UNRESTRICTED REPORT

The effect of Thermostatic Radiator Valves on heat pump performance

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by

Robert Green, Tony Knowles

Summary

Standard radiator systems are often used to distribute heat within properties heated by heat pumps. It is good practice, in such cases, to use Thermostatic Radiator Valves (TRVs) to control the heat output from individual radiators. However, their use will increase the tendency for the heat pump to cycle on and off. It is not clear to what extent, if at all, cycling impairs the energy performance of the heat pump.

A typical fixed speed Air Source Heat Pump (ASHP) was installed in one of the Test Houses at EA Technology and a series of test undertaken to systematically vary the heat rejection capacity of the Central Heating (CH) radiator system. Results are presented for both steady-state performance and for a range of on / off cycling. Results show that provided run-times exceed a minimum value (of between 4 and 8 minutes), on/off cycling has little discernible effect on Coefficient of Performance.

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1 Introduction

Many of the houses in the EST field trial of domestic heat pumps use standard radiator systems to distribute the heat within the property. It is good practice with radiators to use thermostatic radiator valves (TRVs) to control the heat output from individual radiators. Often TRVs are used in every room except one (usually the lounge or the hall) which contains the room thermostat.

As each room reaches its desired temperature, the TRV closes down, reducing both the capability of the system to reject heat and the volume of water being circulated around the system. In the extreme, all the TRVs will close down, and the Central Heating (CH) circuit will be reduced to a small circuit containing a single radiator.

Heat Pumps are sized to meet the CH demand on a cold design day. During milder weather, the heat pump will inevitably cycle on and off throughout the CH period – this is particularly so in the case of fixed speed compressors common in many current designs. The effect of TRVs closing down is likely to increase the frequency of cycling by, as described above, reducing both the heat output capacity of the system and the water volume.

Very rapid cycling is likely to increase the wear of compressors, reducing their working life, and most manufacturers prevent extreme cycling (typically limiting this to 6 starts an hour). However, it is less clear to what extent, if at all, cycling impairs the energy performance of the heat pump, and the results of the EST field trial are not conclusive in this respect.

This short piece of work is designed to provide a greater insight into the effect of TRV induced cycling on the energy performance of heat pumps. A typical fixed speed Air Source Heat Pump (ASHP) was installed in one of the Test Houses at EA Technology and a series of test undertaken to systematically vary the heat rejection capacity of the CH radiator system. Results are presented for both steady-state performance and for a range of on / off cycling.

2 Test House set-up

One of EA Technology's thermally matched Test Houses (see photograph below) was chosen to accommodate this study. The detached, four bedroom, two storey Test Houses were built to a mid-1990s specification but incorporating higher levels of insulation, air-tightness and ventilation than were required under building regulations of the time.

Total fabric (and ventilation) heat loss - 200 W/K
Design heat loss - 4.4 kW (at -1°C external and 21°C internal temperature).

The heat pump installed in the Test House was fixed speed, scroll compressor, ASHP, typical of many of the ASHPs in the EST trial. The unit was installed to only supply central heating and has a nominal capacity of 6kW.

The particular ASHP chosen will supply water at 50°C from ambient temperatures down to -15°C, and 45°C from ambient temperatures between -16°C and -20°C. The following table presents some manufacturer's performance data claims for the unit.

Ambient temperature (dry bulb / wet bulb)	CH water return / flow temperatures	Heat output / Input = COP kW / kW = -
7db/6wb°C	30-35°C	5.92/1.64 = 3.60
2db/1wb°C	30-35°C	5.30/1.57 = 3.4
7db/6wb°C	40-45°C	5.70/1.82 = 3.1
2db/1wb°C	40-45°C	5.05/1.79 = 2.8

The heat pump is controlled by a return temperature set-point – if this is exceeded the heat pump switches off and remains off, with the circulating pump (the CH circulation pump is within the heat pump) still running, until the return temperature has fallen by some 5°C below the set point.

The heat pump flow temperature is a function of the heat output of the unit and the CH water flow rate. A pressure operated bypass is included in the CH system to ensure that a minimum flow rate is maintained even when all of the TRVs are closed.

TRVs are present on all radiators except the one in the hall –the reference zone where the room thermostat is also located. Both the heat pump and the CH circulation pump switch off when the hall temperature exceeds the thermostat setting.

Heat Pump efficiency is usually presented as a Coefficient of Performance or COP. This is the ratio of heat delivered to electrical energy input. To achieve high efficiencies (high COPs) flow temperature should be as low as practicable. For radiator systems, this typically means using lower flow temperatures and hence larger radiators than would be the case for, say, a CH system heated by gas boiler. To be consistent with the performance seen in the EST trial, the radiator system in the Test House was redesigned with a target flow temperature of 50°C.

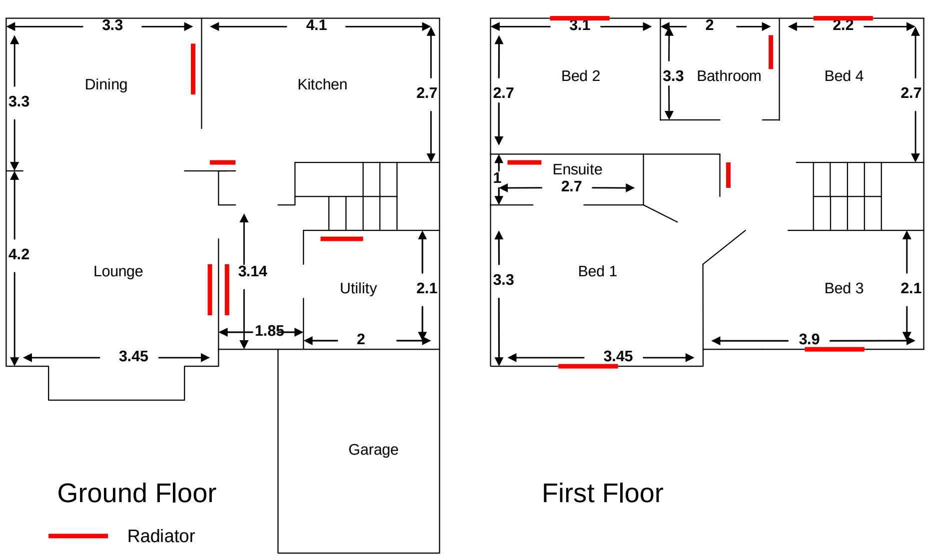
The original radiators in the Test House were specified by British Gas and were designed to be used in conjunction with a 9kW condensing gas boiler delivering a boiler flow temperature of 82°C for conditions where the outside temperature is less than -2°C. The following table indicates the original specification of the radiators.

Original Design Temperatures and Radiator Schedule

Room	Air-change Rate	Radiator size	Type	Output	Design Room Temperature
Lounge	0.7	1 -1400 * 600	P1	1225	21
Dining	0.7	1 – 900 * 600	P1	814	21
Kitchen	1.5	1 – 700 * 600	P1	920	18
Utility	0.7	1 – 400 * 450	P1	297	18
Hall	0.7	1 – 700 * 450	P1	499	18
Landing	0.7	1 – 400 * 450	P1	297	18
Bathroom	1.5	1 – 500 * 600	P1	472	22
Bedroom 1	0.7	1 – 500 * 600	P1	472	18
En-suite	1.5	1 – 400 * 600	P1	384	22
Bedroom 2	0.7	1 – 400 * 600	P1	384	18
Bedroom 3	0.7	1 – 400 * 600	P1	384	18
Bedroom 4	0.7	1 – 400 * 450	P1	297	18

Radiator type Stelrad Elite P1 (single panel)
Total output from radiators 6.445kW
Output required from boiler 8.98kW

The room layouts and radiator positions are indicated in the following diagrams.



Based on the design heat loss of 4.4kW the 6kW ASHP was chosen to meet this load demand. With the heat pumps requirement for the flow temperature to be in the range 40°C - 50°C, the original radiator specification would not have been able to deliver the required power output. For the operating temperatures of 45/35/20°C the original radiators would have delivered 1.6kW. Therefore whilst still utilising the original plumbing the radiators were upgraded to permit higher power outputs at lower delivery temperatures. The following table demonstrates how this increase in radiator capacity was achieved, with larger sizes and the deployment of K2 radiators (double panel, double convection fins).

Upgraded Radiator Schedule

Room	Air-change Rate	Radiator size	Type	Output	Design Room Temperature
Lounge	0.7	1 -1600 * 700	K2	993	21
Dining	0.7	1 -1200 * 700	K2	745	21
Kitchen	1.5	1 - 400 * 700	P1	194	18
Utility	0.7	1 - 800 * 700	K2	496	18
Hall	0.7	1 - 1200 * 700	K2	745	18
Landing	0.7	1 - 400 * 450	P1	57	18
Bathroom	1.5	1 - 500 * 600	P1	57	22
Bedroom 1	0.7	1 - 1400 * 600	K2	765	18
En-suite	1.5	1 - 400 * 600	P1	74	22
Bedroom 2	0.7	1 - 1400 * 600	K2	765	18
Bedroom 3	0.7	1 - 1400 * 600	K2	765	18
Bedroom 4	0.7	1 - 1400 * 600	K2	765	18

Radiator type Myson Select Standard K2 (double panel, double finned)
or Stelrad Elite P1 (not changed)
Total output from radiators 6.421kW
Output required from heat pump 6kW

With the inclusion of TRVs on the radiators there will be moments of operation of the heating system when TRVs will be closed, flows will be interrupted and the volume capacity of the heating system will change. The table below indicates the volumes of particular circuits within the heating system.

Circuit	Volume(litres)
Common circuits	10.2*
Lounge	16.3
Dining	12.7
Kitchen	4.7
Utility	9.3
Hall	12
Landing	1.5
Bathroom	2.5
Bedroom 1	12.7
En-suite	2.3
Bedroom 2	12.4
Bedroom 3	12.5
Bedroom 4	12.4
Total	**121.5**

* System also includes a 35 litre expansion vessel, this is not included in the system volumes.

3 Instrumentation and data logging

The performance of the heat pump is monitored using similar fiscal quality energy meters as were used in the EST Field Trial.

The heat output is measured using a Sontex SuperCal / Superstatic heat meter, with the pulse output set at 1000 pulses per kWh. The claimed accuracy for the meter is typically ± 2.5%.

The electricity consumption is measured at three points:

- Total used by ASHP
- The outdoor air-coil fan
- The CH circulation pump (built into the ASHP)

The ASHP total includes the fan, pump, electronics etc. as well as the heat pump compressor. All of the electricity meters are class 2 meters with pulse outputs set at 1000 pulse per kWh. Accuracy is ± 2%.

In addition a high accuracy "magflow" water flow meter is used to measure the CH circulation rate. This, combined with a well matched pair of thermistors measuring temperatures within the flow and return pipe-work, allows a second calculation of heat output to be made.

All of the above parameters are logged using a dedicated, hard-wired, logger. Data logging intervals during the trial ranged from 1 sec to 1 minute – with most tests being performed with a logging interval of 10 sec.

Temperatures were also measured both within the room and at the radiators (the latter using surface mounted probes attached to pipe-work). These temperatures were logged at 5 minute intervals using a wireless (radio) data logger.

Voltage was also recorded at 10 minute intervals during the trial.

Comparisons of the heat output measurements show that the Sontex gives totals slightly higher than those calculated using the logged data for flow rate, and flow and return temperatures. The difference was 2.6% in a quasi-steady-state condition and 4.6% during one of the cycling tests (using data logged at 1 sec intervals). For consistency with the EST trials, where totals are used (i.e. for calculating COPs over particular time periods) the heat meter readings are used. However, for graphing purposes, the heat meter does not give a smooth output from time interval to time interval, and so the calculated values are used.

The graphs of electricity use (presented as average kW per logged interval) do use the pulse outputs from the kWh meters. Consequently there is some scatter in these values in the graphs although trends are clear (this would not be the case if the heat meter kWh readings were graphed).

4 Test procedure

The weather during the test period (April to early May 2011) was typified by warm days and relatively cold nights. Test were performed overnight to approximate to mild weather heating periods.

The initial tests were performed with all of the TRVs fully open and the room thermostat turned-up high. This had the desired effect of producing long continuous run periods for the heat pump. The aim was to establish a heat pump return temperature that would allow continuous running with all radiator TRVs open, but would induce cycling as the TRVs were closed. These quasi-steady-state results are presented in Section 6. A return temperature set-point of 40^{o}C was selected.

The next test involved closing all of the TRVs and setting the by-pass valve to ensure a minimum flow rate of 10 litres per minute. The heat pump was then run overnight in this condition and the expected short cycle operation resulted. Subsequent tests involved opening up one TRV at a time, and repeating the overnight run. These results are presented in Section 7.

Finally, the CH was placed in its normal, whole house, mode of operation, with all TRVs set to typical mid-range values. The results (and TRV settings) are provided in Section 8.

5 Results format

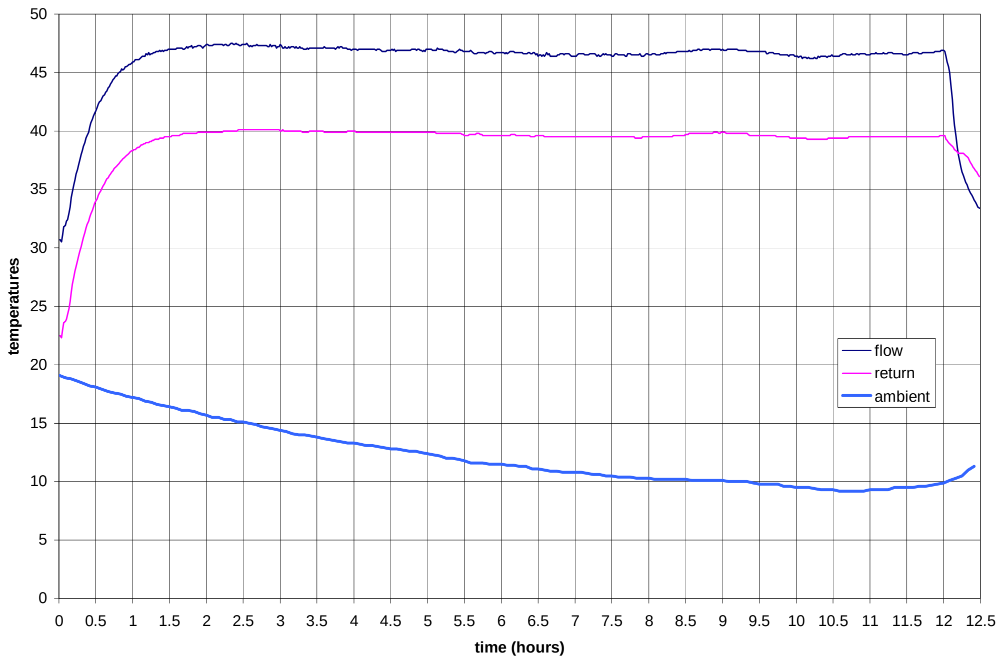
The results are presented in a similar format in each case. Two graphs are provided – the upper graph showing ASHP flow and return temperatures plus the ambient air temperature, and the lower graph showing power (both heat and electrical) along with (in all bar the steady-state case) the per cycle COP.

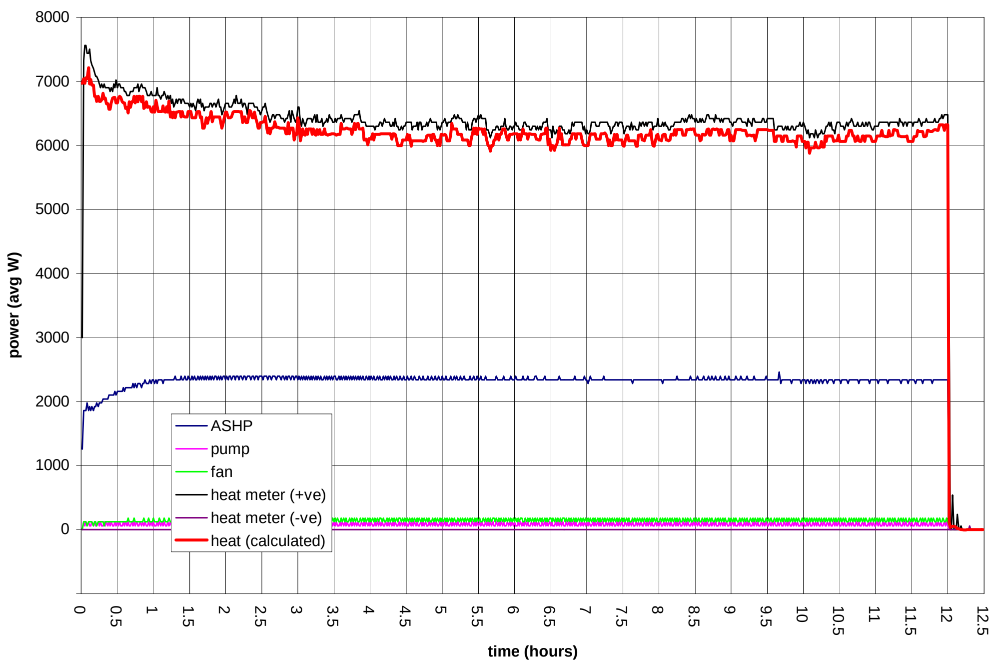
The steady-state results (Section 6) are supplemented by a third graph showing the COP averaged over half-hour periods and plotted against ambient temperature. These graphs are overlaid with the manufacturer's claimed performance for the heat pump.

The whole house results (Section 8) are also supplemented by a third graph – this time showing radiator temperatures.

Due to the repetitive nature of the results (and to maximise the space available for each pair of graphs on a single page), figure numbers and titles are deliberately omitted.

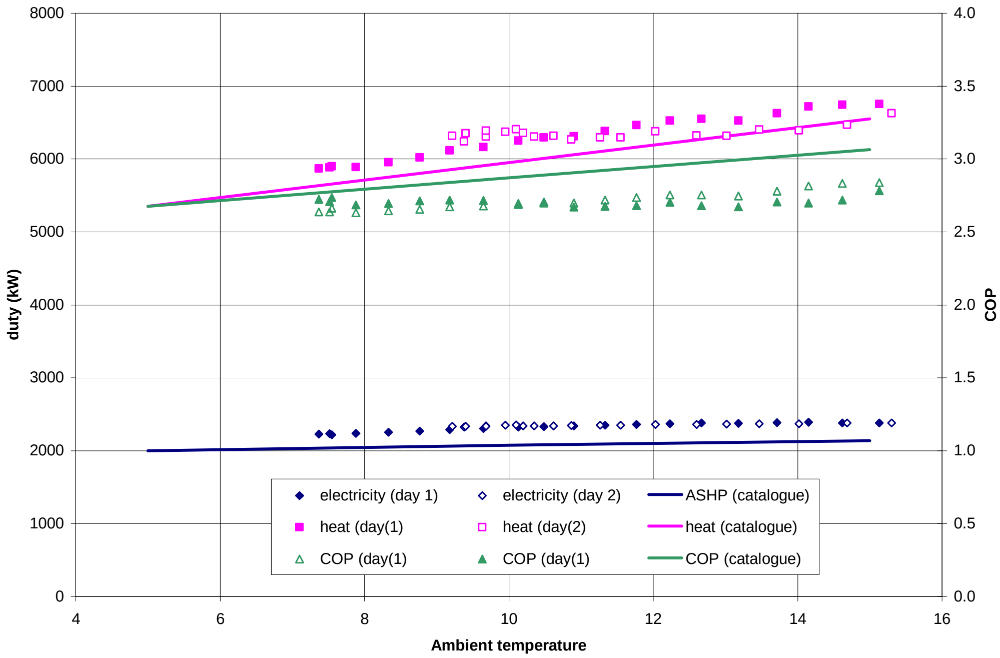
6 Steady-State Results





Results for 10-11th April (Day 2).

Fan power is approximately 150W and CH circulation pump power is ~ 90W



Two days of quasi-steady state testing were undertaken. Both days followed similar ambient temperature patterns, with a warm start and a steady fall in temperature overnight – day 1 being the slightly colder of the two.

The above graph shows COP calculated from half-hourly totals through out each run (i.e. both heat and electricity in kWh total for the half-hour), plotted against half-hourly average ambient temperature. Whilst strictly speaking these are not steady-state values, the ambient temperature changes only slowly (and smoothly) during each half hour slowly and it would be expected that steady-state values will be similar.

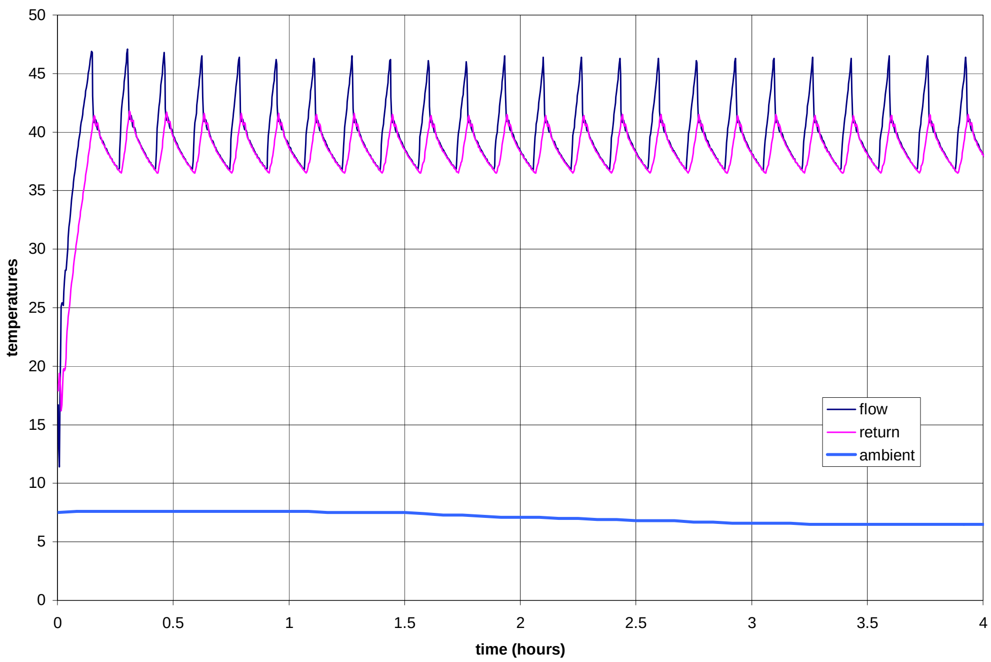
Included in the figure are values derived from the manufacturer's Technical Manual (the solid lines labelled as 'catalogue'). The values were derived from graphs of heat output and COP. The technical manual includes performance curves for flow temperatures of 40 and 50^{o}C, and the values used here are the average of these. The COP curves in the technical manual do not include the power of the circulation pump and a value of 90W has been added to the "ASHP (catalogue)" line here.

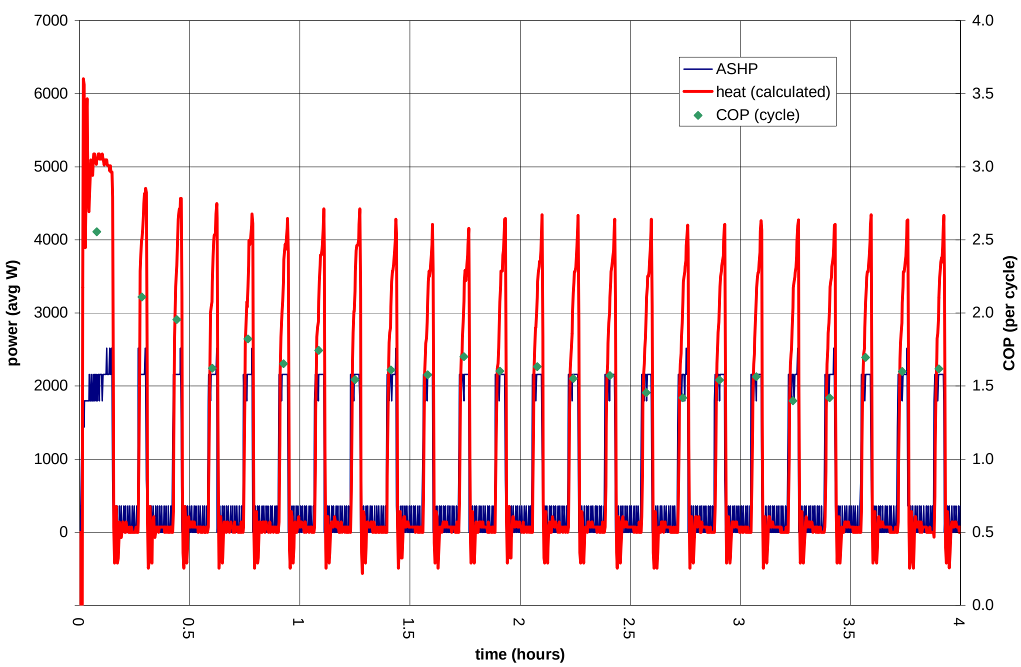
The catalogue electricity power is some 10% less than the measured power. This might be partly due to the slightly higher voltage in the Test House than the UK nominal voltage of 230 V (the voltage was reasonably steady at between 240 and 242 V throughout the test period).

Heat output is similar to the catalogue values, although the measured values show less of a downwards trend with falling ambient temperature. This is likely to be due to high overnight humidity levels in the experimental tests (typical of warm days and cold nights) keeping evaporating temperature relatively high (capacity falls with falling evaporating temperature). The slightly unexpected result of this is that the measured COP shows only a slight fall with falling ambient temperature (the flow temperature also fell slightly by around 2^{o}C during the coldest period of day 1).

7 Forced cycling results

7.1 All TRVs closed

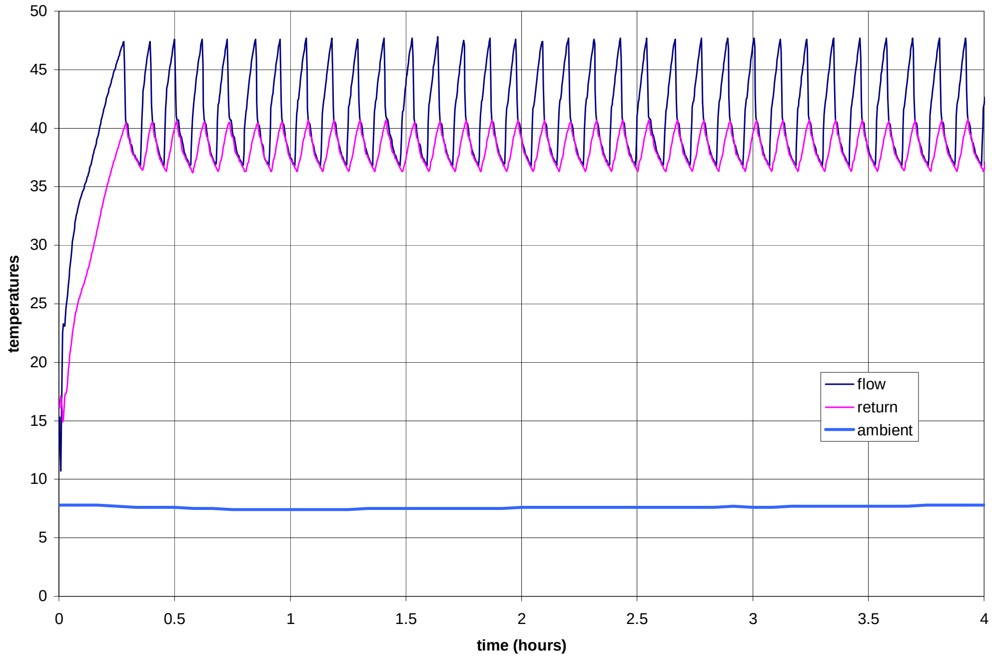


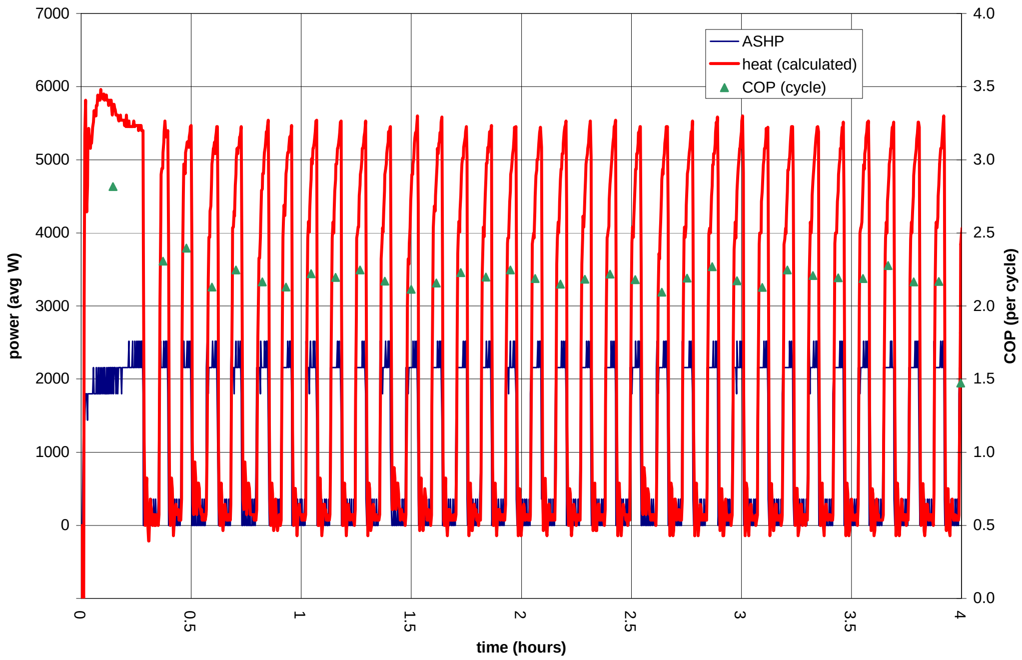


Results for 12-13th April

1st cycle	COP = 2.55	9 min run time		System volume ~ 20.6 litres
Other cycles	COP ~ 1.6	3 min run time	6 cycles / hour	

7.2 Lounge TRV open

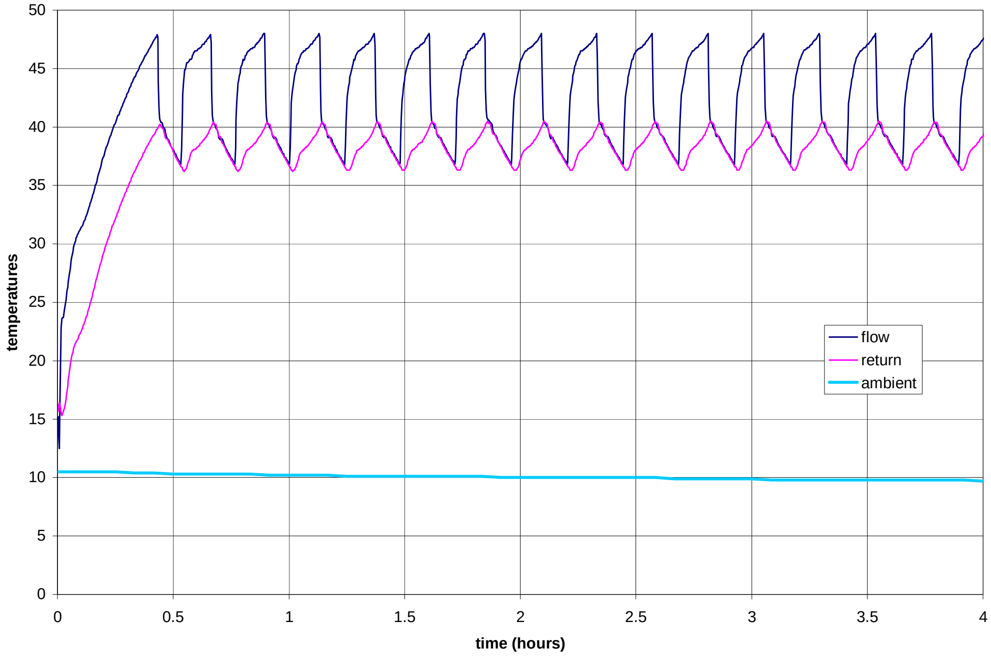


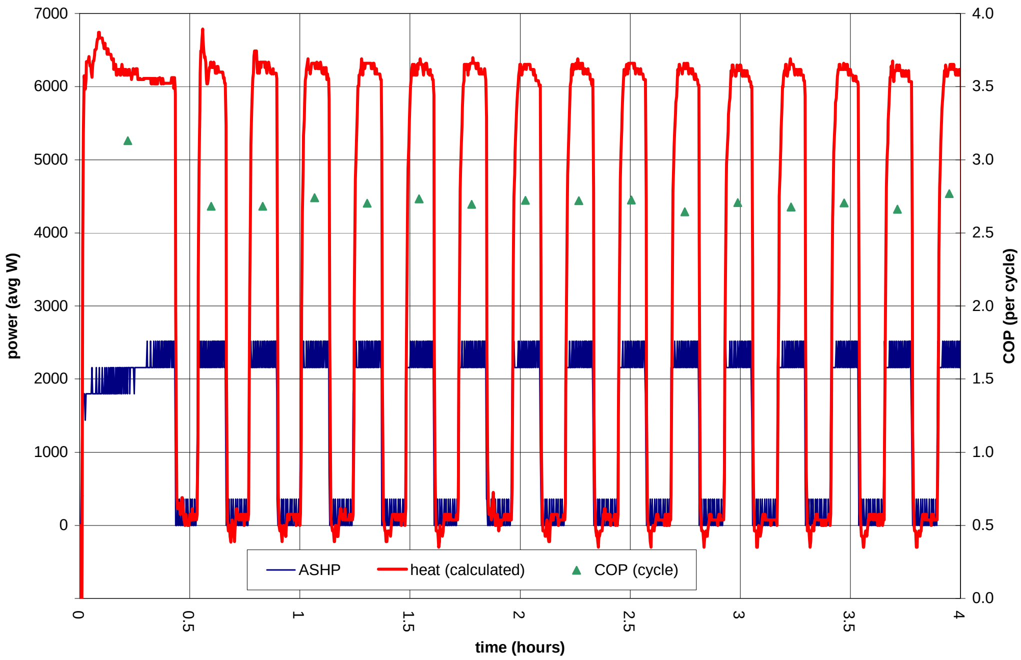


Results for 13-14th April

1st cycle	COP = 2.8	17 min run time		System volume ~ 36.9 litres
Other cycles	COP ~ 2.2	3.5 min run time	9 cycles / hour	

7.3 Lounge and dining room TRVs open

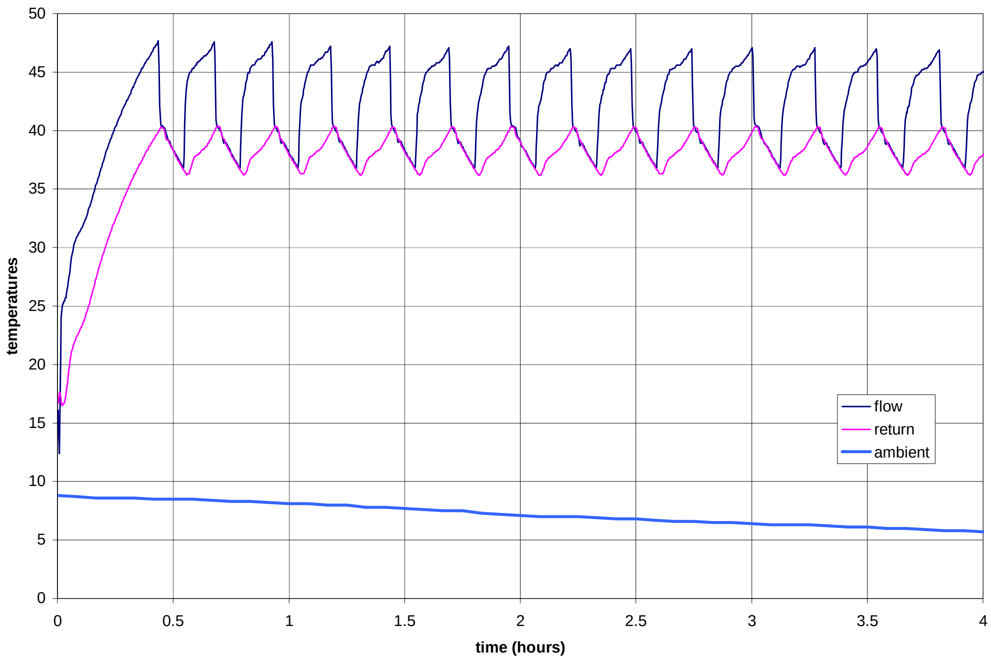


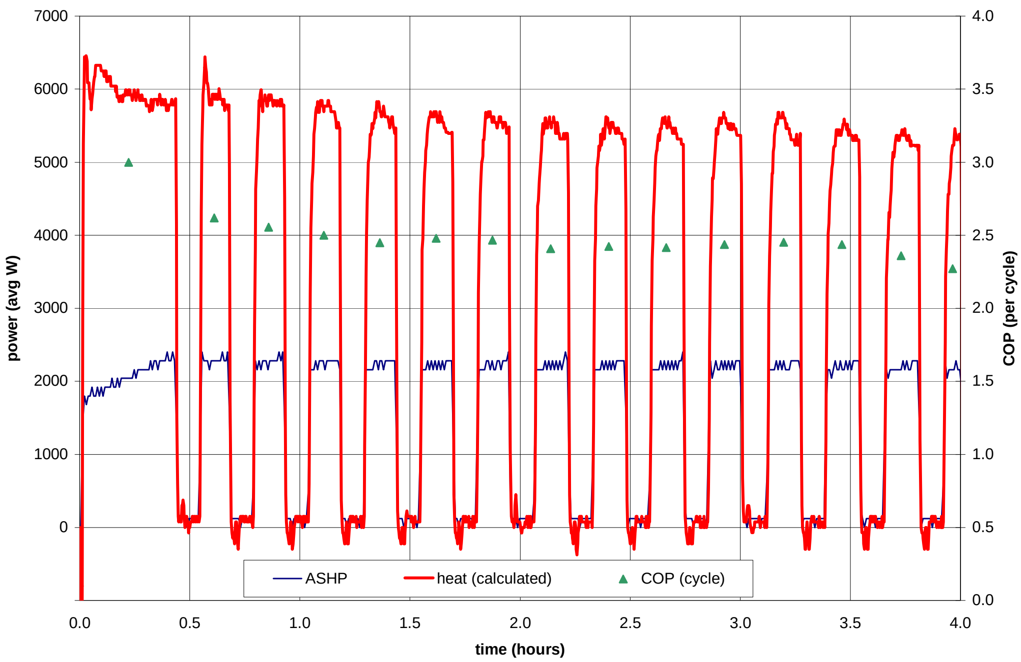


Results for 14-15th April

1st cycle	COP = 3.1	26 min run time		System volume ~ 51.9 litres
Other cycles	COP ~ 2.7	8.3 min run time	4 cycles / hour	

Repeat of previous test (lounge & dining room TRVs open) at lower ambient temperature



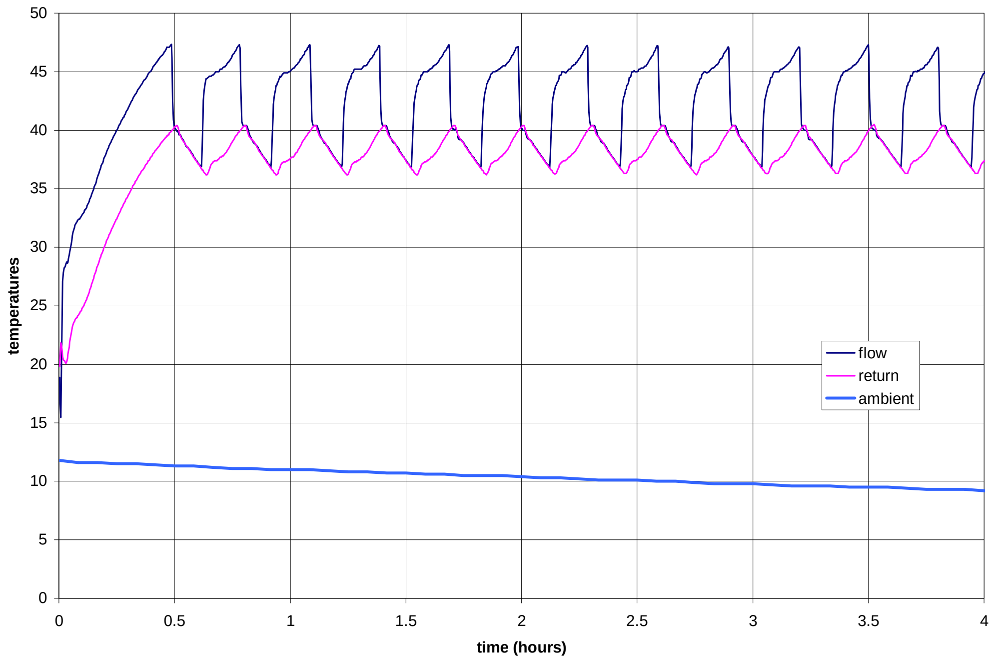


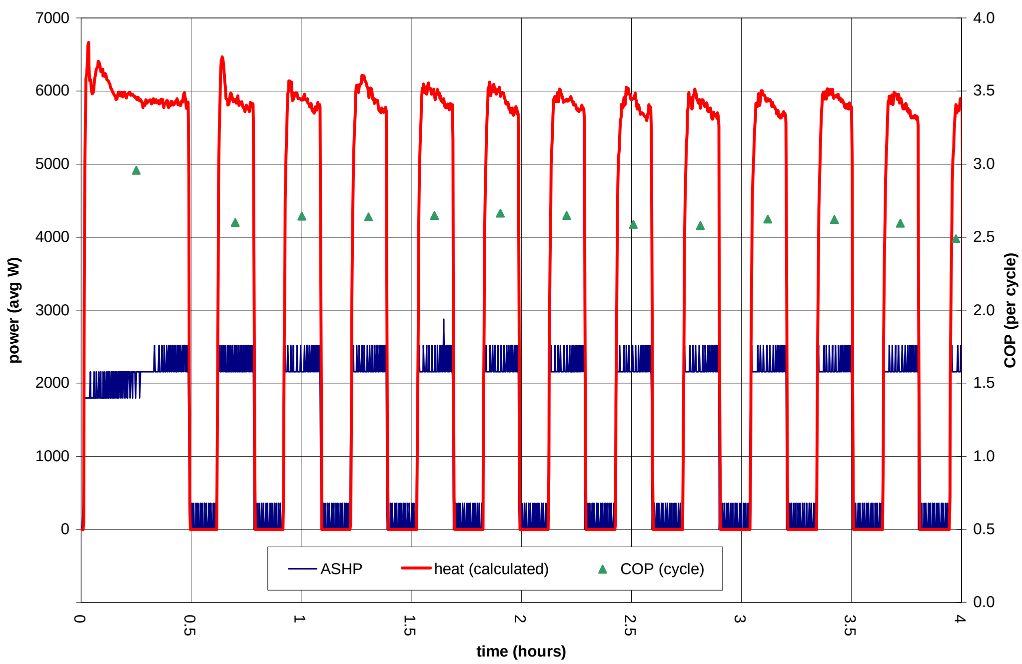
Results for 16-17th April

1st cycle	COP = 3.0	26 min run time		System volume ~ 51.9 litres
Other cycles	COP ~ 2.4	9.2 min run time	4 cycles / hour	

(Note that the scatter of the electricity readings have been reduced in this case by plotting as 30 second averages, rather than the 10 sec averages used in the other graphs).

7.4 Lounge, Dining room and main bedroom TRVs open

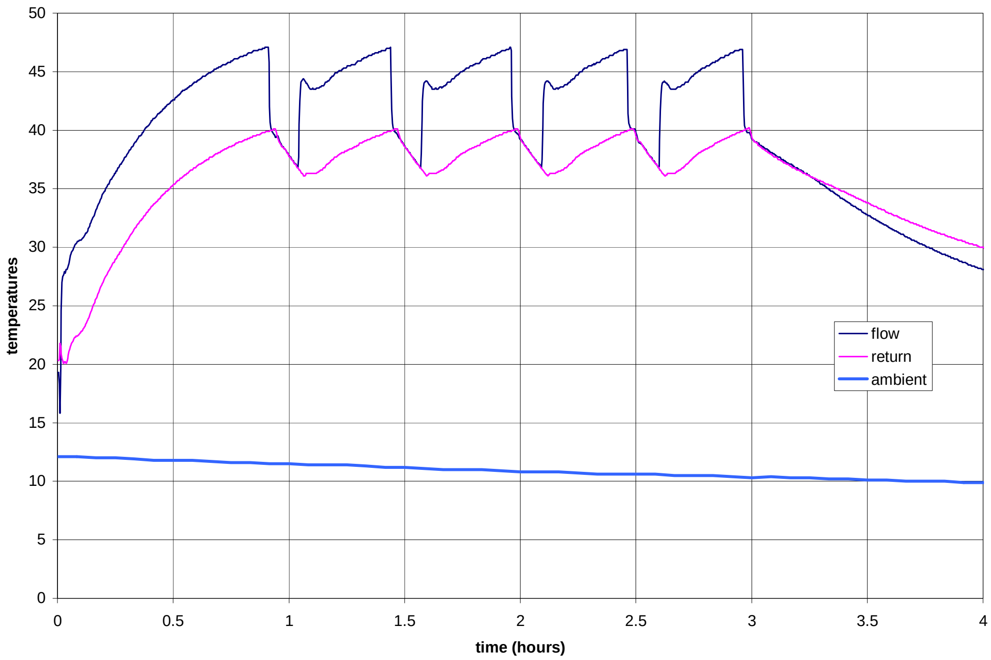


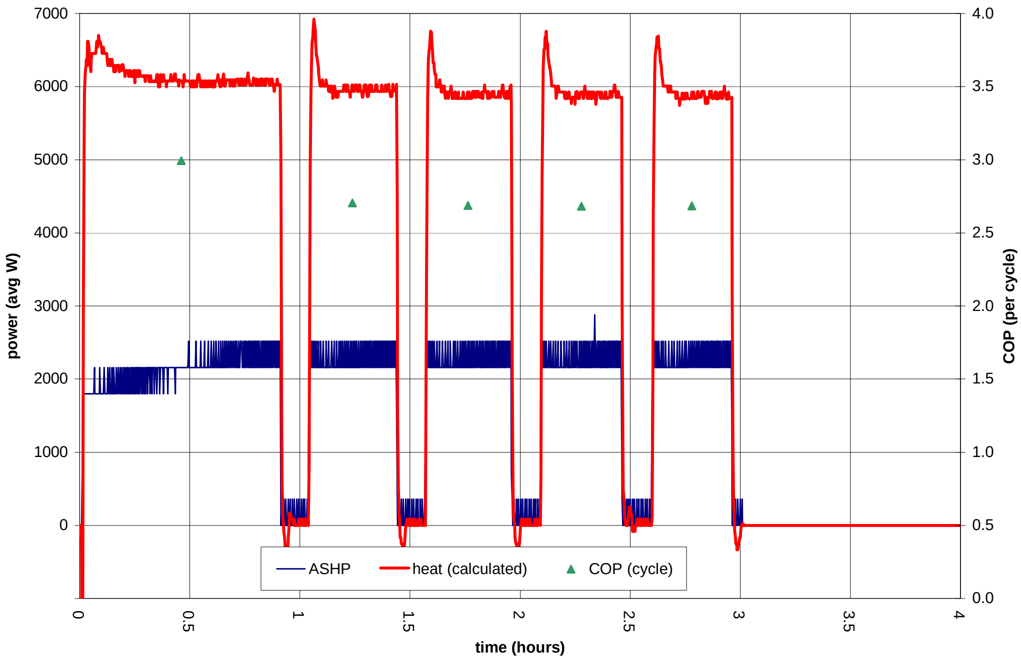


Results for 20-21st April

1st cycle	COP = 2.96	29 min run time		System volume ~ 65.2 litres
Other cycles	COP ~ 2.65	10 min run time	4 cycles = 72 min	

7.5 Lounge, Dining room, and two bedroom TRVS open



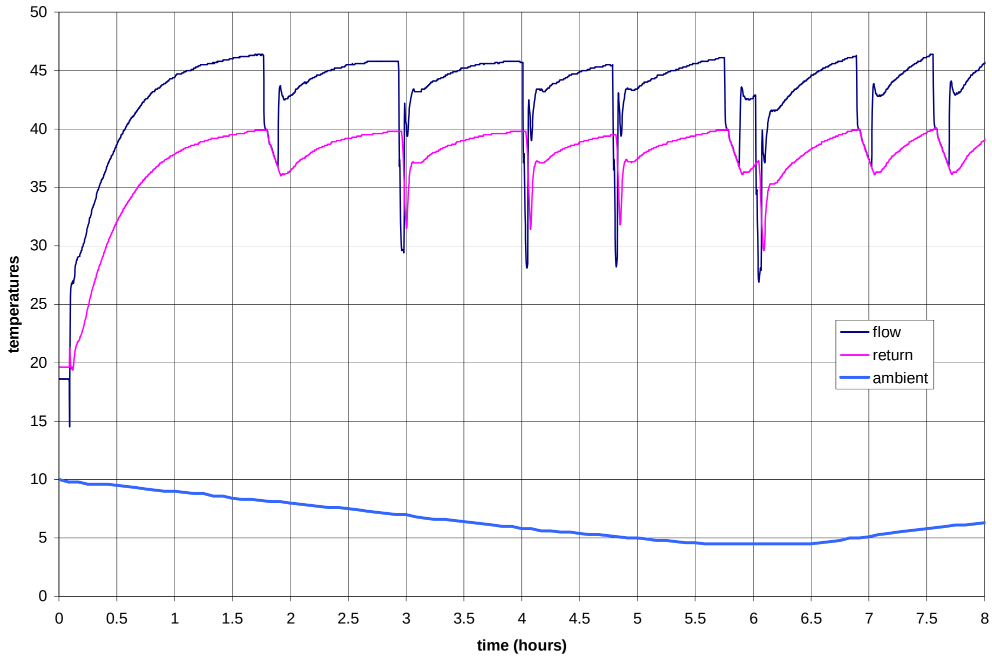


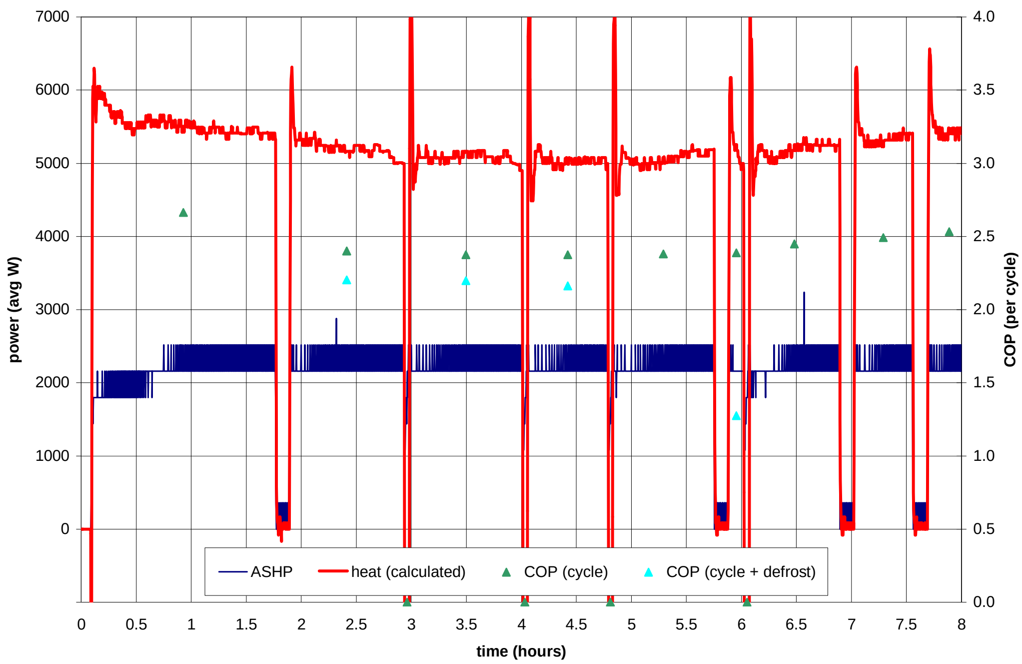
Results for 20-21[st] April

1st cycle	COP = 2.99	54 min run time		System volume ~ 77.7 litres
Other cycles	COP ~ 2.7	23 min run time	2 cycles / hour	

(Note that the CH period was accidentally curtailed by an error in setting the time clock. There is, however, sufficient data here to establish the cyclical pattern).

Repeat of previous test (lounge, dining room and two bedroom TRVs open) at lower ambient temperature. System now goes periodically into defrost mode and operation is continuous apart from this. Duty and COP are lower than previous tests suggesting a lower evaporating temperature in this test.



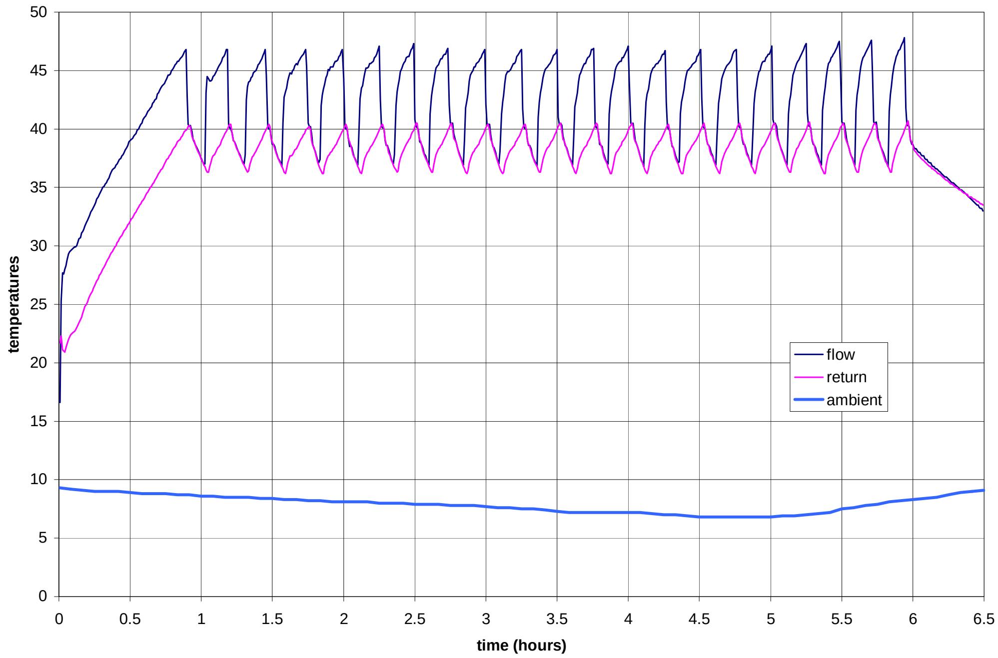


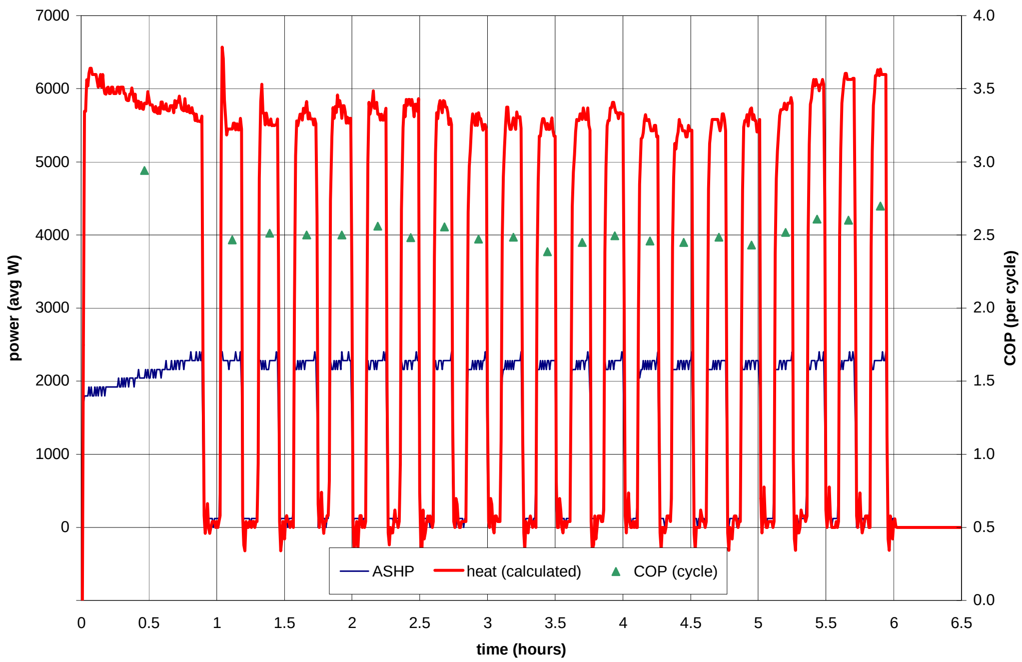
Results for 27-28th April

1st cycle	COP = 2.7	100 min run time		System volume ~ 77.7 litres
Other cycles	COP ~ 2.4 or 2.2 including defrost	Variable due to defrost	2 cycles / hour	

8 Whole house system results

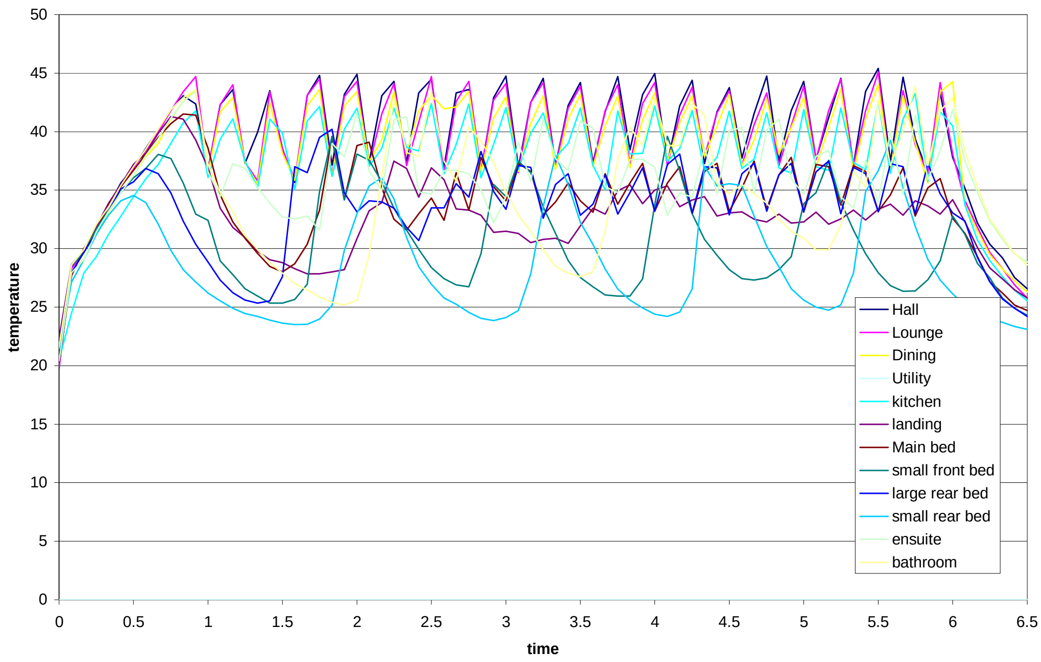
All of the TRVs were opened - downstairs set at 3.5, which approximates to 22°C and upstairs set at 2.5, which approximates to 18°C (TRV settings are variable from 0 – 5).





Results for 24-25th April

1st cycle	COP = 2.94	54 min run time		System volume max ~ 121.5 litres
Other cycles	COP ~ 2.5	10 min run time	4 cycles / hour	

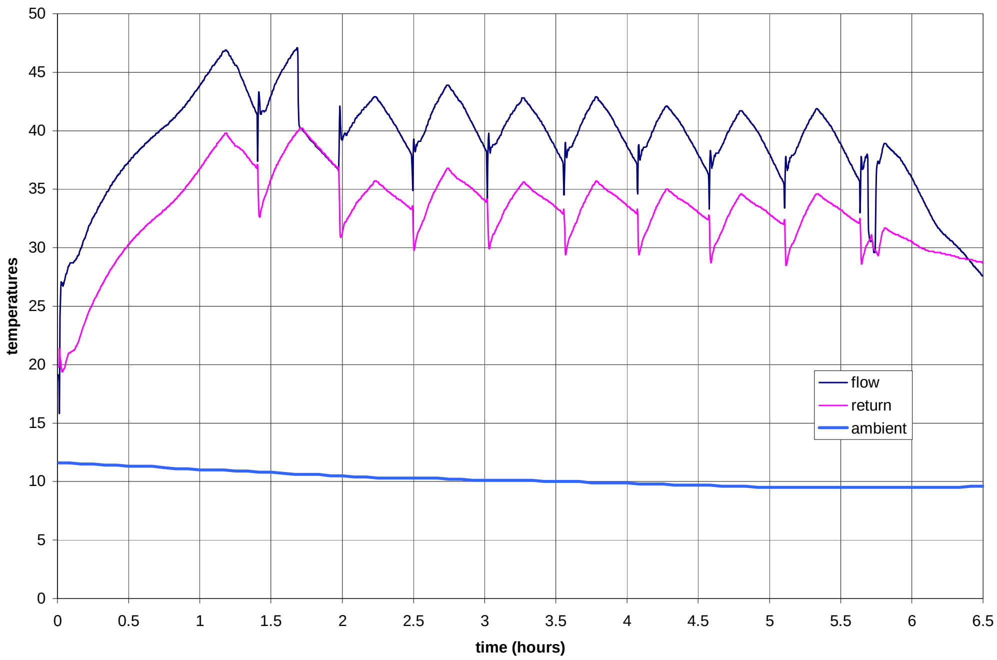


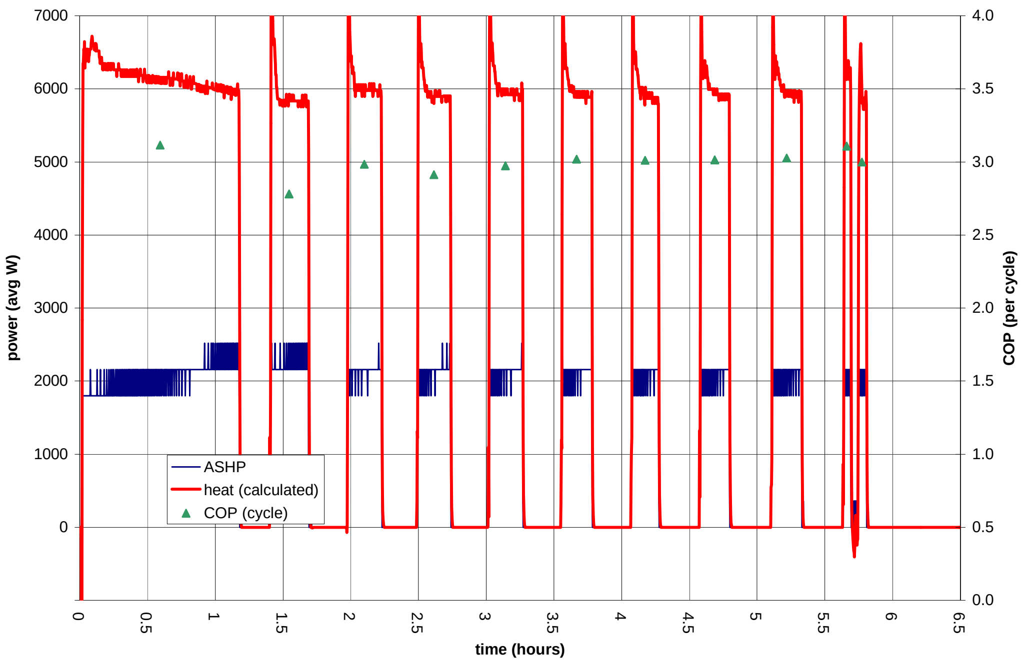
This additional plot shows the flow temperatures as measured at all of the radiator inlets. Downstairs flow temperature tends to follow a similar pattern to the heat pump, where as upstairs radiators show the effect of closing down and re-opening.

Throughout this test, there is no sign of the ASHP switching off due to the room thermostat (flow / return pattern follows the previous on/ off patterns and the pump runs continuously).

The next set of results shows how the room thermostat effects cycling (only achieved once the thermostat had been recalibrated).

Over riding control is now with the room thermostat rather than the ASHP return temperature, hence flow / return temperatures are lower than previously.

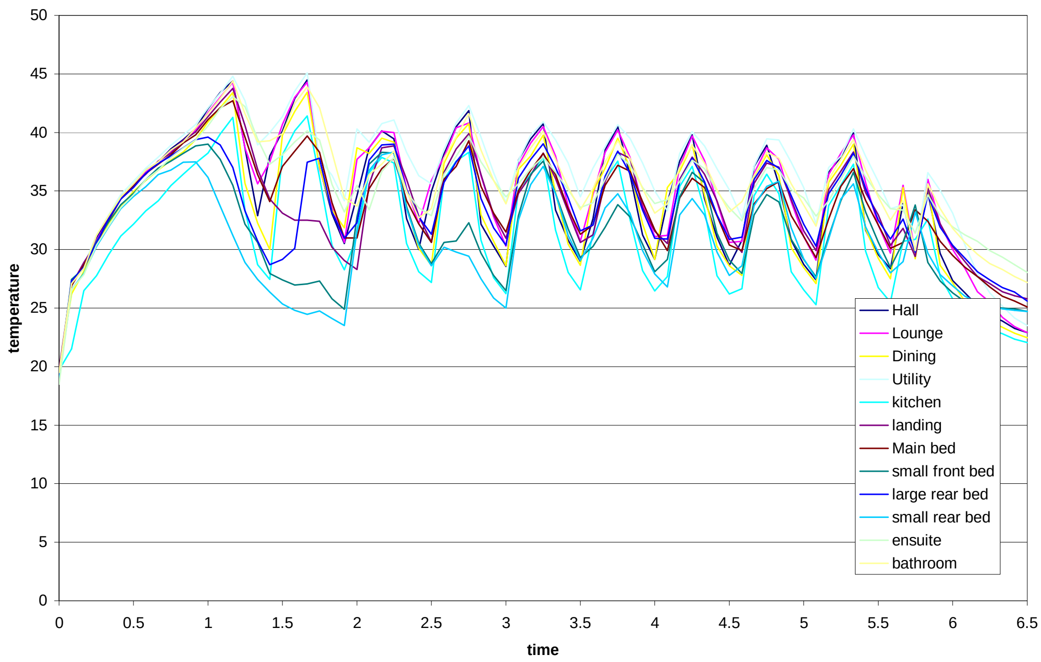




Results for 4-5th May

1st cycle	COP = 3.12	70 min run time		System volume max ~ 121.5 litres
Other cycles	COP ~ 3.0	13 min run time	~ 2 cycles / hour	

Note the truncated run at around 5.7 hours is due to the unit briefly going into defrost mode.



This final plot again shows the flow temperatures as measured at all of the radiator inlets.

9 Discussion and conclusions

It is clear form the results of Section 7 that very short run times of less than 3.5 minutes will result in a lowering of the COP. This may in part be due to difficulties in measurement of heat with rapidly changing temperatures (the flow rate remains constant as the pump continues to run when the heat pump cycles off). However, it is likely to be predominantly a real effect, with the heat output failing to reach the steady-state value.

The COP is similar to the expected (steady-state) values when run times exceed 8 minutes (cycle times between 3.5 and 8 minutes were not achieved in these tests). Maximum cycle CH heat outputs are also similar to the steady-state values.

Whilst these trends, that there is no discernible effect on COP with run times in excess of 8 minutes, seem clear, making a definitive statement to this effect (i.e "if run times exceed 8 minutes then there is **no** effect on COP") is not possible due to the many variables in the trial. In particular, the finding that both COP and heat output fall only slowly with falling ambient temperature is perhaps surprising, although this is likely to be consistent with raised humidity levels during the trial (c.f. manufacturer's lab test results). Assuming that the result that there is little or no effect on COP is valid, the trials have also not definitively defined the minimum run time. This will be somewhere between 3.5 and 8 minutes.

The minimum run time for a given CH system will be a function of:

- The heat supply (from the ASHP) minus the heat output available from the reference zone radiator(s) - i.e. the hall radiator in the case of the Test House;
- The water volume within the open CH pipe-work and reference zone radiator;
- The dead-band in the Return Temperature set-point (roughly 5°C in these trials).

The minimum run time can be increased by one or more of the following:

- Adding a buffer tank
- Widening the return temperature dead-band (e.g. from, say, 5°C to 10°C)
- Altering the CH zoning to incorporate more radiators (and more water volume) within the reference zone.

In the case of the Test House, moving the room thermostat from the hall to the lounge and making the lounge + dining room the reference zone (i.e. adding a TRV to the hall radiator and removing the lounge and dining room TRVs) would increase the minimum heat output from 745W to 1738W and the minimum water volume from ~ 21 litres to ~40 litres.

The choice of reference zone must, however, be made with care. In the case of the Test House, moving the reference zone from the hall to the lounge / dining room should not be a problem. However, if the lounge contained a secondary heat source (stove / focal-point fire etc.) then this would not be advisable.

On the assumption that severe short cycling is only likely to happen during mild weather, the return temperature dead-band could be incorporated into a weather compensation strategy – increasing the dead-band when heat demand is low.

One feature of all of the results is that the first, start-up, cycle always produces a good COP. When starting from cold (room temperature) radiators, the heat pump flow temperature gradually ramps-up from a low value to a maximum value (generally around 47°C in these tests) corresponding to the return temperature set-point. Thus, design / operation strategies that allow the radiators to cool after each cycle are to be encouraged. This effect is seen in the final whole house test result presented here (final graphs of Section 8).

Thus, in conclusion:

- on/off cycling has little discernible effect on Coefficient of Performance provided that a minimum run-time (some where between 3.5 and 8 minutes) is achieved;
- minimum run time is a parameter that can be readily designed for, provided information is known about heat outputs and water volume;
- minimum run-time can be increased by one or more of:
    - use of buffer tanks
    - careful selection of the reference zone (the area of the house where the room thermostat is positioned and the radiator(s) have no TRVs
    - widening the dead-band on the return temperature set-point;
- the highest COPs are achieved by cycling from "cold" (i.e. the first / start-up cycle and, to a lesser extent, room thermostat induced cycling).

It is recommended that further tests be undertaken to provide more definitive advice. These could include:

- laboratory tests to define the desired minimum run-time more accurately
- operation of the Test House system rezoned with the lounge / dining rooms as the reference zone
- comparison of performance in the Test House with and without a buffer tank.