ² K) [#]	0	0.03	0.06
Party Wall <i>U</i> -value (W/m ² K)	0	0	0.5
SEDBUK Boiler Efficiency (%)	85	91.3	85
Air Permeability (m ³ /(h.m ²) @ 50Pa)	5	5	4.5
Glazing Ratio	0.25	0.20	0.20
Dwelling Carbon Emission Rate (kgCO ₂ /m ²) [*]	20.6	19.9	24.4
Fabric Heat Loss Coefficient (W/K)	57.8	55.2	79.4
Ventilation Heat Loss Coefficient (W/K)	37.2	37.2	37.2

* ADL1a 2006 Target Emission Rate for an 80 m² semi-detached dwelling = 23.2 kgCO₂/m²

[#] Linear thermal bridging incorporated in elemental *U*-values for EPS08 standard

148 The dominating influence of the party wall bypass in some types means that as-built performance will vary between mid-terraced, semi-detached and detached house types (Table 23).

Table 23 – As-built performance for 80m² Stamford Brook dwellings

	Mid-terrace	Semi-detached	Detached
ADL1a 2006 TER	21.0	23.2	25.6
EPS08 Target	19.4	20.6	21.9
Stamford Brook Designed	18.7	19.9	21.1
+ air permeability=4.5	18.6	19.8	21.0
+ boiler efficiency=85%	19.5	20.8	22.1
+ thermal bridging γ=0.06	19.9	21.4	23.0
+ wall <i>U</i> -value=0.25	20.0	21.6	23.3
+ party wall <i>U</i> -value=0.5	25.5	24.4	23.3

149 It can be seen in Figure 70 that, when factors other than the party wall bypass such as boiler efficiency and thermal bridging are taken into account, the mid-terrace dwelling type remains the dwelling type with the lowest as-built carbon emission rate. In the case of semi-detached and mid-terrace dwellings types, if the effect of the party wall bypass is excluded, the as-built carbon emission rate stays below that the ADL1a 2006 target emission rate and for detached dwellings the as-built emission rate is always lower than the ADL1a 2006 TER. When the party

wall bypass is taken in to account the detached dwelling types become the best performing in terms of as-built carbon emissions.

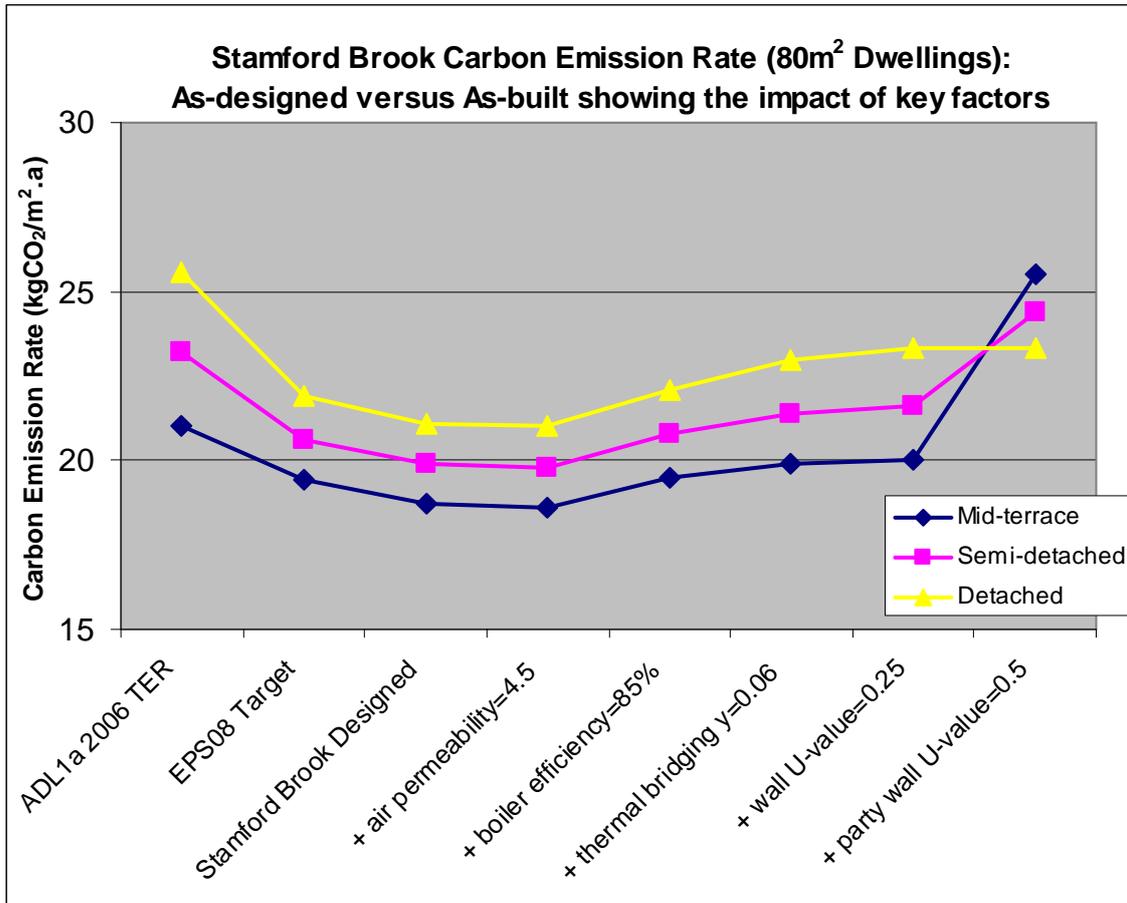


Figure 70 – Carbon emission rates: as-designed versus as-built – 80m² dwellings

- 150 A comparison of measured annual gas use for the four monitored households versus the heating and hot water energy use predicted using the Leeds Met parametric SAP spreadsheet is given in Table 24. The monitoring period analysed for dwellings A, C and K was the same (April 2006 to March 2007) but for dwelling B was from a slightly earlier period (November 2005 to October 2006). There will be some level of uncertainty around the data used as we can only estimate the actual amount of gas used for cooking and are only able to extrapolate domestic hot water use from actual usage during the summer. From these data we can see that SAP gives a reasonable prediction of annual energy use for dwellings B, C and K but underestimates usage in A by around 5500 kWh. In order to improve the prediction for all four test dwellings, the inputs into the Leeds Met parametric SAP spreadsheet were corrected as necessary for various factors such as occupancy, measured internal temperature, thermal bridging, actual external heat demand during the monitoring period and actual effective ventilation rate. The methodology for the corrections is given in Appendix 4.
- 151 If we look first at the data for dwelling A it can be seen from Table 24 that there is a 5547 kWh discrepancy between the actual gas supplied (12618 kWh) and the combined heating and hot water energy predicted by SAP taking into account the

actual occupancy (7071 kWh). The difference between the actual domestic hot water use extrapolated from summer usage (3926 kWh) and that predicted by SAP from occupancy (3482 kWh) is only 444 kWh and cannot therefore account for the difference between predicted total energy and that actually used. The SAP prediction for central heating energy was corrected to allow for an effective U -Value for the party wall of $0.5 \text{ W/m}^2\text{K}$, the measured mean internal temperature during the heating season of 20.4°C , the effective ventilation rate of 1.0 ach that we have already estimated for dwelling A (see paragraph 140 above) and also the actual local heating demand for the region during 2006-2007¹⁹. The remaining discrepancy could be potentially accounted for by the fact that the real boiler efficiency will be somewhat less than the official SEDBUK rating of 91.3%, especially as, being of the same house type as dwelling C, the heating system in dwelling A will have the same extended length of uninsulated primary pipe between boiler and cylinder. We therefore assume that the true seasonal efficiency for dwelling A is around 85% (same as K - see Table 19). Another variable to consider in these calculations is some additional heat loss due to the likelihood that thermal bridging is higher than expected. If we assume that the thermal bridging ΔU is double the optimum $0.03 \text{ W/m}^2\text{K}$ at around $0.06 \text{ W/m}^2\text{K}$, then this would increase the predicted annual heating energy further. The final factor to take into account is the additional internal heat gains over and above standard SAP assumptions that would result from the very long uninsulated primary pipe in this dwelling type. We have already estimated the heating season primary pipe loss for dwelling C to be 1210 kWh (Table 19), which is 600 kWh higher than the standard SAP 2005 allowance of 610 kWh (BRE 2005). If we assume the same primary loss for dwelling C at the 80% utilisation factor used in SAP, then we need to reduce the prediction by 480 kWh, giving a final prediction of 8548 kWh. By taking into account all these factors we have shown that the prediction is in very good agreement with the actual annual energy use for space heating (8509 kWh) and, given the relative crudeness of the SAP model, would give some confidence both for the methodology used and for our estimates of additional energy use due to factors such as the party wall bypass, boiler inefficiencies and ventilation loss. We have illustrated that a large part of the very high annual energy use for dwelling A compared to the standard SAP prediction is purely down to occupant behaviour in terms of the internal temperature set point and ventilation strategy. This has important implications for the design of low energy housing. Part of the solution to reducing energy usage will therefore be in providing better information to householders in terms of how best to set up the heating and ventilation systems and the effect that they can have on performance.

¹⁹ The winter of the 2006-2007 heating season was very mild compared to that in 2005-2006. The official annual heating degree days (at 15.5°C base temperature) for the West Pennine region over the monitoring period for dwellings A, C and K (April 2006 to March 2007) was only 1657 compared to 2149 for the dwelling B monitoring period from November 2005 to October 2006 (Degree Days Direct 2007). Using the mean daily external temperature data from the Stamford Brook weather station, the calculated number of degree days at a 15.5°C base temperature for the period April 2006 to March 2007 was only 1806 compared to 2123 for the period November 2005 to October 2006. The milder conditions during the winter of 2006-2007 would have the effect of reducing actual heating demand compared to that predicted using the degree day table in SAP. Table 10 in SAP 2005 (BRE 2005) gives the number of degree days at a 15.5°C base temperature as 2130. This would mean that the heating demand during the monitoring period for dwelling for dwellings A, C and K the actual heating demand would be much lower than that used by SAP. The predictions for dwellings A, C and K given in Table 24 will therefore have been overestimated by a factor of around 300 degree days. The overestimate of degree day heating demand for dwelling B is smaller at around 60 degree days.

This would make it more likely that the occupants would use the dwelling in the most efficient way.

- 152 In the case of dwelling C, allowances were made to the SAP prediction for a party wall U -Value of $0.5 \text{ W/m}^2\text{K}$, mean internal temperature of 19.34°C , a reduction in heating demand of 300 degree days during the monitoring period, a boiler efficiency of 85%, a thermal bridging ΔU of $0.06 \text{ W/m}^2\text{K}$ and a reduction of 480 kWh due to heat gains from the primary pipe. These corrections combine to give an annual space heating energy prediction of 5011 kWh. This compares reasonably well to the actual combined gas and electrical energy used for space heating in dwelling C of 4494 kWh as shown in Table 24. The SAP prediction for domestic hot water use in C (2898 kWh) is also in good agreement with actual gas usage for hot water of 3070 kWh.
- 153 For dwelling K, allowances were made to the SAP prediction for a mean internal temperature of 17.54°C , a reduction in heating demand of 300 degree days during the monitoring period, a boiler efficiency of 85% (Table 19), a thermal bridging ΔU of $0.06 \text{ W/m}^2\text{K}$ and reduction of 184 kWh due to heat gains from the primary pipe to give an annual space heating prediction of 4188 kWh. This correlates well with the actual combined gas energy used for space heating in dwelling K of 4601 kWh as shown in Table 24.
- 154 The SAP prediction for the mid terrace dwelling B was corrected for a party wall U -Value of $0.5 \text{ W/m}^2\text{K}$ and mean internal temperature during the heating season of 19.15°C . It was also assumed that the true SEDBUK boiler efficiency would be around 85% and that the actual thermal bridging ΔU would be $0.06 \text{ W/m}^2\text{K}$. There was only a small correction for heating demand of 60 degree days, as the measured external temperature data for the 2005-2006 winter were much closer to the standard SAP value. The final predicted space heating use of 4485 kWh is in reasonable agreement with the measured use of 4033 kWh. It is likely that actual space heating use would have actually been closer to the prediction, as domestic hot water use in summer may have been higher than that during the winter due to additional summer occupancy (3 adults) in the summer compared to the winter (2 adults), which would mean the annual domestic hot water use would actually have been lower than that extrapolated from the summer usage pattern.

Table 24 – Comparison of actual versus predicted energy use

	Dwelling A	Dwelling C	Dwelling K	Dwelling B
Monitoring Period	April 06 to March 07	April 06 to March 07	April 06 to March 07	November 05 to October 06
Actual Total Annual Gas Use (kWh) - from meter readings	12618	7587	8849	6444
Actual Occupancy	3	2	2	2*
Actual Mean Internal Temperature ($^\circ\text{C}$) - during heating season	20.42	19.34	17.54	19.15
Annual Gas Use for Cooking (kWh) - estimated at 0.5 kWh/day	183	183	183	183
Annual DHW Gas Use (kWh) - extrapolated from summer usage pattern	3926	3070	4065	2228
Annual Gas for Space Heating (kWh) = Total - (DHW + Cooking)	8509	4334	4601	4033
Annual Supplementary Electrical Heating (kWh)	None	160	None	None
SAP Predicted DHW + Space Heating Use (kWh) – uses actual permeability test data but otherwise uncorrected	7162	7023	8817	5809
SAP Predicted DHW + Space Heating Use (kWh) – corrected for	7071	6598	8257	5564

actual occupancy				
SAP Predicted DHW Energy Use (kWh) – corrected for actual occupancy	3482	2898	2898	2898
SAP Predicted Space Heating Energy Use (kWh) – corrected for actual occupancy	3589	3700	5359	2666
SAP Predicted Space Heating Use (kWh) - corrected for internal temp, party wall U -value = 0.5 W/m ² K, effective ventilation rate = 1 ach, 300 degree day reduction in demand, SEDBUK efficiency = 85%, thermal bridging ΔU = 0.06 W/m ² K and primary pipe loss	8548	-	-	-
SAP Predicted Space Heating Use (kWh) - corrected for internal temp, party wall U -value = 0.5 W/m ² K, 300 degree day reduction in demand, SEDBUK efficiency = 85%, thermal bridging ΔU = 0.06 W/m ² K and primary pipe loss	-	5011	-	-
SAP Predicted Space Heating Use (kWh) - corrected for internal temp, 300 degree day reduction in demand, SEDBUK efficiency = 85%, thermal bridging ΔU = 0.06 W/m ² K and primary pipe loss	-	-	4188	-
SAP Predicted Space Heating Use (kWh) - corrected for internal temp, party wall U -value = 0.5 W/m ² K, 60 degree day reduction in demand, SEDBUK efficiency = 85%, thermal bridging ΔU = 0.06 W/m ² K	-	-	-	4485

* Occupancy in dwelling B from April to Sept was 3 but was 2 for the rest of year.

- 155 By taking into account factors that reflect the way occupants use the dwellings, such as temperature and ventilation, and also factors that allow for the difference between designed performance and actual construction, such as the party wall effect and true boiler efficiency, we have shown that the SAP/BREDEM model gives a reasonable estimate of annual energy use that is typically within 500 or 600 kWh of measured use.
- 156 We have observed several different energy use patterns from the occupants of the four monitored dwellings as shown in Table 25. The pattern of occupation of A with the high internal temperature set point, over ventilation during the heating season and higher than normal use of domestic hot water resulted in very high energy use. Dwelling K had the lowest energy use per unit floor area, mainly as a result of the low mean internal temperatures during the heating season.

Table 25 – Occupant behaviour patterns and effect on annual energy use

Dwelling	Ventilation during Heating Season	Internal Temperature during Heating Season	Domestic Hot Water Use	Annual Space Heating Energy Use (kWh/m ² /annum)	Annual Domestic Hot Water Energy Use (kWh/m ² /annum)
A	High	High	High	81.0	37.4
B	Average	Average	Low	48.0	26.5
C	Average	Average	Average	42.8	29.2
K	Average	Low	High	35.7	31.5

Comparison of energy performance with other low energy housing developments

157 It was difficult to find energy performance data from a UK development built to an energy standard similar to that used at Stamford Brook. The exception to this is the Gallions Ecopark in Thamesmead, London for which there is published energy use data for the period 2003-2004 (DHV 2004). Gallions Ecopark is a social housing development of 39 timber-framed terraced houses arranged in four blocks. Heating is provided by individual gas condensing boilers with hot water supplemented by 5.5 m² of solar hot water panels on each dwelling. The fabric specification has a wall *U*-Value of 0.25 W/m²K, roof *U*-Value of 0.18 W/m²K, floor *U*-Value of 0.3 W/m²K and whole window *U*-Value of 1.3 W/m²K. Ventilation was provided by a whole house mechanical extract system (except type B which had ventilation heat recovery systems) and the measured air permeability was 7 m³/(h.m²)@50 Pa. The published energy data for the 13 monitored dwellings on the Ecopark development are given in Table 26 along with SAP predictions of energy use obtained using Leeds Met Parametric SAP.

Table 26 – Gallions Ecopark monitored energy data (DHV 2004)

Dwelling Type	Dwelling Form	No in Monitoring Sample	SAP Predicted Space Heating and DHW Energy (kWh)*	SAP Predicted Space Heating Energy (kWh)*	SAP Predicted DHW Heating Energy (kWh)*	Mean Measured Total Gas Use (Including gas for cooking) (kWh)
Gallions Type A	78 m ² 2-storey mid-terrace	3	4760	2827	1933	11929
Gallions Type B	91 m ² 2-storey mid-terrace	1	4970	2878	2098	12833
Gallions Type C	95 m ² 2-storey mid-terrace	5	5583	3435	2148	9386
Gallions Type D	110 m ² 2½-storey mid-terrace	4	5958	3621	2337	11109

* Predicted using Leeds Met Parametric SAP using fabric and heating system specification from Gallions Monitoring Report

158 It can be seen from Table 26 that actual gas use was significantly higher than would be predicted for all four dwelling types. Allowing for gas for cooking of 183 kWh/annum, the additional energy use ranged from +63% for type C to +155% for type B. Given the relatively large sample of dwellings in this study, it cannot be argued that these large differences are due solely to occupant behaviour effects as these would be expected to balance out. It is therefore more likely that there are some major construction defects in the building fabric and unaccounted for inefficiencies in the heating system that are mostly responsible for the higher than expected energy use. By comparison, the discrepancies at Stamford Brook between actual energy used for space heating and domestic hot water with the uncorrected SAP prediction for space and water heating +74% for dwelling A, -3% for dwelling B, +8% for dwelling C and -2% for dwelling A. This suggests that the undiagnosed fabric defects and system problems that are likely to exist on the Gallions development could be significant and almost certainly worse than those we have identified at Stamford Brook. Unfortunately, as far as we are aware, no attempt has been made to identify, understand or rectify the apparent problems with the Gallions Ecopark buildings. The lack of a detailed analysis of the data reinforces the importance of the need to both measure energy use and to understand the gap between designed and expected performance. These data

also emphasise that the size of the gap between designed and realised performance can be significant. For the 13 monitored Ecopark dwellings the additional energy use over the predicted performance was 68989 kWh, which is equivalent to 17.2 tonnes CO₂ per annum. Extrapolated to all 39 dwellings on the development, this would be equivalent to an extra 51.6 tonnes CO₂ per annum over and above the designed performance²⁰. Another way of looking at the excess gas use is to see how far back in the Part L series one would have to go to find a predicted gas use equal to the actual. The excess at Gallions Ecopark is roughly 100%, suggesting the equivalent performance is roughly equal to 1995 Part L.

- 159 The measured space heating energy use for the 14 passive house developments monitored as part of the European CEPHEUS project ranged from 7.6 to 33.2 kWh/m²/annum, with predicted use obtained using the PHPP energy model ranging from 12.3 to 27.2 kWh/m²/annum (Feist Peper & Görg 2001). In comparison, the measured space heating use for the 4 monitored dwellings at Stamford Brook was 81.0 kWh/m²/annum for dwelling A, 48.0 kWh/m²/annum for dwelling B, 42.8 kWh/m²/annum for dwelling C and 35.7 kWh/m²/annum for dwelling K (Table 25). These data show that the better performing dwellings at Stamford Brook used only slightly more space heating energy than the worst performing passive houses in the CEPHEUS programme.
- 160 A recent study of the space heating energy consumption of several single storey dwellings built in Denmark to the 2006 Danish energy regulations (Tommerup, Rose & Svendsen 2007) provides a good comparison of measured space heating with the monitored dwellings at Stamford Brook. The Danish dwellings were heated by district hot water system, had mechanical ventilation with heat recovery (MVHR) and overall predicted heat loss parameters (HLP) ranging from 0.7 to 1.0 W/m²K. This compares to the predicted and unadjusted heat loss parameters for Stamford Brook dwellings of 1.0 W/m²K for dwellings A and C, 1.2 W/m²K for dwelling K and 1.1 W/m²K for dwelling B. The published Danish data are given as delivered space heating in kWh over variable test periods during the 2004-2005 heating season. In order to compare the data with Stamford Brook, the data have therefore been normalised by the mean inside to outside temperature differences over the test periods, by the dwelling floor areas and per day of the test period. The normalised measured space heating for the Danish houses ranged from 0.009 kWh/K/m²/day (HLP = 0.7 W/m²K) to 0.014 kWh/K/m²/day (HLP = 1.0 W/m²K). These values compare to normalised space heating use at Stamford Brook of 0.016 kWh/K/m²/day for dwellings B, C and K and 0.028 kWh/K/m²/day for dwelling A. Given that the Danish data is for delivered heat whereas the Stamford Brook data is for delivered gas we must adjust the Stamford Brook data for the efficiency of the gas heating system. As the true heating system efficiencies at Stamford Brook are around 85% this would give normalised space heating usage for dwellings B, C and K of around 0.014 kWh/K/m²/day. Given that the true HLP values for the Stamford Brook dwellings range from 1.2 to 1.4 W/m²K after taking into account the party wall bypass for those dwellings with party walls, this makes the performance of the Stamford Brook dwellings B, C and K comparable with the

²⁰ The difficulty of not undertaking the gap analysis is that promotional material and general statements within the industry tend to continue to quote the modelled numbers and ignore the real picture. This results in no improvement in knowledge or practice. We continue in the belief that we can produce energy efficient dwellings when the evidence is to the contrary. This leads us to wonder whether the first task is to persuade the house building industry to come out of denial.

performance of the Danish dwellings, especially taking into account the Danish houses are equipped with MVHR systems.

Ventilation and air quality

VENTILATION SYSTEM PERFORMANCE

161 Measurements of extract flow rates of the mechanical ventilation systems were taken by the research team in 9 dwellings at Stamford Brook during 2005 and 2006, and were reported in Interim Project Report No.5 (Wingfield, Bell, Bell & Lowe 2006). The results are shown in Table 27. It can be seen that in 8 out of the 9 dwellings tested, the measured extract rates failed to meet the required performance standard by between 37% and 57%. The reason why this poor system performance had not been discovered earlier was that the ventilation systems in dwellings built during the early phases had not been fully commissioned. This was due to a lack of communication between the installers and on-site management teams whereby each had assumed that the other was responsible for commissioning. It is also interesting to note the lack of commissioning data was also not picked up by the NHBC who are responsible for building control at Stamford Brook. A technical analysis of the ventilation system underperformance identified that the measured low flow rates were caused by a flow restriction at low profile terminal vents on the roof. These tile vents were not specified in the original ventilation system design, which required terminal vents on the ridge line whose extract performance would not have restricted the system flow. From discussions with the developers it transpired that the ridge vents had been substituted with the low profile tile vents for reasons of aesthetics but that the performance implications of such a change had not been properly discussed between the developers and ventilation system supplier. In order to improve the extract rates a second roof tile vent was added to the system design and a rectification programme was initiated to install an additional roof vent to systems in dwellings already constructed. This demonstrates the importance of a stringent and robust commissioning process to ensure the effective performance of both ventilation and heating systems.

Table 27 – Ventilation system flow rates

Developer	Plot No	Measured Flow in normal mode ²¹ (m ³ /h)	Design Flow in normal mode (m ³ /h)
Redrow	403	104	101
Redrow	324	< 55	101
Redrow	309	< 56	130
Redrow	402	63	101
Redrow	405	< 37	101
Redrow	406	< 64	101
Bryant	13	< 59	86
Bryant	14	< 68	86
Bryant	69	< 91	144

²¹ In most cases the total measured flow could not be accurately measured as the flow rate from some of the vents was below the 13 m³/h measurement threshold of the fan flow meter. In these cases each vent for which a measurement could not be obtained was assigned a value of 12 m³/h and the total flow is shown as a figure with a less than sign (<).

162 Further measurements of ventilation system performance were carried out on three Stamford Brook dwellings by BRE in February 2007. The measurements taken included total ventilation extract rate in standard mode and power consumption of the fan unit in standard mode. The results are shown in Table 28.

Table 28 – Ventilation system performance at Stamford Brook

Test Dwelling	Number of Extract Vents	Fan Speed Setting	EPS08 Design Extract Rate (l/s)	Total Measured Extract Rate at Standard Setting (l/s)	Measured Power Consumption at Standard Setting (W)	Calculated Specific Fan Power (W/l/s)
3-storey end terrace house	6 (2 in kitchen)	4 Person Mode (75% of Max)	32	31	9.6	0.31
1-storey apartment	2	2 Person Mode (50% of Max)	16	17	5.8	0.32
2-storey duplex apartment	4 (2 in kitchen)	2 Person Mode (50% of Max)	24	23	5.9	0.26

- 163 The measured extract rates in all three dwellings are given in Table 28 and were in close agreement with the design extract rates, indicating that the systems had been commissioned effectively. The calculated specific fan power ranged from 0.26 to 0.32 W/l/s. This is not quite as good as the specific fan power range of 0.18 to 0.24 W/l/s given in the SAP Appendix Q test results for this system (BRE 2006) but, nonetheless, a specific fan power of around 0.3 W/l/s would still be considered low power consumption. For a typical 3-bedroom house this would equate to an annual fan energy consumption of only 88 kWh. For calculations of annual carbon emissions for Stamford Brook dwellings, a specific fan power of 0.4 W/l/s was used in the Leeds Met Parametric SAP spreadsheet to allow for potential variability between dwellings.
- 164 The issue with the ventilation system terminal vent at Stamford Brook highlights the importance of having a rigorous product approval system and appropriate training in order to prevent materials and products being used on site that do not meet the desired performance standards. Such a quality system would also need to be flexible enough for on-site situations where there may be the occasional need for product substitution, for example where a particular component or material is in short supply or temporarily unavailable.
- 165 The occupants of the four monitored households said that they had no problems with condensation in bathrooms or kitchens. This indicates that the ventilation system is dealing effectively with removal of moist air from the wet rooms. This finding is backed up by the humidity data from the monitored dwellings that show that the dwell time of moist air in either bathroom or kitchen is very short. The occupants of three out of the four monitored households voiced concerns about the noise levels from the mechanical ventilation system during their final interviews, indicating that the noise was “intrusive” and “louder than anticipated”. However, the occupants did note that the noise levels from the ventilation system reduced following the remedial measures to the terminal vents detailed in paragraph 160, which would have resulted in lower fan speeds.

CARBON DIOXIDE CONCENTRATION

166 A carbon dioxide sensor was installed in the master bedroom of all 4 monitored households. The measurement range of the sensors used was from 0 to 2000 ppm. On occasions where the logged CO₂ level exceeded 2000 ppm then a nominal value of 2000 ppm was assigned to that data entry. Due to the fact that there was only one sensor in each dwelling, the measured CO₂ level would have been influenced not just by respiratory CO₂ emissions from the occupants but also to a large extent by the local ventilation rate in the bedroom and the location of the sensor relative to the main ventilation air paths in the bedroom. As such the CO₂ levels can only be considered indicative of air quality and general trends in ventilation rates. It would not be appropriate to compare CO₂ levels between dwellings. The monthly mean CO₂ concentrations are plotted in Figure 71. These data show that the general trend is for higher CO₂ concentrations in the winter and lower CO₂ concentrations in the summer. This is indicative of increased ventilation in the summer in response to higher temperatures and lower ventilation in the winter to minimise cold draughts.

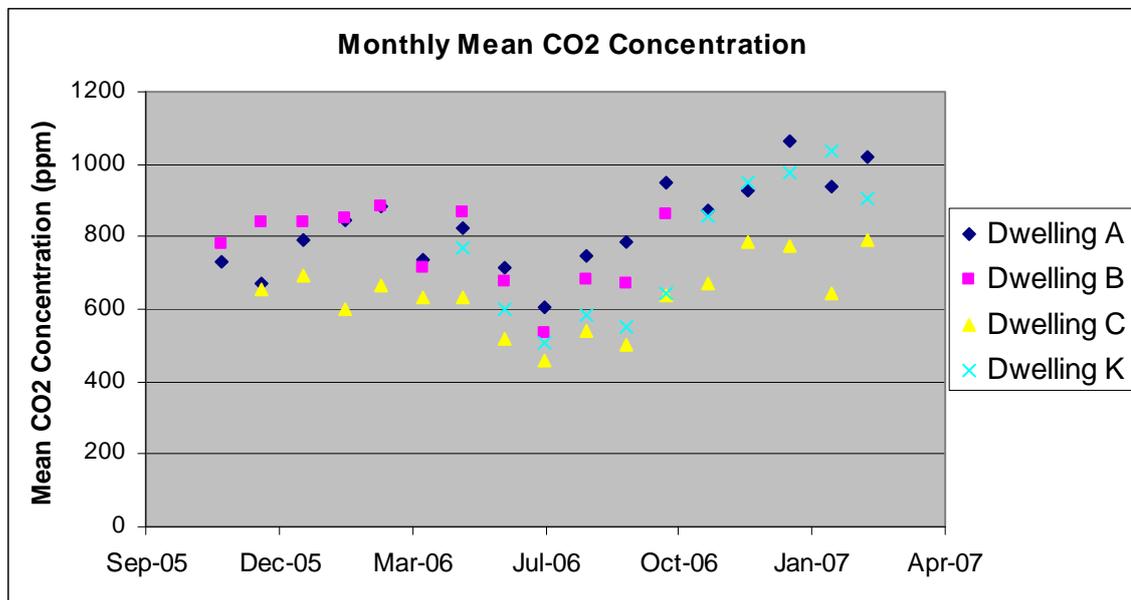


Figure 71 – Monthly mean CO₂ concentration

167 The general levels of CO₂ in the dwelling throughout the year shown in Figure 71 are consistent with those of an acceptable air quality standard and in most cases are well below 1000ppm. The ASHRAE standard for air quality (ASHRAE 2001) indicates that comfort criteria are likely to be met if “ventilation results in indoor CO₂ concentrations less than 700ppm above the outdoor air concentration”. As CO₂ is a surrogate for other indoor contaminants the CO₂ levels at Stamford Brook are indicative of acceptable overall air quality in general.

168 A plot of daily mean external temperature versus daily mean CO₂ concentration for the 4 dwellings is shown in Figure 72. This shows a general trend for all dwellings such that, as external temperature increases then internal CO₂ concentration decreases. This is indicative of more frequent window opening behaviour during periods of higher external temperature.

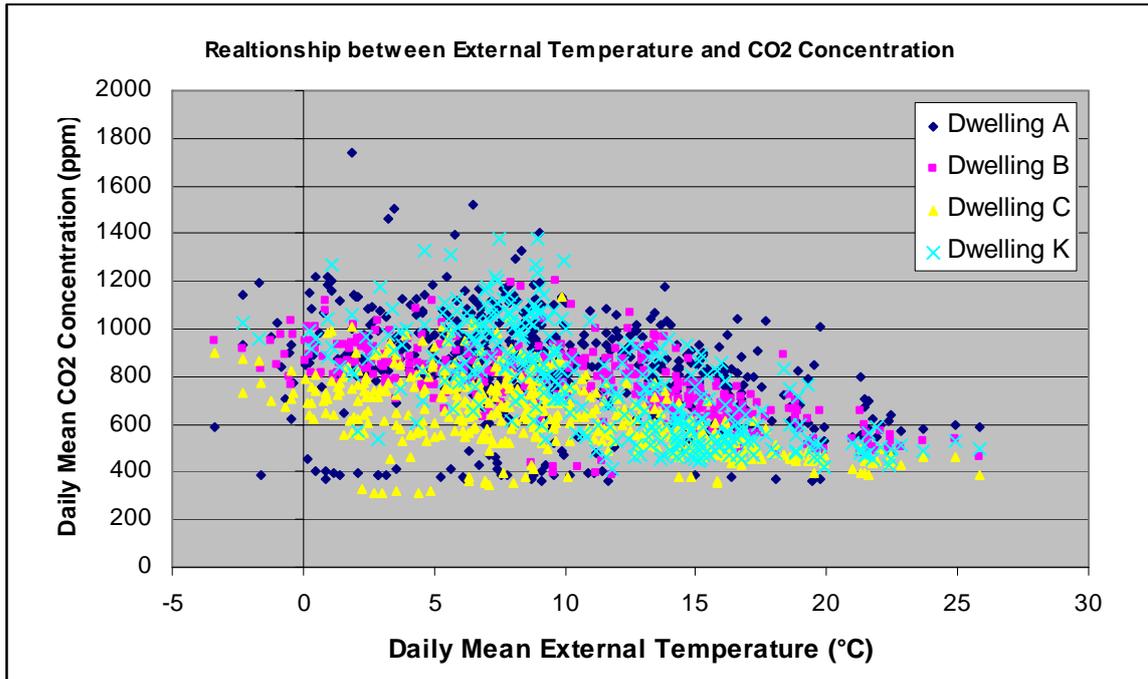


Figure 72 – Daily mean external temperature versus daily mean CO₂ concentration

169 The measurement of carbon dioxide decay rates is a simple and effective technique for the estimation of effective background ventilation rates (Roulet & Foradini 2002). Carbon dioxide data from monitored Dwelling C were collected from periods when the occupants went on holiday, and these data were used to estimate ventilation rates using the decay rate methodology. The occupants were asked to confirm the precise time when they left the house to go on holiday and also to confirm that the MEV system had been switched to the “unoccupied house” setting. Data were obtained for four different holidays over the monitoring period as shown in Table 29. A typical carbon dioxide decay curve is illustrated in Figure 73. The effective ventilation rates obtained by this method varied from 0.28 to 0.41 air changes per hour. This range of ventilation rates is slightly higher than that estimated from the air permeability measurements on Dwelling C. With the measured air permeability of 4.64 m³/h.m² and using the n/20 rule and sheltering factor of 0.85, the predicted ventilation rate would be 0.2 air changes per hour. The difference between the predicted rate and the measured rate will likely be due to a combination of the height effect of the 3-storey dwelling, air leakage distribution effects, some of the trickle vents being left open during the holiday periods and the wind speed variability.

Table 29 – Carbon dioxide decay half lives and effective ventilation rates

Date	1/e Half Life (mins)	r ² Coefficient of Determination	Effective Ventilation Rate (h ⁻¹)
Feb-06	210	0.99	0.29
Jul-06	141	0.89	0.41
Aug-06	212	0.95	0.28
Feb-07	211	0.99	0.28

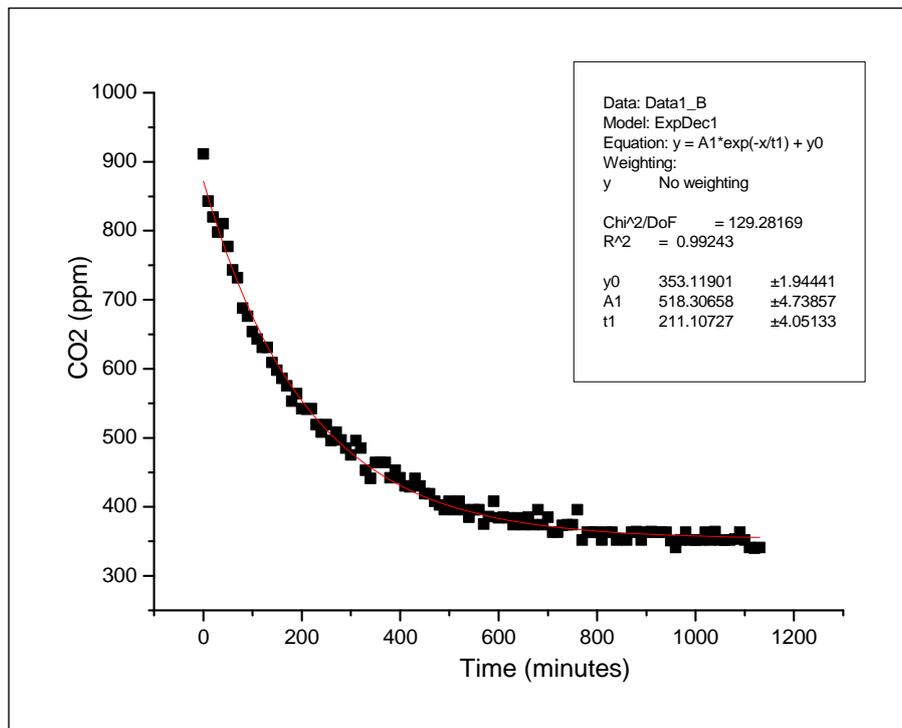


Figure 73 – Carbon dioxide decay curve

NITROGEN DIOXIDE CONCENTRATION

170 Electrochemical nitrogen dioxide sensors were installed in the kitchens of the monitored dwellings and had a measurement sensitivity range of 0.1ppm to 10ppm. This meant that typical household readings of below 0.1ppm were not recorded by the datalogger. It was found that the sensors recorded at least 1 and sometimes as high as 5 instantaneous readings per day which exceeded the 0.1ppm threshold. The timings of the high readings usually coincided with meal preparation times, indicating that the internal generation of nitrogen dioxide was associated with use of the gas hob. The highest individual reading recorded was 1.3 ppm. World Health Organisation guidelines on limits for exposure to nitrogen dioxide are $200 \mu\text{g}/\text{m}^3$ (0.1ppm) over a 1 hour period or a mean exposure of $40 \mu\text{g}/\text{m}^3$ (0.02ppm) (WHO 2000). The data from Stamford Brook is consistent with occasional short term exposure to high levels of nitrogen dioxide above WHO guidelines.

Construction costs

171 An analysis of the initial costs of the additional materials and components needed to meet the requirements of EPS08 versus meeting the targets in ADL1 2002 was reported in the Stamford Brook interim project report 4 (Roberts, Andersson, Lowe, Bell & Wingfield 2005). The extra over cost was defined in this report as the difference between the actual costs of building Stamford Brook dwellings to EPS08 minus the costs that developers would normally expect building to their standard specification to meet the building regulations in force at the time. The average construction cost increase at that time was 9 % compared to the developers' standard ADL1 2002 construction specification. The top two contributors to the over cost burden were the windows and doors (38% of the over cost) and the wall construction (27% of the over cost). It was also apparent during the development of the construction specification and discussions with materials

suppliers that it can be extremely difficult to obtain accurate pricing information during the initial design stages, especially for the more unusual components such as the plastic wall ties. In some cases the final costs fell to as low as 20% of initial costs.

- 172 A summary of the actual over costs for Stamford Brook dwellings are given in Table 30 (Andersson 2007). These costs have been split according to those initial dwellings built during the time period where they would have had to otherwise comply with ADL1 2002 and those more recent dwellings built after the introduction of ADL1a 2006. It should be pointed out that the mean over cost per dwelling is significantly influenced by the mix of dwelling types and dwelling sizes in the two samples, so it is difficult to directly compare the two sets of figures with any confidence²². It should also be borne in mind that costs in a demonstration project such as Stamford Brook are not a very good indicator of actual costs in the long term. In the longer term, costs will tend to decrease over time as new products, construction techniques and technologies become the norm and as the industries supplying these products adapt and improve their processes to meet the increases in demand as performance specifications and building regulations change. This can be demonstrated by the cost of windows in some Scandinavian countries, where triple glazed units are actually cheaper than the same size double glazed units, as the standard product specification in Scandinavia is now for triple glazing. The fact that the windows used at Stamford Brook had to be sourced from Denmark is indicative that window technology for mass market windows in the UK is lagging behind that of the continent. Some specialist low volume manufacturers in the UK were able to produce windows to the desired specification but could not match the pricing of the Danish company who manufacture high performance windows in large volumes. This is perhaps an indication that the construction supply chain in the UK will have to adapt and improve its process technology and efficiency if it is to compete with companies from mainland Europe. The over cost for the post 2006 dwellings of around £2800 is in line with estimates published by the Housing Corporation & English Partnerships of between £1600 (detached house) and £2200 (apartment) over cost for a Code 2 compliant dwelling compared to a 2006 compliant dwelling, where these improvements are mostly achieved using fabric measures (Cyril Sweett 2007).

Table 30 – Construction extra over costs to meet EPS08 standard

	Construction Phases Required to Comply with ADL1 2002	Construction Phases Required to Comply with ADL1a 2006
Number of dwellings constructed as of June 2007	250	48
Total EPS08 mean over cost per dwelling (excluding MEV system)	£3,401	£2,813
Wall design mean over cost per dwelling	£666	£898
Parging mean over cost per dwelling	£607	£370
Window mean over cost per dwelling	£1,995	£1,459
Plastic wall tie mean over cost per dwelling	£109	£67

²² The post-2006 sample of 48 dwellings had a much higher proportion of apartments than the pre-2006 250 dwelling sample.

Loft access mean over cost per dwelling	£24	£20
MEV system over cost range per dwelling	£500 to £700	£500 to £700

Implications for domestic construction in the UK: Key findings

- 173 In a highly detailed study of construction and energy performance, such as that reported here, it is inevitable that the focus will be on those aspects that need to be addressed. However, as indicated above, it would be quite wrong to conclude, from the results of performance testing and the catalogue of construction observations, that, overall, the dwellings did not meet specification requirements or that the developers involved produced housing that did not meet the quality standards expected from the house building industry. In fact, given the limited experience within the industry of low energy construction, what has been achieved at Stamford Brook represents a significant step forward and demonstrates a considerable achievement within a relatively short time scale. A number of the construction features adopted at Stamford Brook some six years ago, such as using separate lintels to minimise thermal bridging and the introduction of parging as a means of improving airtightness, are only now beginning to be identified as good practice within the industry at large. Even allowing for the observed gap in performance when measured against the enhanced energy standard, the energy performance of the dwellings remained significantly in advance of the 2002 building regulations standard in force at the time they were constructed.
- 174 In interpreting the results of the study (as presented in this report and earlier project outputs) it is important to recognise that the observations made and conclusions drawn are focused primarily on the energy and carbon performance of the dwellings and the implications for the achievement of government targets for low and zero carbon new housing. The comments made should not be interpreted as having a direct bearing on other aspects of dwelling performance, such as structural integrity, weather tightness, standard of finish and the like. In these other respects we consider the overall performance and the quality achieved to be almost certainly commensurate with and, in all likelihood, better than that achieved on any other housing development being constructed by the UK house building industry.

The gap between designed performance and realised performance

- 175 We have shown at Stamford Brook that there can be a significant discrepancy between the designed and predicted energy performance of a dwelling when compared with the realised performance either in use or when tested under experimental conditions. We have been able to quantify the size of the performance gap at Stamford Brook for a range of conditions and have also determined the key variables, both in terms of the design and construction of the dwellings and in the operation of the heating and ventilation systems that have contributed to the observed discrepancies in performance. However, the root causes of the gap in performance are much more complex than a simple list of design flaws, construction faults and system inefficiencies and relate to the

interrelationship of the various parts of the construction process from design conception right through to occupation. The potential size of the performance gap has considerable implications both for the housing industry and the regulatory environment that supports it. It is clear that a high level of investment in research, development, testing and training will be required to close this gap in order to fully realise the performance expectations outlined in the green paper – *Building for a Greener Future* (DCLG 2006b). This in turn will require close cooperation between the house building industry and its supply chain, and also with regulatory bodies and supporting research infrastructure.

Getting the fabric right first

176 The design ethos for the energy performance of the dwellings at Stamford Brook was to concentrate on maximising the benefit of the fabric whilst at the same time using efficient but relatively standard systems for space heating, domestic hot water and ventilation. A deliberate decision was made not to use any renewable technologies such as solar hot water or heat pumps as these would have complicated the issue of fabric performance and also reduced the available funding from the National Trust to pay for the over costs of fabric measures to meet the EPS08 energy standard and other components to meet the requirements of the Environmental Performance Standard. The Leeds Met team and the National Trust have received some criticism for this stance but we believe that the results and data generated by the PII project have more than justified this decision. We strongly believe that the starting point for any low carbon house design should be to optimise the basic fabric performance and dwelling form rather than to rely on designs that offset relatively poor fabric performance with low carbon energy systems. The lifetime of the building fabric is much longer than any of the systems incorporated into it and it is also much more difficult to correct major fabric faults once a building has been constructed.

Rethinking the construction process

177 The main aim of the Stamford Brook project was to demonstrate that an advanced energy standard could be successfully introduced by volume house builders on a large scale development in the UK. To a certain degree this aim has been achieved and we have been able to demonstrate that significant in-use energy savings are possible compared to existing dwellings and new dwellings built to current building regulation standards. However, the actual level of performance achieved fell short of design expectations and performance targets. In normal circumstances, the discrepancies in performance would not have been identified at all since house builders carry out almost no routine performance testing and occupants would be unlikely to notice. Even if performance had been measured but not scrutinised to the level of detail as has been the case at Stamford Brook, then, in all probability, discrepancies would have been simply attributed to failures of components or materials, occupant behaviour patterns or poor workmanship during construction. In fact, the reasons for the relatively poor performance are much more complicated than this and relate not just to the specific construction issues identified in this report but more importantly to system issues within the whole process right from regulation, planning and specification through to design, research and development, procurement and supply, training, construction, testing and inspection and finally to occupation of the completed dwellings. The research

findings from Stamford Brook also emphasise the importance of a detailed and comprehensive testing and monitoring programme in order to fully understand the complex nature of the underlying system and process issues that affect the construction and performance of domestic buildings.

- 178 We have identified several specific areas of concern within the process and these are all symptomatic of general performance issues of the system as a whole. For example, we have demonstrated that the thermal bypass in party cavity walls is a major source of heat loss from terraced and semi-detached houses. However, the mechanisms of thermal bypassing and their implications for effective thermal design of building envelopes have been known about since the late 1970s and even as recently as 2000 the potential problems that can be caused by thermal bypassing were reiterated in the literature (Lowe & Bell 2000). Despite this existing knowledge, houses have been constructed in the UK for the past 40 years with party cavity walls that improve acoustic performance but that also give rise to a significant degradation in thermal performance. The system issues in this case are therefore a combination of failures of the system of regulatory advice, a lack of integration between different aspects of building regulation, problems with levels of understanding within the design process, inadequacies in design tools and modelling protocols, failures in the training of designers and building physicists, a lack of comprehensive energy performance testing and prototyping of dwelling designs and details, a lack of feedback of performance data into the design process and the need for significant changes in planning and executing construction processes.
- 179 The organisational problems and inefficiencies in the construction industry are well known and have been described in the National Audit Office report on Modernising Construction (NAO 2001), the Egan report (DTI 1998) and the Latham report (Latham 1994). The recommendations from these reports concentrated on the potential benefits of re-engineering the construction process in terms of profitability, productivity, efficiency and quality. If it is to achieve the target of zero carbon houses by 2016, the UK housing industry (in its widest sense) and regulators can no longer ignore these deep seated system problems, many of which are embedded within industry cultures. As energy performance targets approach levels of Passive House and zero carbon standards, then even small inadequacies in the construction process can result in significant levels of under performance in terms of carbon emissions, energy efficiency and other sustainability indicators. There is therefore an imperative for the UK housing industry to embrace modern process improvement tools and methodologies along with systems thinking, as widely used in other manufacturing industries. These system approaches include lean manufacturing, six sigma, constraint theory (Nave 2002), system dynamics, organizational cybernetics and complexity theory. Indeed, some research has already been carried out to assess the impact of modern manufacturing systems and processes in the construction industry. For example a lean systems approach has been applied to service improvement in social housing provision (ODPM 2005) and also to the construction of concrete frame buildings (Darzentas, Deasley & Rogerson 2000). Systems thinking recognises that real manufacturing processes are a combination of different sub-processes and that it is the relationship between these sub-processes that is critical to the performance of the system as a whole.
- 180 Although the recommendations on detailed design and advice on specific construction faults observed at Stamford Brook will apply mainly to cavity masonry

construction and gas heating systems, the lessons on improvements to construction processes and systems in general, and in the application of the underlying mechanisms, design principles and general design advice, will apply to all construction techniques and heating systems, whether they be traditional such as masonry and timber frame or whether they are modern methods of construction (MMC) such as structural insulated panels or insulating concrete formwork or novel heating systems such as heat pumps or fuel cells. Indeed, the general view, promoted by enthusiasts for MMC, that by adopting new MMC techniques and novel heating technologies the industry will somehow overcome construction process problems and related performance issues is, in our view fatally flawed. Although it is recognised that so called, modern methods of construction may well play an important part in delivering low carbon dwellings, we see no evidence that the adopters of such systems are addressing the fundamental culture and processes changes that are likely to be required. The reality is that, if the underlying system shortcomings in the whole design and construction process are not addressed, then similar problems will still occur in new construction processes and construction techniques. Of course, these issues may manifest themselves in different ways to those usually observed in traditional construction, a position that may make the diagnosis of faults and underperformance in MMC systems more problematic. This will be especially so if the level of comprehensive product testing and process evaluation carried out by the housing industry remains at the current low level.

- 181 In the discussion section of the report below, we have identified the various sub-processes within the overall construction process and have described how they might be improved in light of the observations and measurements undertaken at Stamford Brook. In describing these conclusions, we have sought to reinforce a systems approach by showing how the various sub-processes relate to each other and their interdependency on each other.
- 182 A clear demonstration of the potential benefits of a systems methodology is provided by the approach to airtightness taken at Stamford Brook. During the initial discussions on the environmental performance standard it was identified that high levels of airtightness would be crucial to achieving a low energy design. Clear and measurable performance targets for air permeability were therefore agreed as part of the EPS08 energy standard. From these discussions also evolved the use of the parging layer as a key component in the design of the air barrier. Before being used at Stamford Brook, parging was first tested on another site and was shown to be effective (Roberts, Johnston & Isle 2005). A training programme was then implemented to ensure that the site management teams, sub-contractors and site operatives were all aware of the criticality of achieving good airtightness and those key construction variables that were important in order to achieve the desired levels of airtightness. Monitoring of the construction process and the programme of pressure testing of completed dwellings then provided feedback on adherence to design details, construction quality and trends in airtightness performance which were then used to identify areas of improvement to improve performance. Like any true systems approach this is an ongoing continuous improvement process and we would expect performance to improve. The outcome of this approach at Stamford Brook was levels of airtightness for cavity masonry mass housing that were significantly better than the UK norm and can be expected to improve further as new processes and techniques are adopted. It should be pointed out that the resources and level of effort put into the airtightness testing programme and

construction observations by the Leeds Met research team were considerable and this is perhaps an indicator of the resources that will be required by the house building industry in the short to medium term if it is to achieve similar improvements in performance across the board as it moves towards zero carbon housing targets. Although the initial costs of implementing such an approach would be expected to be relatively high, over time the process costs will reduce and it would be expected that there will be other long term benefits such as improved quality, reduced snagging, less waste, faster cycle times and other efficiencies and savings that will more than offset the initial investment cost.

Building regulations

- 183 The findings at Stamford Brook have significant implications for regulatory change, particularly in terms of supporting research, design guidance and advice on construction practice. Based on the experience of Stamford Brook, we have some confidence that the expected energy performance levels that will be required in the 2010 review of Part L could be achievable by the UK housing industry now, using existing technologies and relatively standard construction techniques. However, this assumes that actions are taken by the industry to tackle some of the specific issues that we have highlighted in this report such as the party wall bypass, heating system design and typical construction faults and also to address the underlying system and process failures.
- 184 The DCLG forward thinking paper on likely future energy standards for 2010 and 2013 (DCLG 2007b) recognises that there can be a considerable gap between designed and realised performance and that this would have implications for the proposed regulatory programme in terms of supporting research, design guidance and construction practice. The findings at Stamford Brook reinforce these concerns and point the way to making the changes necessary to address the problem.
- 185 It is critical to future regulatory changes to the Building Regulations that we understand the level of compliance of dwellings with respect to the current ADL1a 2006 carbon emission targets and also with respect to expected future changes to the regulations. The experience at Stamford Brook suggests that there is likely to be a significant level of underperformance as between the designed Dwelling Emission Rates (DER) for new dwellings built to Part L1a 2006 and the actual realised performance, both in terms of fabric performance and energy in use. Indeed, given the level of input at Stamford Brook by the Leeds Met research team into the design process, construction process and performance testing and also the high level of commitment from the developers and National Trust, the level of performance at Stamford Brook would be expected to represent a best case scenario, and it is therefore likely that the performance of other new dwellings across the UK will be much worse. However, this cannot be said for certain since, to our knowledge, there have been no comprehensive studies that have attempted to measure the performance of 2006 compliant dwellings and the existence or otherwise of a performance gap and, if present, its size. This feedback loop of real performance data back into the regulatory process is however essential if the industry is to realise the targets for reduction in carbon emissions for housing set out in the Energy White Paper (DTI 2007). Given the complexity and likely timescale of an appropriate performance testing programme it is critical that such a programme is put in place as soon as possible in order to provide the necessary

- 186 A key factor in the success of future revisions of Part L will be in the enforcement and compliance regimes that support it. There is considerable pressure from the industry to develop an accredited details approach for Part L along the lines of the Part E Robust Details for acoustics. We have an open mind on this issue. We can see the attraction but there remain questions about the efficacy of this approach as a generic method. As we have demonstrated at Stamford Brook it can be extremely difficult to develop a comprehensive catalogue of details that meet all the requirements of thermal performance and airtightness and which also properly consider the implications of robustness and buildability. We also suggest that it is almost impossible to devise a list of standard details for Part L that would not require some additional inspection and testing regime to support them. We have shown both at Stamford Brook and also from work carried out by Leeds Met looking at levels of compliance with Part L 2002 Robust Details (Bell, Smith, Miles-Shenton 2005) that general compliance levels are poor. An accredited details approach reduces the need for the designer to think in detail about the basic principles of good thermal design. The potential lack of application of thermal principles and the lack of experience in designing and modelling according to such principles can result in difficulties when it is necessary to design details that are not in the catalogue. Another drawback of the accredited details approach is that it does not show how to assemble all the details into a buildable, coherent and thermally effective dwelling design. Some of these problems could be overcome and it is possible to envisage a set of exemplar details that, if used in the right hands could have a positive impact. However, like every other aspect of the low carbon housing problem, there would need to be an industry wide evaluation of the impact of an accredited details approach on actual performance. Without such a feedback loop there could be little confidence in the approach, as either a design or compliance tool. Critical to the success of an accredited details system would be to demonstrate by performance testing that the desired levels of compliance are being achieved.
- 187 It is known that the requirements for the different parts of the building regulations can interact and that they can conflict, sometimes in very subtle ways. The starkest demonstration of the potential conflicts between regulations is provided by the party wall in cavity masonry construction. We have shown at Stamford Brook that the party wall, whilst constructed to meet the acoustic performance requirements of Part E, will act as a thermal bypass with an effective U -Value of around $0.5 \text{ W/m}^2\text{K}$. An example of one of the more subtle interactions between regulations is demonstrated by the fact that the self-closing fire doors required under the Part B fire regulations for 3-storey dwellings will sometimes not close properly in some of the very airtight dwellings at Stamford Brook (Roberts, Andersson, Lowe, Bell & Wingfield 2005). It is likely that such conflicts will become more frequent as regulations are updated and new requirements are introduced. For example, planning requirements for flood resilient dwellings in flood risk areas (Wingfield, Bell & Bowker 2005) could give rise to a potential conflict between the

need for a dwelling fabric that is free draining with the requirements for airtightness. There is clearly a need for a more integrated approach across the range of building regulation in order to identify and address these conflicts.

188 In term of designing dwellings to minimise thermal bridging, the indicative design y value for a typical Stamford Brook dwelling was 0.03 W/m²K, which is 60% less than current default value in SAP of 0.08 W/m²K (BRE 2005). Thermal bridging factors for Passive House designs would be expected to be even lower than at Stamford Brook as a result of the application of the design concept of “thermal bridge free” construction as defined in the four Passive House rules for thermal bridge free construction (see Table 31) (Feist Peper & Görg 2001). This is not to say there will be no thermal bridging in a Passive House, just that it will be very low. The conclusion is therefore that designing out the majority of thermal bridges is not an unrealistic expectation. Similarly it should be possible to design out all thermal bypasses but the investigation of the practical implications of this phenomenon is in its early stages, particularly when it comes to regulation. Perhaps more difficult will be to ensure that the details are constructed as designed.

Table 31 – Passive house design rules for thermal bridge free construction (Feist et al 2001)

Design Rule	Description
Prevention Rule	Where possible, do not interrupt the thermal envelope.
Penetration Rule	Where an interrupted insulating layer is unavoidable, thermal resistance in the insulation plane should be as high as possible.
Junction Rule	At building element junctions, insulating layers should meet without any gaps. Insulating layers should join without interruption or misalignment.
Geometry Rule	Design edges to have as obtuse angles as possible.

189 It is likely that energy performance will always fall short of the design targets to some degree as the majority of large house developers will normally design to just meet regulatory targets rather than exceed them. This is in part due to economic and competitive pressures and also because at the current time it is difficult to gauge the marketing advantages or price premiums for selling homes with energy performance in excess of that needed to meet the minimum requirements. Realised performance will nearly always be degraded by some degree compared to design expectations and therefore there is always likely to be some level of non-compliance with the regulations. This means that, when taken as a whole, the carbon emissions of new UK dwellings will most likely be higher than the projected figures, even after taking into account variability due to occupant effects.

Code for Sustainable Homes

190 In the autumn of 2006 the government announced its intention to achieve zero carbon new housing within 10 years. In support of this two documents have been published which define the policy objectives in more detail and set out a path to that goal. Both documents, the *Code for Sustainable Homes* (DCLG 2006a) and the green paper – *Building for a Greener Future* (DCLG 2006b), are likely to form the basis of regulatory standards and the programme by which they are implemented. Figure 74 sets out the energy standards required for the Code for

Sustainable Homes levels relative to the Target Emission Rate (TER) in ADL1a 2006. The Government has said that their aim is that the requirements in future revisions of the Building Regulations will mean that in 2010 new homes will have to meet the Code 3 standard, in 2013 the Code 4 standard will apply and by 2016 all new dwellings will have to meet the Code 6 standard.

Minimum standards		
Code Level	Category	Minimum Standard
	Energy/CO₂	
1(★)	Percentage improvement over	10%
2(★★)	Target Emission Rate (TER)	18%
3(★★★)	as determined by the	25%
4(★★★★)	2006 Building Regulation	44%
5(★★★★★)	Standards	100%
6(★★★★★★)		A 'zero carbon home' (heating, lighting, hot water and all other energy uses in the home)

Figure 74 – Code for Sustainable Homes energy standards (DCLG 2006a)

191 To put the energy performance of Stamford Brook dwellings in the context of the Code for Sustainable homes, the carbon emissions for an 80m² semi-detached dwelling have been plotted for the various proposed standards and compared to the Stamford Brook emissions as-designed and as-built (see chart in Figure 75)²³. Also included on the graph is the Target Emission Rate TER) for an 80m² semi-detached dwelling, Unfortunately, as there is currently no published data on the true performance of typical dwellings built to ADL1a 2006 requirements, we do not have a value for the true performance of as-built post 2006 dwellings. However, given our experience at Stamford Brook we would expect that the realised performance of post ADL1a 2006 dwellings will be comparatively worse than that achieved at Stamford Brook, and would likely lie in the range of 23 to 35 kgCO₂/m² and probably in some cases even higher.

²³ The carbon emissions for a typical 80m² Stamford Brook dwelling as-built include the heat loss contribution from the party wall bypass for one party wall. The relative carbon emissions for a detached house at Stamford Brook would be lower as they have no party wall and for a mid-terrace would be higher as they have two party walls.

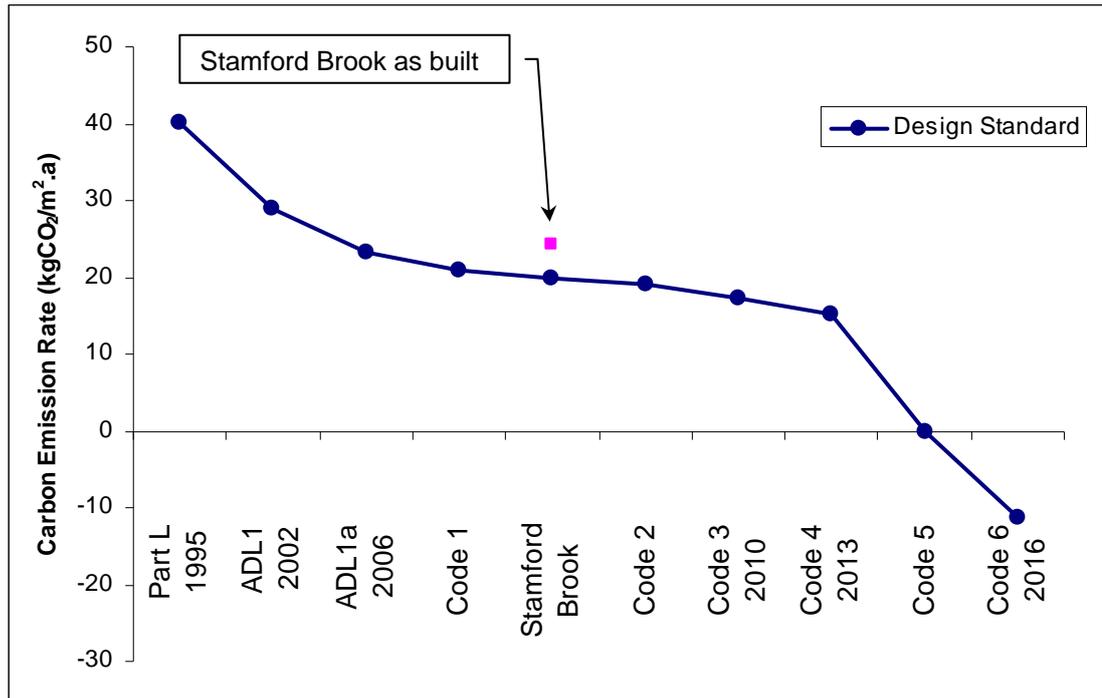


Figure 75 – Carbon emission rate for various proposed regulatory standards compared to Stamford Brook for 80m² semi-detached dwelling (as designed and as built)

- 192 It is likely that post 2006 dwellings may have worse levels of airtightness and higher levels of thermal bridging than measured at Stamford Brook, and will also have similar construction defects to those observed at Stamford Brook. In particular, thermal bypasses such as the party wall cavity in masonry construction and the degradation of fabric *U*-values caused by air movement around gaps within insulation layers (Lecompte 1990) are likely to be prevalent in new dwellings and these will both combine to give much higher fabric heat loss coefficients for post 2006 dwellings as-built compared to the predicted heat loss coefficients used in SAP.
- 193 An exploration of different compliance packages for the different standards would suggest that for gas heated dwellings from 2010 a typical combination of fabric measures and system efficiencies needed to meet the regulations would be similar to the design values for Stamford Brook, albeit with an enhanced wall *U*-Value of around 0.15 W/m² (see Table 32). This indicates that Stamford Brook could act as a template for Code 3/2010 compliant dwellings. The actual carbon emissions achieved by such dwellings would of course depend upon how many of the design, construction and process deficiencies identified at Stamford Brook are addressed by the house construction industry in the period between now and 2010.
- 194 In the absence of abundant carbon free generation, it is our view that dwellings designed to meet code level 4 (the target level regulation in 2013) will need to achieve passive house standards as shown by the example compliance package in Table 32. In addition to *U*-values of around 0.1 W/m²K for opaque elements, it would be necessary to reduce airtightness to somewhere around 1 m³/(h.m²) @

50Pa and require thermal bridge free construction. This sort of level will be particularly important if the ventilation design includes the use of a balanced mechanical ventilation system with heat recovery (MVHR). Even allowing for the fact that a limiting value as low as $1 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa may be difficult to sustain in regulatory terms, it is likely that achieving the required carbon standards is unlikely to be possible unless dwellings are consistently below $2 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa. Achieving 2013 standards would also rely on levels of linear thermal bridging better than that designed at Stamford Brook and significantly better than that actually achieved at Stamford Brook after taking into account the observed construction faults and process errors. Achieving Code Level 4 will therefore require a step change in performance compared with that achieved at Stamford Brook. However it is worth noting that achieving passive house standards need not preclude the use of masonry or any other traditional form of construction. For example, the lowest air leakage achieved ($1.75 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa) suggests that passive house air leakage levels could be within reach, given design and construction improvements.

Table 32 – Example compliance packages for gas heated dwellings in 2010 and 2013 (Bell 2007)

	2010	2013
Roof (<i>U</i> -value - $\text{W/m}^2\text{K}$)	0.16	0.08
Wall (<i>U</i> -value - $\text{W/m}^2\text{K}$)	0.15	0.10
Ground Floor (<i>U</i> -value - $\text{W/m}^2\text{K}$)	0.15	0.09
Doors & Windows (<i>U</i> -value - $\text{W/m}^2\text{K}$)	1.00	0.70
Thermal bridging allowance (<i>y</i>)	0.04	0.02
Airtightness ($\text{m}^3/\text{h.m}^2$ @ 50Pa)	5	2
Ventilation	Natural	MVHR
Space and Water Gas Heating System Efficiency	93%	93%
Area of Solar Thermal Collector (m^2)	0	4

Dwelling design process

- 195 House design is a process that seeks to balance the sometimes conflicting and contradictory requirements of cost, planning constraints, aesthetics, building regulation and buildability with the requirements of performance. The design requirements for volume house builders are complicated further by the need to ensure replicability and adaptability of standard house designs and the availability of materials and components. The Stamford Brook project has identified a range of weaknesses in typical house design processes and the consequent impacts that these shortcomings can have on the thermal performance and airtightness of dwellings when constructed.
- 196 There are several basic principles that can be applied to the design of the external envelope of a dwelling in order to minimise heat loss from a building. These basic principles are listed in Table 33. It is apparent from an analysis of the designs of the dwellings at Stamford Brook that, although the overall design intention would have been to follow these general design rules, in many cases this intention has been compromised or neglected in the overall design process. We have observed that there was no proper link either between the design process and the

construction process or between the design process and the final occupation of the constructed dwellings. It is also clear that there was relatively little feedback of the realised performance of dwellings back into the design process other than that undertaken by the Leeds Met research team.

Table 33 – Basic principles of thermally effective dwelling envelope design

Ensure that insulation layer is continuous around the building envelope and in the same plane.
Ensure that air barrier is continuous around the building envelope and in the same plane.
Ensure that insulation layer and air barrier are in direct contact at all times.
Minimise penetrations through the air barrier.
Minimise repeating and point thermal bridges through the insulation layer.
Detailing at junctions between elements and around windows and doors must minimise heat loss via linear thermal bridges.
Detailing at junctions between elements and around windows and doors must ensure continuity of the air barrier and insulation layer.
Detailing at junctions between heated and unheated spaces and voids must minimise potential for heat loss via air leakage or thermal bypassing.
Use compact dwelling forms with low surface to volume ratios and house types that minimise the exposed envelope area.
Avoid complex design forms and details that could give rise to difficulties in construction.

197 An example of these design related flaws are the discontinuities in the air barrier at various locations around the building envelope. There are for example gaps in the parging layer around the intermediate floor joists, at the floor-wall junction and behind service voids. There are gaps in the barrier at the ceiling-wall junction, at partition-ceiling junctions and around windows and doors. Some airtightness problems relate to specific details such as recessed front doors, Juliet balconies and at the wall-roof junction and the knee wall for room-in-roof dwelling types. Some of these problems arise due to a lack of sufficiently detailed documentation (drawings and specifications) that describe the exact construction sequences and the importance of the various components and materials that create the air barrier. This means that the effective installation of the barrier relies to a great extent on the on-site interpretation of design drawings, not all of which are at the most appropriate level of detail. In the case of some constructions such as dormer windows, Juliet balconies and recessed front doors, design drawing were not provided at all, which meant that the detail was essentially designed ad-hoc on site and therefore based solely on the experience of the site management team and sub-contractors. The lack of clear sequencing information in design and construction planning gives rise to a range of options for some of the construction activities which can then directly affect airtightness. This is most clearly demonstrated by the plasterboard ceiling which can be erected either before the top floor partitioning or after the partitioning. In the case of the former this gives a continuous ceiling air barrier but in the case of the latter there are multiple discontinuities at the ceiling-partition junctions. The use of plasterboard on dabs means that the design of the air seal at the junction between the wall and ceiling is totally reliant on achieving a solid and continuous bead of plasterboard adhesive around the edge of the board. However, the evidence from Stamford Brook is that this is virtually impossible to achieve in practice suggesting that the detail as designed is effectively not buildable. The complexity of some of the junctions and

details as designed also made it difficult to properly define the location of the air barrier and ensure that continuity is maintained, as demonstrated by the recessed door detail.

- 198 Even apparently mundane and simple details can become important in low energy house designs and will need to be addressed with the same rigour as other more complex details. For example, the precise design information for the sealing of door thresholds is frequently overlooked in design drawings, with the assumption that this is something that can be sorted out on site. Yet, if not sealed effectively, thresholds can be a significant point of air leakage. At Stamford Brook there were no detailed drawings for thresholds or any specific information within the construction specification on detailing, appropriate materials or sequencing for door sills. Consequently, we observed a range of ad-hoc interpretations of this apparently simple detail, which in some cases were effective but in most were not, giving rise to observed air leakage around the threshold during pressure tests. It is important that designers fully consider implications of all junctions and details no matter how apparently insignificant or routine, both in terms of thermal performance and in terms of the air barrier.
- 199 As part of their remit, developers in conjunction with concept designers will introduce elevational design features such as bay windows, door recesses and balconies and other measures such as steps and staggers in terraces in order to add interest to the overall visual appeal of a development. It was clear during the design of the elevations for the house types in phase 1 that insufficient attention was given to the difficulties that would be created for the detailed designers. In some areas of engineering design this is often referred to as the “over the wall” problem in that concept designers simply throw the problem “over the wall” to the detail designers with little thought for the consequences. As we have observed at Stamford Brook, sufficiently detailed drawings of geometrically complex features are often not provided to the on-site teams, which of course makes the job of constructing them much more difficult, another example of passing the problem “over the wall” because it cannot be resolved. Designers need to recognise that extra design effort will be required to detail complex junctions and complicated dwelling forms in order to maintain the required thermal performance and to ensure that the designs are buildable and robust. Complex designs will undoubtedly require more up front thermal analysis of junctions, a higher level of consideration of sequencing issues and better communication of the design requirements to the construction teams. Clearly, with some of the details such as the recessed door used at Stamford Brook this was not carried out. This also suggests that the design culture, training and tools are not yet fully embedded within the developers design teams. We are not suggesting that house designers should only design simple rectilinear dwelling forms with no interesting detailing, but that when they design complex forms they need to balance the aesthetic and other concept requirements with the difficulties of achieving the required thermal performance. In the end, if combating climate change means anything at all, designers need to ensure that they apply the same thermal design principles and procedural rigour to complex designs as they do to the simpler house types. The need for aesthetic complexity should be no defence!
- 200 The integration of heating and ventilation systems into the design of the building fabric will become progressively more important in 2010, 2013 and 2016. The impacts of a design process that does not fully optimise and integrate the layout and design of the building services were clearly demonstrated at Stamford Brook

with both the design of the heating system and the ventilation system. In the case of the heating system, insufficient thought had been given during design to the relative positioning of the boiler and water cylinder and to the requirement for insulation of the primary pipework. In the extreme case this resulted in heating system efficiencies significantly below that of an ideal system. In the case of the ventilation system, the routing of the ductwork and placement of the fan unit was apparently a secondary design consideration which resulted in a multitude of complex ducting layouts across dwelling types which in some cases had a significant impact on flow rates. These duct layouts were sometimes routed through the insulation layers which would have given rise to a degradation of thermal performance. The placement of wet rooms and their associated service risers and soil stacks also appeared to be a secondary consideration. In some dwelling designs this resulted in multiple risers which added to the design complexity and created difficulties in maintaining the continuity of the air barrier. Better designs of servicing routes that are located inside the air barrier and insulation layer and that have good access for maintenance would of course have added benefits in terms of access for future upgrades and modifications.

- 201 In terms of overall site design and master-planning, there are other energy design considerations such as the orientation and relative placement of dwellings for solar access both for passive solar gains and to maximise the future potential for the installation of solar renewable technologies such as solar thermal heating and photovoltaic panels. Passive solar design was considered at Stamford Brook. Other design considerations at the site level would include the potential for district heating systems and their associated centralised plant.
- 202 The lessons from Stamford Brook in terms of house design can be summarised as follows:
- a) House designers should strive to maintain the principles of effective thermal design in terms of thermal insulation and the air barrier, and these should become embedded in the organisational culture. This applies to design at every level. There is much that can be done at the level of house type and elevation design as well as detailed design.
 - b) Detailed design needs to consider to a greater extent the requirements for construction in terms of buildability, sequencing, minimisation of complexity and robustness. This requires designs to be tolerant of construction variation or to be designed in such a way as to minimise the potential for variations to occur through the use of appropriate materials, components and build sequences. The use of standard detailing may help this process but, as we observe below, the use of standard or accredited details should not be seen as a substitute for a solid understanding of thermal design principles and appropriate modelling tools.
 - c) In order to achieve the desired final performance characteristics, designs need to take account of inspection requirements and performance checks during the construction phase to ensure that the various elements have been built in accordance with the original design specifications.
 - d) A culture of continuous improvement in design should be adopted that actively seeks feedback into the design process of realised energy performance data from completed buildings and also information of the performance of the construction process such as buildability and sequencing issues. This will require a higher level of integration and cooperation between design and

construction departments within companies and also between developers and their sub-contractors, suppliers and design consultants.

- e) Communication between design departments and the construction teams should be improved especially in terms of the actual design information that is provided to site. Design drawings need to be more comprehensive and should be supported by detailed construction and sequencing information that fully detail the construction sequence and that identify appropriate control measures, quality issues and measurable performance indicators.
- f) The design process requires some form of change control procedure that can monitor and evaluate any modifications in design or any material or product substitutions to ensure that such changes do not negatively impact on buildability or any performance criteria such as energy use or ventilation. This change control procedure will have to link with both the construction process and also to the procedures used by the supply chain.

Construction process

- 203 At a high level, the construction process at Stamford Brook was ordered and followed a logical sequence. However, at lower levels of detail, it was apparent that there was some variation in the way that many detailed tasks were organised and sequenced, and that monitoring or checking of compliance with design details was not always easy to do. The approach, in which build sequences were allowed to vary within some overall build programme may provide flexibility but can lead also to processes that make it almost impossible to ensure continuity of the air barrier or insulation layers. Although such an approach may be capable of achieving non energy performance requirements, the scope it provides for inconsistencies in construction and different interpretations of design details is likely to give rise to a degradation in energy performance when compared with design expectations.
- 204 Construction observations illustrate that very often site teams have to cope with insufficient detailed design and sequencing information and this often results in the need to work round problems as they arise and to engage in on-site detail design without access to the necessary knowledge, understanding or modelling tools. Such an approach may be adequate to deal with other aspects of performance but, as we have observed, are not conducive to increasingly high levels of thermal performance. Quality is often seen primarily in terms of finish and the level of service provided by installed equipment and systems. However, many construction problems relating to such things as airtightness, continuity of insulation or installation of pipe insulation remain hidden in completed dwellings and the associated performance reduction remains unresolved. There is therefore a need to introduce systems and procedures for the continuous monitoring and inspection of the whole construction process that would ensure dwellings are constructed as designed and that the necessary thermal performance requirements are fully built-in.
- 205 There is a general reliance by house builders on the routine and final inspections normally carried out by the NHBC or Building Control in order to assess construction performance and quality. However, these inspections are not really designed to monitor or check compliance of the dwelling fabric in terms of impacts on thermal performance or airtightness. Indeed at those times when such inspections are carried out, those aspects of design important for thermal

- 206 The need to re-engineer the construction process has wider implications for developers in terms of their relationships with subcontractors and suppliers, buying policies, subcontracting contract terms, how subcontracts are let and how risks are shared between developer, client and subcontractor. This of course leads into partnering approaches to such relationships. The potential benefits of partnering have been well documented (DTI 1998). Stamford Brook demonstrates some of these benefits. For example, it is unlikely that the impressive levels of airtightness achieved at Stamford Brook would have been possible without the close cooperation between the National Trust, developers, suppliers, subcontractors and the Leeds Met research team. Perhaps the best example of partnering in action was the reaction of the Stamford Brook partners to the measured underperformance of the installed ventilation systems. The response to this situation at Stamford Brook was that all the partners sat round a table, discussed the problem and identified a course of action that would resolve the situation to the satisfaction of all parties. Similar levels of cooperation between developers, suppliers, subcontractors and regulatory authorities will be required in order to achieve the levels of performance improvement needed to meet future reductions in carbon emission targets.
- 207 A major influence on scheduling and build times are the time constraints and pressures that result from site teams striving to meet house completion targets as companies near the end of their financial years. These pressures can distort the construction process and may result in reduced performance for those homes built at the end of financial year compared to those built at other times. Better planning and monitoring of completion targets throughout the year could help smooth out these pressures and result in a more consistent level of performance across the year.
- 208 A critical step in improving the performance of the housing construction process will be to improve the process mapping of the various construction activities. The use of detailed process flow charts in construction is not new, as shown by the examples of flow charts for concrete frame construction illustrated in Figure 76 (BCA 2000). Process maps and work flow charts will be needed to develop and monitor proper sequencing and integration of the various construction tasks. These process maps could then be used to support the development of detailed design documentation and training programmes.

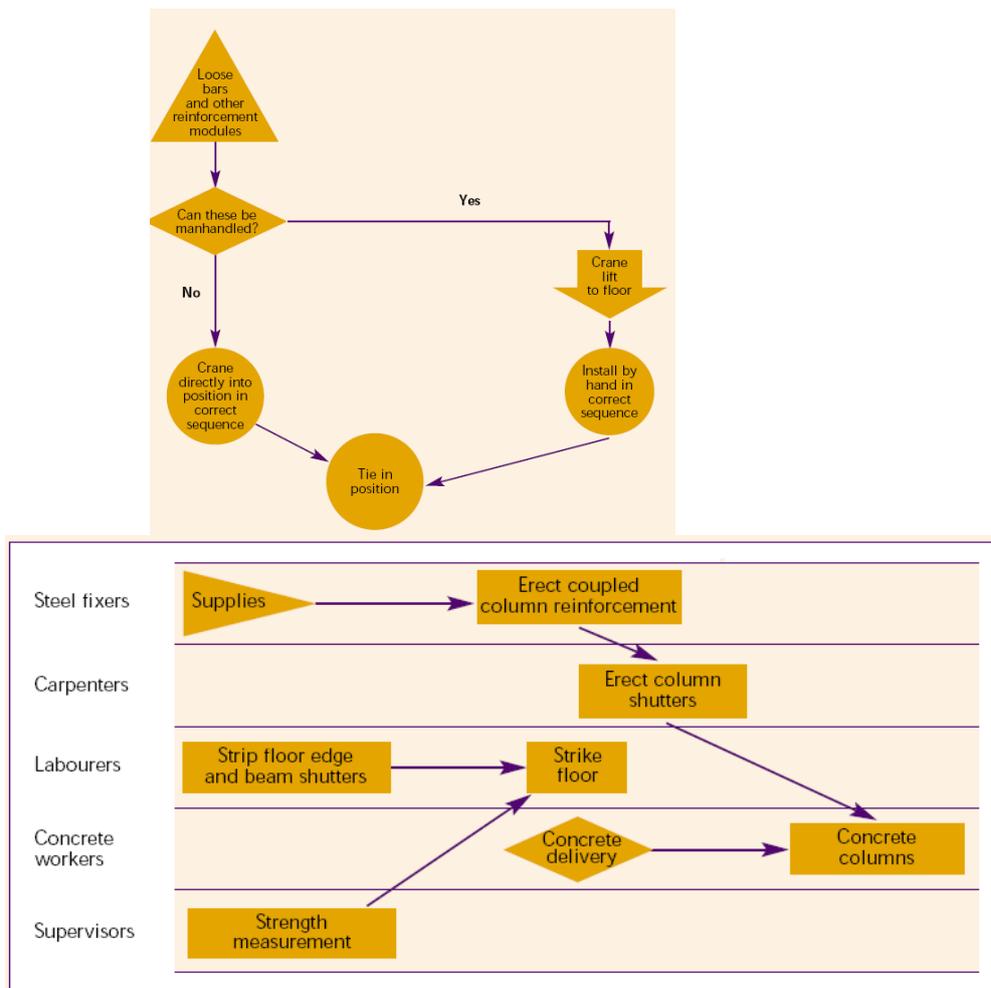


Figure 76 – Task flow chart and process flow chart for activities for concrete frame construction (BCA 2000)

209 There will clearly be some inertia in the housing industry to any significant change to typical house construction processes. This is perhaps best illustrated by a response given by the chief executive of one of the UK's biggest house builders to the House of Commons Environmental Audit Committee (2007) during evidence submitted as part of discussions relating to the Code for Sustainable Homes. The response to a question from the committee asking whether making compliance with the Code statutory would put companies at a commercial disadvantage was as follows:

".....Again, perhaps an example helps. Over a period of time the industry has developed its production methods, and one simple long term way that that has happened is moving from wet plasterwork to dry lining, which is more environmentally friendly, much better in terms of customer service, much quicker on site, much better in terms of deliverability of consistency. Recent changes in the building regulations to deal with sound insulation between buildings have meant that, in a number of instances, most of the industry has reverted to wet plaster at a stage in the construction process, when they would have been away from those kind of trades which impact on quality, on customer service, on costs and on a number of other things. That is a completely unforeseen consequence of actually a very detailed legislation that was trying to make a level playing field. It is the right objective, but the problem with it is that when it interacts with the other

legislation you end up moving backwards because it is the only way that you can deliver the absolute requirements of a set of legislation. If it really was a level playing field you would say this is it, there is the code for sustainable buildings and that covers those areas absolutely, but I just do not think we are there.”

- 210 This response suggests a lack of understanding of the way that performance based regulation works and the freedom it gives to developers in terms of design and construction techniques, and indicates a reliance on the accredited/robust detail approach to detailed design and a general resistance to make changes to processes which have become embedded in the industry. It also shows that, at a high level within these organisations, the perception of quality is mostly about those physical and visible aspects of house construction that are most noticeable by customers such as the wall finish, rather than about issues of realised energy and acoustic performance which are much more difficult to quantify.
- 211 The observations of the construction process at Stamford Brook have identified a range of general process improvement themes that will need to be addressed as part of the drive to reduce the gap between designed and realised performance. Most of these themes relate back to the design process showing how the two processes are inextricably linked. These themes can be summarised as follows:
- a) Improved buildability of designs is needed to ensure that details can actually be built as intended in order to achieve the desired level of thermal performance. This will require close cooperation between design and construction teams and with the supply chain, and will also necessitate some form of testing and prototyping of designs and construction processes. It will be critical that any issues of buildability or any problems arising during construction that are a result of the complexity of details and junctions are fed back to the design teams so that designs can be adapted and improved.
 - b) A culture of continuous improvement is needed to ensure that process problems are identified and fixed during construction, and that there are procedures to record and capture this information to feedback into the design and construction processes.
 - c) Robust procedures are needed for the control of changes to the construction process and for product and material substitutions. This will ensure that any changes are identified and that the potential effects of such changes on performance are assessed before being implemented.
 - d) Improved sequencing of construction tasks and more comprehensive documentation of preferred construction sequences would be expected to result in closer correlation between details as designed with the same details as actually constructed. There is also a need for developers to analyse existing and new construction processes in order to identify opportunities for improvement in terms of performance characteristics such as airtightness and thermal bridging.
 - e) It is clear that robustness of thermal design is an important characteristic and further research is needed to find ways of quantifying robustness and repeatability of the designs of junctions and details and how variability can influence thermal performance and airtightness. In the shorter term, an empirical approach to the problem based on observations such as those carried out at Stamford Brook may suggest design solutions, construction products and processes that could be considered more robust than existing techniques.

- f) Improvements to the level of detail of process documentation allied with comprehensive process flow charts and detailed construction planning will make it more likely that junctions and details are constructed as designed and that the correct build sequences and materials are used. This in turn will make it more likely that the desired thermal performance targets will be achieved.
 - g) Measurement of the performance of completed dwellings will become a crucial aspect of the feedback of realised performance back into the design and construction processes and as an indicator of the efficiency and effectiveness of the construction process itself. Existing testing regimes such as airtightness pressure tests will have to become routine and more comprehensive than that required merely for regulatory compliance checks and systems commissioning. Additional tests will have to be developed that are capable of determining thermal performance in a resource efficient manner.
- 212 There are many synergies that can be realised in conjunction with the introduction of the improvements in construction methods, processes and systems suggested in this report. These synergies would be expected to improve performance across a range of criteria, lower costs, reduce waste and result in faster construction times. Examples of some of these potential synergies include the following:
- a) The use of a solid wet plastered finish in preference to plasterboard on dabs would be expected to improve airtightness and as an added benefit would also potentially increase usefulness of the thermal mass of the dwelling as the plasterboard would have acted to decouple the mass of the block wall from the conditioned space. The additional thermal mass would serve to reduce the risk of summer overheating if used in conjunction with a suitable ventilation regime.
 - b) By erecting the ceilings before partitioning this will both minimise air leakage via the partition wall heads and also make it easier to move partition walls thus making the living space more flexible for future changes in space requirements.
 - c) The introduction of a robust quality control system would be expected to improve measurable performance characteristics such as acoustics, airtightness and thermal performance. There would also be synergistic benefits in terms of improved customer satisfaction levels, cost savings due to reduced wastage and fewer call backs to fix faults.

Supply chain

- 213 To a large extent house design in the UK is driven by the type and availability of components and materials from construction product manufacturers and materials supply industries. It is our belief that the introduction of new materials and components is dominated by the in-house research and new product development programmes of the companies within the supply chain rather than in response to demand for new products from housing developers. Although this may be seen as inevitable it suffers from problems of narrow vested interests and does not stem from a desire on the part of developers to extend and improve their design portfolios or to re-engineer their construction processes. What is needed are closer and more effective working relationships between house builders and their supply chain, working together to design products suitable for low energy houses, a process that starts with the whole dwelling working down to the particular components that are required to achieve the required performance. This more integrated approach is more likely to solve some of the construction process and

performance issues that we have highlighted in this report such as buildability, robustness, sequencing and build tolerances.

- 214 Part of the response of the supply chain to the low carbon housing challenge has been to offer one-stop-shop whole house solutions based mainly on MMC technologies. Examples of these whole house design concepts include the Stewart Milne Sigma house (Stewart Milne 2007), the Kingspan Tek Building System Lighthouse (Kingspan 2007), ecoTECH Organics house (Ecotech 2007) and the Hanson House 2 (Hanson 2007). Although in theory these MMC-based solutions would appear to offer some advantages in terms of thermal performance, buildability and consistency, we have been unable to find any published performance data of completed dwellings to substantiate the performance claims. As we observe above, such “off the peg” solutions may suffer from the same underlying cultural and systems failures as we observe in traditional construction.
- 215 We have identified many potential areas of performance improvement for construction products and components at Stamford Brook. For example, we have observed high levels of air leakage both around the trickle vents and around the seals of rooflight windows which will have to be resolved by the rooflight manufacturers. There will therefore be many opportunities for materials suppliers and component manufacturers to develop new products and improve existing ones. This would be best achieved through close co-operation between housing developers and the construction product supply chain which would help identify those new products, components and materials that will best assist house builders to reduce general construction variability and improve thermal performance and airtightness, especially at junctions between elements. Such products would need to minimise the potential for sequencing errors and poor workmanship and thus make it easier, for example, to achieve the desired low levels of thermal bridging at openings without requiring high levels of accuracy in component placement. Products could be developed to address some of the specific difficulties in cavity masonry construction that we have highlighted in the work at Stamford Brook.
- 216 An example of one of the detailing problems identified that could be solved with a new product is the window and door head. What is needed is a component that would minimise the variability in the placement of separate steel lintels at window and door heads and at the same time would also ensure that there are no gaps in the insulation between the lintels. A potential solution to this particular issue would be a combined insulated spacer/cavity tray which separates the lintels by the necessary distance for the desired cavity width and where the lintels are pre-insulated with an insulation material shaped to provide the slope of the cavity tray as shown in Figure 77. Such a product would overcome problems with missing insulation, close the cavity, maintain the correct gap between the two lintels and also provide a surface to which the reveal boards could be attached.

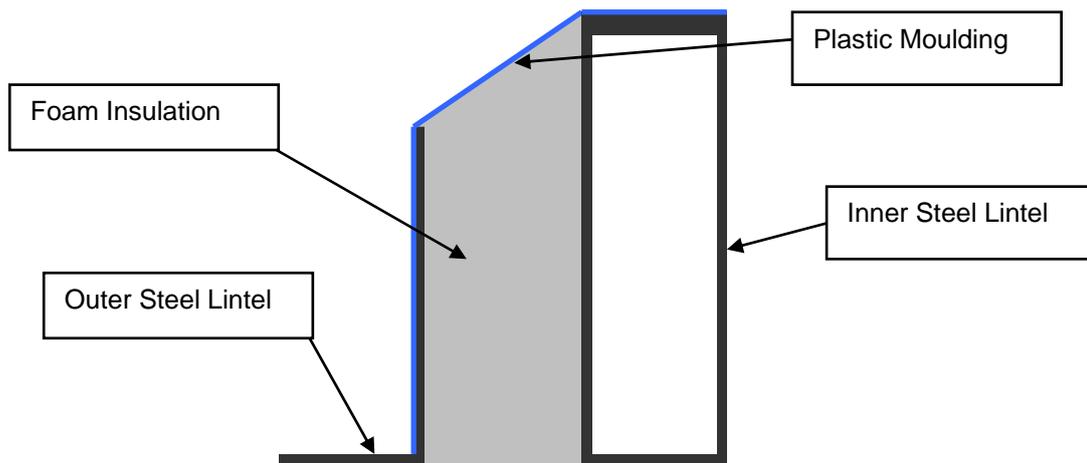


Figure 77 - Separate window head lintels with combined insulated spacer and cavity tray

217 Similar products to the one outlined above are already available on the UK market and could be readily be modified to suit some of the details at Stamford Brook. This is illustrated by the example of an insulated cavity tray product shown in Figure 78. This product is designed for use at the bottom of a cavity (hence the additional edge insulation for the slab) but small adaptations by the manufacturer would make it suitable for use with separate lintels at a window head.

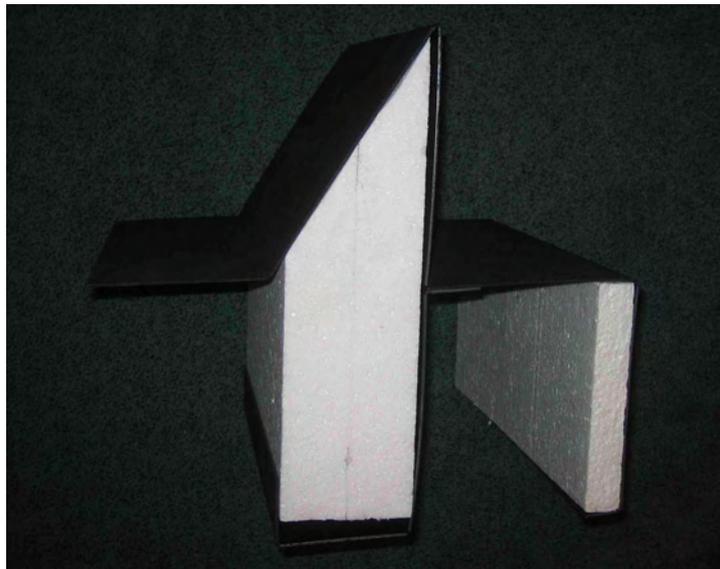


Figure 78 - Commercially available insulated cavity tray product

218 Another critical detail that presents opportunities for new products from the supply chain is the junction between the ceiling and wall. The evidence from Stamford Brook is that the ceiling-wall junction is a major air leakage path and that this junction is not properly sealed using the beads of plasterboard adhesive that currently serve as the designed seal for this junction. A better solution would be to provide a physical seal using a membrane or plastic strip. Indeed, working in collaboration with Leeds Met and Bryant, one of the companies supplying components to Stamford Brook has developed just such a product as shown in Figure 79. This is an L-shaped plastic channel with preformed sealant strips

bonded to the two outer faces of the channel as shown. This product is applied to the inside of the ceiling-wall junction before the plasterboard is fixed and could provide an effective airtight layer as well as continuity between the wall air barrier and ceiling air barrier. It is possible, however to question the performance of this prototype and it will be important to test the performance of such products in real dwellings. However that is what prototyping is designed to do. In order to have confidence in such a product and detail the supply chain would need to work closely with house developers to assess the viability of such new components, not only in terms of cost and performance, but also in terms of other construction and process factors such as buildability and sequencing.



Figure 79 – L-shaped channel with sealant strips for sealing wall-ceiling junction

Training and education

- 219 The knowledge transfer process at Stamford Brook took several forms and included formal training sessions, focus groups, review meetings and on-site discussions and demonstrations. However, the process of diffusion of this training and awareness within the different organisations remains unclear and we do not know how well the lessons from Stamford Brook have been retained and applied or how internal processes and procedures have changed, if at all. We have concluded from our observations that, if the focus on training and feedback is weakened, as in the case of the airtightness results, then this can result in a resumption of previous patterns of working with a consequent degradation in performance. It was also evident from the design of later details at Stamford Brook, (e.g. Juliet balcony and recessed door) that some of the key thermal and airtightness design principles and tools developed in the earlier phases of the project had not yet taken hold within the design teams. Given the experience within this project and others it is almost certain that UK house builders lack the capacity, in depth knowledge and training infrastructure that will be required to implement and sustain the changes that would be needed to meet the design and performance requirements of low and zero carbon energy standards.
- 220 There is therefore a need for improvements in training and awareness of the issues at all levels for designers, on-site professionals, trades people, the construction supply chain and regulatory authorities. The information and learning from Stamford Brook could be developed further as a comprehensive case study

for the industry in order to reinforce the key messages highlighted by this report. However, issues related to the fractured structure of the housing industry and its reliance on large numbers of small subcontractors may make the dissemination of the key messages difficult. There will also be concerns relating to the current trend for mergers and consolidation between some of the UK's largest house builders²⁴, which is leading to the loss of skilled technical and design staff from centralised office functions as a result of merger efficiency savings. This reduction in the housing industries' skill base and technical capacity is occurring just when the demand for such skills is likely to increase, and the need to retrain and retool becomes imperative.

- 221 Improving knowledge levels will be a difficult task since it is likely that the changes will require a move away from a reliance on a pattern book approach to detailed design and the reliance on the supply chain to provide component based design solutions that can be bolted together. It is perhaps unfortunate that such an approach is reinforced by the move to accredited details as a means of regulation. Although there may be merit in accredited details as part of a design culture that has the necessary understandings backed up by robust modelling tools, a reliance on an accredited pattern book is unlikely to deliver low carbon housing on a reliable and robust basis. In our view there is a need to change the culture of house design to reflect a more holistic and integrated approach and this will require a greater level of thermal design expertise within the house building industry and the consultants that support them.
- 222 The responsibilities for ensuring that the necessary training and re-education takes place will rest with several organisations. At the level of professional designers, site-based management and trades, it will be the professional and trade institutions that will have to take this on board as part of their CPD requirements and the supporting educational institutes will have to make available the resources to help this take place. There will also be an onus on universities and colleges to continually refresh and update their own staff so that course content reflects the demands for low carbon design and construction so as to ensure that the next generation of professionals are ready for the expected changes.

Communication

- 223 The findings from Stamford Brook have highlighted the critical nature of communication. It is clear that there is considerable scope for improvement in flows of information both upwards and downwards throughout the organisations involved whether developer, designer, subcontractor or individual trade. Very often, design information affecting thermal performance was not available, not at the right level of detail, confusing or just not referred to by operatives. This led to a rather diffuse process as operatives followed their own judgement based on their trade skills and knowledge rather than using detailed design information. In the better understood areas of structure, weather tightness and the like, this may not result in performance degradation but it is not conducive to robust thermal performance. At a more general level, there did not appear to be any particularly well developed mechanism for feeding back information on performance, nor was

²⁴ The UK's top ten house builders accounted for around 86,000 completions in 2006 (after taking into account mergers that have taken place in 2007), with the top five house builders responsible for around 70,000 completions (Macdonald & Kliman 2007). This compares to around 70,000 completions for the top ten UK house builders in 2002 (Barker 2003).

it clear how the design and construction lessons were being absorbed for use in making improvements to processes or actual designs. To a large extent this is linked with our conclusions on the need for a more detailed and clearly defined process control system, for without such a system there can be no definition of problems, identification of their causes or framing of solutions.

- 224 If the industry is to improve energy and carbon performance, improve its control of construction processes and better integrate design with construction, then an important task will be to look at the way information is communicated within developer and other organisations and between themselves, their partners and subcontractors in the supply chain. It will be necessary to review the whole range of communication channels to ensure that they are effective, responsive and that there are feedback mechanisms to allow a two way flow of information. Perhaps the most critical aspect of communication in terms of energy performance relates to the availability and precision of design drawings and associated process information and procedural documentation. The experience at Stamford Brook is that this is often not at the right level of detail and that this lack of detailed information can have a significant impact on the measured energy performance of completed dwellings.

Process improvement

- 225 The observations and analysis of the design and construction processes indicate that the control of processes was not always clear, with a number of personnel playing similar but different roles and with very little feedback on thermal performance. An analysis of the control systems being used indicated a very strong reliance on inspection with problems being dealt with informally and on the spot, but with less clarity when it came to the collection, collating and interpreting of process control data and the provision of feedback on performance. Similarly, the roles played by independent site agents and building professionals, such as NHBC inspectors, building control officers, National Trust staff and the Leeds Met research team, were not clear. In general there was no obvious formal framework to provide consistent quality control feedback on particular thermal performance characteristics such as airtightness. With increasing outputs and workloads being placed on the site management teams as the quantity of production stepped up, proportionately less resources were available for the quality control programme. Under such pressures, the quality of the final finishing effectively became higher priority with less control over hidden areas of construction that are important for thermal performance and airtightness.
- 226 In general there was no obvious formal framework to provide consistent quality control feedback on particular thermal performance characteristics such as airtightness. It was also apparent that as construction progressed, the original construction specification was increasingly being overtaken by changes in construction. Various changes in techniques, procedures and materials had been adopted on site since the final version of the specification had been written and these alternative methods had effectively become standard practice, but the construction specification had not been updated to take account of any of these changes. This suggests a need to review the systems control aspects of the process. In our view this situation on large housing developments is not untypical of operations within the housing construction industry in the UK.

- 227 Ad-hoc changes and product substitutions were made to details on site, and in several cases no design information was readily available such that the details had to be designed on site as construction progressed, based on experience and prior knowledge, again with little control of how such procedures were undertaken, recorded or fed back into the design process for verification. As we have already observed such an approach may be satisfactory when dealing with performance characteristics such as standard of finish but very often such an informal approach leads to a degradation in thermal performance. The recurrence of common problems with the placement of insulation or maintenance of the air barrier particularly in hidden areas cast further doubt on the effectiveness of existing approaches to systems control in the context of low carbon housing. Taken together, all these observations are symptomatic of an underdeveloped system of process improvement and control.
- 228 The need for a change in the way that the UK housing industry approaches issues of quality control, process improvement and performance measurement is therefore critical if it is to realise the carbon reduction targets set by government. Quality control systems for UK house construction need to emulate the standards achieved in modern manufacturing processes such as in the automotive and telecommunication industries. This will require a fundamental reassessment of all processes including both design and construction, and will need to include the buy-in of subcontractors and companies in the supply chain, and there are signs that this is beginning to be acknowledged. Of course, the sort of reassessment considered to be necessary will have significant implications for the structure of the industry and the relationships involved but it is hard to see how change can be avoided if over 200,000 low and zero carbon dwellings are to be produced per annum in a robust and consistent way
- 229 A range of process management tools and quality systems have been developed in other manufacturing industries, of which the most widely used are Six Sigma, Lean Manufacturing and Constraint Theory (Table 34). These tools and systems provide a framework and set of guiding principles by which companies can control and measure their manufacturing processes, as well as a range of techniques for creating a culture of continuous process improvement. These processes and tools would need to be adapted for the specific requirements of the house building industry, but it makes much more sense to build on the experience of other industries rather than to attempt to create a whole new set of management tools. By necessity any quality control system will have to cover the whole range of activities that can affect performance, and as such will include the development of specifications, the design process, design qualification, change control, process control, commissioning and testing, right through to the sales process and customer care.

Table 34 – Comparison of characteristics of common process management tools

Process Management Tool	Underpinning Theory	Focus	Main Effect
Six Sigma	Reduce Process Variation	Problem Focussed	Uniform Output
Lean (Toyota Production System)	Remove Waste	Flow Focussed	Reduced Cycle Times
Theory of Constraints	Manage Process Constraints	System Constraints	Faster Throughput

- 230 An example of how modern process management tools are already being used in the construction industry is illustrated by the use of control charts by Robust

Details Ltd to monitor the ongoing field performance of the various construction details in the Robust Details catalogue. The control chart in Figure 80 shows the airborne acoustic test data for the EWM4 robust detail (Baker 2007). By using such control charts and other statistical methods Robust Details Ltd are able to identify and monitor trends in performance and to assess the effect of changes in specification details or advice. There is no reason why such tools could not be used to monitor other performance criteria such as airtightness.

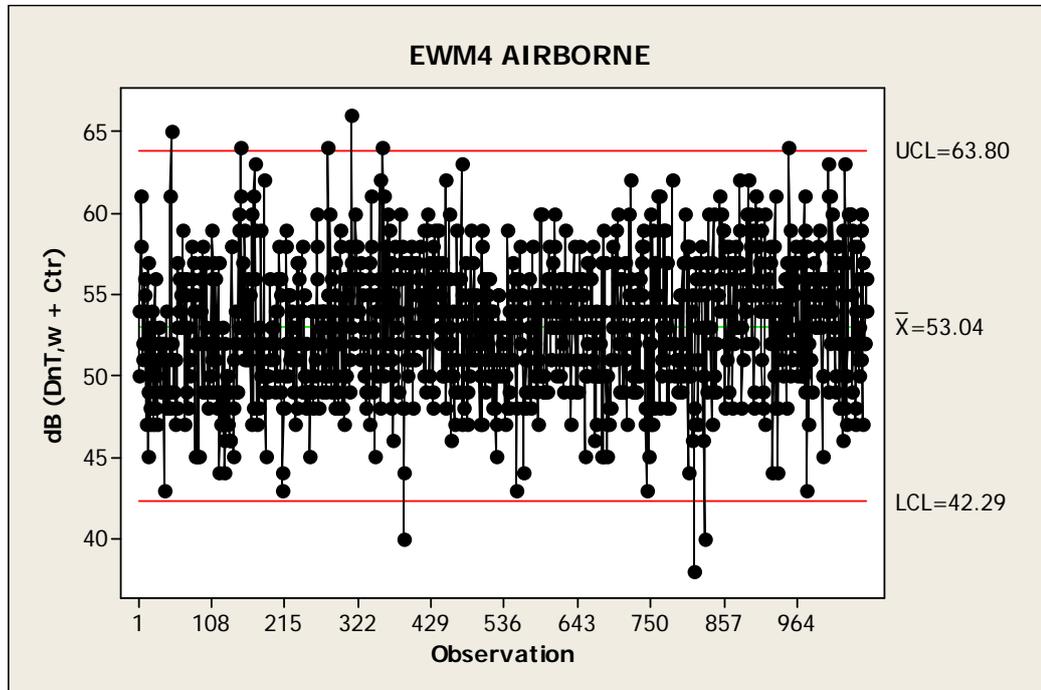


Figure 80 – Control chart for EWM4 robust detail tests (Baker 2007)

231 It is interesting to note that the Energy Star housing programme in the United States has developed a series of protocols and quality control checklists for the assessment of dwelling designs in terms of thermal bypassing (USEPA 2007a, 2007b). The Energy Star thermal bypass checklist is shown in Appendix 5. The use of similar checklists and their associated design advice is perhaps an improvement on the current accredited details approach used in the UK.

Energy models

232 There are no specific requirements in Part L1A 2006 of the Building Regulations (ODPM 2006b) to take account of heat loss by thermal bypasses. Part L1A 2006 requires that the *U*-values should be calculated according to the methods and conventions set out in BR443 (Anderson 2006) and that CO₂ emission rates are calculated using the 2005 edition of the Standard Assessment Procedure (BRE 2005). The conventions in BR443 do not include any guidance for calculating heat losses via party wall cavities between adjacent heated dwellings, as it is assumed, incorrectly, that these losses would always be negligible. The assumption made in SAP 2005 is also that losses via party walls are insignificant. It states in SAP 2005 that "Losses or gains through party walls to spaces in other dwellings or premises that are normally expected to be heated are assumed to be zero" (BRE 2005). It will therefore be necessary to update BR443, SAP 2005 and all other supporting

documentation to take account of the potential for the party wall cavity thermal bypass and other similar bypass mechanisms.

- 233 The observed variability in construction quality and the potential effect that this can have on thermal performance raises the question as whether such variability should be accounted for in models. One approach could be to apply a general correction factor such as a percentage increase on U -values and Ψ -values in order to account for variability. However, such an approach would have to be supported by data on real fabric performance of dwellings for example by coheating tests and/or heat flux measurement and would be a large, complex and time consuming task.
- 234 The indication from boiler efficiency and heating system efficiency measurements conducted at Stamford Brook is that the official SEDBUK efficiency ratings for gas boilers may not accurately reflect the true performance of heating systems as installed and as operated by the householder. We have shown that during the heating season boiler efficiencies are close to the declared SEDBUK ratings but that outside of the heating season these efficiencies can fall dramatically suggesting that the SEDBUK ratings may not properly reflect a seasonal average efficiency. The Energy Savings Trust is currently undertaking a major study of installed boiler efficiencies due to similar concerns (EST 2006).
- 235 Evidence from overseas is that mean internal temperatures tend to be higher in low energy homes, in some cases as high as 25°C. Of the four monitored occupied dwellings at Stamford Brook we saw no compelling evidence of this trend. However, with such a small sample this may not be indicative of typical behaviour so it is recommended that an important aspect of any future monitoring programmes for low energy housing in the UK will be to investigate whether there are similar rises in internal temperatures as seen on the continent. If typical temperatures are found to increase, this may necessitate some adjustment to the internal temperature assumptions in the SAP model at some point in the future. It is also important that we understand the drivers for such increases as these high internal temperatures will of course reduce the effectiveness of the fabric and heating system improvements of low energy house designs.

Design tools

- 236 From our experience at Stamford Brook developers have not yet begun to make use of detailed energy design tools such as thermal modelling or whole house energy modelling software as a design aid in any significant way. The approach appears to be one of design first then check compliance rather than a more holistic approach where compliance is an inherent part of the design process. It is likely that the somewhat restrictive approach to design stems from the general reliance on the pattern book approach to detailed design as supported by the Robust Details catalogue for Part E and Accredited Details catalogue for Part L. Compliance checking is also usually outsourced, so developers have in the past seen little need to develop in-house expertise in thermal modelling and analysis. It is also possible that developers see the development of in-house expertise as expensive, costly and complex to maintain. If house builders are instead to rely on outsourcing for the majority of their design and modelling functions then they will have to develop much stronger relationships with their consultants and ensure that communication and quality control procedures between companies are well integrated.

- 237 It is apparent that both the Part L Accredited Details and Part E Robust Details contain classes of junction that include some form of thermal bypass. It will therefore be necessary to examine these catalogues to identify any suspect details that have the potential to give rise to a thermal bypass. It is also recommended that a desk study is undertaken to identify other classes of bypass mechanism that may be present in the design of common UK house types or that may be related to specific construction methods and technologies used in the UK.
- 238 The findings from Stamford Brook and other similar projects such as the work carried out by Leeds Met on airtightness and condensation risk under the Building Regulations Operational Performance Framework (Johnston, Miles-Shenton & Bell 2006, Bell, Smith & Miles-Shenton 2005) have illustrated that the level of design compliance using the accredited details approach can be poor and that this can have significant detrimental effects on thermal performance when the defects are modelled or dwellings tested for airtightness. We have shown that even small differences in construction variability can have a significant impact on measured thermal performance which suggests that more work is required to support and verify the robustness of accredited details and whether indeed the approach of using a system of standard approved details will actually achieve the desired levels of performance.

Performance monitoring protocols and performance testing

- 239 The research findings from Stamford Brook emphasise the importance of a detailed and comprehensive testing and monitoring programme in order to fully understand the complex nature of the underlying system and process issues that can affect the construction process and realised performance. It is clear that the assessment of performance both during the construction phases and from post completion testing is a crucial factor in understanding the construction and design processes. The monitoring and feedback of such test data will also be important as part of any quality control system and continuous improvement process. We have used a range of performance monitoring techniques at Stamford Brook such as detailed photographic records, thermal imaging and coheating tests and it is likely that further methods and techniques will need to be developed in order to provide the required level of data to feed back into the design and construction processes. It is crucial that further methods and techniques are developed in order to provide developers with the required level of data to feedback into the design and construction processes.
- 240 The use of coheating tests is we believe likely to be one of the main tools for the assessment of the fabric performance of different dwelling designs and construction techniques. However, there is very limited recent published data on the use of coheating tests to measure the real fabric performance of dwellings. A recent coheating test of a detached house in Belgium built to Passive house fabric standards showed the fabric losses were actually less than those predicted from modelling (De Meulenaer, Van Der Veken, Verbeeck & Hens 2005). In this case the coheating heat was carried out over a 6 week test period and the daily heat energy input data was analysed using a multiple regression against the inside-outside temperature difference, solar insolation and wind speed. Further research will be required to develop the coheating test methodology and data correction protocols.

Occupant behaviour and usage patterns

241 Real dwelling performance in use is a function of fabric and system performance and the interaction of these factors with occupant behaviour. We have shown at Stamford Brook that some occupant effects can be significant. For example, over ventilation of dwellings in winter can give rise to large increases in energy consumption and even small changes to the timer settings of heating systems can significantly improve system efficiencies. Improvements in advice and information provided to householders could potentially be very powerful with opportunities to influence these behaviour patterns for the better and lead to improvements in in-use energy performance. However, it is notoriously difficult to effect such changes in human behaviour and we do not really know the true extent or impact that such advice is likely to have. It may also be possible to achieve reductions in in-use energy consumption through the use of smart technology and intelligent system controls.

Existing housing stock

242 Many of the observations and lessons from the project can also be applied to the existing stock of houses and have the potential to generate significant energy savings. These include for example:

- a) The fundamental principle of removing uncontrolled heat loss from heating systems by insulating primary pipework and minimising the length of primary pipe runs is something that is applicable to both new and existing dwellings. The guidance in the Domestic Heating Compliance Guide (ODPM 2006a) makes no mention about the length of primary pipes and is ambiguous about the need to insulate primary pipework. The guide states that for gas-fired central heating systems:

“In new systems...primary circulation pipes for hot water service should be insulated throughout their length, subject only to practical constraints imposed by the need to penetrate joists and other structural elements...For replacement systems, whenever a boiler or hot water storage tank is replaced in an existing system, any pipes that are exposed as part of the work or are otherwise accessible should be insulated as recommended in this guide.” (ODPM, 2006, p16)

In existing dwellings it may not always be possible or practical to expose and insulate all existing primary pipework or to relocate the boiler or cylinder in order to reduce the length of primary pipes. However, the potential benefits of doing so in terms of energy saving and improved system efficiency should be considered. It is recommended that the Domestic Heating Compliance Guide is updated so that such benefits are explained.

- b) Coheating tests and thermal cameras give reasonably accurate estimates of a buildings true thermal performance and can identify major zones of heat loss. The use of such techniques as part of a condition assessment survey would be invaluable in the decision making process for local authorities or housing associations when considering replacement heating systems or improvements to the fabric such as new windows or additional insulation.
- c) It is likely that there will be a range of thermal bypasses in existing buildings such as the party wall cavity and that the heat loss via many of these bypasses could be reduced using relatively simple interventions. For example, it would be possible to retrofit a mineral wool filled cavity sock at the top of existing party

wall cavities. It might even be cost effective to fully insulate a party wall cavity at the same time as any work that might be carried out to insulate the external wall cavities of an existing dwelling with blown mineral fibre.

- d) We have demonstrated a range of relatively cheap technologies such as infra-red thermal cameras, pressure testing and leak detection using smoke tests that, especially when used in combination, could be used to identify 'quick wins' in home energy efficiency improvements more effectively and to target those insulation and draught-proofing measures that are likely to be most effective.

A research vision for Zero Carbon Homes

- 243 A large part of the success of the Stamford Brook research project lies in the action research approach taken and the high level of trust between the research team and the site teams. This trust was built up gradually over the seven years that the Leeds Met worked with the National Trust, the two developers, sub-contractors and other partners. This created a non-adversarial relationship and no-blame culture in which the research team has been able to observe and record construction activities and design outcomes that might have been hidden or otherwise distorted. We have also shown the benefit of detailed observation of the design and construction processes combined with a comprehensive performance testing programme. This has resulted in a much clearer understanding of heat loss mechanisms, system inefficiencies and the underlying system causes. The research methodologies and analysis techniques employed at Stamford Brook could therefore act as a blueprint for future field studies of low carbon housing.
- 244 Appendix 6 sets out, in outline, the shape of a possible research programme designed to support, government and the industry as we seek to ensure that all housing built from 2016 onwards is as close to zero carbon as possible. Achieving zero carbon, “on the ground” will require a robustness in design and construction that is well beyond anything that the industry has achieved so far. This is an exceptionally difficult task and will be impossible without a matching R&D effort that is itself robust. The paper in appendix 6 sets out the following types of study that are likely to be required.
- a) **Design process studies** – This type of study is primarily a qualitative study that seeks to understand the low carbon design process in general and, in particular, the means by which carbon performance is integrated into design. It should identify the issues involved and the barriers to the development of acceptable solutions. In many studies it is likely that mistakes will be made in design that will not become apparent until post construction and it would therefore require an open approach and a willingness to accept mistakes on the part of the design team and researchers.
- b) **Construction studies** – The process by which designs are translated into completed dwellings is crucial to achieving robust carbon performance. As we have observed, existing processes result in significant degradation in designed performance. This is for a variety of reasons not all of which have their roots in construction quality but in design. Studies of construction are likely to have two complementary objectives depending on how the study fits into an overall research project or programme. In the first place it will be important to understand the processes by which design material is translated into construction, including the approach to quality control and on site performance

assessment as construction proceeds and, in the second observations of realised construction will provide important contextual material to support post construction performance monitoring.

- c) **As-built studies** – Such studies should be designed to verify, as far as is possible through the measurement of fabric and systems in unoccupied dwellings, the extent to which designed performance is achieved. Where in-use performance monitoring of occupied dwellings is to be undertaken, the measurement of as-built performance provides a very important base line against which to set the results of the longer term in-use studies. With some exceptions, such as where new technologies are being evaluated, as-built performance should involve real commercial schemes developed at a scale that is representative of the industry as a whole.
- d) **Intensive energy in-use studies** – The purpose of this type of study is to generate as clear a picture as possible of performance in use at a detailed, disaggregated, level. This type of study is able to provide data on the different energy flows (space and water heating, cooking and electricity consumption etc.), the performance of services (efficiencies, air flows/air quality etc.) and internal temperatures as well as overall energy consumption. However, use is extremely variable and it is often very difficult to disentangle the impact of different household structures and use patterns on energy consumption. For this reason such monitoring projects require a particular blend of physical and social science so as to understand what performance may be use related and what relates more directly to the design and construction of the dwellings. Despite the difficulties, such studies are essential if we are to understand the performance of low energy housing and the likely impact on the way dwellings are used and perceived by occupants. Given the complexities involved, studies should be as comprehensive as possible so as to gain maximum understanding. One of the most important aspects of such studies is a good understanding of the physical and social context of the dwellings in occupation. Without contextual information it becomes almost impossible to make sense of energy and other monitoring data.
- e) **Extensive energy in-use studies** – This type of study should be designed to provide a statistically robust measure of actual energy consumption within a particular development or a number of developments designed to achieve the same performance standard. Unlike intensive studies, this type of approach concentrates on gathering a small amount of data from a large number of dwellings and its value lies in being able to determine just what level of energy performance is being achieved across a particular cohort. Results from such studies would have considerable benefit in providing timely feedback on energy performance and highlighting areas of underperformance (or, indeed, over-performance) that should be investigated in more detail.

245 In shaping a long term research programme (10 years and more) the overriding objective will be to enable the industry to learn how to produce low carbon housing in a robust and reliable way, the early phases of any programme should be biased towards intensive studies of processes and detailed performance studies that have a considerable explanatory power. Such work would have to be designed so that results can be disseminated in a phased way, as they are obtained and analysed, rather than waiting for the end of what can be quite long projects. As the programme matures and as regulations change, more extensive studies of impact

and general performance will be necessary so as to measure overall progress within the industry at large.

- 246 All types of study will be required and they will need to be used in different combinations. Above all, however, the programme must be focused on what is done and achieved on site and in use, with backup provided as required by laboratory studies designed to tackle particular problems of detail derived from the site based work. Of course, if such a focus is to be maintained, the programme will require a supply of real test-bed schemes provided by a willing and enthusiastic house building industry.
- 247 Achieving low and zero carbon standards in all new housing will require a coordinated effort in which data is shared and compatible, and where researchers collaborate with each other, the industry and government. Clear leadership will be necessary at all levels and adequate funding will be required to support the programme. All this will be possible only if there is a strong coalition of government, industry and the research community that is committed to long term and fundamental change.

Concluding statement

- 248 Our principal conclusions from the Stamford Brook field trial are contained within the implications for domestic construction section above and summarised in the executive summary. However, in seeking an overarching statement that captures the single most important message from the 6 or more years we have been involved, we return continually to the notion of paradigm shift, a term coined by Thomas Kuhn (1962) in his discussion of the development of scientific thought. In broad terms Kuhn presents a picture of scientific development that exhibits a series of step changes involving the rejection of an established order or an existing set of shared understandings (a paradigm) and the adoption of a new one. Such shifts almost always create a sense of crisis and not a little controversy as the new paradigm supplants the old. In an earlier project at St, Nicholas Court in York (Lowe, Bell & Roberts, 2003) we invoked Kuhn's analysis of the development of science to reflect on the issues in designing for a low carbon future, concluding that there were important parallels between paradigm shift in science and the current state of flux in the development of new housing.²⁵ In the 4 years since the completion of the St. Nicholas Court project the "crisis" has deepened and, particularly with the publication of UK government plans to regulate for zero carbon housing within 8 or 9 years, has reached a point where fundamental change is inevitable.
- 249 We have concluded from our work that, even when one tries hard, mainstream housing is very unlikely to meet its designed (or regulated) performance standards and that the reasons for this are deeply embedded in the culture, processes and practice at all levels of the house building industry. Further, we have concluded that change at the level of construction technology and techniques or design tools and the like are unlikely to effect any change at all since they would remain embedded in the same cultures and processes as the old technology and would

²⁵ We are aware, of course, that the imperatives of climate change and the general acknowledgement that urgent action is required have led to a more general shift in the paradigms within which the world works. Housing is only one area where a major shift in thinking is required and takes its place alongside transport, industry, agriculture and many other sectors.

be just as prone to underperformance. Stamford Brook in particular and the UK in general are not alone in experiencing the sort of systems failures we identify. Evidence from the United States suggests that similar problems exist within at least some parts of the house building industry on the other side of the Atlantic Ocean. In a study of code compliance in Fort Collins, Colorado during the late 1990s and early 2000s (City of Fort Collins, 2002) the authors concluded that designers rarely understood or took serious notice of energy performance issues, particularly when it came to detail design, constructors followed previous, usually flawed, experience and rules of thumb and failed to notice many problems of energy efficient construction. They identified the “wall board” (the internal finish) as the separating layer between those things that impacted on appearance and those that determined thermal performance airtightness, pointing out that anything out of sight “behind the wall board” was given much less priority than those things that resulted in poor surface finish. They point also to a lack of understanding of performance at a systems level:

“An understanding of how the house performs as a system shows that focusing on individual components may miss important consequences. For example, design decisions and construction practices regarding the height of the house, air sealing, ventilation equipment, fireplace, ductwork and water heater all affect whether the water heater will vent combustion products safely out of the home. The energy code is largely based on a prescriptive, component-based approach that does not adequately address such systems-level complexities. Likewise, the building industry delegated a lot of responsibility to individual subcontractors, each of whom knew a lot about their own area of expertise but none of whom had the whole-house picture. In this environment, important systems aspects could be overlooked.” (City of Fort Collins, 2002, p106)

- 250 Although the remit of the work at Fort Collins is much broader and less focused on the detail of design and construction than the work at Stamford Brook the similarities in conclusion are uncanny. The task that is before us in the UK and, so it would seem, others elsewhere, is to bring about fundamental change in the way houses (and other buildings for that matter) are built. House building is a manufacturing system, like any other, and if the required change is to take place we need to re-engineer the whole system based on sound systems principles. To return to Kuhn:

“So long as the tools a paradigm supplies continue to prove capable of solving the problems it defines, science moves fastest and penetrates most deeply through confident employment of those tools. The reason is clear. As in manufacture so in science – retooling is an extravagance to be reserved for the occasion that demands it. The significance of crises is the indication they provide that an occasion for retooling has arrived” (Kuhn 1996, p76)

Old tools may have served us reasonably well in a past characterised by undemanding environmental imperatives but in a low and zero carbon future they are redundant and to continue to use them would be foolish indeed. We believe that we have reached a crisis point. As in Science so in construction – it is time for the industry to retool.

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Appendix 1 – Bibliography of Stamford Brook Interim Project Reports

Deliverable 1: St Nicholas Court Final Project Report (April 2003)

This report describes the EPS08 energy standard, its first application on the St Nicholas Court housing development in York, as well as a detailed description and analysis of the design process and costings for the St Nicholas Court project.

LOWE, R.J., BELL, M. & ROBERTS, D. (2003) *Developing Future UK Energy Performance Standards – St Nicholas Court Project Final Report*, Leeds Metropolitan University, Leeds

Available to download at:

http://www.leedsmet.ac.uk/as/cebe/projects/stnicks/pdfs/st_nicks_final_report.pdf

Deliverable 2: Design Process (April 2004)

This report documents the progress of the Stamford Brook project up to spring 2004. This includes the drafting of environmental and energy standards, design team assembly, site layout and dwelling design.

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

Available to download at:

<http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del2design.pdf>

Deliverable 3: Monitoring Plan (April 2004)

This report discusses the original methods proposed to monitor occupied households and the construction process. A wireless monitoring system was eventually used in preference to the equipment described in this report.

ROBERTS, D. (2004) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 3 Monitoring Plan*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

Deliverable 4: Construction Process (July 2005)

This report describes site observations from the early stages of construction at Stamford Brook undertaken during 2004 and early 2005.

ROBERTS, D., ANDERSSON, M., LOWE, R.J., BELL, M. & WINGFIELD, J. (2005) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 4 – Construction Process*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

Available to download at:

<http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del4const.pdf>

Deliverable 5: Post Construction Testing and Envelope Performance (July 2006)

This report details the results of a range of dwelling performance tests carried out on completed dwellings at Stamford Brook. The tests included measurements of airtightness, ventilation system flows and whole house heat loss coefficients. The results are discussed in the context of the performance requirements of the EPS08 standard and also in relation to Approved Documents Part L and Part F of the Building Regulations.

WINGFIELD, J., BELL, M., BELL, J. & LOWE, R.J. (2006) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 5 – Post Construction Testing and Envelope Performance*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

Available to download at:

<http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del5postconst.pdf>

Deliverable 5a: Technical Note – Initial Results of Household Monitoring and Occupant Interviews (June 2006)

This report summarises the results of the first six months of intensive energy monitoring of four households at Stamford Brook. Also described are some of the opinions and initial experiences of the four householders.

WINGFIELD, J., BELL, J., BELL, M. & LOWE, R.J. (2006) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 5a – Technical Note – Initial Results of Household Monitoring and Occupant Interviews*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

Deliverable 6: Airtightness Monitoring, Qualitative Design and Construction Assessments (July 2007)

This report describes the results of detailed construction observations and airtightness tests on nine dwellings at Stamford Brook. A critical analysis of the data is given in relation to the design and construction of airtight dwellings.

MILES-SHENTON, D., WINGFIELD, J. & BELL, M. (2007) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 6 – Airtightness Monitoring, Qualitative Design and Construction Assessments*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

Available to download at:

<http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del6airtight.pdf>

Available to download at:

<http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del6appendices.pdf>

Deliverable 7: Coheating Tests and Investigation of Party Wall Thermal Bypass (May 2007)

This report describes coheating experiments designed to explore the mechanism and magnitude of the thermal bypass via the party wall cavity between semi-detached and terraced dwellings and investigates methods of blocking the bypass.

WINGFIELD, J., BELL, M., MILES-SHENTON, D., LOWE, R.J. & SOUTH, T. (2007) *Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Interim Report Number 7 – Coheating Tests and Investigation of Party Wall Thermal Bypass*, PII Project CI 39/3/663, Leeds Metropolitan University, Leeds

Available to download at:

<http://www.leedsmet.ac.uk/as/cebe/projects/stamford/pdfs/del7coheating.pdf>

Refereed Journal Papers

ROBERTS, D., JOHNSTON, D. & ISLE, J. (2005) *A Novel Approach to Achieving Airtightness in Dry-lined Load-bearing Masonry Dwellings*, Building Services Engineering Research & Technology, Volume 26, Issue 1, pp 63-69

LOWE, R.J., WINGFIELD, J., BELL, M. & BELL, J.M. (2007) *Evidence for Heat Losses via Party Wall Cavities in Masonry Construction*, Building Services Engineering Research & Technology, Volume 28, Part 2, pp 161-181

Appendix 2 – Key Individual Contributors

Leeds Metropolitan University, School of the Built Environment

Professor Malcolm Bell (Professor of Surveying & Sustainable Housing)

Dr Jez Wingfield (Senior Research Fellow)

Dominic Miles-Shenton (Research Fellow)

Tim South (Senior Lecturer)

Jonathan Bell (Research Assistant)

Dr David Roberts (Senior Lecturer)

University College London, Bartlett School of Graduate Studies

Professor Bob Lowe (Professor of Energy & Buildings)

Department for Communities and Local Government

Ted King

AEA Technology

Kate Dapré

Susan Batt-Rawden

Julian Wilczek

Tony Wilson

The National Trust

Catherine Prasad (Project Manager)

Rob Jarman

Steve McGlade

David Houston

Sara Braune

Maria Andersson

Redrow Homes

Paul Brickles (Project Manger)

Allen Bradshaw (Site Project Manager)

Jonathan Moss

John Bennet

John Grime

Bryant/Taylor Wimpey

Mark Mainwaring

Joe Isle

Dave Poole

Dave Finnegan (Site Manager)

Steve Birch (Site Manager)

Allen MacInnes (Project Manager)

Cathy Partington (Project Manager)

Gavin Charlton

Concrete Block Association

Gerry Pettit

NHBC

Neil Smith

Ventaxia

Brian Walton

Paul Davis

Andy Cowell

Mike Massey

Construction Skills

Ben Cartwright

Pilkington

Rick Wilberforce

Appendix 3 – Household Monitoring Test Equipment

Component	Equipment Used	Equipment Specification
Datalogger	Eltek RX250 Receiver Logger	250 channel radio receiver logger Set at 10 minute logging interval
GSM Modem	Wavecom M1206B GSM Modem	1 per logger
Internal Temperature/Humidity Sensor	Eltek GC-10 Temp/RH Radio Transmitter	5 per dwelling in hall, kitchen, living room, master bedroom and bathroom
Heat Meter	Aquametro Amtron E Heat Meter	1 kWh pulse output 1 on CH circuit, 1 on HW circuit (dwellings C and K only)
kWh/Wh Pulse Transmitter	Eltek GS-62 Pulse Radio Transmitter	1 per heat meter
CO ₂ Sensor	Vaisala GMW25 CO ₂ Sensor	1 per dwelling in master bedroom Maximum reading 2000ppm
CO ₂ Sensor Transmitter	Eltek GS-42 Voltage Radio Transmitter	1 per CO ₂ sensor with 24v supply
NO ₂ Sensor	Oldham CTX 300 NO ₂ detector	1 per dwelling in kitchen, fixed below wall mounted cupboards next to hob
NO ₂ Sensor Transmitter	Eltek GS-42 Voltage Radio Transmitter	1 per NO ₂ sensor with 24v supply Range 0.1ppm to 10ppm
Current Clamp	SC 100A Clamp on Current Sensor	1 on electric oven in kitchen (dwellings A and C only)
Current Clamp Transmitter	Eltek GS-42 Voltage Radio Transmitter	1 per current clamp
External Temperature/Humidity Gauge	Rotronic Hydroclip S3 External Temperature/Humidity Sensor	Positioned at 2m on 4m mast Protected by Stephenson Radiation Screen
External Temperature/Humidity Transmitter	Eltek GS-13 Hydroclip Radio Transmitter	Located in weather proof box on mast
Pyranometer	Kipp & Sonnen CM3 Pyranometer	Vertical & horizontal orientations South Facing Positioned at 3m on 4m mast
Pyranometer Transmitter	Eltek GS-42 Voltage Radio Transmitter	Located in weather proof box on mast
Anemometer 1	Schiltknecht Meteo Anemometer/Wind Vane	Positioned at 4m on 4m mast Instantaneous wind speed in m/s
Anemometer 1 Transmitter	Eltek GS-42 Voltage Radio Transmitter	Located in weather proof box on mast
Anemometer 2	Vector Instruments AN1 Anemometer	Positioned at 4m on 4m mast Mean wind speed in m/s over the 10 minute logging period
Anemometer 2 Transmitter	Eltek GS-62 Pulse Radio Transmitter	Located in weather proof box on mast

Appendix 4 – Procedure for Correcting Parametric SAP Calculation for Non-standard Variables

1. Occupancy

Step 1 – Replace the GFA derived value for N in the parametric SAP spreadsheet with the occupancy level given by the householders in their interview.

2. Base Temperature

Step 1 – Run parametric SAP with standard settings to obtain the base temperature.

Step 2 – Using the base temperature from Step 1, identify the start and end of the heating season using the external temperature data from Stamford Brook weather station.

Step 3 – From monitored household database calculate the mean internal temperature for the dwelling during the heating season derived in Step 2.

Step 4 – Replace the derived mean internal temperature in SAP spreadsheet with the value calculated in Step 3.

Step 5 – Note the new base temperature and new heating degree day total.

Step 6 – Read off the heating and hot water energy (kWh) from the SAP spreadsheet to obtain predicted energy consumption.

Step 7 – Add in an estimate for gas energy for cooking (kWh) (Typical usage estimated at ~0.5 kWh/day).

3. Ventilation, Thermal Bridging and Party Wall Bypass

Step 1 – For higher than predicted ventilation rates replace the overall calculated effective ventilation rate in the parametric SAP spreadsheet (h^{-1}) with the measured value.

Step 2 – For higher than predicted thermal bridging add in the additional ΔU value ($\text{W}/\text{m}^2\text{K}$) in the user defined field in the parametric SAP spreadsheet.

Step 3 – To add in a party wall U -Value calculate the total area of party wall (m^2) and multiply by the effective party wall U -Value ($\text{W}/\text{m}^2\text{K}$) to obtain the heat loss coefficient for the party wall (W/K). Add this additional heat loss coefficient to the calculated whole house heat loss coefficient in the parametric SAP spreadsheet.

Appendix 5 – Energy Star Qualified Homes Thermal Bypass Inspection Checklist

(USEPA 2007a)



ENERGY STAR Qualified Homes Thermal Bypass Inspection Checklist

Home Address: _____		City: _____		State: _____	
Thermal Bypass	Inspection Guidelines	Corrections Needed	Builder Verified	Rater Verified	N/A
1. Overall Air Barrier and Thermal Barrier Alignment	Requirements: Insulation shall be installed in full contact with sealed interior and exterior air barrier except for alternate to interior air barrier under item no. 2 (Walls Adjoining Exterior Walls or Unconditioned Spaces)				
	All Climate Zones:				
	1.1 Overall Alignment Throughout Home	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	1.2 Garage Band Joist Air Barrier (at bays adjoining conditioned space)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	1.3 Attic Eave Baffles Where Vents/Leakage Exist	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Only at Climate Zones 4 and Higher:				
	1.4 Slab-edge Insulation (A maximum of 25% of the slab edge may be uninsulated in Climate Zones 4 and 5.)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Best Practices Encouraged, Not Req'd:				
1.5 Air Barrier At All Band Joists (Climate Zones 4 and higher)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1.6 Minimize Thermal Bridging (e.g., QVE framing, SIPs, ICFs)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
2. Walls Adjoining Exterior Walls or Unconditioned Spaces	Requirements: • Fully insulated wall aligned with air barrier at both interior and exterior OR • Alternate for Climate Zones 1 thru 3, sealed exterior air barrier aligned with RESNET Grade 1 insulation fully supported • Continuous top and bottom plates or sealed blocking				
	2.1 Wall Behind Shower/Tub	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.2 Wall Behind Fireplaces	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.3 Insulated Attic Slopes/Walls	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.4 Attic Knee Walls	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.5 Skylight Shaft Walls	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.6 Wall Adjoining Porch Roof	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.7 Staircase Walls	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.8 Double Walls	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3. Floors between Conditioned and Exterior Spaces	Requirements: • Air barrier is installed at any exposed insulation edges • Insulation is installed to maintain permanent contact w/ sub-floor above • Optional until July 1, 2008 , insulation is installed to maintain permanent contact with air barrier below				
	3.1 Insulated Floor Above Garage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	3.2 Cantilevered Floor	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4. Shafts	Requirements: Openings to unconditioned space are fully sealed with solid blocking or flashing and any remaining gaps are sealed with caulk or foam (provide fire-rated collars and caulking where required)				
	4.1 Duct Shaft	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	4.2 Piping Shaft/Penetrations	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	4.3 Flue Shaft	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5. Attic/ Ceiling Interface	Requirements: • All attic penetrations and dropped ceilings include a full interior air barrier aligned with insulation with any gaps fully sealed with caulk, foam or tape • Movable insulation fits snugly in opening and air barrier is fully gasketed				
	5.1 Attic Access Panel (fully gasketed and insulated)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	5.2 Attic Drop-down Stair (fully gasketed and insulated)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	5.3 Dropped Ceiling/Soffit (full air barrier aligned with insulation)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	5.4 Recessed Lighting Fixtures (ICAT labeled and sealed to drywall)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	5.5 Whole-house Fan (insulated cover gasketed to the opening)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6. Common Walls Between Dwelling Units	Requirements: Gap down drywall shaft wall (common wall) and structural framing btwn units is sealed at all exterior boundary conditions				
	6.1 Common Wall Between Dwelling Units	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Rater Inspection Date: _____		Builder Inspection Date: _____			
Home Energy Rating Provider: _____		Builder Company Name: _____			
Home Energy Rater Company Name: _____		Builder Division Name: _____			
Home Energy Rater Signature: _____		Builder Employee Signature: _____			

Appendix 6 – Research Outline for Low and Zero Carbon Housing

(Paper presented to a meeting of the Energy Saving Trust New Build Housing Research Group, June 2007)

Towards Low and Zero Carbon Housing: 2007 – 2016:

The Development of a Research & Monitoring Programme for Practical Learning

Malcolm Bell, Leeds Metropolitan University, June 2007

Introduction

This brief note seeks to set out the types and nature of studies that would support the house building industry in its attempt to acquire the knowledge, expertise and practical know-how that will be required for the routine production of low carbon housing by 2016. The note is limited to the new-build agenda and is based on the assumption that a significant number of development and demonstration schemes will be constructed in both the private and social housing sectors and that these will be subjected to some form of study. One of the key requirements of these schemes is that they are built, as far as possible, within the house-building mainstream.

The following sections identify the range of studies that that should be considered when setting up monitoring arrangements for pilot and demonstration schemes. The sections set out also the main design requirements for each type of study. In many projects it will be necessary to integrate the studies into a single project, with interim deliverables, so as to paint a more comprehensive picture of the demonstration scheme as a whole. Indeed, it is likely that many of the early studies will need to adopt such a comprehensive strategy in order to provide input into the design and construction of the later schemes. This is a point that is picked up later in a discussion of the shape of a research programme over the next 10 years.

Design process studies

This type of study is primarily a qualitative study that seeks to understand the low carbon design process in general and, in particular, the means by which carbon performance is integrated into the design process. It should identify the issues involved and the barriers to the development of acceptable solutions. In many studies it is likely that mistakes will be made in design that will not become apparent until post construction and it would therefore require an open approach and a willingness to accept mistakes on the part of the design team and researchers.

Study design

Studies would need to address the following areas:

- The definition of the carbon standards to be achieved, how they are interpreted and how they are couched.
- The principal reasons for key design decisions. This will normally relate to a number of decision gates at the end of each design phase.

- The make up of the team, the roles and influence of its members and the input by actors external to the main team. In particular the role of the supply chain.
- The development of knowledge and understanding among the design team.
- The modelling tools used to determine the likely carbon performance of the emerging designs. Models are likely to be based around SAP but other tools such as dynamic simulation programs and detailed thermal modelling tools are likely to be relevant.
- Processes of detailed design and the way details are modelled (drawings, calculations etc.) and evaluated against performance criteria.
- Communication within the team and from the design team to the construction team.
- Cost estimating, its role in decision making and influence on design thinking.

The data sources would usually consist of design documentation such as design reports, performance calculations and the final drawings and specifications, together with qualitative interviews and/or workshops designed to elicit reasons for decisions and views on the process and individual roles. If possible studies should involve the research team from the outset, operating in an action research mode, but this may not always be possible and data may have to be gathered through a retrospective review.

Construction studies

The process by which designs are translated into completed dwellings is crucial to achieving robust carbon performance. Existing processes often result in the significant degradation in the performance predicted at the design stage. This is for a variety of reasons not all of which have their roots in construction quality but in design. Many problems relate to the way in which design, particularly at the detailed level, is communicated. It is not uncommon for construction details to be designed on site by operatives and site management as construction proceeds. Studies of construction are likely to have two complementary objectives depending on how the study fits into an overall research project or programme.

These are:

- To understand the processes by which design material is translated into construction, including the approach to quality control and on site performance assessment as construction proceeds, and
- To observe realised construction to provide important contextual material designed to support post construction performance monitoring.

Study design

Process studies would need to address the following areas:

- The design context. Where a construction study is not linked to a detailed study of the design process for the scheme under study, an explicit description

of the design will be necessary so as to provide a reference point for the construction study.

- The make up of the construction management team and the roles within it.
- The contractual relationships, the sub-contractors and their management.
- The development of knowledge and understanding within the whole constructing team from general site management and sub-contractor management to operatives.
- The nature of formal management processes, including materials ordering & stock control, quality control and the role of external inspectors such as building control and NHBC.
- Communication between design and construction in general and, in particular, the information provided, its form and level of detail.
- The nature of cost control processes and their impact on such things as the letting and enforcement of sub-contracts, materials and component ordering decisions and overall project programming.

Construction observation studies would be largely concerned with maintaining a photographic record of construction at key stages. The objective is to provide a visual database that could be interrogated and analysed to help to explain certain observations and anomalies that may be picked up during later performance monitoring work. The key to the success of such studies would be:

- Careful choice of construction stage at which to take photographs.
- Accurate dating and location of the construction depicted in each photograph.
- The maintenance of the data base and effective access arrangements during later analysis.

As in the case of design, studies of the construction phase lend themselves to an action research based approach. This has the advantage of identifying explicitly where observer interaction with the process has taken place and any modification to practice (if any) that has resulted. Any change in construction can be included in the record and used in the interpretation of monitoring results.

As-built studies

As-built studies should be designed to verify, as far as is possible through the measurement of fabric and systems in unoccupied dwellings, the extent to which designed performance is achieved. Where in-use performance monitoring is to be undertaken this type of monitoring provides a very important base line against which to set the results of longer term in-use monitoring.

Studies of the performance of building fabric could take a number of different forms depending on the detailed objectives of the study and the resources available. Studies may involve some of the following techniques:

- Direct measurements of thermal flux through elements and junctions and the derivation of as-built U values and psi values.
- Whole house measurements of heat loss using co-heating test methods
- Whole house measures of airtightness using fan pressurisation
- Whole house measures of ventilation using tracer gas methods
- Thermal imaging, which may be used on its own or in support of other methods so as to assess in a quasi-quantitative/qualitative approach to the identification of heat loss paths and areas.
- Standing losses from services, for example, domestic hot water, heat stores etc.

Studies of as-installed performance of building services would be based mainly on commissioning test results and confirmed commissioned performance. These tests can be carried out following occupation to verify the commissioned settings and initial commissioned performance. In addition to standard commissioning testing, other approaches to verifying performance should be explored, where possible, that make use of diagnostic information built into appliances such as heating boilers and ventilation units. The longer term performance of such things as efficiencies and energy consumption of services would normally be undertaken as part of in-use monitoring.

In all cases studies should include contextual material on the design and construction of the dwellings, including observations of the completed fabric and services.

Intensive energy in-use studies

The purpose of this type of study is to generate as clear a picture as possible of performance in use at a detailed, disaggregated, level. This type of study is able to provide data on the different energy flows (space and water heating, cooking and electricity consumption etc.), the performance of services (efficiencies, air flows/air quality etc.) and internal temperatures as well as overall energy consumption. However, use is extremely variable and it is often very difficult to disentangle the impact of different household structures and use patterns on energy consumption. For this reason such monitoring projects require a particular blend of physical and social science so as to understand what performance may be use related and what relates more directly to the design and construction of the dwellings.

Despite the difficulties, such studies are essential if we are to understand the performance of low energy housing and the likely impact on the way dwellings are used and perceived by occupants. Given the complexities involved, studies should be as comprehensive as possible so as to gain maximum understanding. One of the most important aspects of such studies is a good understanding of the physical and social context of the dwellings in occupation. Without contextual data it becomes almost impossible to make sense of the energy and other monitoring data.

Study design

The precise data monitoring arrangements for each study will depend on the main objectives of the study and the details of the design. However, it is anticipated that studies would include the following:

- A comprehensive description of the physical context setting out the expected performance of the fabric and services. Wherever possible this should consist of data from as-built or as-installed studies as well as design predictions. However the balance between the two will depend on a number of practical and resource factors.
- External environmental contextual factors such as external temperature, wind and solar.
- A comprehensive description of the user context setting out such things as household structure, use patterns (heating, hot water, ventilation etc.) operation of equipment, and ownership of appliances.
- Continuous monitoring of air temperatures in a number of places in the dwelling so as to assess differentials and to provide a good estimate of average temperatures.
- Continuous monitoring of energy flows depending on the level of detail required by the study. However in most studies energy input to space and water heating and lights and appliances should be considered as a minimum.
- Continuous monitoring of services inputs and outputs so as to characterise performance such as efficiency, and effectiveness.
- Almost all low carbon dwellings will need to have high levels of airtightness and ventilation design will become more critical. In most cases it will be necessary to monitor indicators of air quality including, as a minimum, humidity and CO₂.
- Other aspects of use and/or performance such as window opening behaviour, operation of services controls or water consumption may be included depending on the individual requirements of the study.

Extensive energy in-use studies

This type of study should be designed to provide a statistically robust measure of actual energy consumption within a particular development or a number of developments designed to achieve the same performance standard. Unlike intensive studies, this type of approach concentrates on gathering a small amount of data from a large number of dwellings and its value lies in being able to determine just what level of energy performance is being achieved across a particular cohort. Results from such studies would have considerable benefit in providing timely feedback on energy performance and highlighting areas of underperformance (or, indeed, over-performance) that should be investigated in detail.

Study design

The key issues in study design will be:

- The nature of the cohort/population to be characterised. To a large extent this will hinge on the extent to which the population is to be split into sub-groups such as construction type and region.
- The practicalities of achieving randomisation and its influence on the number of dwellings from which to collect data.
- The source of data and negotiating access to it. This category will include methods of contacting and obtaining the cooperation of households and/or the ability to obtain and work with utility data, cross referenced with other sources such as building regulation approval data.
- Ethical considerations in relation to the use of personal data, obtaining approvals and the safeguarding of anonymity.

Data exchange/data archiving

A comprehensive research programme is likely to produce a lot of data and it will be important to ensure that the different data sets from specific studies are capable of being compared so as to build up as comprehensive picture as possible. This means that questions of data archiving and data exchange need to be addressed at the beginning of any national programme rather than waiting until data has been collected. The issues of compatibility of data formats storage and access arrangements will all need to be discussed at an early stage and resource provided to enable standards to be established which can be used by all studies.

The shape of a 10-Year programme

Given that the overriding objective of a new build research programme is to enable the industry to learn how to produce low carbon housing in a robust and reliable way, the early phases of any programme should be biased towards intensive studies of processes and detailed performance studies that have a considerable explanatory power. Such work would have to be designed so that results can be disseminated in a phased way, as they are obtained and analysed, rather than waiting for the end of what can be quite long projects. As the programme matures and as regulations change, more extensive studies of impact and general performance will be necessary so as to measure overall progress within the industry at large.

Concluding remarks

This note is tentative and designed to stimulate a discussion about how we focus the new-build research effort. However it is clear that all types of study will be required and that they will need to be used in different combinations. It is clear also that the programme must be focused on what is done and achieved on site and in use, with the backup that can be provided by laboratory studies designed to tackle particular problems of detail derived from the site based work. Of course, if such a focus is to be maintained, the programme will require a supply of real test-bed schemes provided by the house building industry. Achieving the cooperation of industry at all levels and across all its sectors will be vital and this, in turn, will require a strong coalition of government, industry and the research community.

The other issue that needs to be stressed is the ability of the programme to engage in the development of skills and cultures at all levels within the industry. The studies should be linked directly to clear education and training programmes so that the lessons learned are fed back quickly and effectively.