
Developing future energy performance standards for UK housing: The St Nicholas Court project – Part 1

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Abstract

This paper (and Part 2, to appear in the next issue) set out the results of a housing field trial designed to evaluate the impact of an enhanced energy performance standard for dwellings. The project was designed to inform the next review of Part L of the Building Regulations for England and Wales, which, following the publication of the UK government's white paper on energy policy, is expected in 2005. The project explores the implications of an enhanced standard in the context of timber frame construction. Although for programming reasons it was necessary to terminate the research project at the end of the design phase, the results suggest that the standard investigated is well within the capacity of the industry but it was clear that the whole supply chain will need to take a positive approach to the development of new solutions. The secret to a smooth and cost optimised transition is for the necessary development work to begin immediately, not when regulation changes.

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Introduction

The seeds of this project were contained in a report commissioned by the Joseph Rowntree Foundation at the start of the review of Part L in 1998 (Lowe and Bell, 1998)[1]. In this report the authors argued for the 1998 review to set out a programme of improvements that looked at least ten years ahead with firm proposals for 2000 and an outline standard for 2005 that could be subjected to field testing during the intervening quinquennium[2]. The St Nicholas Court Project was set up to carry out such a field trial with particular reference to the design, construction and performance of timber framed dwellings. A companion project involving masonry housing (Lowe and Bell, 2002) is currently underway involving the construction, by commercial developers, of some 600 dwellings on a site in the Northwest of England. The energy performance standard adopted for both studies (EPS08[3] – Lowe and Bell, 2001) is modelled on proposals made by Lowe and Bell (1998) together with those set out by the DETR[4] in June 2000 for a possible review in the second half of the present decade (DETR, 2000). The overall goal of the project was, therefore, to support such a review through an enhanced body of qualitative and quantitative evidence on options and impacts.

The St Nicholas Court Development involved the design and construction of a group of 18 low energy and affordable semi-detached two and three bedroom dwellings for the York Housing Association on a brown field site in York as part of a larger speculative housing development (see site plan, Figure 1)[5]. The research project was

This field trial was supported financially by the Joseph Rowntree Foundation, by the DTI (previously DETR) Partners in Innovation Programme and the Housing Corporation. The project was hosted by the York Housing Association and received support in kind from Wates Construction Limited, Constructive Individuals, Baxi Heating Ltd, City of York Council Department of Building Control, NHBC and CITB. The support of the staff in these organisations is gratefully acknowledged. In particular we would pay tribute to the dedication and professionalism of the project team; without them there would have been no project. The views expressed in this paper are, however, those of the authors who take full responsibility for the paper and any errors or omissions that may exist.

Figure 1 Layout of houses at St Nicholas Court (original scheme layout)



established in two stages. Initial funding was provided by the Joseph Rowntree Foundation in the spring of 1999. This ensured the involvement of the research team from the outset of the development process. Additional funding was provided from late 2000 by the Housing Corporation and by the DETR through the Partners in Innovation programme, responsibility for which now lies with the Department of Trade and Industry (DTI).

The project implementation plan defined the aims of the project as follows:

... to make it possible for both DETR and the house-building industry to consider a wider range of options in a possible 2005 review of Parts L, F and J of the Building Regulations, as they affect dwellings. To this end, the project seeks to:

- comprehensively evaluate the impact of enhanced energy performance standards designed for possible incorporation into a 2005 amendment to the Building

Regulations, in the context of a development of [approximately] 20 houses to be built for York Housing Association by Wates Construction Ltd; and to

- communicate and disseminate the results of this evaluation effectively to all stakeholders.

The enhanced performance standards referred to here have been designed to achieve significant reductions in CO₂ emissions from new dwellings compared with dwellings built to current regulations [ADL95]. The project will explore impacts and experiences arising from the application of the improved standards, on all participants in the procurement process, including client, architect, contractor, site workforce and building control officers. These impacts and experiences will be evaluated together with costs and performance of the dwellings in-use. (Lowe and Bell, 2000a)

The research project was originally divided into five phases

- (1) project definition;
- (2) design;
- (3) construction;
- (4) occupation; and
- (5) communication and dissemination.

Delays in site acquisition initially allowed the design phase to be extended, but ultimately forced the abandonment of the construction and occupation phases, and the scaling down of the communication and dissemination phase. Despite the delays, the development itself is now expected to go ahead, with construction starting in mid-2003. Sadly, it has not been possible to resume the research project. However many of the lessons learned are informing Government thinking and are contributing to the companion masonry project [6] which is expected to begin construction towards the end of 2003.

The purpose of this paper is to summarise the results from the design phase of the St Nicholas Court project and to discuss their implications for regulators, housing developers and the house building industry in general. Detailed results and discussion are contained in the final project report, Lowe *et al.* (2003).

The partnership

The design and development of the project was based on a partnering approach that included all key players in the development process. Table I sets out the organisations who made a direct contribution throughout

the design phase. Plans were also in place to expand the team, as construction got underway, to include all sub contractors.

Summary of the Energy Performance Standard (EPS08)

The St Nicholas Court Project was conceived from the outset as revolving round a clearly defined energy performance standard, used in place of the then-current version of Part L (Approved Document L, 1995 - ADL95 - DoE and Welsh Office, 1995). The first version of the “Energy and Ventilation Performance Standard”, written in 1999, was based on an expansion and revision of the proposals for 2005 contained in Lowe and Bell (1998). The opportunity was taken to review the elemental U values that had been proposed in 1998, to provide a much clearer indication of the relationship between three compliance modes – elemental, target or mean U value and carbon index and to define, more precisely and procedurally in terms of the raft of British, European and International standards that had, by then, emerged, what was meant by U value. The opportunity was also taken to begin to explore approaches for integrating other developments – such as the British Fenestration Rating Council (BFRC) window energy rating system – into the standard, and to outline a possible format for the ventilation provisions of Part F in order to ensure compatibility with the proposals for Part L.

The elemental requirements of EPS08 are presented in Table II. The U values in Table II are defined as whole element values. They include contributions to total heat loss from all linear thermal bridges. U values calculated on this basis are more difficult to achieve than those calculated according to procedures laid out in the current Part L Approved

Table I The design team

Organisation	Role
York Housing Association	Client
Constructive Individuals	Architect
RWS Partnership	Quantity surveyor
Wates Construction Ltd	Partnering contractor
Oregon Timber	Timber frame supplier
Baxi Air Management	Heating and ventilation supplier
LEDA	Planning supervisor (Health and Safety)
York Building Control	Building control authority

Table II EPS08 elemental performance requirements

Exposed walls	0.25W/m ² K
Roofs	0.16W/m ² K
Floors	0.22W/m ² K
Windows, outer doors and rooflights (no more than 25 per cent of gross floor area)	1.3 W/m ² K (or window energy rating > 70)
Air permeability at 50Pa	5m/h
Maximum carbon intensity for space and water heating	70kg/GJ

Document. Crudely, a wall with a U value of 0.25W/m²K calculated according to EPS08 requires 10-15 per cent more thermal insulation than one calculated according to ADL02. The precise amount depends on the care taken to reduce thermal bridging, both within the wall, and at junctions between it and other elements of the building thermal envelope.

Research methodology

The research project was conducted using an action research approach. The appeal of action research stemmed, to paraphrase Greenwood *et al.* (1993), from the fact that it:

- addresses real-life problems;
- is change-oriented;
- emphasises a participatory approach in which participants and researchers generate knowledge and understanding through collaborative processes in which all participant's contributions are valued;
- 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;
- does not insist on classical experimental methods as the only way of establishing truth, particularly in the social domain;
- maintains the validity of meanings negotiated by free agents in the course of undertaking and reflecting on a shared task.

This approach worked well with the partnering approach to design and construction, which was laid down as a requirement, from the outset, in York Housing Association's Innovations Brief (Gilham, 1999). This, in turn, drew on the Egan Report, *Rethinking Construction* (Construction Industry Task Force, 1998).

The key features of the research process were:

- the acceptance by all partners of the performance standard EPS08, which defined the performance target to which the dwellings and their sub-systems were ultimately designed.
- reflection on and evaluation of the design process and the performance standard throughout the design process and through a series of group and individual interviews conducted by the research team.

The research team participated throughout the design process and were considered to be an integral part of the design team. They provided technical support through a series of formal and informal meetings, workshops, demonstrations, e-mail exchanges and working papers. The data set consisted of formal minutes of design and project team meetings, minutes and notes of informal meetings, relevant correspondence, research notes and material such as flip charts sheets produced during meetings and a series of open-ended interviews with individual team members conducted towards the end of the design process in October and November 2000. All formal minutes, interview transcripts and, wherever possible, informal notes were circulated to support the processes of individual and collective reflection. In many cases, meetings were tape-recorded and, in a small number of cases, video recorded to provide additional material for subsequent reflection.

The design process

York Housing Association's decision to adopt the partnering approach was perhaps the most important determinant of the design process. As a result of this decision, up-stream suppliers – in particular Oregon and Baxi – were involved from the start of the design process. Within the design team, the primary role of the architect was as an information broker. Within this structure, the prototype standard provided a very clear focus for the design process and was used, in place of ADL95, to assess emerging design solutions. The research team acted partly as the guardian of the standard and partly as a facilitator of training and provider of technical support. The atmosphere within the design

team was characterised by open debate and a positive attitude to the achievement of the standard. This atmosphere was the result of clarity of purpose, reinforced by the client, and the partnering approach.

Early design discussions focused on conceptual reorientation as the design team grappled with the changes required by the new standard. Thermal bridging, airtightness and the need for a whole house ventilation system were key areas to be addressed. Initial attempts at solutions for the dwelling envelope tended to seek the achievement of the required U values using conventional approaches that did not take account of thermal bridging and with little appreciation of the implications for airtightness. This was to be expected and these early attempts provided an essential starting point for raising awareness of the practical significance of these issues. The conceptual principles involved were grasped very quickly - in the case of the wall design bridging through the studs and at openings and junctions was illustrated at a single meeting, leading to a rapid redesign (from a conventional frame using 189×38 mm studs to an externally insulated frame using standard 89×38 mm studs). The resulting solution remained largely unchanged through subsequent design iterations. Airtightness was addressed in a general way by raising awareness of the importance of continuity of the primary air barrier, and of the need to minimise service penetrations. Practical impacts of this on the design included the choice of roof construction, the decision to use a combi-boiler, the incorporation of a polythene vapour barrier in the wall construction and the provision of a service-space between it and the plasterboard.

Considerable effort was centred on the design of the roof. Initially, a low pitch, trussed rafter roof with insulation at ceiling level was designed. This was challenged both by the research team and ventilation designer/supplier and an I-beam warm roof was proposed. Despite an acceptance that such a solution was technically superior and provided an opportunity for additional living space, it was rejected on cost grounds. Considerable effort was then put into making the trussed rafter solution work, a process that promised to produce some complicated details. The delay in the project programme coupled with the client's desire to realise the

benefits of additional habitable volume resulted in a review of this decision and the adoption of the warm roof design.

The issue of the roof design illustrates the problems that are likely to arise when standards begin to push the boundaries of conventional technology. Although the trussed rafter solution could be made to work, it is likely that improved performance standards will progressively erode the advantages of this form of construction. We would expect the technical and environmental merits of Ibeam construction coupled with evidence of falling costs to make this an increasingly common choice for timber frame construction.

The proposed airtightness standard requires the design of a whole house ventilation system. Early hopes that the levels of insulation envisaged by EPS08 would enable heating and ventilation systems to be combined, proved infeasible and separate systems were designed.

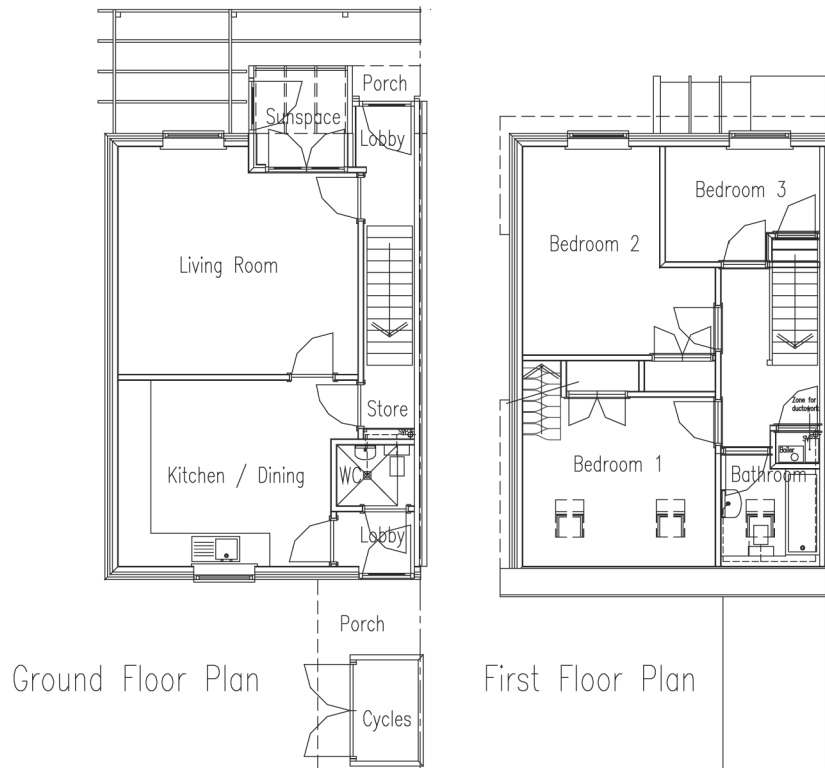
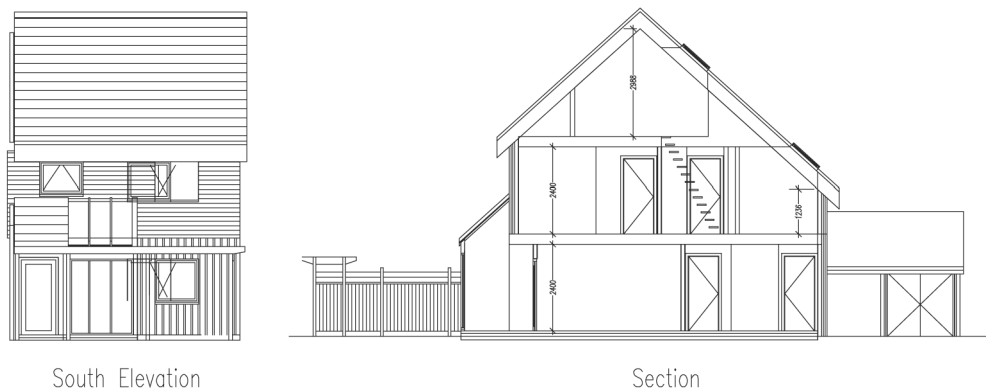
The proposed requirements for the comprehensive treatment of thermal bridging require efficient mechanisms for accounting for thermal bridges. In this project the calculations were done by the research team and the resulting values provided to the design team through a modified SAP[7] spreadsheet. This was designed to simulate an approach based on a catalogue of pre-calculated values or on certified values provided by suppliers for standard construction details. This approach demonstrated considerable promise with the architect reporting that the modified SAP spreadsheet was easy to use. However any system that relied on designers to use thermal modelling software to calculate their own values, is unlikely to meet with widespread success.

The design solution

The design solution is illustrated in the plans and section for the three bedroom, five person house type shown in Figures 2 and 3. An analysis of the design indicates that it will meet and, in some respects, exceed the requirements of the EPS08 performance standard.

Wall construction

The construction of the proposed St Nicholas Court dwellings is shown in Figure 4. The

Figure 2 Floor plans – three bedroom five person house type**Figure 3** Elevation and section – three bedroom five person house type

most obvious change is to the wall construction, which is to consist of conventional 89mm studwork clad externally with 40mm of rigid polyurethane insulation. This construction:

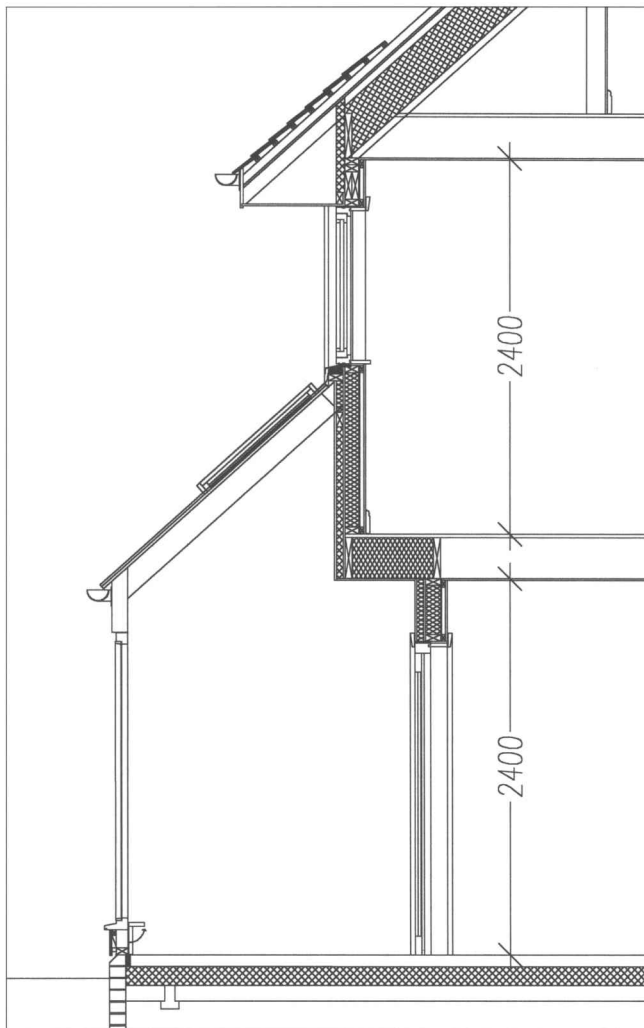
- significantly reduces thermal bridging through studwork and at junctions;
- makes the overall thermal performance less sensitive to detailed design of the timber frame; and
- achieves the required whole wall U value of approximately $0.25\text{W/m}^2\text{K}$.

An alternative construction using timber I-beams in place of conventional studwork was considered, but was rejected mainly on

grounds of cost[8], practicality and lack of familiarity on the part of the timber frame supplier.

Roof construction

Two roof constructions were developed for the scheme – a cold roof variant using a conventional timber truss structure and a warm roof variant using an I-beam structure with 200mm of insulant (mineral or cellulose fibre). The costing exercise also explored the option of a warm roof design using conventional 150mm rafters, over-clad with approximately 50mm of rigid insulation

Figure 4 Construction section – three bed five person house type

board. This option was estimated to be more expensive than the I-beam option.

Ground floor construction

The U value requirement for the ground floor was to be met through a modest increase in insulation thickness coupled with improved edge detailing. The method chosen was a beam-and-block construction, insulated with approximately 60mm of polyurethane insulation. Incremental reductions in ground floor U value can be achieved, without qualitative changes in construction, by increasing the thickness of the insulation board.

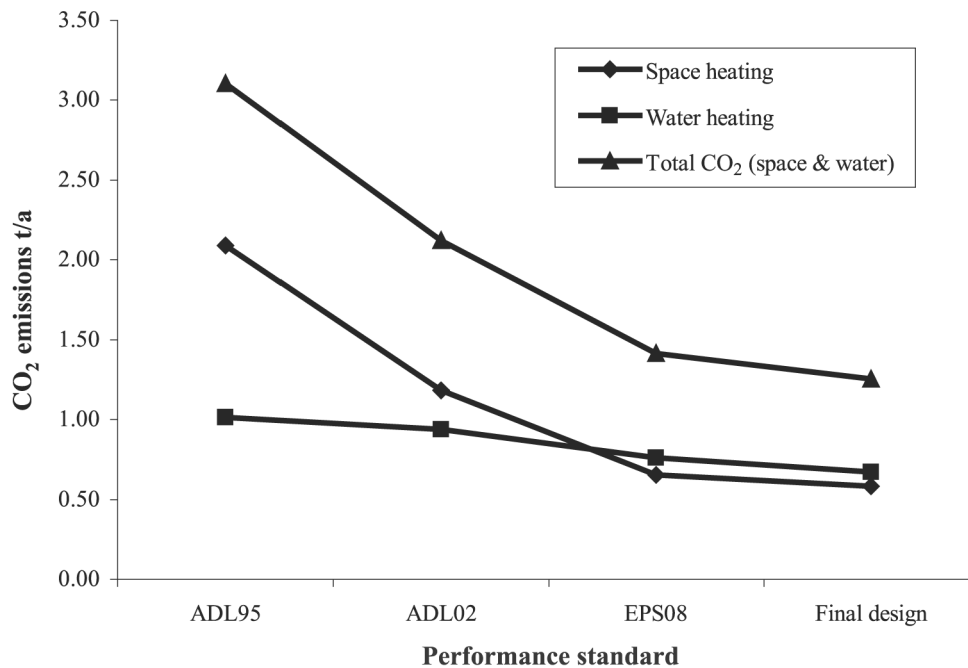
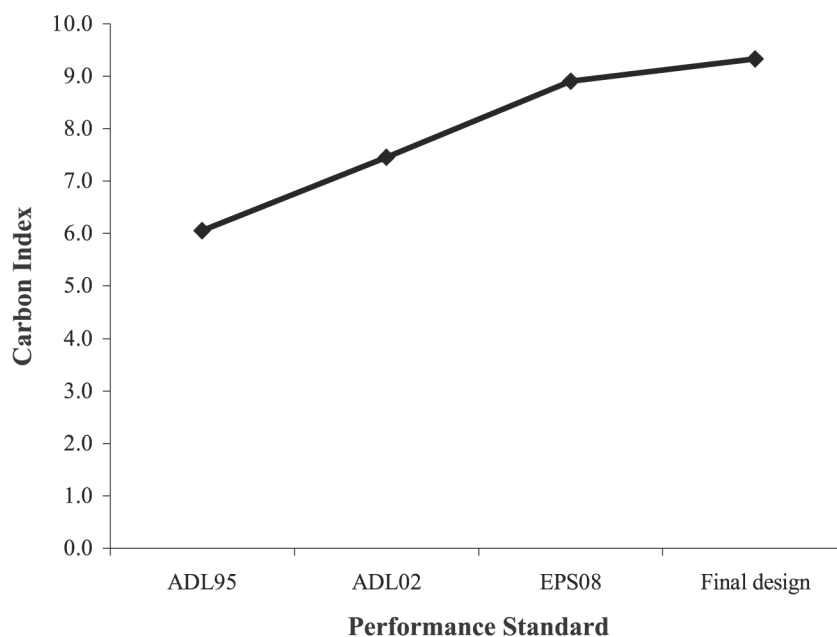
Windows

Windows are to be double glazed in softwood timber frames from a UK supplier. Sealed units are to incorporate a high performance low emissivity coating and argon filled gas space. Currently it is not intended to use

insulating glazing spacers. The resulting window U value is estimated to be in excess of $1.6\text{W/m}^2\text{K}$ – failing to meet the elemental requirement of EPS08 and falling just outside the acceptable range for trade-off. Clearly, further design iterations will need to be carried out with the manufacturer to seek to achieve the required values. Work with a second, European manufacturer, undertaken as part of the companion Brookside Farm project (Lowe and Bell, 2002), has led to the development of a specification for a double glazed window in a softwood timber frame which does achieve the elemental target U value of $1.3\text{W/m}^2\text{K}$. The key differences between this window specification and that envisaged for the St Nicholas Court dwellings was the inclusion of insulated edge spacers in the glazing unit and the adoption of a lower timber frame profile giving a lower frame U value. The absence of certified window performance data made it significantly more difficult for the design team to confirm window performance claims and generally impeded the process of window selection.

Impacts on performance

The primary impact of EPS08 is to reduce energy use and CO_2 emissions for space heating from new dwellings. The predicted impact of the elemental performance requirements on CO_2 emissions and carbon index for the three bedroom five person semi-detached house type (floor area 98m^2) is shown in Figures 5 and 6. The predicted reduction attributable to space heating is of the order of 50 per cent compared with ADL02 and around 70 per cent compared with ADL95. Overall reductions in carbon emissions for space and water heating and ventilation amount to some 40 per cent against ADL02 and just under 55 per cent against ADL95. Total CO_2 emissions (1.58 tonnes – including an estimate for emissions attributable to lights and appliances) are within sight of the psychologically significant one tonne mark, raising the rather appealing prospect of the development of a “one tonne house”. The carbon index (Figure 6) for this dwelling rises from 6.06 to 8.91. Figures 5 and 6 also demonstrate a slight improvement over EPS08 from the final design with total emissions, including lights and appliances, of 1.41 t/a and a carbon index of 9.33. This

Figure 5 Comparisons of carbon emissions for the three bedroom, five person house type (floor area 98m²)**Figure 6** Comparison of carbon index for the three bedroom, five person house type (floor area 98m²)

illustrates the rather obvious expectation that if the standard represents a minimum hurdle some dwellings will clear it by a significant margin. Given the rigorous application of a revised Part L, coupled with the constraints imposed by real-world design and specification one would expect most designs to exceed the standard.

There are reasons for believing that this picture is conservative. The most important of these is that, in our view, ADL02 is likely to lead to a wider range of performance than

EPS08. This is due to the fact that, unlike EPS08, ADL02 does not explicitly allow for structural and geometric thermal bridges nor does it require the airtightness requirement to be verified through testing. This is likely to mean that average energy consumption and CO₂ emissions from dwellings built to ADL02 will be significantly higher than indicated in Figures 4 and 5. However, given the fact that, at the time of writing, very few dwellings have been built to ADL02, statistically reliable data on the impacts on

energy use and other parameters is not available and this makes it difficult to be certain on this point.

The impact of EPS08 on gas consumption is important, given that UK domestic gas production has now peaked and most, if not all, UK natural gas will need to be imported within 20 years (Cheshire, 2001). EPS08 reduces gas consumption by approximately 33 per cent compared with ADL02 and by approximately 54 per cent compared with ADL95.

The main impact of EPS08 is on space heating, although improved boiler efficiency and an assumed reduction in losses from hot water distribution and storage also lead to a reduction in water heating. In two-storey houses built to EPS08, space heating is likely to use less energy than water heating. In compact dwelling types (for example flats) water heating may exceed space heating by a factor of 5 or more.

Related to the declining importance of space heating are the reduction in the length of the heating season and the increase in the temperature that is likely to be achieved in unheated dwellings. The balance temperature of houses built to EPS08 will be in the region of 10°C, giving a heating season length of approximately six months. The “free temperature rise” in such houses will be around 9°C, sufficient to maintain a heating season mean internal temperature of around 15°C and of perhaps 12°C even in January[9]. While we have not reached a point where space heating is unnecessary in conventional dwellings, it is clear that very modest inputs of space heat will be enough to eliminate the physical effects associated with fuel poverty[10]. Minimum temperatures in compact dwelling types such as flats may be as much as four degrees higher still.

A reduced demand for space heating in principle reduces the rating of space heating systems and allows their geometry to be simplified. Radiators can be smaller and fewer and can be positioned with more flexibility. In practice, given the paucity of data on the performance of heating systems in highly insulated dwellings, design teams tend to be reluctant to omit radiators. However, the St Nicholas Court design team and the client were able to agree to a reduction in the number of radiators in dwellings with heat recovery ventilation (MVHR).

Costs and cost effectiveness

The overall picture of impacts of EPS08 on costs is complex and indeed was the final aspect of the project to be fully understood. In the three bed five person dwelling (warm roof design), the change in standard from 1995 to 2002 adds just over £1,470 to cost. The step from 2002 to EPS08 adds a further sum, either £1,130 or £1,900[11] depending on whether the cost of the internal service-space is taken into account[12]. In percentage terms, the 2002 standard adds some 2.6 per cent to construction cost. EPS08 adds a further 1.9 per cent if the cost of the service space is not counted, rising to 3.3 per cent if it is.

Annual energy cost savings of just under £70 were calculated for the shift from 1995 to 2002 and a further £50 from 2002 to EPS08. If the value of the carbon saved is added, the figures increase to £93 and £67 respectively. Simple pay back times (based on energy cost savings) are:

- 1995 → 2002: 22 years
- 2002 → EPS08: 23 years (excluding cost of services space) to 39 years

Although these payback times are relatively long compared, for example, with the payback rates expected in manufacturing industry, they straddle the range of payback times (25 to 30 years) expected in similar social housing developments.

The discount rate currently recommended for long-term investment in such areas as building regulations is 3 per cent (HM Treasury, 2002). The economic benefit of moving to EPS08 from ADL02, expressed as an average annual equivalent saving over a 60 year life, and including the value of carbon saved[13], ranges from +£26 to -£2, depending on whether the cost of the service space is included or not. The corresponding internal rate of return, including the shadow price of carbon, is between 2.9 per cent and 6.0 per cent. A rate that can be compared with the 3 per cent test discount rate proposed in the latest edition of the Treasury Green Book (HM Treasury, 2002). The tentative conclusion that can be drawn is that, at current energy prices and median estimates of the shadow cost of carbon emissions, EPS08 is likely to represent a cost effective approach.

Although we were able to arrive at reasonable cost estimates we were acutely aware of a number of issues relating to what

are inherent uncertainties in costs and the way they are developed during the design stage.

Three key issues emerged:

- (1) Costs are largely design rather than standard dependent – put another way, cost is, almost self evidently, sensitive to design choices. In fact one can never be sure that the cheapest options have been arrived at since there may always be a more cost effective solution that has not been thought of. The standard merely acts as spur to the development of other solutions. Indeed there are situations where the standard can force design choices that reduce costs. In any case the cost estimates for meeting EPS08 at St Nicholas Court suggest that the standard is not so challenging that the additional costs became a dominant feature of the predicted overall cost.
- (2) In all cases where cost iterations beyond what would be normal practice for a small housing scheme were undertaken, cost estimates have fallen – the harder we looked, the smaller they got. Although it is yet to be formally documented, this effect appears even more clearly in the companion Brookside Farm Project (Lowe and Bell, 2002) where initial estimates of over-cost have consistently fallen as review cycles have proceeded and quantity surveyors have become more familiar with the changes in construction and removed uncertainties associated with the sourcing of new materials and components.
- (3) Industry procedures for producing budget costs in the context of novel projects appear likely to overestimate costs of improved standards: cost differences in individual elements are small; construction details and building services systems are often not fully resolved until designs move to site[14]; up-stream suppliers on whom cost estimates are based, are often unsure of their own costs for supplying to currently non-standard specifications; and, finally, potentially beneficial synergisms between individual measures are unlikely to be captured without multiple iterations, an open book partnership approach and significantly higher overall costs in the design phase.

These conclusions relate to a series of more general observations. Network effects and

economies of scale are major determinants of costs and cost dynamics within the construction industry over the long run.

These effects, which in principle operate at all levels in the procurement process, could be seen at work in the St Nicholas Court Project[15]. Formally, the construction industry consists of a series of sub-systems. Uncertainties about costs associated with new performance standards are present within each of these sub-systems. Complete information about cost is rarely passed across boundaries between sub-systems. Loss of information at sub-system boundaries involves replacing relatively complex internal cost models with simplified models or constants. Coupled with this loss of information, where costs are for non-standard specifications, costing becomes defensive to ensure that downside risks are low[16]. The ability of such a process to accurately reflect the marginal changes involved in a change in energy standard is weak.

The implication of the above discussion is that predictions of the costs of implementing improved performance standards nationwide, in advance of such a change, are likely to be systematically over-estimated by conventional costing approaches. This tendency to over-estimate in the face of uncertainty is understandable but unless it is allowed for, at strategic and policy making levels, it is likely to inhibit the development of both energy performance standards and the technology required to support them. The St Nicholas Court Project has enabled us to observe shifts in cost estimates consistent with this picture. For example, the over-cost for an I-beam warm roof fell from an initial value of approximately £2,000 per dwelling to something close to zero as the design was firmed up and more definitive cost estimates were obtained. Our current view is that it is likely that costs associated with the EPS08 standard will continue to fall.

It is necessary to utter a final word of caution on costs and cost effectiveness. The project was not able to cover the construction phase of the St Nicholas Court development, or the performance of the dwellings in use. While we hope that projects currently in the pipeline will shed light on the measured cost and performance of dwellings constructed to EPS08, our conclusions must at this stage remain tentative.

In Part 2 of this paper (see next issue) further conclusions arising from this project are drawn including the impacts of EPS08 on construction technology, the design process, training, and professional development. The implications for regulation and the direction of future work by the research team will also be considered.

Notes

- 1 Material from this report was also published as part of a series of journal articles in *Structural Survey*, see Bell and Lowe (2000), Lowe and Bell (2000b) and Bell and Lowe (2001)
- 2 The review eventually resulted in the current 2002 Approved Documents L1 and L2.
- 3 Throughout the project the standard has been continually refined and clarified and the latest version is referenced here. In addition, the expected implementation programme for a part L review changed early in the course of the project from 2005 to 2008 but has recently reverted to 2005 following the publication of the UK Government's white paper on energy policy (DTI, 2003).
- 4 Department of the Environment, Transport and the Regions. Following UK Government reorganisation the this department no longer exists. The building regulation function now resides with the Office of the Deputy Prime Minister (ODPM).
- 5 Initial plans for the development were for some 24 dwellings, but following negotiations with the commercial developers the number was reduced to 18.
- 6 Lowe and Bell (2002) – Partners In Innovation Contract CI 39/3/663
- 7 The UK Government's Standard Assessment Procedure for the energy rating of dwellings (BRECSU, 2001)
- 8 The question of cost was an interesting one. The initial proposals from the partnering contractor acknowledged the technical superiority of a timber I-beam solution but put the additional cost at over £3,000 per dwelling. This was very influential in the decision to use a more conventional design. Costing work on I-beams carried out for the roof design some three years later suggested that this cost is likely to be much lower but the wall design is unlikely to be revisited.
- 9 Older readers will remember a time, not so long ago, when the heating season average temperature in Scottish houses was reported to be around 13°C.
- 10 The difference between air and surface temperatures in these dwellings will be tiny, essentially eliminating surface condensation and improving comfort conditions.
- 11 For an alternative design that adopted a cold roof the range was from £960 to £1,600.
- 12 It is not clear that the whole cost of the services space should be set against the airtightness standard. As well as reducing the risk of air leakage through service penetrations of the air barrier the services space was provided in the final design to

enable flexibility of services routing. It could be argued that this space is a matter of good design rather than compliance with any given airtightness standard.

- 13 The cost of carbon (£93.84/te(C)/a) was derived from the recommendations of Clarkson and Deyes (2002) published by the UK Treasury. A more detailed discussion is contained in the final project report (Lowe *et al.*, 2003)
- 14 Our more experienced and care-worn readers may accuse us of unjustified optimism at this point.
- 15 One of the best analyses of the impact of network effects on innovation may be found in de Almeida's (1998) study of the French market in electric motors.
- 16 It is, of course, prudent to seek a fail-safe cost direction and at budget and design stages a QS will seek to maintain an amount of "bunce" to cover unforeseen contingencies. In general, the larger the uncertainty the larger one would expect the "bunce" to be.

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