EVALUATING THE IMPACT OF AN ENHANCED ENERGY PERFORMANCE STANDARD ON LOAD-BEARING MASONRY DOMESTIC CONSTRUCTION

Partners in Innovation Project: CI 39/3/663

Report Number 8 – Final Report - Executive Summary

Lessons from Stamford Brook

Understanding the Gap between Designed and Real Performance

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Executive Summary

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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 has 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.

The 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.

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 DTI (now BERR) and DETR (now CLG), 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 thermal envelope performance 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 AR 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/m^{2}K, 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 AR 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 7 years) and the difficulties of keeping the whole project team together over this period. However, we acknowledge that there was limited previous experience of AR within the research team and that in future projects a greater emphasis will needed on the AR 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 6 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 $m^3/(h.m^2)$ @ 50Pa which is below the target of 5 $m^3/(h.m^2)$ @ 50Pa 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 $m^3/(h.m^2)$ represents a remarkable improvement on existing UK practice as represented by the mean of 9.2 $m^3/(h.m^2)$ @ 50Pa 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 tests[1] were carried out on six attached dwellings at Stamford Brook. The results of these tests showed that the measured whole house heat loss 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 W/m^2K to 0.6 W/m^2K. This is more than twice the notional *U*-value of the external wall (0.23 W/m^2K) and around three times

[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).

the notional *U*-values of the floor (0.17 W/m^{2}K) and ceiling (0.14 W/m^{2}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 W/m^{2}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. 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 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 constructions 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.

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[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 W/m^{2}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 W/m^{2}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.

Implications for New Housing Development

21. As we move towards low and zero carbon housing standards, many, 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** - 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 has been the case at Stamford Brook, then, in all probability, discrepancies would have been simply 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. All of these issues will become of increasing importance as the industry moves towards higher and higher energy and carbon performance standards. 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. As energy performance targets approach levels of Passive House and Zero Carbon standards, even small inadequacies in the construction process can result in significant levels of under performance in terms of carbon emissions and energy efficiency. There is now therefore an imperative for the UK housing industry to rethink the whole construction process and to 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 W/m^{2}K for opaque elements, air permeability somewhere around 1 m^3/(h.m^2) @ 50Pa and thermal bridge free construction. With air permeabilities at 1 m^3/(h.m^2) @ 50Pa, 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 m^3/(h.m^2) @ 50Pa) 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. 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 the use of appropriate modelling tools.

- ***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 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. 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, 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. 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. 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.

h) **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 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. 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.

i) **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, 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. 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. The need for a change in the way that the UK housing industry approaches issues of control, process improvement and performance measurement is therefore critical if it is to realise the exacting carbon reduction targets set by government. Performance control systems for UK house construction need to seek 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 other companies in the supply chain. It is encouraging that informal discussions with the developer partners on this project and elsewhere suggest that the need for process change along the lines indicated is beginning to be acknowledged within the industry. 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.

j) **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.

k) **Performance Monitoring Protocols & 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.

l) **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.

m) **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.

22. 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.

23. 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.