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CeBE

Whole House Heat Loss Test Method (Coheating)

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Introduction

1 In the UK, as in most industrialised 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 (DECC, 2011). This is a substantial figure given that the UK housing stock is categorised 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 both new and existing dwellings will be required.

2 One factor that can have a significant impact on the energy use and CO_2 emissions attributable to dwellings is the performance of the building fabric. However, the performance of the building fabric is very rarely understood and is often taken for granted, particularly in in-use monitoring studies. Therefore, in the past, 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 (see Wingfield et al., 2009 and Zero Carbon Hub, 2010) has found that the performance of the building fabric can have a significant influence on overall energy and CO_2 emissions. Consequently, very few 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 domestic building fabric in the UK tends to have long physical lifetimes and slow replacement cycles. Therefore, it is crucial that we not only measure and analyse the performance of the building fabric as built, but in doing so, take the opportunities that arise to improve our understanding of fabric performance under real life conditions and the factors that influence this performance. Otherwise, there is a very real risk that we will leave a legacy of dwellings with poorly performing building fabric for generations to come.

3 Other factors that can have an influence on the overall performance of a building include the performance of the various services and the occupancy. It is also important to realise that the external environment also has an important influence on the building fabric, the services and the occupants (see Figure 1).

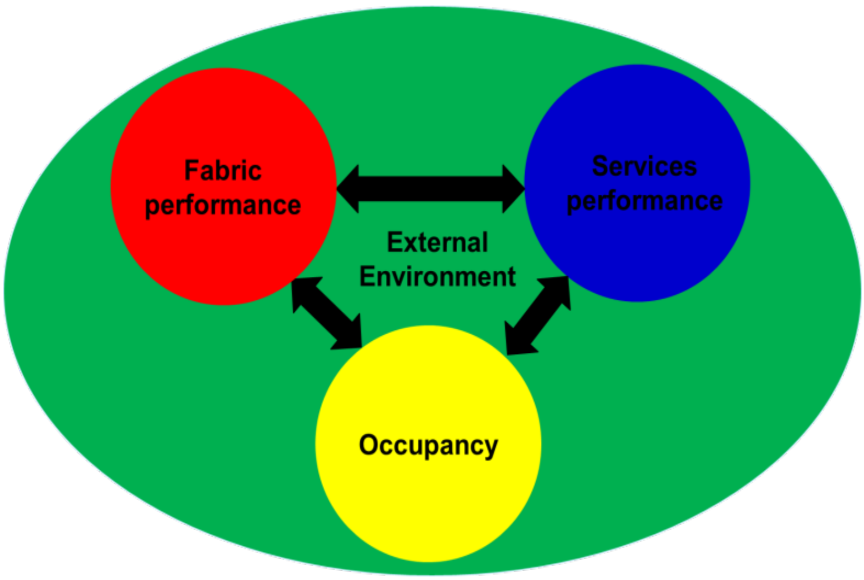

Figure 1 Factors that influence the performance of a building.

4 A wide range of techniques are available that can be used to measure the performance of various aspects of the building fabric once constructed. These include pressurisation testing, leakage detection, tracer gas measurement, cavity temperature measurement, differential pressure measurement, heat flux measurement, thermal imaging, partial deconstruction and air flow measurements. Central to all of these techniques is the co-heating test (see Figure 2).

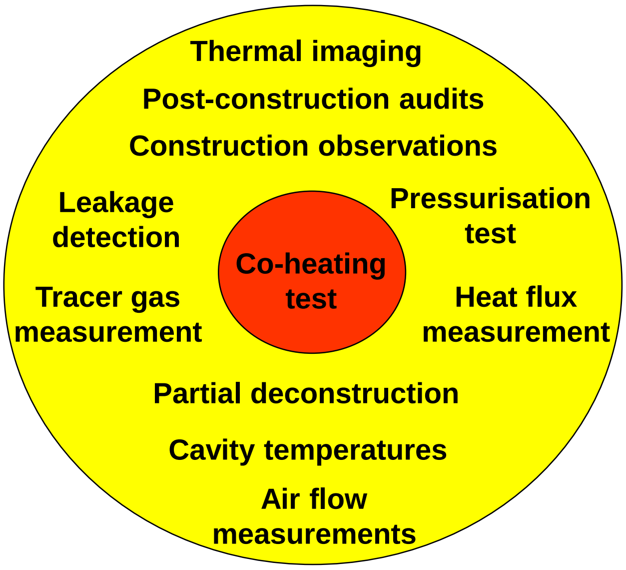

Figure 2 The relationship between the coheating test and other fabric measurement techniques.

Coheating test – what is it?

5 The coheating test is a quasi-steady state method that can be used to measure the whole dwelling heat loss (both fabric and background ventilation) attributable to an unoccupied dwelling. It is one of only a few aggregate methods (another is the PSTAR method – see Subbararo et al., 1988) that are currently available to measure whole dwelling heat loss in the field. An alternative would be to adopt a disaggregated approach to heat loss, where the background ventilation heat loss and fabric heat loss of the building are measured independently of one another, and the results aggregated together to obtain a total heat loss. Background ventilation heat loss can be obtained by undertaking a pressurisation test and then approximating the background ventilation rate by using the simple n/20 *'rule of thumb'*, which involves dividing the air leakage rate in ach @ 50Pa by 20. A correction factor can then be applied to the figure to take account of the leakage exponent, the building geometry, the height of the dwelling and any sheltering from neighbouring buildings. Alternatively, normalised leakage can be used, which can be calculated from the results of a pressurisation test and the buildings geometry. Elemental heat loss for each element of the building fabric can be obtained by strategically positioning heat flux plates on various elements of the building fabric and measuring the amount of flux flowing through each element for a given temperature difference. However, there are a number of limitations associated with such a disaggregated approach. First of all, significant questions remain as to whether the simple n/20 *'rule of thumb'* is applicable to UK dwellings. It is highly likely that it will not always be applicable to all types of buildings in the UK all of the time. Secondly, heat flux measurements are only obtained from a small proportion of the total thermal element surface area, so the amount of flux measured may not be representative of the thermal element as a whole. Thirdly, it is very difficult to take into account all of the areas of thermal bridging within a dwelling using heat flux measurement alone.

6 Although the coheating test is not a new concept (it has been around since the 1970's – see Sonderegger et al. 1979a and 1979b), the methodology is very much in its infancy, and in the UK, is currently the subject of much research and debate. It involves heating the inside of an unoccupied dwelling electrically, usually using electric resistance point heaters, to a mean elevated internal temperature (typically 25 °C) over a number of days. The period of time taken to undertake the test can vary enormously, but typically ranges from 1 to 3 weeks once the dwelling has been heat saturated. Whilst heating the dwelling, a number of parameters are measured, namely total electrical energy input to the dwelling, internal temperatures and relative humidity, and various external climatic conditions. By measuring the total amount of electrical energy that is required to maintain the mean elevated internal temperature each day in response to the external environmental conditions, 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 (ΔT). The resulting slope of the plot gives the raw uncorrected heat loss coefficient in W/K. An example of such a plot can be seen in Figure 3.

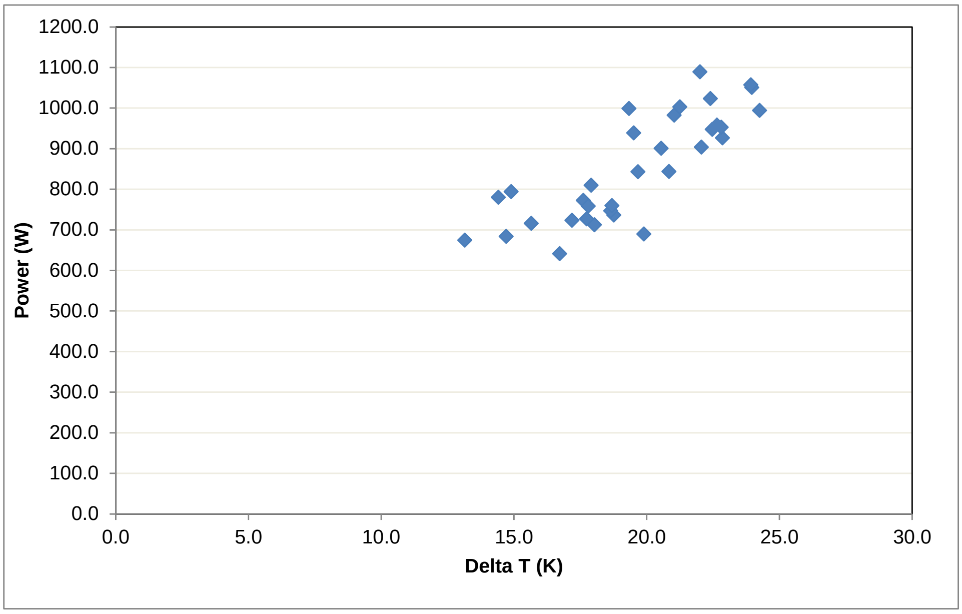

Figure 3 Example plot of the raw data obtained from a coheating test.

7 The uncorrected raw data illustrated within Figure 3 can then be corrected using a range of different data analysis techniques, to take account of effects such as solar radiation.

Data analysis techniques

8 Central to the analysis of the coheating test data is the assumption that the following energy balance holds true:

$$Q + R.S = \left(\Sigma U.A + \frac{1}{3}nV\right).\Delta T$$

where $Q =$ Total measured power input into the dwelling (W)
$R =$The solar aperture of the house (m^2)
$S =$ The total amount of South facing solar radiation (W/m^2)
$\Sigma U.A =$ Total fabric heat loss (W/m^2)
$n =$ Background ventilation rate (h^{-1})
$V =$ Internal volume of the dwelling (m^3)
$\Delta T =$ Temperature difference between the inside and the outside of the dwelling (K)

9 The above equation can be rearranged as follows:

$$\frac{Q}{\Delta T} = \left(\Sigma U.A + \frac{1}{3}nV\right) - \frac{R.S}{\Delta T}$$

10 By plotting Q against ΔT, as is the case in Figure 4, the slope of the line (the raw heat loss coefficient) equates to $\left(\Sigma U.A + \frac{1}{3}nV\right) - \frac{R.S}{\Delta T}$. To account for the effects of solar gains ($\frac{R.S}{\Delta T}$), which reduce the amount of raw heat loss measured, a range of techniques can be used to solar correct the raw heat loss coefficient data.

11 It is important to realise that solar gains will occur through the opaque elements of the building fabric as well as through the transparent elements of the building fabric. They will also have an effect on the amount of heat that is lost through non-habitable areas of the dwelling that are outside the buildings thermal envelope. Such areas include cold ventilated roof spaces and knee walls. To account for all of these solar gains, linear regression techniques are preferred, as these techniques

are capable of modelling the relationship between solar gains and the total heat loss from the dwelling.

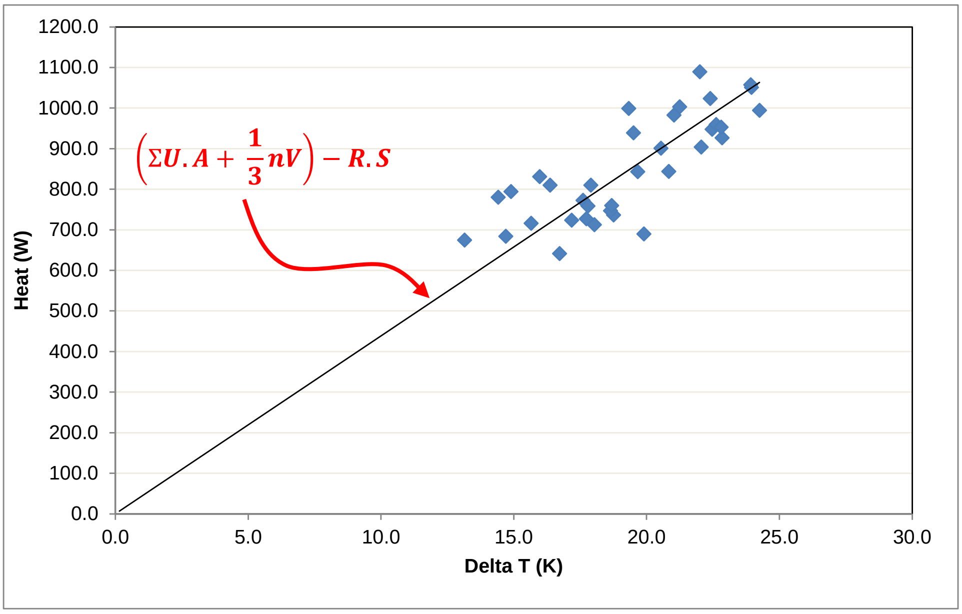

Figure 4 Example plot of the raw heat loss coefficient.

Linear regression techniques

12 The most common method of analysing the data obtained from a coheating test is to use linear regression techniques. There are a number of different techniques that can be adopted. These include:

a) **Simple linear regression –** Two separate simple linear regression methods are available, the *'Siviour'* method and the *'Thermal calibration'* method. The *Siviour* method was first suggested by Jack Siviour in the early 1980's (cited in Everett, Horton & Doggart, 1985) and involves plotting $Q/\Delta T$ against $/\Delta T$. An example of such a plot is illustrated in Figure 5. The resulting slope of the line is the solar aperture R in m^2 and the y-intercept is the total solar corrected heat loss coefficient in W/K. An alternative, is to adopt the *Thermal calibration* method. This method was developed by Everatt, Horton and Doggart (1985) and is based upon a modified version of the *Siviour* method. In the *Thermal calibration* method, heat loss through the floor (in this case a solid slab on ground) was separated from the rest of the dwelling fabric heat loss, as the heat loss through this element behaved differently than that through the other elements of the building fabric (walls, floor, roof, windows and doors). In other words, it was not driven by the temperature difference between the inside and the outside of the dwelling. In addition, the heat loss attributable to background ventilation was also separated, as it was constantly varying with wind speed and ΔT. The heat balance equation was therefore rearranged as follows:

$$\frac{Q-F}{\Delta T} - \frac{1}{3}nV = \Sigma U.A - \frac{R.S}{\Delta T}$$

where F = Total ground floor heat loss (W)

Such an approach is unlikely to be applicable when the ground floor is not of a solid slab on ground construction, as in these circumstances, the heat loss through the floor is likely to be related to the temperature difference between the inside and outside of the dwelling. An example of a plot using the *Thermal calibration* method is illustrated in Figure 6. The resulting slope of the line is the solar aperture R in m^2 and the y-intercept is the total solar corrected fabric heat loss coefficient, excluding the ground floor, in W/K.

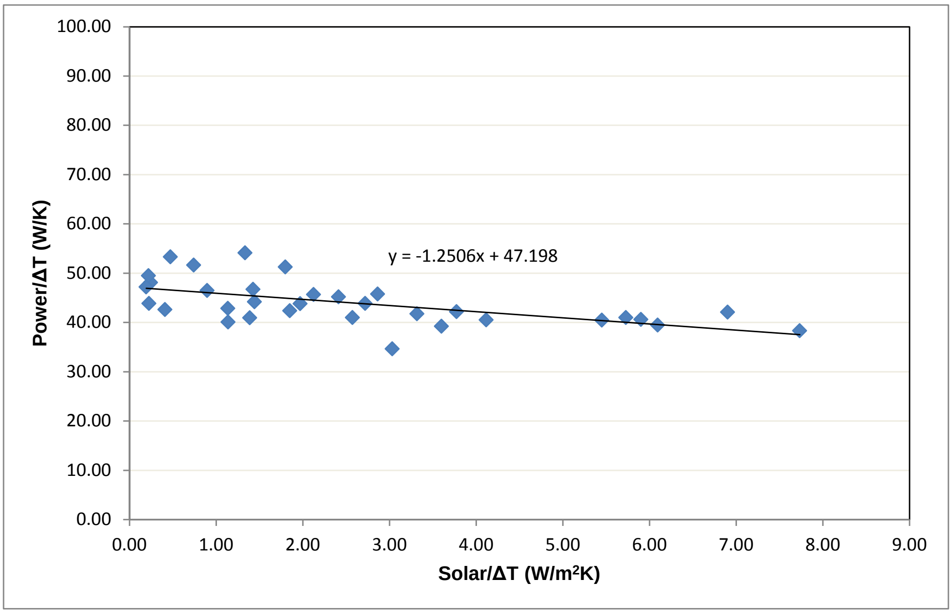

Figure 5 An example of the *Siviour* method of analysis.

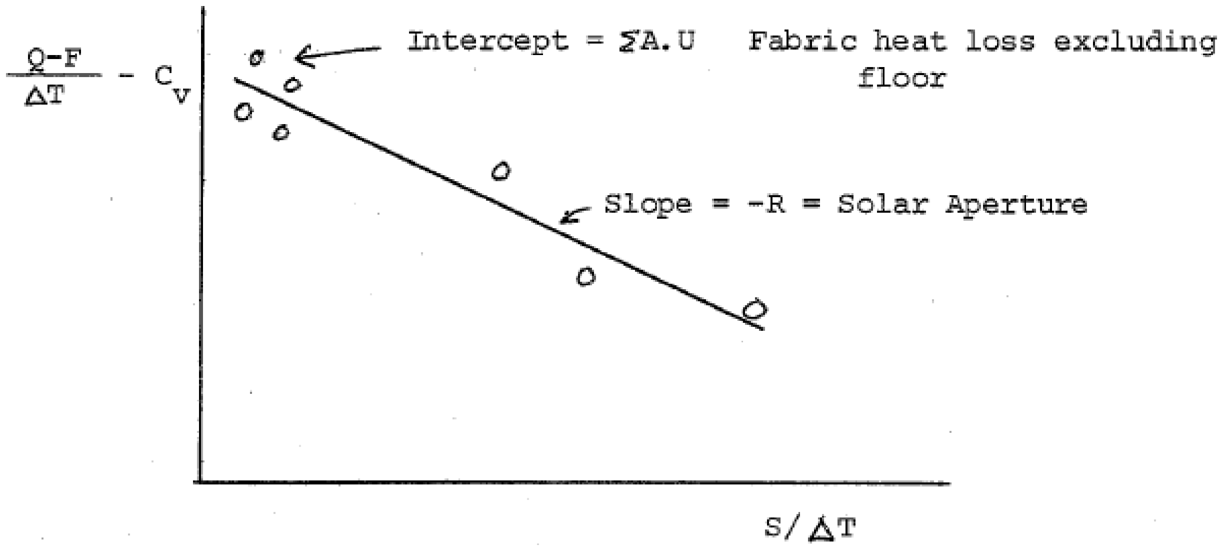

Figure 6 An example of the *Thermal calibration* method of analysis

[Source: Everatt et al. (1985) p.8.2].

b) **Multiple linear regression –** In this method, multiple regression techniques are used to determine the solar aperture R for the dwelling over the test period. The solar aperture R can then be used, along with the measured daily mean solar radiation S, to calculate the daily mean solar gains $R.S$. These gains can then be added onto the daily measured total power input into the dwelling Q and linear regression used to determine the total heat loss coefficient. A number of assumptions are made when using this analysis technique. These are as follows:

- It is assumed that daily power input Q is the dependent term and daily mean ΔT and daily mean solar gains $R.S$ are the independent variables.
- It is assumed that ΔT and $R.S$ are not related to one another. During the heating season, this tends to be true, but outside of the heating season, days of high daily mean ΔT tend to correlate with days that have a high mean solar insolation. If a correlation exists between ΔT and solar insolation this analysis technique becomes ineffective.

- If the regression is forced through the origin (intercept set to 0,0), it is assumed that when there is no temperature difference between the inside and the outside of the dwelling, there is no heat input required, i.e. there is no heat loss from the dwelling. In reality, it is possible to have some heat loss from the dwelling even though there is no temperature difference between the inside and the outside of the dwelling, due to the effects of night time radiative cooling.
- It assumes that the relationship between power input Q and temperature difference ΔT is linear.
- It assumes that there are no other factors that are likely to have an influence on the heat input into the dwelling. In reality, there are a number of other factors that can influence heat input, such as wind speed, wind direction and moisture levels.

An example of a plot using the multiple linear regression analysis method is illustrated in Figure 7. The resulting slope of the line is the total heat loss coefficient in W/K.

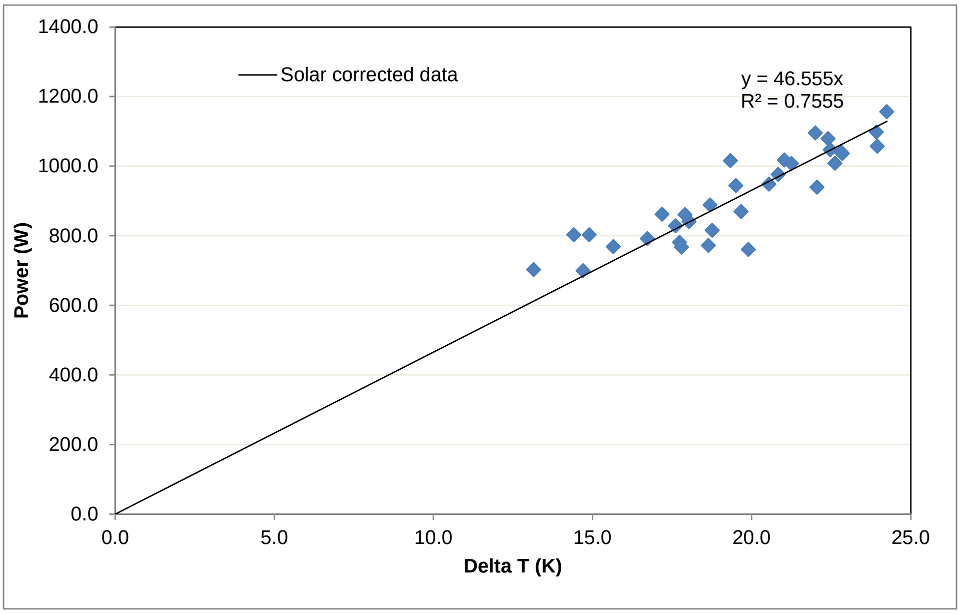

Figure 7 An example of the multivariate linear regression method of analysis.

It is also possible with multiple linear regression to add-in additional independent variables into the analysis, such as wind speed.

c) **Linear regression using a calculated solar aperture** – In instances where it is not possible to undertake an effective multiple regression, *Siviour* or *Thermal calibration* analysis, the raw uncorrected heat input into the dwelling can be corrected to account for solar gains by using a calculated solar aperture. The solar aperture R can either be calculated manually or using a computer program. Information of factors such as the total glazing area, the orientation of the glazing, the glazing solar transmittance, the solar access factor, the frame factor and the average incidence factor are likely to be required to calculate the solar aperture. Once calculated, the solar aperture R can then be used, along with the measured daily mean solar radiation S, to calculate the daily mean solar gains $R.S$. The solar gains $R.S$ can then be used to correct the raw heat input into the dwelling. Linear regression analysis can then be performed on the solar corrected data to determine the solar corrected heat loss coefficient.

Quantification of errors and validity of the test data

13 Errors associated with undertaking a coheating test can be separated into two main types; systematic errors and random errors.

Systematic Errors

14 Systematic errors in the coheating test will in the main be related to the experimental set up, measurement errors, calibration issues and the resolution of the sensors. The key factors that influence systematic errors are as follows:

a) Calibration and resolution of the internal and external temperature sensors.

b) Location and number of internal temperature sensors.

c) Location of the external temperature sensor and the effectiveness of the Stephenson screen in shielding the sensor from the effects of solar radiation.

d) Calibration and resolution of the temperature controllers.

e) Calibration and resolution of the kWh meters.

f) Stability and variation in the internal temperature throughout the volume of the test dwelling. This will be related to the zoning and placement of fan heaters and circulation fans as well as the hysteresis of the temperatures control.

g) Calibration and resolution of the solar pyranometer.

h) Location of the solar pyranometer on the test building. This will be related to the orientation of the sensor with respect to South and the vertical plane, the height of the sensor above ground level and the level of overshading.

i) Measurement of building dimensions and the calculation of elemental areas and volumes. For example, there will be differences between building measurements taken from the design drawings and those measured on the actual building. There are also different national conventions in calculating derived measurements such as volumes, where for example in some conventions one calculates the building volume based on the overall internal dimensions of the building shell, and other conventions use the internal volume minus the space occupied by partition walls, intermediate floors and other solid objects such as door and staircases. Dimensions, should always be based upon those obtained using a measured survey of the building.

Random Errors

15 Random errors associated with the coheating test will be related to unknown and unpredictable variations that occur during the test. The key factors that influence random errors are as follows:

a) Effect of different weather conditions on the building fabric.

b) Construction defects.

c) Variability in construction tolerances.

d) Unexpected thermal effects, such as thermal bypasses, heat recovery mechanisms and wind washing.

Disaggregation of heat loss components

16 The amount of heat loss that is measured during a coheating test comprises two main components; fabric heat loss (Q_{fabric}) and background ventilation heat loss ($Q_{background\ ventilation}$). The proportional split between these two components can be estimated if the magnitude of one of the components is known. In the case of the background ventilation heat loss, it is possible to undertake various measurements during the test in order to determine the background ventilation rate. The background ventilation rate can then be used to calculate the background ventilation heat loss during the test. Three separate approaches can be adopted to determine the background ventilation rate. These are as follows:

a) Fan pressurisation technique.

b) Tracer gas decay method.

c) Constant concentration tracer gas method.

Fan pressurisation technique

17 This involves undertaking a pressurisation test immediately before the commencement of the coheating test and immediately after the end of the coheating test. The average of the two measurements is then used to give a reasonable approximation of the average air leakage rate achieved within the building over the period of the coheating test. An average air leakage rate is used to account for any change in the air leakage rate that may occur over the period of the coheating test (quite often the air leakage rate increases over time due to the accelerated drying and associated shrinkage that may be caused by the elevated temperatures used during the coheating test). The pressurisation tests that are undertaken should comprise a series of both pressurisation and depressurisation measurements.

18 The background ventilation rate can then be approximated using the simple n/20 'rule of thumb'. This involves dividing the air leakage rate in ach @ 50Pa by 20. A correction factor can then be applied to the figure to take account of the leakage exponent, the building geometry, the height of the dwelling and any sheltering from neighbouring buildings. Suitable values for the correction factor are normally given in the national calculation methodologies for the energy performance of buildings. Alternatively, normalised leakage can be used, which can be calculated from the results of a pressurisation test and the buildings geometry.

19 The background ventilation rate (n) can then be converted into the background ventilation heat loss ($Q_{background\ ventilation}$) in W/K by multiplying by the internal volume of the building (V) in m^3 and by the specific heat capacity of air (0.33 Wh/m^3K).

$$Q_{background} = 0.33nV$$

20 The fabric component of heat loss (Q_{fabric}) in W/K can then be calculated by subtracting the background ventilation heat loss ($Q_{background\ ventilation}$) in W/K from the total solar corrected heat loss ($Q_{solar\ corrected}$) in W/K.

$$Q_{fabric} = Q_{solar\ corrected} - Q_{background\ ventilation}$$

21 It is important to realise that inherent within the above procedure is the assumption that ventilation heat loss has a linear relationship with ΔT. This is unlikely to be the case, as ventilation heat loss is likely to increase the greater the ΔT due to convection, stack and pressure effects.

Tracer gas decay method

22 This involves introducing an inert tracer gas into the building and measuring the concentration of the gas inside the building at specific time periods throughout the coheating test. The tracer gas decay method will give a direct measure of the background ventilation rate averaged over the decay period. To conduct a tracer gas decay measurement, an appropriate quantity of a suitable tracer gas is injected into the test house upstream of a mixing fan. The concentration of the tracer gas is measured at regular intervals at various locations throughout the test dwelling using an appropriate gas analyser. Suitable test gases include sulphur hexafluoride (SF_6), carbon dioxide (CO_2), carbon monoxide (CO) and nitrous oxide (N_2O). The background ventilation rate (n) in units of air changes per unit of time can be calculated from the following formula:

$$n = \left(\frac{1}{t}\right) xln \left(\frac{C_t}{C_o}\right)$$

where t = is the measurement period.

C_0 = is the initial concentration of the tracer gas.

C_t = is the concentration of the tracer gas at the end of the measurement period.

23 Carbon dioxide is frequently used as a tracer gas in unoccupied buildings due to the ready availability of the test gas and the availability of inexpensive infra-red gas sensors. Carbon dioxide is generally unsuitable for ventilation measurements in occupied houses as it is a metabolic gas. Its

use as a tracer gas is further complicated as carbon dioxide is also present in the atmosphere in concentrations of around 400 ppm.

Constant concentration tracer gas method

24 The constant concentration gas method involves introducing an inert tracer gas into the building and measuring the rate at which the tracer gas needs to be introduced into the building to maintain a specific concentration. This gives real time data on the ventilation rate for the duration of the coheating test. However, it is very expensive and would normally be outside the scope of a coheating test.

Issues to consider

25 Drawing on our experience of undertaking in excess of 50 coheating tests in both new and existing dwellings over the last decade or so, it is clear that a number of issues need to be carefully considered when planning to undertake a coheating test. These issues are as follows:

a) Testing period.
b) Duration of the test.
c) The determination of daily average data.
d) Building type and form.
e) Thermal mass.
f) Level of insulation.
g) Airtightness.
h) Wind speed and direction.
i) Drying out.
j) Proportion of glazing.
k) Adjacent dwellings.
l) Access to dwelling during coheating test.
m) Loading the domestic ring main.
n) PAT testing.
o) Calculating the predicted heat loss

Testing period

26 The period within the year in which testing should be undertaken is dictated by the requirement to obtain a sufficient value of ΔT (generally 10 K or more[1]). Consequently, the coheating 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 also minimised.

27 In dwellings that have a large proportion of South-facing glazing, particularly if they are also well insulated (for instance, Passivhaus dwellings), it is advisable to try and undertake the test in those months that have the lowest levels of solar insolation, notably December and January. This is to minimise the risk of the temperature within any of the South-facing rooms increasing above the mean internal temperature within the dwelling due to the effects of solar gains. However, it is recognised that this may not be possible.

Duration of the test

28 Careful consideration must also be given to the duration of the coheating test. The amount of time required to undertake a co-heating test can vary considerably and is dependent upon a range of factors. Such factors include: the thermal characteristics of the dwelling, the amount of residual moisture contained within the fabric of the dwelling, external environmental conditions, the time taken for the dwelling to become heat saturated and the objectives of the test. Ideally, the test should be undertaken for a sufficient period of time to enable there to be a number of data points plotted on the power versus ΔT graph, at as wide a range or spread of ΔT's as possible, such that an appropriate correlation coefficient can be obtained for the data. However, in some cases this will

[1] The figure of 10 K has been commonly referred to as it ensures that the majority of the heat flow that occurs through the dwelling during the test is from the inside to the outside.

not be possible, as access to the dwelling will either be time constrained or external environmental conditions are such that a wide range of ΔT's are not possible. It should also be remembered that time will have to be built into the test to account for setting up and removing the coheating test equipment, undertaking the pre-and post coheating test pressurisation tests, and the time taken to heat the dwelling and its fabric to the chosen mean elevated temperature (at this point the dwelling is said to be heat saturated).

29 Our experience suggests that as a minimum, the test should be undertaken for one week after heat saturation of the dwelling has occurred. In most cases a test should be able to be undertaken in 2 to 4 weeks. However, generally speaking, the longer the testing period, the greater the potential spread of the data obtained.

30 Coheating test data should be collected 24 hours a day during the length of the test. Only measuring night-time data, say from 6pm to 6am, is not advised, as it tends to ignore mass effects. This can be particularly problematic in heavyweight dwellings.

The determination of daily average data

31 The analysis of coheating data is normally undertaken using the average of the daily data, where daily data is defined as that data recorded over the period 00:00 to 23:59 inclusive. Analysing the data using daily figures will tend to smooth out the short-term (daily) effects of thermal mass and diurnal variations in temperature and solar radiation. By averaging the data over the period 00:00 to 23:59 inclusive it is assumed that all of the solar radiation absorbed by the fabric of the dwelling is re-radiated back to the space by midnight of the day in which it was absorbed. This may be true in buildings of lightweight or even medium weight construction, but is unlikely to be true in dwellings of heavyweight construction. In such dwellings, it may be more appropriate to average the daily data over the period 06:00 to 05:59 inclusive, although it is recognised that in some dwellings, it make take more than a day for all of the absorbed thermal radiation from one day to be re-radiated back to the space.

Building type and form

32 Careful consideration has to be given to the type, the form and the method of construction used on the dwelling that is to be tested. In dwellings that have a large number of relatively small rooms, additional equipment may need to be installed (fan heaters and/or air circulation fans) to ensure that the mean elevated temperature is achieved within all of the rooms within the dwelling.

33 In dwellings that comprise two or more storeys, difficulties can be encountered maintaining the mean elevated temperature throughout the dwelling, due to stack effects. Additional air circulation fans may need to be positioned within the dwelling to blow any warm air that is naturally rising up through the dwelling back down to the lower floors to enable adequate mixing of the internal air.

34 In dwellings that have a large proportion of South-facing glazing in relation to external envelope area, the South-facing rooms are likely to be susceptible to overheating, particularly if they are tested either at the beginning or towards the end of the coheating testing season. Therefore, care needs to be taken to ensure that any excess heat, particularly in South-facing rooms, is adequately distributed around the rest of the dwelling. This is a particularly important issue with passive solar or Passivhaus dwellings.

35 One of the most difficult dwelling forms to undertake a coheating test on is an apartment. When testing apartments, careful consideration needs to be given to any heat loss that may occur through any party elements of construction (such as party walls, party floors, etc.) or to any unoccupied spaces (such as stairwells, communal areas, etc.), which are often not heated. Ideally, access to adjacent apartments or spaces should be obtained to maintain these spaces at the same mean elevated internal temperature as the test apartment. By doing so, any heat loss through the party elements of construction that would have occurred due to the existence of non-isothermal conditions between the test apartment and the adjacent spaces, is likely to be minimised. However, it should be remembered that this will not necessary eliminate all of the heat losses through the party elements of construction, as heat loss will still occur if any thermal bypasses or thermal bridges in the construction exist. For instance, if the building is constructed using a concrete structural frame, heat may pass through the concrete columns and frame from one apartment to another. In some cases, access may need to be gained to a significant number of apartments to undertake a coheating test, which will have implications for the amount of equipment required and the amount of data analysis that will need to be undertaken. However, it should be recognised that it may not always be possible to gain access to all of the surrounding apartments or spaces when undertaking a coheating test. If this is the case, the temperature of all of these spaces should be

recorded throughout the coheating test, and if at all possible, a heat flux sensor placed on the plane elements so that the amount of flux passing through these elements can be measured.

36 In apartments that have a small proportion of external envelope area in relation to floor area, the heat loss from the apartment may be so low that it is difficult to obtain a reliable coheating test result, due to the influence of various external factors, such as solar gains. In these circumstances, it may be more appropriate to maintain a constant temperature differential between the test apartment and any adjacent apartments or spaces to artificially increase the amount of heat loss from the test apartment. For example, if the test apartment is maintained at a mean elevated internal temperature of 25°C, the adjacent apartments and space could be maintained at a constant mean temperature of 20°C. If heat flux plates are placed in appropriate locations on the party elements of the test apartment, then an approximation can be made for the amount of heat flowing through the party elements. This heat flow can then be subtracted from the total heat input to the dwelling that was measured during the coheating test.

Thermal mass

37 Lightweight dwellings will heat up quickly but may be prone to overheating in certain areas, particularly if the dwelling is well insulated and airtight and there is a large amount of South-facing glazing. If this is the case, additional air circulation fans may need to be installed to remove any excess heat from those areas of the dwelling that are prone to overheating.

38 Heavyweight dwellings, on the other hand, will take much longer to become heat saturated, but may be susceptible to mass effects that have a considerable time delay. For instance, the solar radiation absorbed on one day may not be re-emitted to the space until the next day. This needs to be taken into consideration when analysing any results.

39 The amount of thermal mass within the dwelling will also determine how quickly the dwelling will respond to internal and external temperature fluctuations and heat inputs[1]. The greater the thermal mass, the longer the time that it will take for the dwelling to respond to these effects, whilst the more lightweight the dwelling is, the quicker it will take to respond to these effects.

40 It is possible to average out the time dependent thermal effects by increasing the duration of the test. Generally speaking, the longer the test, the more these effects are averaged out.

Level of insulation

41 In dwellings that are very well insulated, only a small amount of heat input may be required at one or two strategic points within the dwelling. Air circulation fans can then be used to distribute this heat evenly throughout the dwelling. The converse is also true of dwellings that are poorly insulated. In poorly insulated dwellings, additional heat input and/or air circulation fans may be required in order to achieve the desired mean elevated internal temperature. In extreme cases, it may even be necessary to reduce the mean elevated internal temperature in very poorly insulated dwellings, to reduce the potential for overloading the domestic ring main circuit. The converse is also true in very well insulated dwellings, where it may be necessary to increase the mean elevated internal temperature beyond 25°C. However, considerable care must be taken to ensure that the mean elevated internal temperature is not increased to such a level that it has an adverse effect on the building fabric.

Airtightness

42 In very airtight dwellings, such as those constructed to Passivhaus standards, the background ventilation rate may be so low that it takes 2 to 3 days for all of the air within the dwelling to be removed and replaced with ‘fresh’ air from outside. In such dwellings, it may not be possible to use a CO_2 dispersal system to disperse CO_2 into the dwelling and then measure the CO_2 decay over time. However, it may be possible to undertake decay measurements by simply measuring the CO_2 decay rate after the dwelling has been occupied for a short period of time.

Wind speed and direction

43 Wind speed and wind direction can have an impact on the results obtained from a coheating test. The effect that these will have on the test result will be dependent upon a number of factors. These include: the airtightness of the test dwelling, the distribution of the leakage paths within the dwelling, orientation of the dwelling, location and the effects of any sheltering.

[1] It should be remembered that solar gain can occur through opaque as well as transparent elements of the building fabric.

44 In some cases, it may be possible to account for wind speed by introducing wind speed as an additional independent variable within a multivariate linear regression analysis. However, our experience suggests that attempting to correct for wind speed and direction is inherently problematic due to the number of complex interrelated variables involved.

Drying out

45 It is important that the dwelling is sufficiently dried out prior to the commencement of the coheating test. If the dwelling is not sufficiently dry, then some of the heat input will be used to evaporate any residual moisture within the structure rather than heat the dwelling to the required mean elevated internal temperature. This will result in a higher heat input that would otherwise be required. In addition, in very airtight dwellings, any excess moisture generated during the heat-up phase may not be adequately ventilated during the test, potentially resulting in surface condensation and mould growth within the dwelling.

46 It is also important to realise that any residual moisture that is present within the structure will also have an impact on the thermal conductivity and heat loss attributable to various elements of the dwelling. The greater the amount of residual moisture present, the greater the thermal conductivity of the materials and the greater the corresponding heat loss.

47 In some cases, it may be possible to undertake a number of calculations to account for the effects of any residual moisture within the dwelling. However, our experience suggests that attempting to correct for moisture is not advised due to the number of complex interrelated variables involved.

Proportion of glazing

48 Dwellings that incorporate a large proportion of South-facing glazing may have rooms that are susceptible to overheating. Care needs to be taken to ensure that any excess heat in these rooms is adequately distributed around the rest of the dwelling. This is a particularly important issue with passive solar or Passivhaus dwellings. Alternatively, attempts should be made to ensure that the dwelling is tested in those months that have the lowest levels of solar insolation, notably December and January.

49 In dwellings that are very well insulated, care may even need to be undertaken if the dwelling incorporates a large proportion of East or West facing glazing, as these rooms on these orientations may also be prone to overheating.

Adjacent dwellings

50 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 party elements of construction (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 elevated internal temperature as the test dwelling. This can be achieved by installing additional fan heaters, air circulation fans, thermostatic controllers and temperature and humidity sensors in these spaces. In doing so, any heat loss through the party elements of construction that would have occurred due 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 party elements of construction, as heat loss will still occur if any thermal bypasses or thermal bridges in the construction exist.

51 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 important limitations. These are as follows:

a) The heat flux measured will relate to a particular point on the construction and may not be representative of that construction as a whole. It is therefore imperative that attempts are made to position the heat flux sensors such that they are likely to give as representative a value for that particular element of construction as possible. For instance, if the construction comprises a timber-frame stud wall, heat flux sensors should be positioned on both the studded and non-studded portion of the wall, so that the effects of thermal bridging through the timber stud can be taken into consideration.

b) If a thermal bypass is present in the construction, such as at the party wall, then the amount of heat flux measured by the heat flux sensors will be a function of the thermal bypass, rather than any temperature difference between the adjacent dwellings.

c) The heat flux measured by the heat flux sensors will relate only to the ΔT monitored. It may be that the heat flux will vary depending on the value of ΔT.

52 In very well insulated dwellings or in some apartments, the amount of heat loss may be so low that it is difficult to obtain a reliable coheating test result, due to the influence of various external factors, such as solar gains. In these circumstances, it may be more appropriate to maintain a constant temperature differential between the test dwellings and any adjacent dwellings or spaces to artificially increase the amount of heat loss.

Access to the dwelling during the coheating test

53 Throughout the test, entry to the test dwelling should be kept to a minimum and limited only to those times when adjustments are required to be made to equipment. If entry to the dwelling is required, it should be for as short a time as possible and the use of any electrical equipment within the dwelling, such as lights, should be minimised where possible. Any dates of entry to the dwelling should be recorded and referred to when analysing the coheating data, as entry to the dwelling may have an important impact on the result. This is particularly the case is the dwelling is very well insulated or has been designed to have a very low level of heat loss.

54 It is also important to realise that the coheating test described within this protocol is not a *'fit and forget'* test. Access to the test dwelling and any adjacent dwellings or spaces may be required during the test, particularly if additional measurement techniques, such as heat flux measurements, are been conducted at the same time as the coheating test. Data obtained from the coheating test should be downloaded and analysed at regular intervals, to ascertain that the test is still commencing as planned and that there are no issues associated with the data obtained. For instance, to ensure that all of the monitoring equipment is recording data as planned and to ensure that none of the rooms in the test dwelling are overheating. In some cases, it may even be necessary to undertake interventions during the coheating test, such as increase the mean elevated temperature within the test dwelling, to increase the amount of heat loss from the test dwelling.

Loading the domestic ring main

55 Care needs to be taken to ensure that if power is to be taken off the domestic socket ring main, it is not overloaded. In new multi-floor dwellings, one ring circuit is normally installed per floor and at least two ring circuits are normally installed in apartments. In the UK, the ring circuit is likely to be rated at 30 amps (7200 Watts) and will be protected by a 32 amp RCD connected to the consumer unit. In addition, each socket on the ring circuit will be rated at 13 amps. This will limit the number of items of equipment that can be connected to each ring main, particularly fan heaters which may be rated at 3kW each. If possible, it is advisable that adjustable output fan heaters and air circulation fans are used to limit the load on the ring main.

56 The consumer unit will also be limited to 100 amps. Although this is unlikely to be an issue in new build dwellings, it needs to be considered in older, leaky, poorly insulated dwellings, as it will limit the amount of electrical equipment that can be connected to the various ring mains within the dwelling.

PAT testing

57 All equipment used to undertaking a coheating test should have an up-to-date PAT test for electrical safety to ensure that they in a safe working condition.

Calculating the predicted heat loss

58 The results obtained from a coheating test are often compared with a predicted heat loss in order to establish if there is any discrepancy between the predicted and measured values. In order to undertake such a comparison, it is important that the prediction is as best an informed view as possible of what was actually built. The predicted heat loss should be calculated based upon the following:

a) A steady state analysis of the building.

b) The dimensions of the plane elements should be obtained from a measured survey of the building, rather than the dimensions contained within the SAP worksheets. In most cases, these are not quite the same.

c) The U-values for the plane elements of the building should be calculated using the protocols contained within BR443 for U-values (Anderson, 2006). They should also be based upon the data supplied by the designer/developer coupled with observations of what was actually built on-site, rather than the original design intent. This should hopefully capture any product substitutions that may have taken place.

d) The ventilation heat loss should include background ventilation only and should not include any purpose provided ventilation.

e) The quantification of thermal bridges should ideally be based upon an individual assessment of each thermal bridge within the building, rather than using an approximated y value. If this is not possible, then an appropriate y value should be used, rather than the default SAP worksheet figure of 0.15 if details of the thermal bridging are not known.

59 The prediction heat loss is frequently confused with the figure obtained from either design or as-built SAP worksheets. Although a number of the figures contained within these documents may be similar, they are not the same.

Equipment required

60 A number of items of equipment are required in order to be able to undertake a coheating test on a dwelling. The main items of equipment required within the dwelling to be tested (the test dwelling) are as follows:

a) **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 coheating test, as they can give an indication of whether the dwelling has been drying out during the test.

b) **Fan heaters** – These are used to heat the air inside the dwelling. A variable output model is preferred as it enables a degree of adjustment to be undertaken if required.

c) **Fire resistant mats** – These should be placed directly under the fan heaters to protect the flooring and for Health and Safety reasons. In some cases, it may be necessary to elevate the fan heaters off the ground by around 100mm to prevent hot spots occurring on the floor directly below the fan heaters

d) **Air circulation fans** – These are used to mix the internal air within the dwelling. A variable speed fan with an adjustable tilt is preferred as it enables a degree of adjustment to be undertaken if required.

e) **Thermostatic controller** – These will be pre-set to the mean elevated internal temperature and are used to control the heat output from the fan heaters.

f) **kWh meters** – These are used to measure the electrical energy consumption of all of the electrical equipment installed within the dwelling, such as fan heaters, the air circulation fans and the datalogger (if mains powered). The kWh meters are required to have a pulsed output that can be read by a datalogger. A transmitter may be required to transmit the pulsed output to the datalogger.

g) **Datalogger** – This is used to record the data obtained from all of the sensors installed 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 air circulation fans. The datalogger may also be used to record all of the data obtained from the external weather station.

h) **Extension leads** – These are used to supply mains power to the fan heaters and air circulation fans, as well as any other items of electrical equipment installed within the dwelling, such as thermostatic controllers or dataloggers that require mains power.

61 A wireless battery powered monitoring system with a mains-powered datalogger is the preferred option within the dwelling, as it removes the need for wiring between the various sensors and the datalogger. This enables unrestricted layout and flexibility in the placement of the sensors and the various items of equipment within the dwelling. It is also advantageous to use a system where the data stored on the datalogger can be accessed remotely, i.e. without access having to be gained to the dwelling. The advantage with such a system is that data can be downloaded as frequently as possible without entry having to be gained to the test dwelling.

62 A photograph illustrating the main items of coheating test equipment installed within a test dwelling can be seen in Figure 8.

Figure 8 Main items of test equipment installed within a test dwelling.

63 It is important to note that additional items of equipment, such as transmitters, modems, etc. may also be required within the test dwelling depending upon the type of monitoring equipment used. Various items of equipment may also need to be installed within any adjacent dwellings (sometimes termed control dwellings), particularly if the intention is to achieve isothermal conditions across any party elements of construction.

64 In addition to the above items of equipment, additional equipment is also required to be installed externally in order to collect external weather data. The amount of weather data that can be collected for the coheating test can vary, but generally consists of measurements of external temperature and relative humidity, vertical South facing solar radiation, wind speed and wind direction, barometric pressure and rainfall. In order to obtain this data, the following items of equipment are required:

a) **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, particularly the wind speed and direction sensor, can give invaluable insights when analyzing the data obtained from the coheating test.

b) **Pyranometer** – This is used to measure the vertical South facing solar radiation flux density in W/m^2.

c) **Datalogger** – A separate dedicated datalogger for the weather station (including the 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 in addition to all of the inputs from the sensors located within the dwelling. If a wireless system is used, it may also be dependent upon the proximity of the weather station to the dwelling.

65 A photograph illustrating the weather station can be seen in Figure 9.

Figure 9 **Coheating test weather station installed on a gable wall.**

Location and numbers of equipment

66 The location and number of items of equipment required to undertake a coheating test will vary and will be dependent upon a number of factors. These include the size, the form, the internal layout and the thermal performance of the dwelling. The location and numbers of equipment that are likely to be required in a typical detached dwelling are as follows:

a) **Temperature and relative humidity sensors** – Ideally a temperature and relative humidity sensor should be installed in all of the habitable areas within the dwelling (living room, dining room, kitchen, bedrooms, toilets, bathrooms, en-suites, hallways, etc.). However, this is not always practical, particularly in large dwellings. In this instance, an appropriate number of sensors should be installed to ensure that a realistic measure of mean elevated internal temperature is obtained. They should be distributed throughout the dwelling in such a manner that they are capable of giving an indication of whether the mean elevated internal temperature is being achieved throughout the dwelling or not. Typically, they would be located in the living room, kitchen, hall, master bedroom and bathroom. The sensors also need to be strategically positioned within each room to avoid direct sunlight and to minimise direct heating from the fan heaters or direct air movement from the air circulation fans.

b) **Fan heaters** – The number and positioning of fan heaters will depend upon the size and form of the dwelling. It may be necessary to reduce or increase the number of fan heaters during the warm up period in order to maintain a stable mean elevated internal temperature. It may be possible to split the dwelling into a number of zones, and install a fan heater or number of fan heaters in each zone. The fan heaters should be connected to the extension lead output of the kWh meter and positioned in such a way as to provide as much heating to the zone as possible. They should be strategically positioned to avoid blowing air directly onto any external or party elements of the building fabric or other items of measurement equipment, such as heat flux sensors. Care should also be taken when selecting and installing the fan heaters to ensure that they do not overload the ring circuit that they are connect to and trip out the consumer unit if all the fan heaters and air circulation fans were switched on at once.

c) **Fire resistant mats** – A fire resistant mat should be installed below every fan heater.

d) **Air circulation fans** – Enough air circulation fans should be installed per dwelling to ensure a consistent mean elevated internal temperature and to avoid heat stratification. The air circulation fans should be connected to the extension lead output of the kWh meter and located to provide good mixing of the air within the dwelling. They should also be strategically positioned to avoid blowing air directly onto any external or party elements of the building fabric or other items of measurement equipment, such as heat flux sensors. Additional air circulation fans may be required if adequate mixing of the air throughout the dwelling cannot be achieved or to prevent overheating of rooms in dwellings that have a large proportion of South facing glazing.

e) **Thermostatic controllers** – One thermostatic controller is required per fan heater. The thermostat should be located at working plane height (approximately 0.85m above ground level) and be installed in-line with the fan heater. The thermostat should also be strategically positioned to avoid direct sunlight and to minimise direct heating from the fan heaters or direct air movement from the air circulation fans.

f) **kWh meters** – One kWh meter should be installed in-line with any extension lead that supplies power to the fan heaters, air circulation fans and datalogger. The number of kWh meters required will be dependent upon the number and location of fan heaters, air circulation fans and datalogger within the test dwelling.

g) **Datalogger** – At least one datalogger will be required per dwelling. If mains powered, it should be connected to the extension lead output of one of the kWh meters.

h) **Extension leads** – At least one extension lead will be required per kWh meter. Additional extension leads may be required depending upon the numbers of equipment installed that require mains power. If additional extension leads are required, a kWh meter will have to be installed in-line to measure the electrical energy consumption of any appliances connected to the lead.

i) **Weather station** – One weather station will be required which should be mounted horizontally above ground level on a mast. It should be positioned to avoid any possible overshading or sheltering. If possible, it is advised to install the weather station on the test dwelling.

j) **Pyranometer** – One pyranometer will be required to be mounted vertically above ground level on a mast. It must be South-facing and positioned to avoid any possible overshading. If possible, it should be installed on the same mast as the weather station.

67 If additional tests are being undertaking at the same time as the coheating test, such as heat flux measurements, additional monitoring equipment may be required to be installed externally or in any control dwellings.

68 It should be noted that the location of the equipment within the rooms is not an exact science and is likely to involve a degree of trial and error. It is not uncommon to have to move equipment around or adjust equipment during the early stages of a test to achieve even temperatures throughout the dwelling.

Test procedure

69 Prior to undertaking the coheating test, a pressurisation test should be performed on the dwelling. The pressurisation test should be carried out in accordance with ATTMA Technical Standard L1 (ATTMA, 2010).

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

a) 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 consumer unit 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.

b) All trickle vents, acoustic vents and mechanical supply/extract vents need to be adjusted to the closed position or temporarily sealed.

c) All flues and fire places need to be temporarily sealed.

d) All water traps and U-bends in kitchens, bathrooms, en-suites and toilets need to be filled with water. These will need to be topped-up throughout the test period due to evaporation.

e) All external doors and windows should be inspected to ensure that they are tightly closed.

f) 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.

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

a) Adjust all of the thermostatic controllers to the mean elevated internal temperature setpoint, say 25°C.

b) Switch on all of the fan heaters and adjust them such that they are operating on an appropriate heat and fan speed setting.

c) Switch on all of the air circulation fans and adjust to an appropriate angle.

d) Switch on the CO_2 gas dispensing system.

e) Activate all of the dataloggers to record the internal and external data at an appropriate interval, say 10 minutes.

f) Observe the CO_2 concentrations for the first couple of days to ensure that the gas dispensing system is capable of producing a relatively constant concentration of CO_2 gas throughout the dwelling each day before the dispensing system is switched off and the decay of the gas is monitored.

g) 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 thermostatic controllers (say 25°C).

h) 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.

i) If the mean internal temperature observed throughout the dwelling is not uniform, increase the heat input from the fan heaters 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 air circulation fans. It may also be necessary to adjust the speed of the air circulation fans, alter the angle of the air circulation fans or add additional air circulation fans and fan heaters.

j) 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 elevated internal temperature.

k) 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 (ΔT's) are recorded. As a minimum, this should be for at least one week, but preferably two or three.

l) Download the data from the datalogger/s daily and analyse the data.

72 After completion of the coheating a test, a second pressurisation test should be undertaken on the dwelling once the dwelling has been allowed to cool down. The result from this test should be combined with the pressurisation test result obtained immediately prior to the undertaking the coheating test, to determine the average air leakage rate for the dwelling over the period of the test. This figure can then be used to give an estimate of the background ventilation rate for the dwelling using the n/20 *'rule of thumb'*.

Combining techniques

73 Although the coheating test is a very important tool for measuring whole dwelling heat loss, the results obtained by undertaking the test in isolation have limited value on their own. The result can be used to make comparisons between the as-built measured heat loss and the designed heat loss, but if any discrepancy in performance is identified, it is not possible to be able to identify the reasons why such a discrepancy occurs.

74 It is possible to gain a much richer insight and understanding of the principal heat loss mechanisms that are occurring within a particular dwelling, if the co-heating test is combined with other fabric measurement techniques. In fact, the mean elevated internal temperatures experienced during a co-heating test give favourable conditions for undertaking specific diagnostic techniques, such as a survey of the dwelling using an infrared thermal imaging camera. Other measurements techniques that may be used during a coheating test include: pressurisation tests, leakage detection, tracer gas measurement, cavity temperature measurement, heat flux measurement, thermal imaging, partial deconstruction, differential pressure and air flow measurements, design assessment and site observations. By combining these techniques with the coheating test, a *'forensic'* style investigation of the dwelling can be undertaken.

Alternative test procedure

75 The test procedure described within this protocol is just one method that can be used to undertake a coheating test. Another approach that is currently under development at Leeds Metropolitan University is a simplified whole house heat loss (coheating) test procedure. In this method, the test dwellings installed heating system and thermostatic control is used to maintain the dwelling at the mean elevated temperature, rather than portable electric resistance fan heaters and thermostatic

controllers. Various devices are used to measure the amount of energy consumed by the installed heating system to maintain the mean elevated internal temperature over the test period. In addition, much simpler and cheaper temperature and humidity sensors are used within each of the rooms in the dwelling. As such, this protocol is more of a *'fit and forget'* test, than the existing procedure described within this protocol.

References

ANDERSON,B. (2006) Conventions for U-value Calculations: 2006 Edition. BR443:2006 Garston, Watford, UK, BRE Press.

ATTMA (2010) ATTMA Technical Standard L1. Measuring the Air Permeability of Building envelopes (Dwellings). October 2010 Issue. Northampton, UK, Air Tightness Testing and Measurement Association.

DECC (2011) Statistical Release. UK Climate Change Sustainable Development Indicator: 2010 Greenhouse Gas Emissions, Provisional Figures and 2009 Greenhouse Gas Emissions, Final Figures by Fuel Type and End-user. [Internet]. London, Department of Energy & Climate Change. Available from: <http://www.decc.gov.uk/assets/decc/Statistics/climate_change/1515-statrelease-ghg-emissions-31032011.pdf> [Accessed January 16th, 2012].

Everett, R. Horton, A. and Doggart, J. (1985). Linford Low Energy Houses. Milton Keynes, UK, Energy Research Group, Open University.

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

Sonderegger, R. C. Condon, P. E. and Modera, M. P. (1979a) In-situ measurements of residential energy performance using electric co-heating. ASHRAE Transactions, Vol. 86 (I), 1980. LBL-10117.

Sonderegger, R. C. and Modera, M. P. (1979b) Electric co-heating: A method for evaluating seasonal heating efficiencies and heat loss rates in dwellings, In Proceedings of the Second International CIB Symposium, Energy Conservation in the Built Environment, Copenhagen:1979. LBL-8949.

Subbarao, K. Burch, J. D. Hancock, C. E. Lekov, A. and Balcomb, J. D. (1988) Short-Term Energy Monitoring (STEM): Application of the PSTAR Method to a Residence in Fredericksburg, Virginia. TR-3356. Colorado, USA, Solar Energy Research Institute.

Wingfield, J., Bell, Miles-Shenton, D., South, T and Lowe, R.J. (2009) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Final Report: Lessons From Stamford Brook - Understanding the Gap between Designed and Real Performance, PII Project CI39/3/663. Leeds, UK, Leeds Metropolitan University.

Zero Carbon Hub (2010) Closing the performance gap: Building low carbon housing for real. Report of Topic Work Group 4, Carbon Compliance Tool Policy Assumptions Task Group. July 2010, Milton Keynes, UK, Zero Carbon Hub.