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Analysis of the EST's domestic hot water trials and their implications for amendments to BREDEM and SAP

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Introduction

The results of recent trials of domestic hot water use have been described in some detail in a report to the EST prepared by Chris Martin of the Energy Monitoring Company[1] .

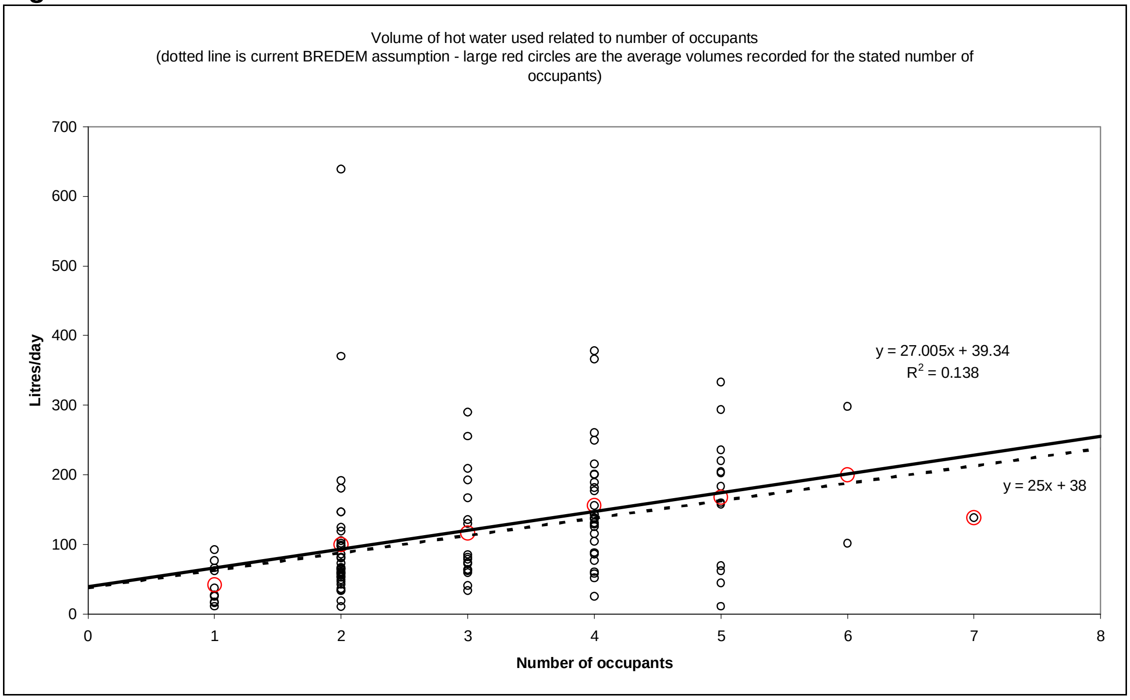
The present note takes the analyses further using the actual data (in summarised form) as supplied by Chris Martin, with the aim of identifying key features shown by the data which it might be sensible to incorporate in an amended BREDEM procedure.

Data are available for 112 dwellings. Of these 68 have regular boilers, 39 have combi boilers, 3 have no boiler, 1 has a multipoint and for 1 it is unknown what form of water heating is present. For the following analyses data for all 112 dwellings has been used.

The analyses have been presented in terms of a series of questions to which we require answers in order to develop BREDEM. This then leads to a proposal for a new procedure and this is tested against the data along with the existing BREDEM procedure.

How does the volume of hot water used relate to the number of occupants?

Figure 1



[1] Measurement of Domestic Hot Water Consumption in Dwellings. Prepared by Chris Martin, Energy Monitoring Company for the Energy Saving Trust. March 2008.

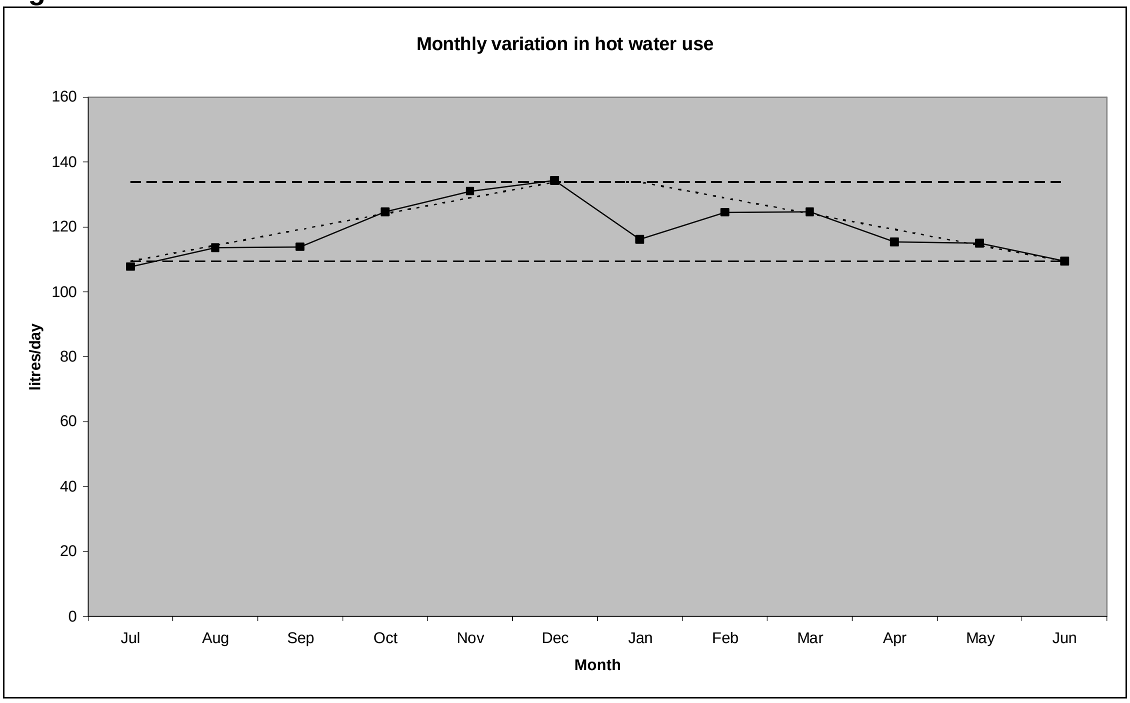
The report to EST concluded that number of occupants was the best variable to use for identifying the volume of hot water usage. Even so, it can be seen from Figure 1 that there is a large variation in the volume use for any particular number of occupants. All that we can hope to do in BREDEM is to develop a relationship that reflects the average position. As the figure shows, the linear trend line implied by the data (all 112 dwellings) is actually very close to what BREDEM already assumes. Only a small change is needed to the model in this respect. Indeed, there is an argument for not altering the BREDEM equation at all because it is so close to the trend line (bear in mind also that the trend line alters as subsets of the data – such as homes with boilers only – are examined, so there is actually no uniquely “correct” equation implied by the data).

Nonetheless, Figure 1 suggests that we should consider altering the volume relationship from 38+25N (N = number of occupants) to 39+27N litres per day (but see later – there is a reason why we should further alter this to 35.5+24.5N – or when rounded, to 36 + 25N).

Does the volume usage vary with month?

Figure 2 shows the average volume use by month (note: all seasonal analyses use data for the period July 06 to June 07. There is some data outside this 12 month period but a data availability check clearly shows that if we use just one 12 month period for looking at seasonal variations then this is the best one to use – see Figure 3).

Figure 2

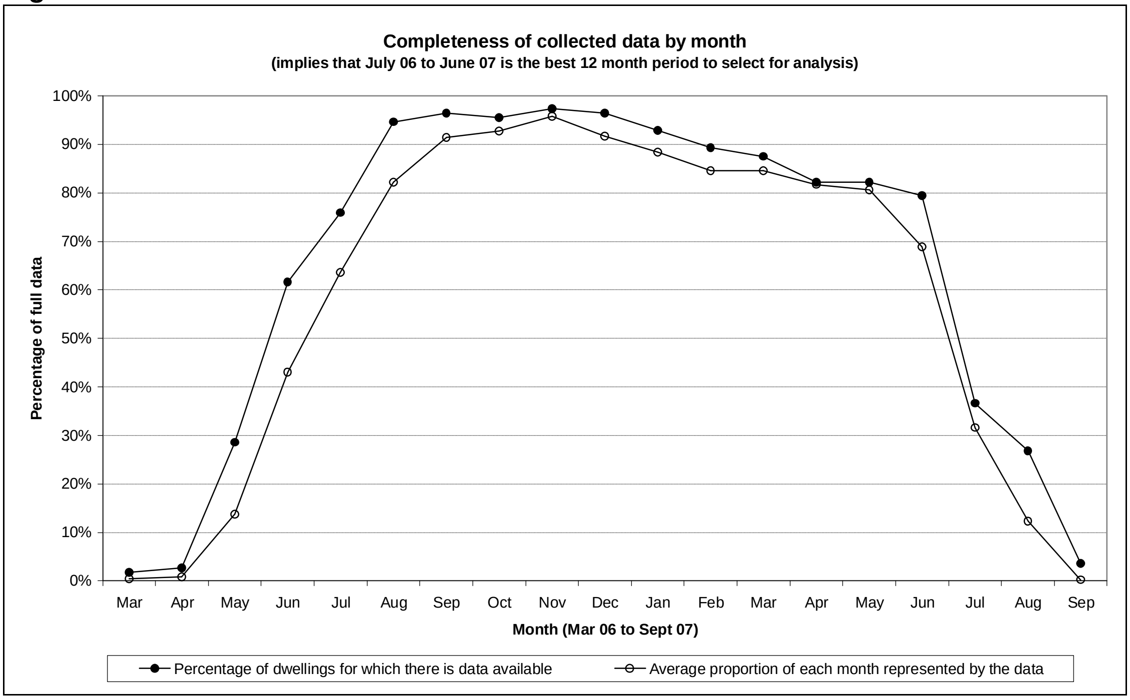


The horizontal dotted lines represent +/-10% variation from the average hot water volume use across the 12 months. Thus it appears, apart from the anomaly in January, that there is a fairly well defined small seasonal effect of +/10% on volume use. Less hot water is used in the summer than the winter. The dotted line shows a suggested profile that could be used in BREDEM to capture the seasonal variation. This is simply a series of month by month factors to apply to the annual use which will still give the same annual volume use and which produces a profile that roughly matches the observed variation:

Table 1

Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
0.9	0.94	0.98	1.02	1.06	1.1	1.1	1.06	1.02	0.98	0.94	0.9

Figure 3



As noted above, Figure 3 shows that the period July 06 to Jun 07 is the best 12 month period to select for analysis when considering seasonal effects. Outside of this period the amount of available data falls off considerably.

Does the cold feed temperature vary with month?

Currently in BREDEM it is assumed that the cold feed temperature is determined by the ground temperature and that this does not vary markedly across the year (it is assumed fixed at 10^{o}C, relative to a delivery temperature of 60^{o}C – i.e. a temperature rise of 50^{o}C is used).

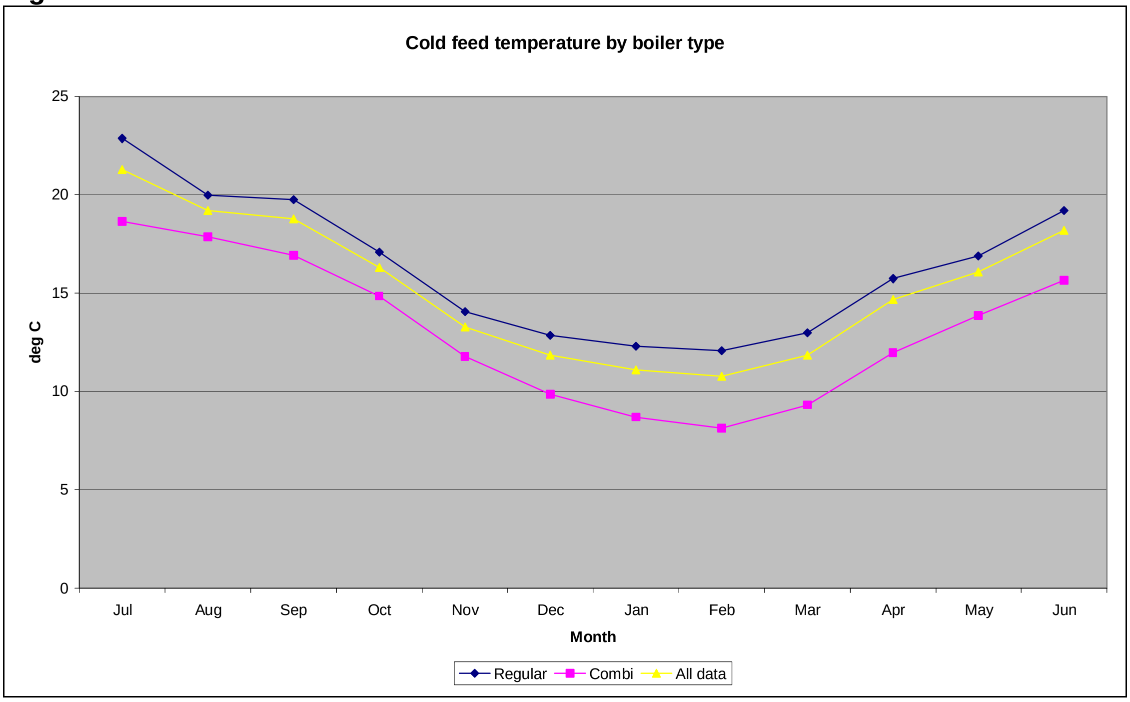
The monitoring has shown that this is actually not true at all, as illustrated in Figure 4. There is a strong seasonal trend in the feed temperatures. Moreover, there is a distinct difference between the feed temperatures for regular boilers and for combi boilers. As the figure illustrates, regular boiler feed temperatures are about 1^{o}C higher than the overall average, and combi boiler feed temperatures are about 2^{o}C lower than the overall average. Over the whole year the average feed temperatures, in ^{o}C, were actually as follows:

Table 2

All	15.3
Regular	16.3
Combi	13.1

This can be readily understood as being related to the fact that the feed to a combi boiler comes straight off the mains, whereas the feed to a regular boiler comes from a cold water storage tank and the water in the tank will warm up slightly (by about 3^{o}C based on the difference between the combi and regular boiler figures).

Figure 4



Although the cold feed temperatures differ for regular and combi boilers there is actually no need to consider this directly in BREDEM because more-or-less the same differences are also reflected in the achieved average delivery temperatures (which, note, are considerably lower than the existing BREDEM assumption):

Table 3

All	52.2
Regular	52.9
Combi	50.0

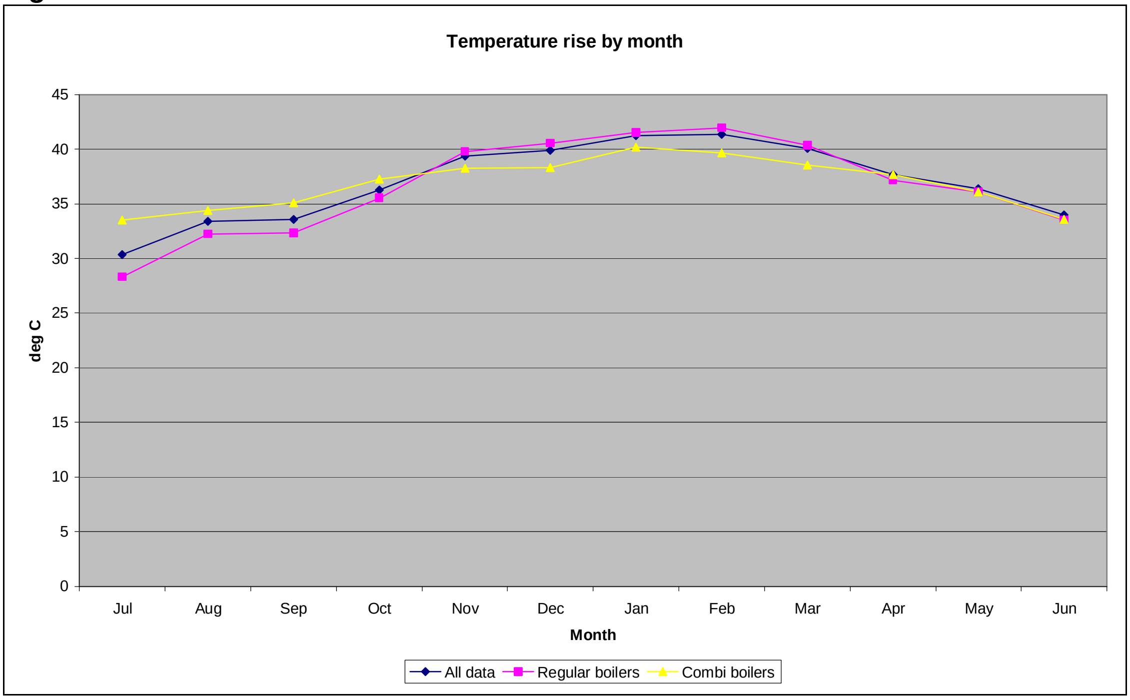
In other words, it is the temperature rise that we should specify in BREDEM, since the data indicates that this is essentially the same regardless of the boiler type. It varies by month as follows:

Table 4

	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Average
All data	30.38	33.40	33.55	36.29	39.37	39.90	41.23	41.35	40.07	37.65	36.36	33.94	36.96
Regular	28.33	32.23	32.33	35.52	39.79	40.55	41.50	41.95	40.33	37.16	36.07	33.53	36.61
Combi	33.53	34.38	35.08	37.24	38.24	38.29	40.21	39.64	38.53	37.67	36.07	33.55	36.87

As can be seen from this table there are some small differences between the temperature rises by boiler type when looked at on a monthly basis but there is no clear pattern to them - and over the entire year they are more-or-less identical. As the following chart illustrates, use of the “all data” temperature rises seems entirely sensible as a way of capturing seasonal variations within BREDEM.

Figure 5



What is the relationship between temperature rise and cold feed temperature?

It is interesting to consider a little more closely the relationship between the temperature rise and the cold feed temperature. The following chart illustrates this for the average across all the data, on a month-by-month basis. It shows exactly what would be expected if the delivery temperature is being controlled, on average, to 52.2^{o}C (i.e. the intercept – compare with the value in Table 3). The slope of -1 just indicates that for each degree by which the feed temperature falls, the temperature rise has to increase by one degree.

Trying a similar analysis for regular and combi boilers separately does not work so well, partly because of the reduced numbers of cases. Nonetheless, Figure 7 suggests that the results are at least roughly consistent with the same slope but with the line displaced downwards by about 2^{o}C for combi boilers and upward by about 1^{o}C for regular boilers, reflecting the different feed and delivery temperatures.

Figure 6

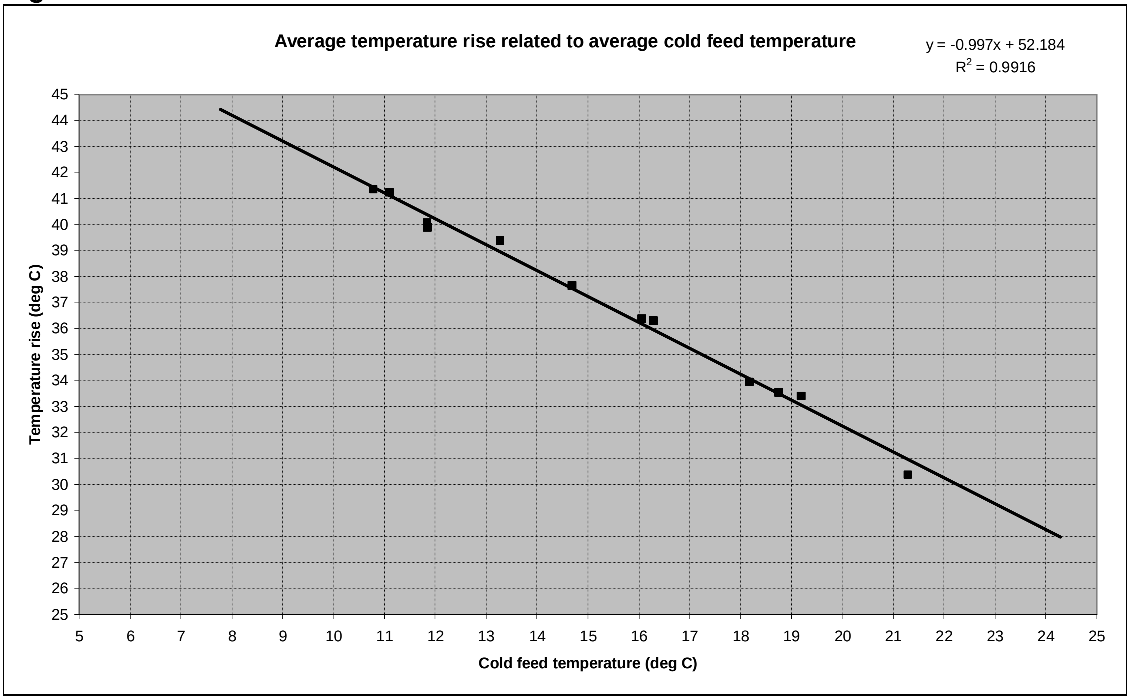
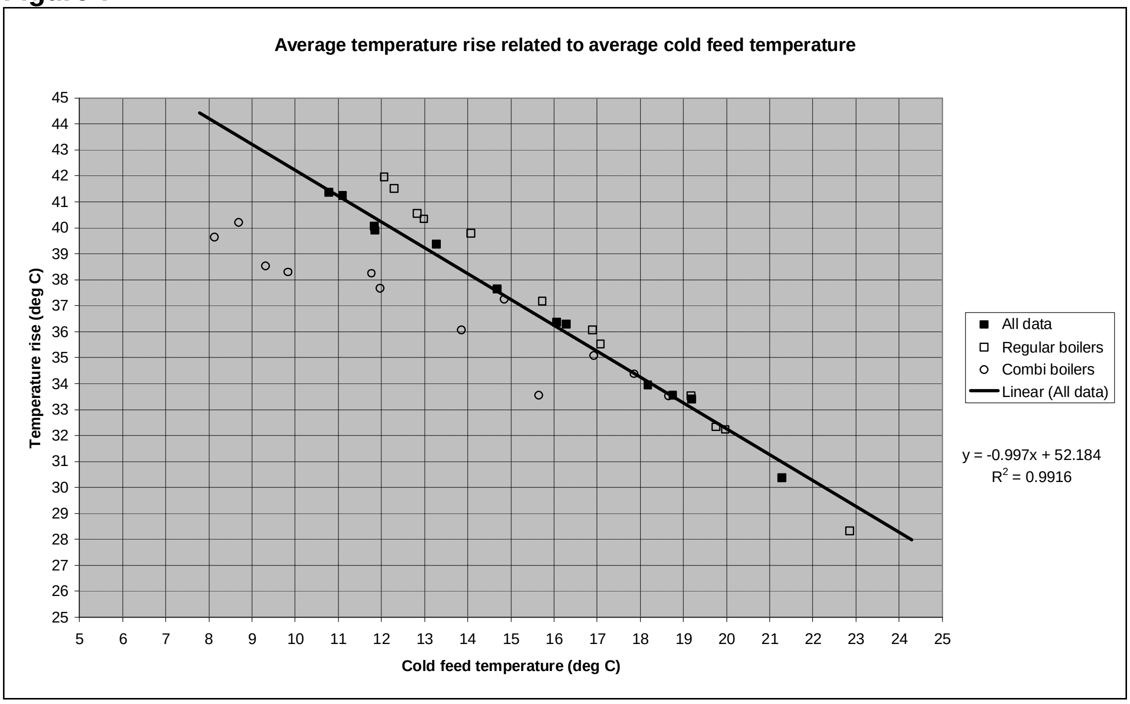


Figure 7

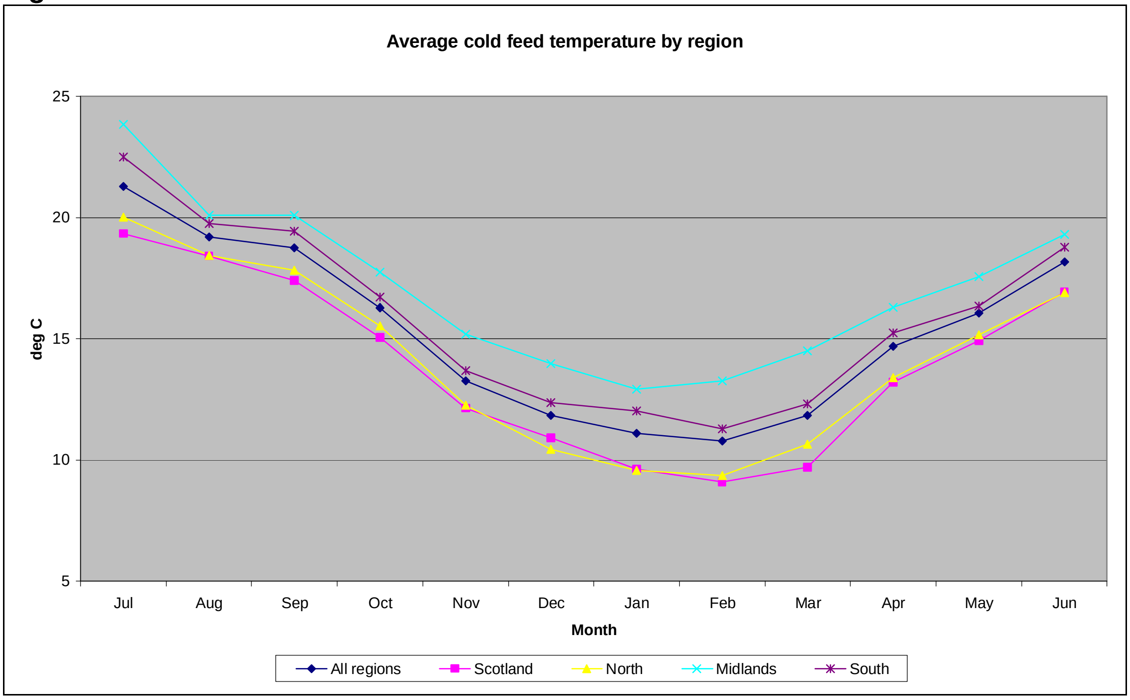


Does the feed temperature (and hence the temperature rise) vary by region?

It might be expected that cold water feed temperatures differ slightly according to the region of the country. If so, we might consider this as an additional variable in BREDEM. The data can only be analysed by very broad regional categories of Scotland, North, Midlands and South (with sample sizes of 19, 31, 17 and 45 respectively) but it does show broadly what might be expected.

Feed temperatures in Scotland and the North are about 1°C lower than the average. Those in the Midlands are about 2°C higher and in the South are about 0.5°C higher. Thus, in BREDEM, the temperature rises shown for all data in Table 4 could be increased by 1°C for homes in Scotland and the North, and decreased by 2°C and 0.5°C for homes in the Midlands and South respectively.

Figure 8



A plot like that of Figure 7 but splitting out the data by region is shown in Figure 9. This rather suggests that the same relationship between feed temperature and temperature rise applies regardless of region (i.e. the same delivery temperatures are being achieved on average), but there is evidence for lower temperature rises (and hence delivery temperatures) in Scotland (however, bear in mind the small sample size). In fact, average delivery temperatures were as follows:

Table 5

Scotland	48.46
North	52.15
Midlands	52.26
South	53.01

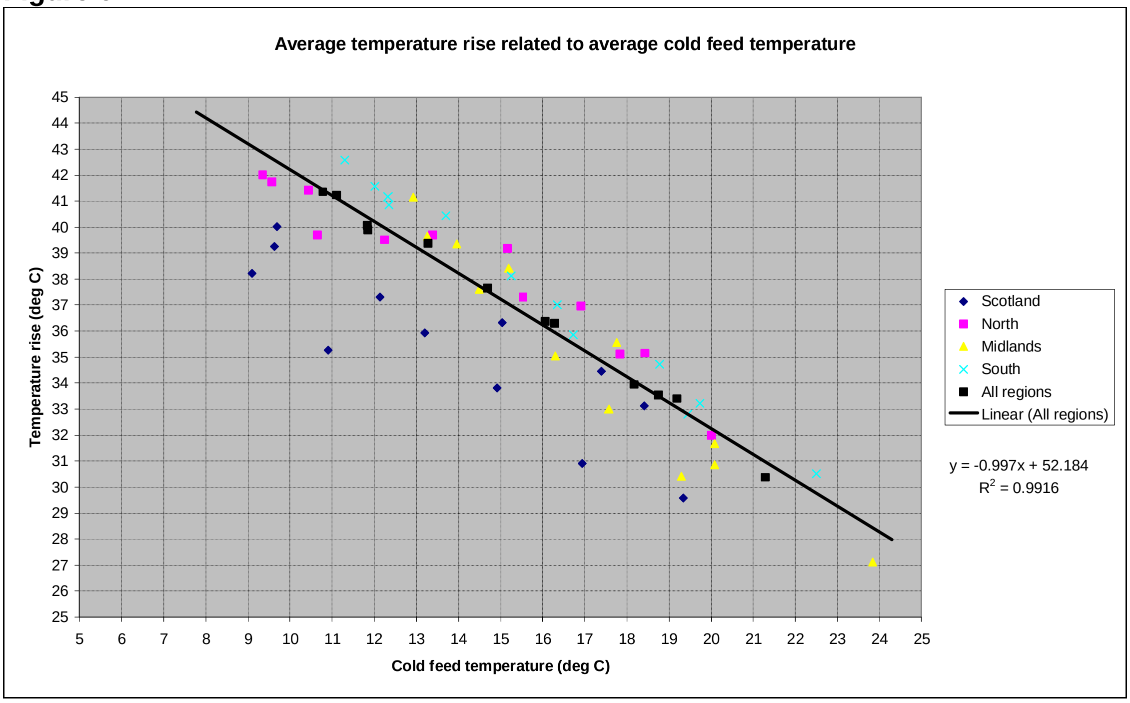
Note, however, that interpretation of these figures is confused by the fact that the mix between regular and combi boilers (and other systems) differed quite markedly between the regions:

Table 6

	Combi %	Regular %	Other %
Scotland	42%	53%	5%
North	65%	32%	3%
Midlands	29%	71%	0%
South	13%	80%	7%
All regions	35%	61%	4%

This indicates that we probably should not be reading too much into the cold feed variations between regions (or, indeed, between boiler types). Moreover, if we were to introduce a regional variation into BREDEM we would need figures for every degree day region and we do not have such figures. Given this, it is suggested that BREDEM simply use the temperature rises already identified (Table 4 "all data" figures) and that no attempt be made to refine these by region.

Figure 9



Proposed BREDEM procedure for domestic hot water

The proposed procedure based on the preceding analysis of the data is as follows. Note that this only goes as far as calculating the energy that was required to heat the hot water that has been used. It takes no account of the efficiency with which the water was heated. That is the subject of separate work which will in due course be combined with the current analyses.

1. Calculate the average litres per day of hot water used according to

   $$Vol = 39 + 27N$$

   where N is the number of occupants.

   (note that there is a reason why this should be modified to Vol = 36 + 25N. See next section)

2. Calculate the average litres per day in each individual month (Vol_m) by multiplying Vol by the following factors

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1.10	1.06	1.02	0.98	0.94	0.90	0.90	0.94	0.98	1.02	1.06	1.10

3. For each month, calculate the energy content of the hot water used (Q_m) as follows

   $Q_m = Vol_m\ N(m)\ \rho\ c\ \theta_m$ (joules)

   Where N(m) is the number of days in the month
   ρ is the density of water (1 kg/litre)
   c is the specific heat capacity of water (4190 J/kg K)
   θ_m is the required temperature rise (^{o}C) in each month, tabulated below

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
41.2	41.4	40.1	37.6	36.4	33.9	30.4	33.4	33.5	36.3	39.4	39.9

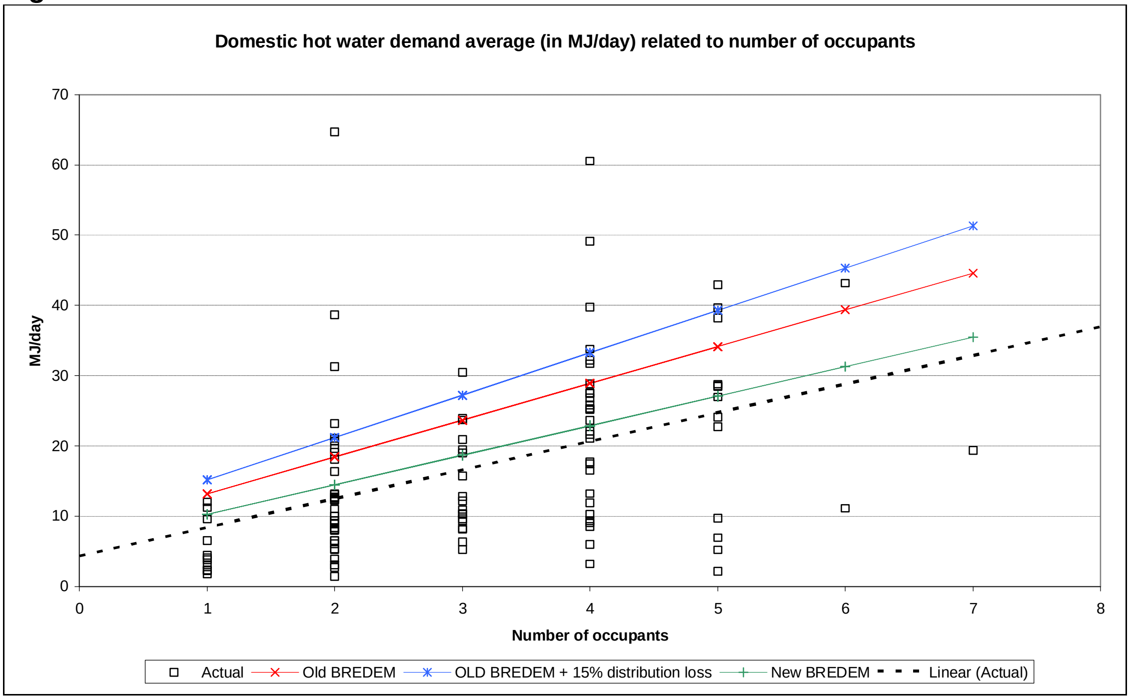
Note: If a simple annual calculation is required, omit step 2, calculate step 3 using a temperature rise of 37.0^{o}C, and set the number of days to 365.

How well does the proposed procedure compare with the monitoring?

The energy content of the hot water was also determined in the trials so we can compare the annual and monthly predictions of the BREDEM model with the monitoring. Figure 10 shows the result of an annual comparison (expressed in MJ/day because that is the most convenient comparison with the monitoring results). The monitored data is plotted against number of occupants and a trend line is shown. Also shown are the predictions of the existing BREDEM procedure and those of the proposed new procedure.

There are two lines for the existing BREDEM procedure – one that excludes and one that includes the 15% that is added on to account for distribution losses between tank (or combi boiler outlet) and tap. Note that there is no need to add such losses on for the proposed new version of the procedure because the monitoring of delivery temperature was done at the tank (or combi boiler outlet) so, by definition, any such losses are already accounted for in the energy calculation (of course, they can still be added on to the incidental heat gains, although there is an argument that any such gains will be balanced out by heat losses to the cold water distribution system).

Figure 10



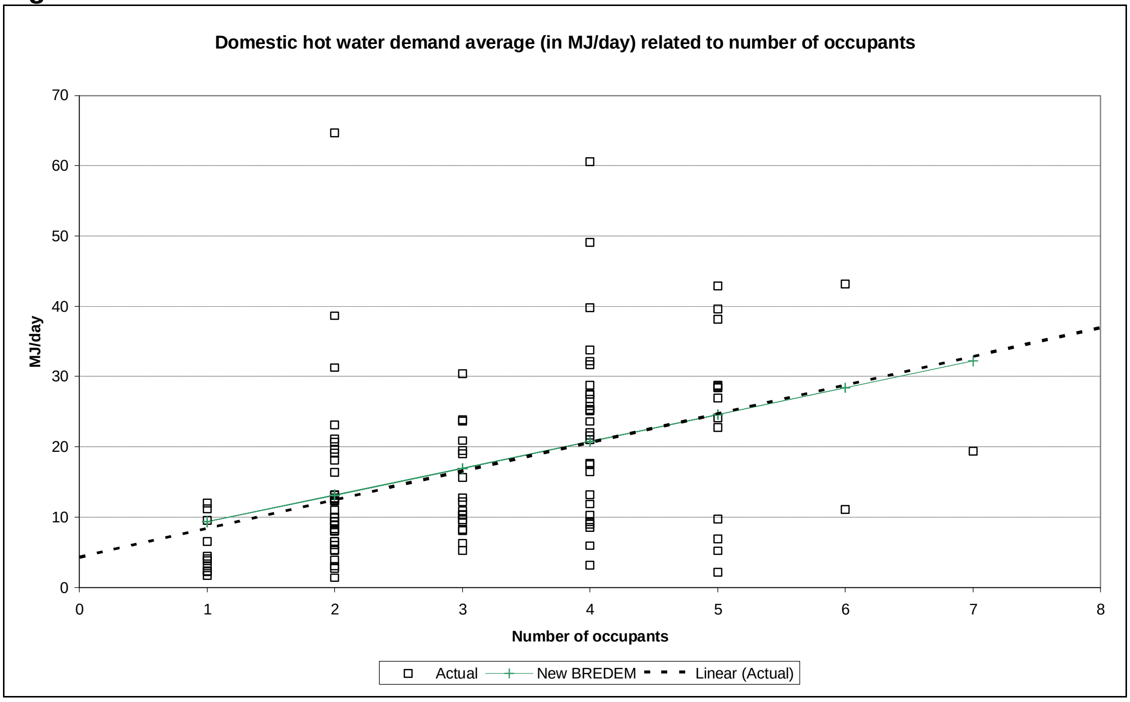
It is clear that the new BREDEM predictions are quite close to the trend line through the data and they are a marked improvement on the existing BREDEM predictions (the upper blue line representing the figures that would actually be used in practice).

There appears to be a fairly constant offset between the new BREDEM predictions and the trend line. This is probably related to the fact that the energy calculations using the monitored data were undertaken using data at 5 second intervals and so they counted all of each draw-off (i.e. including any low temperature parts of each draw-off) whereas the average delivery temperatures were determined allowing time for any cold water in the pipe to first be flushed away. In other words, using the recorded mean temperatures with the total volume will probably very slightly over-state the energy content. The over-statement in any particular case will depend on the draw-off pattern. Where there are a lot of short draw-offs it would be larger. Conversely, where there are fewer and larger draw-offs it would be smaller. The data indicate a very wide range of values but suggest that typically the over-statement is about 10%.

Thus it is necessary to modify the volume use assumption by dividing the equation by 1.1 – i.e. modifying it to 35.5 + 24.5N (which we would round to 36 + 25N).

Figure 11 illustrates the effect of this correction to the proposed procedure.

Figure 11



To illustrate the month by month predictions of the model, and how these compare with what has been measured, Figure 12 shows an example of just one dwelling (chosen simply because the annual prediction was fairly close to the BREDEM prediction, thereby facilitating a direct comparison, but not otherwise selected for any particular reason). This does not include the modification to volume use referred to above.

The dwelling used for the comparison is actually a 3 bedroom terraced house with 5 occupants and a regular boiler, located in the South. It can be seen from Figure 12 that the predicted seasonal variation is reasonably similar to what happened in practice in this dwelling.

To further illustrate the seasonal variation Figure 13 shows how the new BREDEM procedure, when averaged across all dwellings, compares with the measurements averaged across all the dwellings. This time, two options have been shown – using either the 39+27N equation or the 35.5+24.5N equation for the volume of hot water. It will be seen that the latter agrees rather better, as would be expected from Figure 11.

The measurements show a curious flattening in mid-Winter. This is probably related to the anomalously low hot water use figure for January previously shown in Figure 2. Viewed over the whole year, however, the amended BREDEM proposal agrees rather well with the measurements.

Figure 12

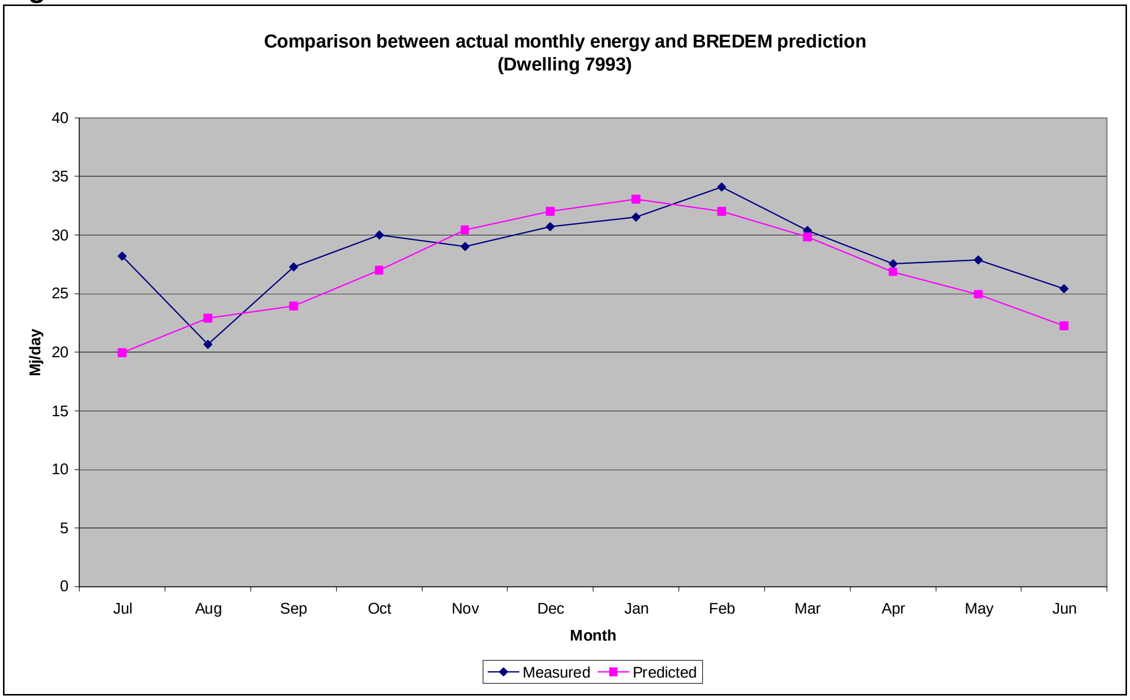
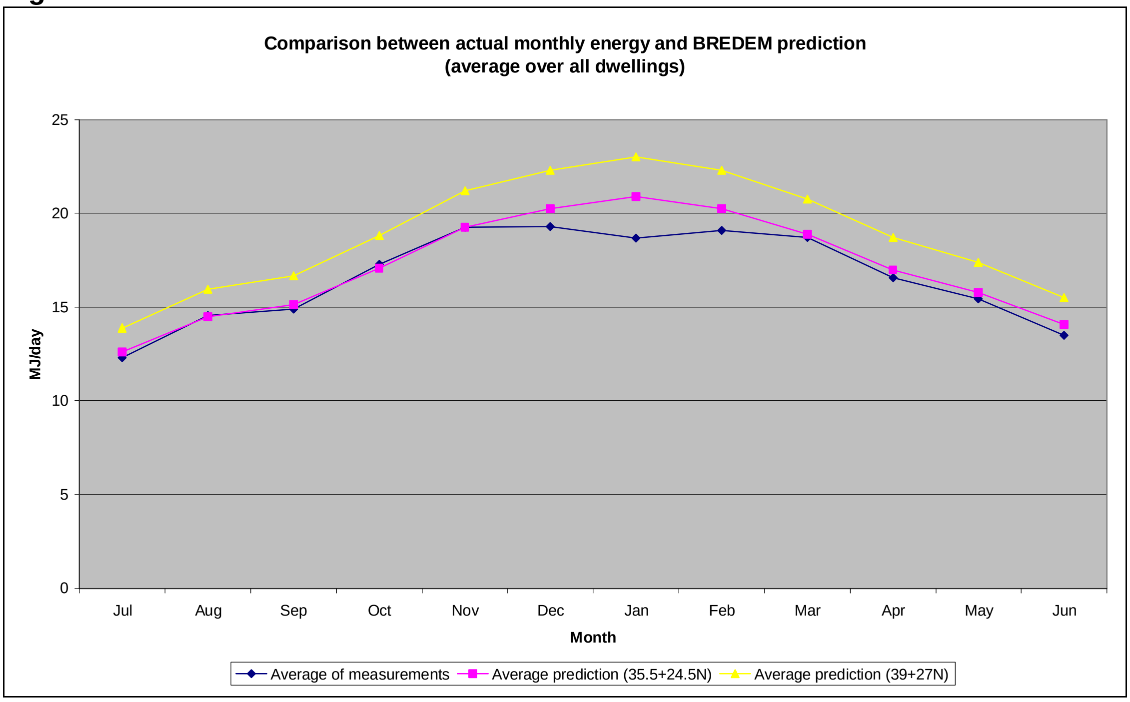


Figure 13



Conclusions and further considerations

Using data from the domestic hot water trials a proposal for a revised procedure for BREDEM has been derived. This has been shown to match the trial results quite well.

As Figure 10 has shown, the proposed new procedure will result in significantly lower estimates of the energy used to heat hot water than those obtained from BREDEM currently (about 68% of the existing model if the 39 + 27N relationship is used and about 62% if the 36 +25N relationship is used).

However, this is before any consideration of the efficiency with which the water is heated. If other work reveals that water heating efficiencies are significantly lower than we currently assume the delivered energy use might not actually be much lower than what BREDEM currently suggests.

For the purposes of SAP, the findings presented here will need to be considered in conjunction with the work on the relationship between floor area and number of occupants and doing this may suggest a need for some further adjustments.

Appendix – Heat gains from the hot water system

There are four sources of internal gains relating to the hot water system:

- Storage losses, Q_t
- Primary pipework losses, Q_p
- Distribution losses, Q_d
- Heat from the hot water at point of use

In the existing version of BREDEM the last two of these are taken to depend on the demand for hot water and, because the demand is not altered by month, a single value applies. This clearly needs to be re-examined now that a monthly variation of demand is being proposed, based on the evidence of the field trials.

Storage losses probably should not depend on the hot water demand to any great extent because it is likely that a full tank of hot water will always be heated regardless of any small variations in the amount of hot water that is actually drawn off (just +/-10% being the variation we are concerned with here). ***Thus the existing BREDEM procedure for calculating storage losses, Q_t, should be retained.***

It seems logical that variations in the amount of hot water used would also be reflected in varying primary pipework losses. However, it is not immediately obvious that the relationship would be direct. Also, given that the variation in water use is small anyway, and that there are no suitable measurements available, there is no reason for altering the existing assumption. ***Thus the existing BREDEM annual primary pipework losses, Q_p,should be retained and should be distributed across the months simply according to the number of days in the month.***

Distribution losses are assumed in BREDEM to be 15% of the energy leaving the tank. This is currently expressed as 17.6% of the energy at the tap, because of the assumption that the energy use calculations relate to the tap rather than the tank. The monitoring on which the new BREDEM proposals are based was very clearly at the tank (or the combi boiler outlet) and so the 15% figure should apply. ***Thus, the distribution losses, Q_d, in each month should be determined on the basis of the energy use calculation (as presented on page 10 of this note – using the Vol = 36 +25N assumption - but converted from joules into Watts) multiplied by 0.15.***

It is currently assumed in BREDEM that 80% of the gains from the storage tank, the primary pipework and the distribution pipes will be useful. There seems no reason to alter this assumption. **Thus, the gains from these sources are 0.8 ($Q_t + Q_p + Q_d$).**

A large proportion of heat from the hot water at the point of use is lost down the drain. Just 25% of the heat in the hot water at the tap is assumed to provide useful internal gains. Assuming 15% distribution losses this is equivalent to 21.25% of the heat in the hot water at the tank (or the combi outlet). Thus, the heat lost to the dwelling each month from the hot water at the point of use should strictly be taken as the energy at the tank (using the Vol = 36 + 25N assumption - but converted from joules into Watts) multiplied by 0.2125. ***However, the 25% figure is uncertain to start with. Thus, adjusting this to 21.25% seems to be unwarranted. For this reason it is suggested that the 25% figure be used to apply directly to the energy at the tank (or the combi outlet).***