MEASURING THE FABRIC PERFORMANCE OF UK DWELLINGS

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An airtight and well insulated thermal envelope is crucial for the development of low energy and low carbon housing. Although this is widely recognized, there is mounting evidence, in housing at least, that the U-values achieved in practice can be much higher than those calculated, and that the gap between the predicted and the actual measured thermal performance of the building envelope can be substantial. This paper describes an approach that can be used in the field to measure the fabric performance of dwellings, a co-heating test. The paper also presents the results from 15 co-heating tests that were undertaken on dwellings that were built to conform to or exceed the insulation requirements contained within Approved Document Part L1A 2006.Whilst the total number of dwellings reported here is small, the results suggest that a significant gap can exist between the predicted steady state heat loss and the measured heat loss, and that this gap can be as much as 125%. This is likely to have significant implications in terms of the energy use and CO_2 emissions attributable to these dwellings in-use.

Keywords: co-heating, CO_2 emissions, fabric performance, low carbon housing.

INTRODUCTION

In the UK, as in most industrialized countries, the domestic sector contributes substantially to national energy use and CO_2 emissions. Currently, there are over 25 million dwellings in the UK accounting for just under 30% of the UK's total CO_2 emissions (Department for Environment, Food and Rural Affairs 2008). This is a substantial figure given that the UK housing stock is categorized by long physical lifetimes and slow stock turnover. Therefore, if we are to mitigate the effects of climate change and achieve the Government's target of an 80% reduction in national CO_2 emissions by 2050 based on 1990 levels, then significant reductions in the carbon emissions from dwellings will be required.

One factor that can have a significant impact on the energy use and CO_2 emissions attributable to new dwellings is the performance of the building fabric. In the UK, it is a regulatory requirement that the building fabric is modelled using SAP during the design process. This requires, amongst other things, a number of calculations to be undertaken to determine the U-values of the various elements of the building fabric. However, evidence from the field indicates that the U values that are achieved in practice are often much higher than those that are calculated, and are highly dependent upon the design and the installation of insulation layers (Hens *et al.* 2007 and Doran,

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2000). Similarly, recent work undertaken by Leeds Metropolitan University has also highlighted that when measurements of whole dwelling heat loss are undertaken, there can be a considerable gap between measured and predicted performance of the building fabric, and that this gap can be in excess of 100% (see Wingfield *et al.* 2009). In addition to this, the performance of the building fabric is very rarely understood and often taken for granted in in-use monitoring studies. Therefore, there has been a tendency for any discrepancies that are found between the monitored and predicted performance of the dwelling to be attributed to occupant behaviour. However, recent work undertaken by Leeds Metropolitan University has found that the performance of the building fabric can have a significant influence on the overall energy and CO_2 emissions. Consequently, very little conclusions can be drawn from in-use monitoring studies unless the performance of the building fabric is understood.

It should also be remembered that the building fabric has long physical lifetimes and slow replacement cycles. Given this, it is crucial that we increase our understanding of how the building fabric performs, the factors that influence its performance and how these factors relate to construction technology, and the design and construction processes. This can only be achieved by measuring and analysing the performance of the building fabric as built.

MEASURING FABRIC PERFORMANCE

A number of techniques are available that can be used to measure the performance of various aspects of the building fabric once constructed. These include pressurization testing, leakage detection, tracer gas measurement, cavity temperature measurement, heat flux measurement, thermal imaging, partial deconstruction and air flow measurements. Central to all of these techniques is the co-heating test, which is the only method readily available in the field to measure whole dwelling heat loss.

CO-HEATING TEST

A co-heating test is a method of measuring the heat loss (both fabric and background ventilation) in W/K attributable to an unoccupied dwelling. It was initially developed in the USA following the energy crisis in the 1970s (Sonderegger and Modera 1979 and Sondereger *et al.* 1980), and has since been used in a small number of occasions in the UK (see Wingfield *et al.* 2009). It involves heating the inside of a dwelling electrically, using electric resistance point heaters, to an elevated mean internal temperature, typically 25°C. By measuring the amount of electrical energy that is required to maintain the elevated mean internal temperature each day, the daily heat input (in Watts) to the dwelling can be determined. The heat loss coefficient for the dwelling can then be calculated by plotting the daily heat input (in Watts) against the daily difference in temperature between the inside and outside of the dwelling (delta-T). The resulting slope of the plot gives the heat loss coefficient in W/K. This is a measure of the instantaneous rate of heat loss from the whole dwelling per degree K. The heat loss coefficient can then be normalized by dividing the total heat loss by the gross floor area of the dwelling to obtain the Heat Loss Parameter (HLP) in W/m^2K. This enables the direct comparison of one co-heating test result with another.

The amount of time required to undertake a co-heating test can vary considerably. In most cases a test should be able to be undertaken in 2 to 4 weeks, but the time required is highly dependent upon a range of factors. Such factors include: the thermal characteristics of the dwelling, the amount of residual moisture contained within the dwelling, external environmental conditions, the time taken for the dwelling to be heat saturated and the objectives of the test. In addition to this, it is also important to obtain data that is relatively free from the noise of experimental error. It is therefore necessary to obtain a sufficient value of delta-T, generally 10°C or more. Consequently, the co-heating test should be carried out in the winter months, usually between October/November and March/April. An added advantage of undertaking the tests during this period is that the effects of solar radiation are minimized.

It is also best if the co-heating test is combined with other techniques. Such techniques include: pressurization testing, leakage detection, tracer gas measurement, cavity temperature measurement, heat flux measurement, thermal imaging, partial deconstruction, air flow measurements, design assessment and site observations. By doing so, a 'forensic' style investigation of the dwelling can be undertaken. This enables a much richer insight and understanding to be gained of the principal heat loss mechanisms within a dwelling.

The costs for a co-heating test can vary greatly and are dependent upon what data is required as output. If all that is required is a single figure for whole dwelling heat loss, then tests can be undertaken relatively cheaply for around £4000. If a much more detailed understanding of the factors that influence the total heat loss of the dwelling are required, then a much deeper forensic style investigation will need to be undertaken. The costs for this can vary considerably from £10,000 to £30,000.

MONITORING AND TESTING EQUIPMENT REQUIRED

A number of items of equipment are required to undertake a co-heating test on a dwelling. The main items of equipment required within the dwelling to be tested (test dwelling) are as follows:

- **Temperature and relative humidity sensors**: These are used to measure internal temperature and relative humidity within the dwelling. As a minimum, only the temperature sensors are required. However, the addition of the relative humidity sensors can be advantageous when analyzing the data obtained from the co-heating test, as they can give an indication of how the dwelling has dried out during the test.
- **Fan heaters**: These are used to heat the dwelling. A variable output model is preferred as it enables a degree of adjustment if required.
- **Circulation fans**: These are used to mix the internal air within the dwelling. A variable speed fan is preferred as it enables a degree of adjustment if required.
- **Thermostats or thermostatic controllers**: These are used to regulate the heat output from the fan heaters.
- **kWh meters**: These are used to measure the electrical energy consumption of the fan heaters, the circulation fans and the datalogger (if mains powered).
- **Datalogger**: This is used to record the data obtained from inside the dwelling. Careful consideration should be given to the choice of datalogger used to ensure that it is capable of recording all of the data that needs to be obtained from the dwelling. This data will include: temperature and humidity data from the temperature and humidity sensors and kWh data from the fan heaters and circulation fans.
- **Extension leads**: These are used to supply mains power to the fan heaters and fans, as well as any other items of equipment, such as the thermostatic controllers or dataloggers that require mains power.

It is important to note that additional items of equipment, such as transmitters, pulse counters, modems, etc. may also be required within the test dwelling depending upon the type of monitoring equipment used.

If the dwelling to be tested is semi-detached, terraced or an apartment, then consideration will have to be given to any heat loss that may occur through any elements of construction that are shared with adjacent dwellings (such as party walls, party floors, etc.) or to any unoccupied spaces (such as stairwells, communal areas, etc. If access to adjacent dwellings or spaces can be obtained, then the ideal solution would be to maintain these spaces at the same mean internal temperature as the test dwelling. This can be achieved by installing additional fan heaters, circulation fans, thermostats and temperature and humidity sensors in the spaces. In doing so, any heat loss through elements of construction that is attributable to differences in temperature between the test dwelling and the adjacent spaces will be eliminated. However, it should be remembered that this will not necessary eliminate all of the heat losses through the elements of construction, as heat loss will still occur if any thermal bypasses in the construction exist.

If access to any adjacent dwellings or spaces cannot be achieved then an alternative approach would be to measure the internal temperature and relative humidity in all of the adjacent spaces and install heat flux sensors on the internal surface of the test dwelling to measure the heat flux through the elements of construction concerned. However, this approach has a number of limitations. These are as follows:

- The heat flux measured by the heat flux sensors will relate only to the delta-T monitored. It may be that the heat flux will vary depending on the value of delta-T.
- The heat flux measured will relate to a particular portion of construction and may not be representative of that construction as a whole.

Equipment is also required to be mounted externally in order to collect external weather data. The weather data required for the co-heating test consists of measurements of external temperature and relative humidity, vertical south facing solar radiation and wind speed. In order to obtain this data, the following items of equipment are required:

- **Weather station:** This is used to measure the external temperature, relative humidity, wind speed, wind direction, rainfall and barometric pressure. As a minimum, only the external temperature and relative humidity sensors are required. However, the addition of the other sensors can give invaluable insights when analyzing the data obtained from the co-heating test.
- **Pyranometer:** This is used to measure the South facing solar radiation flux density in W/m^2.
- **Datalogger**: A separate dedicated datalogger for the weather station (including pyranometer) may be required. This will be dependent upon whether the datalogger installed within the dwelling is capable of recording all of the inputs from the weather station.

TEST PROCEDURE

Prior to undertaking the co-heating test, a pressurization test should be undertaken on the dwelling. The pressurization test should be undertaken in accordance with ATTMA Technical Standard 1 (Airtightness Testing and Measurement Association 2007).

Following the pressurization test, a number of measures are required to be put in place in order to minimize the contributions from other heat gain and heat loss mechanisms during the test. These measures are as follows:

- All heating and electrical systems within the dwelling that are not used during the test need to be turned off. This should be done at the fuse box where applicable. For instance, the space and hot water heating system (including the hot water cylinder), lights, fridge, freezer, oven, hob and any mechanical extract fans.
- All trickle vents, acoustic vents and mechanical supply/extract vents need to be adjusted to the closed position or temporarily sealed.
- All flues and fire places need to be temporarily sealed.
- All water traps and U-bends in kitchens, bathrooms, en-suites and toilets need to be filled with water.
- All external doors and windows should be inspected to ensure that they are tightly closed.
- All internal doors (including wardrobe and built-in cupboard doors) need to be temporarily wedged open to allow free movement of air around the dwelling.

Once the above measures are in place, the test can commence. The test procedure is as follows:

- Adjust all of the thermostats to the elevated mean internal setpoint temperature, say 25°C.
- Switch on all of the fan heaters and adjust them such that they are operating on their maximum heat and fan speed setting.
- Switch on all of the circulation fans and adjust to an appropriate angle and their maximum fan speed setting.
- Activate all of the dataloggers to record the internal and external data.
- Observe the internal temperatures obtained from the temperature sensors for the first couple of days to ensure that they are increasing towards the setpoint on the thermostats (25°C).
- Once the setpoint temperature has been reached, observe all of the internal temperatures obtained from the temperature sensors to determine whether there is a relatively uniform mean internal temperature throughout the dwelling.
- If the mean internal temperature observed throughout the dwelling is not uniform, adjust the thermostats in each zone as necessary to obtain a uniform mean internal temperature. If a uniform mean internal temperature can still not be achieved, it may be necessary to change the position of the fan heaters and circulation fans in the zones. It may also be necessary to adjust the heat output from the fan heaters, the speed of the circulation fans and the angle of the circulation fans.
- If a relatively uniform mean internal temperature is observed throughout the dwelling, but it is marginally different to the setpoint temperature on the thermostats, then the test should be allowed to continue at the different mean internal temperature.
- Once a relatively uniform mean internal temperature is achieved, continue to log all of the data for a sufficient period of time such that a range of internal to external temperature differences (delta-T's) are recorded. Generally speaking, this should be for at least one week, but preferably two or three.
- Download the data from the datalogger/s at regular intervals.

Table 1: Size, built form and construction type of the tested dwellings

	Type of construction	Built form	Gross floor area (m^2)
Dwelling 1	Full-fill masonry cavity	Semi-detached	73
Dwelling 2	Full-fill masonry cavity	Mid-terrace	73
Dwelling 3	Full-fill masonry cavity	Mid-terrace	137
Dwelling 4	Full-fill masonry cavity	End-terrace	111
Dwelling 5	Full-fill masonry cavity	Semi-detached	73
Dwelling 6	Full-fill masonry cavity	Semi-detached	73
Dwelling 7	Insulated timber-frame panel	End-terrace	117
Dwelling 8	Partial-fill masonry cavity	End-terrace	102
Dwelling 9	Partial-fill masonry cavity	Mid-terrace	102
Dwelling 10	Timber-frame	Semi-detached	86
Dwelling 11	Timber-frame	Semi-detached	87
Dwelling 12	Thin joint masonry	Detached	152
Dwelling 13	Structurally insulated panel	Detached	155
Dwelling 14	Partial-fill masonry cavity	End-terrace	101
Dwelling 15	Full-fill masonry cavity	Detached	109

After completion of the co-heating a test, a second pressurization test should be undertaken on the dwelling once the dwelling has been allowed to cool down.

RESULTS OF SOME RECENT CO-HEATING TESTS

This section presents the results of 15 newbuild co-heating tests that have been undertaken by Leeds Metropolitan University over the last 5 years or so (see Bell *et al.* in press and Zero Carbon Hub 2010). Details of the dwellings that have been tested are contained within Table 1.All of the dwellings tested were constructed to either meet or exceeded the insulation standards contained within the 2006 Edition of the Building Regulations Approved Document Part L1 (Office of the Deputy Prime Minister 2006). As can be seen from Table 1, the dwellings tested varied in terms of their size, built form and construction technique.

Due to the small sample size, it has only been possible to make a number of qualitative comments regarding the results. Figure 1 illustrates the measured whole house heat loss (obtained from the co-heating test) versus the predicted steady state heat loss of the tested dwellings in W/K. The results illustrate that the dwellings tested not only varied considerably in terms of their predicted performance, but more importantly the measured performance exceeded the predicted performance in all of the dwellings. In some cases, such as dwellings 8 and 9, the difference or "gap"

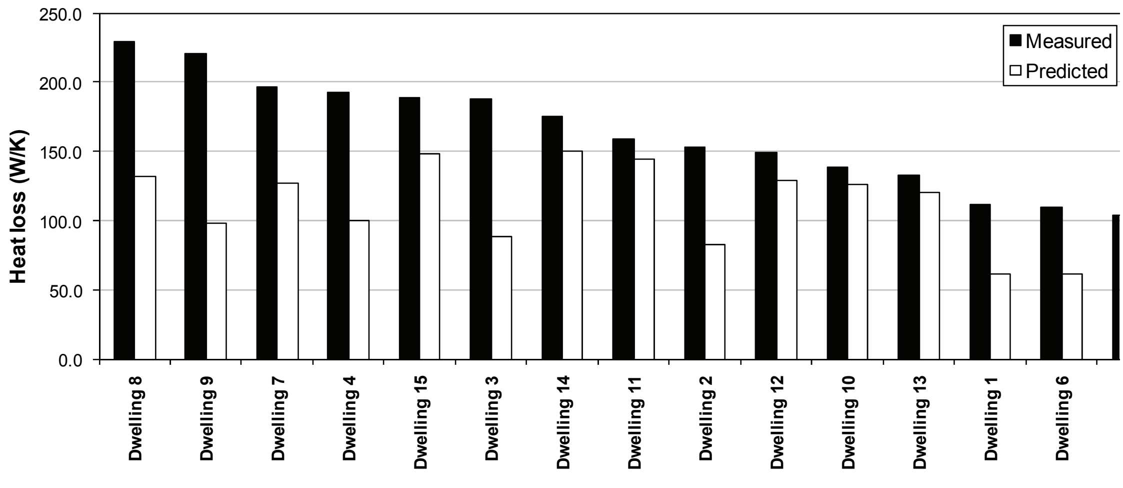

Figure 1: Measured versus predicted heat loss of the tested dwellings

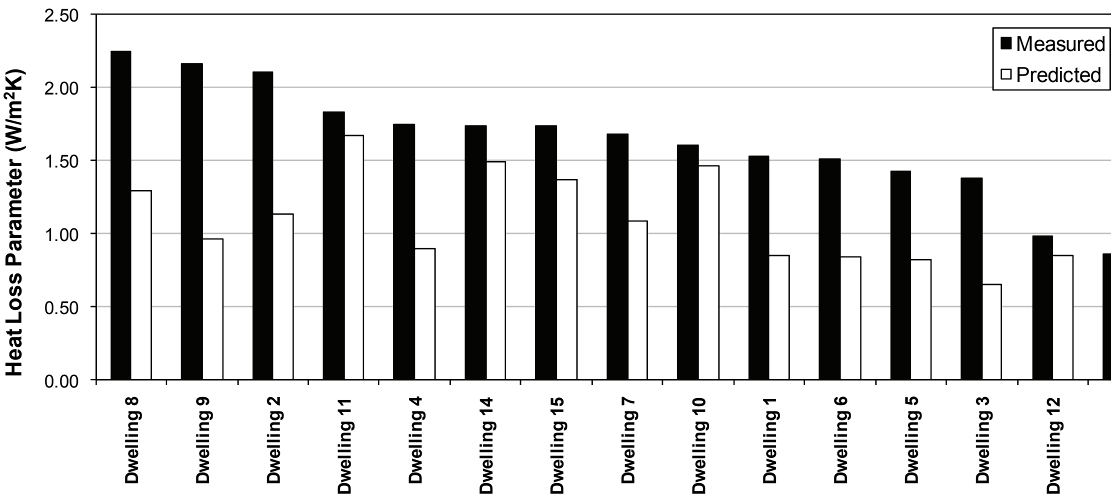

Figure 2: Measured versus predicted Heat Loss Parameter (HLP) of the tested dwellings

between the measured whole house heat loss and the predicted steady state heat loss is considerable.

Even when the co-heating test results are normalized by gross floor area[1], to enable the results from one dwelling to be compared against another, the data shows that a relatively wide range of HLP's was measured for the tested dwellings (see Figure 2) and the range of measured HLP's is greater than the range of predicted HLP's (see Figure 3). The HLP's that were measured ranged from 0.86 to 2.24, with a mean of 1.63 and a standard deviation of 0.39,whilst the predicted HLP's ranged from 0.65 to 1.67, with a mean of 1.08 and a standard deviation of 0.31. In comparison, the HLP for a notional 2006 Part L1A compliant semi-detached dwelling with a gross floor area of $89m^2$, is approximately 1.3.

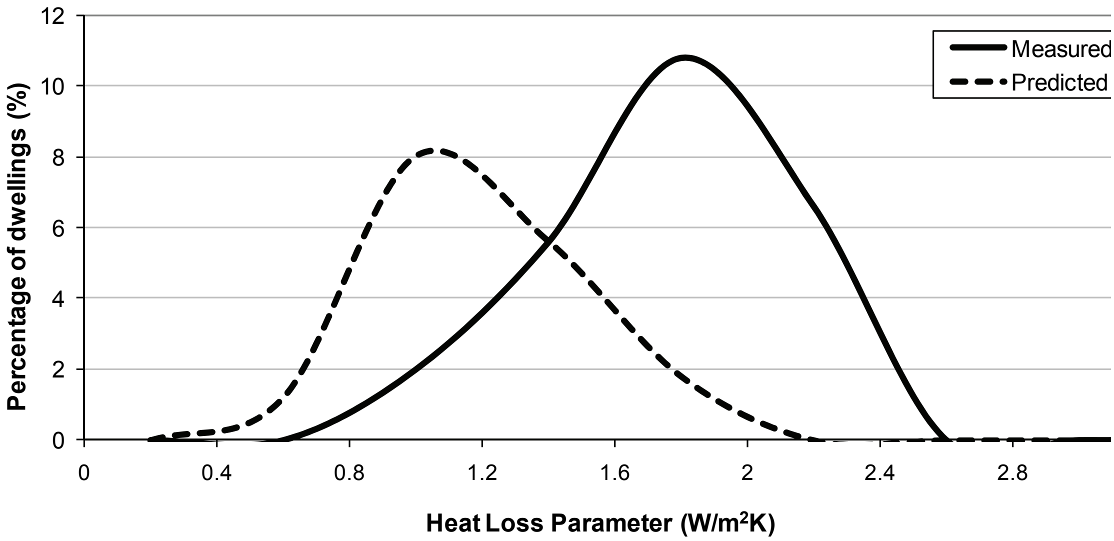

Figure 3: Distribution of Heat Loss Parameter (HLP) for the tested dwellings

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[1] Dividing the measured and predicted total heat loss by the gross floor area of the dwelling results in the measured and predicted Heat Loss Parameter (HLP) in W/m^2K.

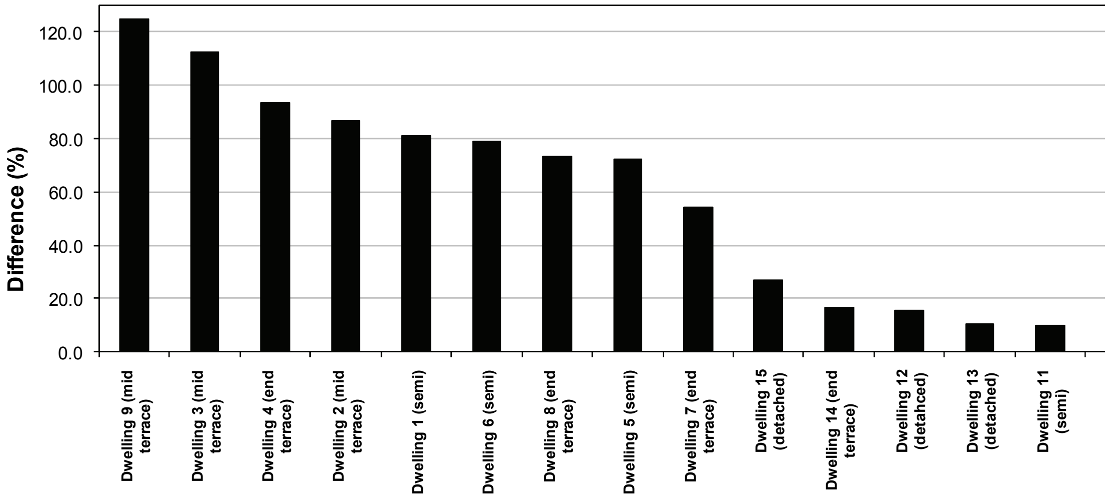

Figure 4: Difference in measured whole house heat loss as a percentage of predicted

Closer analysis of the data (see Figure 4) illustrates the size of the gap that exists between measured and predicted performance. As Figure 5 shows, the size of the gap varies considerably, from just over 9% for dwellings 10 and 11 to as much as 125% for dwelling 9. On average, the size of the gap between measured and predicted performance is 58%. This may have significant implications in terms of the energy and CO_2 emissions attributable to these dwellings in-use.

In all of the dwellings tested, the reasons for the difference in the measured versus predicted performance have been investigated and identified. Although the reasons for the difference in performance tend to vary from dwelling to dwelling, a number of factors have emerged that account for the difference in performance. These are as follows:

- The existence of a thermal bypass at one or more of the party walls. To some degree, this explains why the mid-terraced properties have tended to experience the greatest gap in performance (they have 2 party walls), whilst the smallest gap was experienced in the detached properties (they no have no party walls).
- The existence of thermal bypasses at other areas within the construction.
- Underestimation of the amount of thermal bridging within the building fabric.
- Lack of detailed design, particularly at complex junctions between elements.
- As built construction not as originally designed.
- Product substitutions.
- Over cautious predictions of total heat loss. For instance, using an approximation factor of y = 0.08 when calculating thermal bridging.

In general, the results suggest that the more care that is taken during the design and construction process, the greater the chance of their being a smaller gap between the measured and the predicted performance.

CONCLUSIONS

This paper describes an approach that can be used in the field to measure the fabric performance of dwellings. This approach, known as a co-heating test, involves measuring the amount of electrical energy that is required to maintain an elevated mean internal temperature within an unoccupied dwelling, typically around 25°C, over a set period of time. The daily heat input is then plotted against the daily difference in temperature between inside and outside in order to determine the total heat loss coefficient for the dwelling in W/K.

The paper also presents the results of some co-heating tests that have been undertaken on a small number of dwellings that have been built to either meet or exceed the insulation requirements contained within the Building Regulations Approved Document Part L1A 2006. Although it has only been possible to make a number of qualitative comments regarding the results of the co-heating tests, due to the small number of dwellings tested, the results indicated that a gap existed between the measured whole house heat loss and the predicted steady heat loss in all of the dwellings tested. The size of the gap that was measured varied considerably from dwelling to dwelling, ranging from just over 9% to as much as 125%, with a mean of 58%. This is likely to have significant implications in terms of in-use energy and CO_2 emissions.

Further analysis of the results indicated that there were a number of factors that accounted for this gap performance. These included: the existence of thermal bypasses within the construction (most notably at the party wall), underestimation of thermal bridging, lack of detailed design, construction as built not as design, product substitutions and over cautious predictions of total heat loss. In addition, the analysis also indicted that the more care that is taken during the design and construction process, the greater the chance of their being a smaller gap between the measured and the predicted performance.

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