# Impacts of Building-Level Heat Load Testing on Heat Network Performance

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## Abstract
There is very limited published data on the performance of heat networks across the UK at the practical completion of construction ahead of occupation. Empirical evidence from BRE(1) and AECOM(2) suggests that many heat networks suffer from poor system performance and higher than expected bills, which is likely to be partially linked to inadequate system commissioning.

A "Heat Load Testing" methodology was developed to assess building-level heat network commissioning to ensure that pre-defined performance criteria are met at system handover.

Based upon a number of case studies, a high proportion of building-level heat networks were non-compliant with respect to the required performance criteria during initial testing. The issues observed were associated with non-compliant system controls, system heat losses, high bypass flow and low heat generation efficiencies. Following remedial works, the performance gap was reduced when compared against the performance criteria.

This research intends to inform heat network contractors, commissioning specialists and operators on the following aspects of heat network load testing:

- A methodology to verify performance;
- An overview of typical issues identified during the process; and
- The benefits realised through testing.

It is suggested that the methodology should be adopted as industry best practice within the CP1 guidance(3) to complement the existing guidance within the relevant BSRIA and CIBSE guidance documents.

**Keywords** district heating, acceptance testing, commissioning, plant room

## Introduction
Due to diversity of usage, LTHW systems are commonly run at part or very low load and are subject to rapid changes in demand throughout their lifetime. Figure 1 below shows an example of an annual load profile for a 300 kW peak load system, where load is at 10% of the peak load or less for over 65% of the year. The peak load occurs only briefly and is not seen on the plot of hourly average load.

Standard commissioning procedures do not accurately capture these aspects of the system performance.

Standard industry commissioning documentation such as BSRIA guides BG2(4) & BG8(5) and CIBSE Commissioning Codes M(6) & W(7) provide guidance on typical commissioning processes. The focus of these documents is to standardise and guide commissioning of individual equipment as well as the greater commissioning programme. This provides a commissioning focus on individual equipment and the overall system rather than the combined response of equipment to load, which often leads to incorrect implementation of the Description of Operation (DesOps) and performance issues after handover. These issues are expensive and time consuming to address post occupation, and often come burdened with an unclear contractual responsibility.

Having identified that the industry did not possess a method to assess system performance in a simulation of real system conditions FairHeat developed the heat load testing methodology.

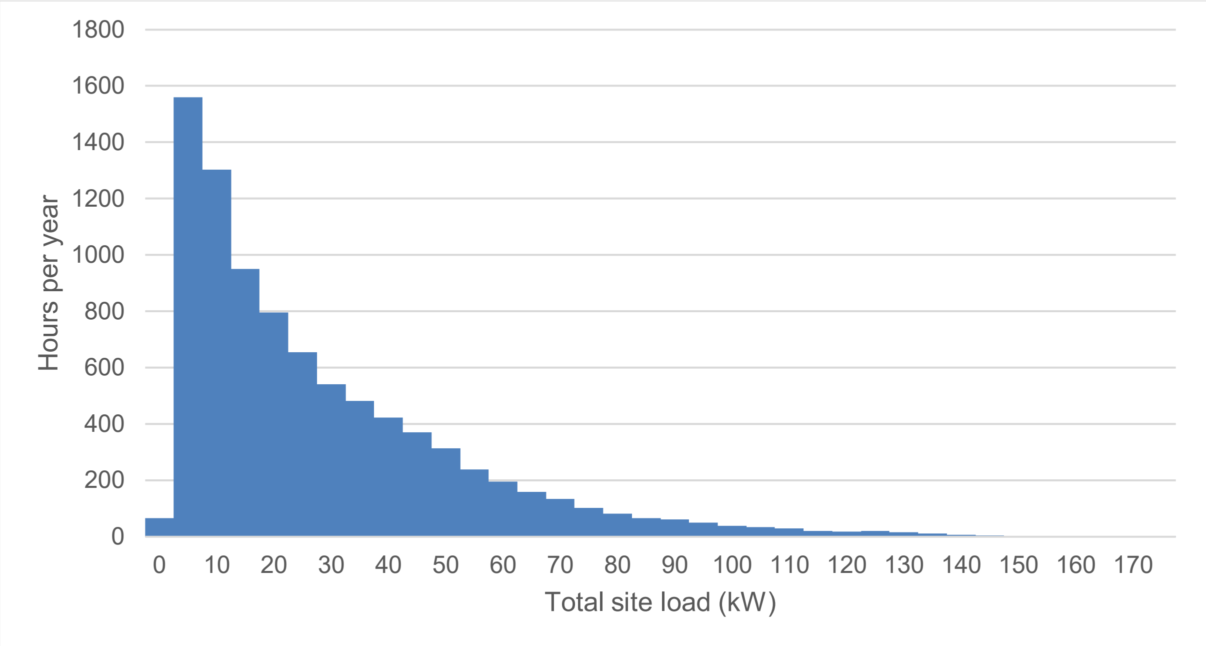


**Figure 1: Annual load profile for a system with a design peak load of 300 kW**

## Brief methodology

Prior to the performance of the heating load test all BMS points should be witnessed, to ensure that all sensors and outputs are correctly implemented and labelled. Once this is complete the implementation of the DesOps should be proved, this includes system start up/shut down, equipment changeover, thermal store charging/discharging and system fault/alarms. Once this operation is confirmed to be correct the full load test can be completed.

The methodology for performing a load test contains 4 main steps:

1. Review operation at minimum load - defined as all end units operating in standby mode (i.e. HIUs in keep warm, heat emitters switched off);
2. Incrementally increase load until peak load is met;
3. Review operation at peak load - defined as the maximum estimated heat demand calculated by the system designer;
4. Incrementally decrease load until system is operating at minimum load.

Where possible the application of load should simulate actual usage scenarios i.e. mixture of space heating and domestic hot water distributed across the site. However, it is common that the use of space heating to apply load is restricted due to the other works occurring on site (e.g. decoration) and the number of flats available. In these scenarios steps should be taken to ensure the system is still tested up to the peak load, and that the anticipated peak load flow rate is simulated. This may be done by applying load using bath outlets in a smaller number of flats, incrementally opening outlets in flats to apply load, and temporarily opening a bypass whilst at peak load to achieve the design peak load flow rate. A typical timeline for a heating load test is shown below in Table 1.

| Tests | Power/flow load | Time (min) | Methodology |
|---|---|---|---|
| Baseload | 4 - 5 l/h (c. 100 W) per HIU | 30 | Verify no bypasses open, no bypassing HIUs/end units, only standby load |
| Dynamic load test | 20 - 30% power | 45 | Apply load across network, based on power |
| | 40 - 50% power | 60 | Apply load across network, based on power |
| | 70 - 80% power | 75 | Apply load across network, based on power |
| | 100% power | 90 | Apply load across network, based on power |
| | 100% power and 100% flow bypass | 120 | Achieve desired peak flow rate through use of bypasses, close after use |
| | 70 - 80% power | 135 | Remove load across network, based on power |
| | 40 - 50% power | 150 | Remove load across network, based on power |
| | 20 - 30% power | 165 | Remove load across network, based on power |
| Baseload | 4 - 5 l/h (c. 100 W) per HIU | 180 | Verify no bypasses open, no bypassing HIUs/end units, only standby load |

**Table 1: An example heating load test timeline**

Throughout the test, the BMS should monitor and record the available sensor data, control outputs and heat meter readings every minute. This data can be retrospectively reviewed to identify the causes of any observed issues and to aid in proposing solutions. It is expected that, as a minimum, all of the following BMS points are collected on a 1-minute basis throughout the load test:

- Heat generation individual and common flow and return temperatures
- Heat generation control signals
- Network flow and return temperatures
- Network flow rate and power
- Pump control signals
- Differential pressure sensors at all index runs available on network
- Thermal storage temperature sensors

Any other reads relevant to the specific site should also be gathered e.g. substation sensors or additional flow rate sensors.

## Common issues and solutions

In experience developing the load testing methodology and performing over 20 load tests across more than 10 schemes multiple common commissioning issues have been identified. Each load test performed to date highlighted issues with equipment or controls commission, which if left unchecked would cause issues delivering heat post occupation. By working collaboratively with the site team it was possible to resolve these issues.

The sections below detail the most common issues observed during load tests, the causes of these issues, the identified solutions to the issues, and the positive impact achieved by implementing the solutions.

## *Unstable performance at low loads – pressure independent control valve (PICV) control*

On a scheme supplied by a plate heat exchanger (PHE) connection to a district heating network instability in secondary flow temperature was observed during low system loads, as is shown in Figure 2. It was observed that the duty PHE control valve would 'hunt' during low demand, causing large fluctuations around the set point and flow temperature to drop as low as 45 °C. These fluctuations posed a risk to the consistent delivery of heat to residents and could lead to future complaints.

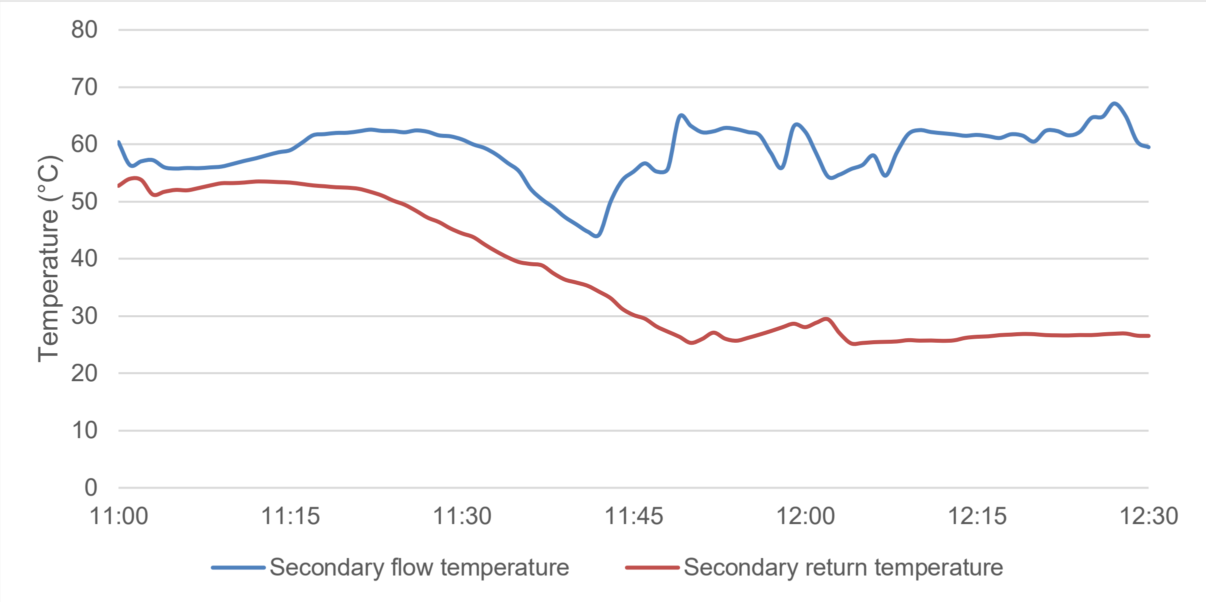


**Figure 2: Unstable secondary flow temperature during low demand on a PHE-fed system**

It was recommended that a separate low demand control loop was implemented for the plate PICV and tuned to prevent the valve from hunting during low demand. The low demand loop was set up to enable when the duty PICV position dropped below 10% and to disable when the duty PICV position increased above 20%, at which point the standard control loop would enable.

As a result of retuning, a second load test confirmed that the new controls provided stable flow temperatures during low loads. As can be seen in Figure 3 the secondary flow temperature dropped to 55 °C, which was considered to require no further action.

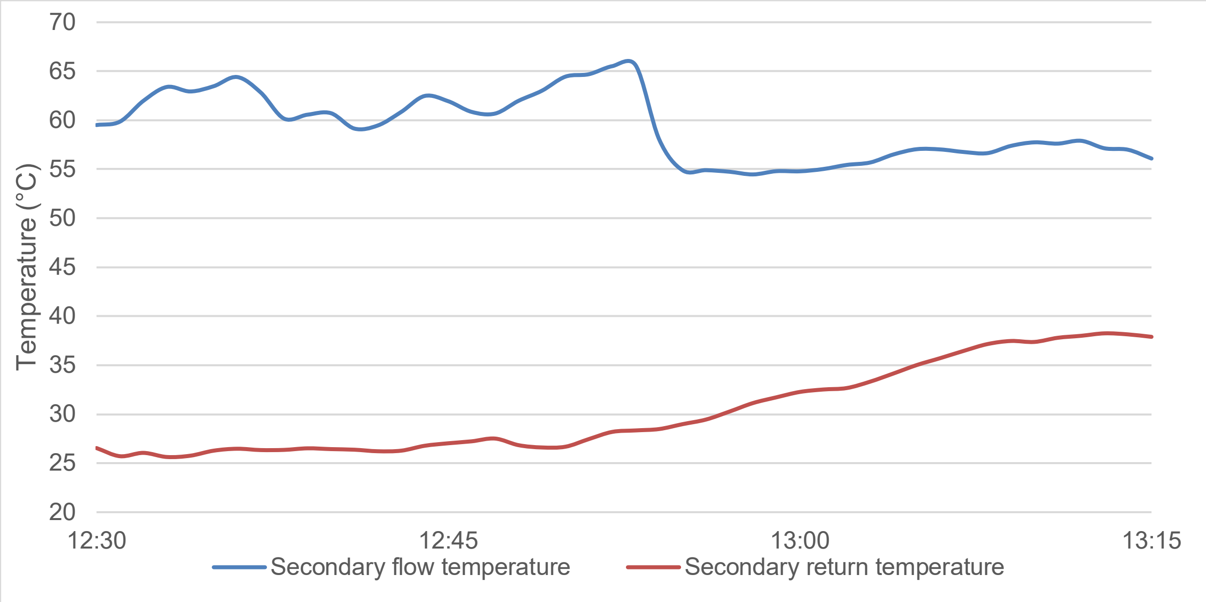


**Figure 3: Stable secondary flow temperature during low demand after control loop retuning on a PHE-fed system**

### *Unstable performance at low loads – boiler control*

It was observed during a load test of a boiler-led system that the network flow temperature was unstable during low load operation. Investigation of the BMS revealed that this was a combination of:

- The BMS not sequencing boilers offline during low demand periods
- Poor outlet temperature control on the boilers causing the BMS to bring additional boilers online

It should be noted that the two issues are linked. The poor outlet temperature stability caused additional boilers to be brought online which were slow to be brough offline.

All 3no. boilers were found to be enabled during low demand, despite the system demand being significantly below the minimum firing rate of the 3 boilers. This led to the flow temperature set point quickly being exceeded, causing all 3 boilers to switch off and for the set point to not be achieved.

It was recommended that the boiler commissioning was reviewed to stabilise the outlet temperatures from individual boilers. In addition to this it was recommended that the BMS sequencing parameters were reviewed to reduce the time taken to bring boilers offline when additional boilers were not required. This work ensured that a single boiler operated during low load periods and that the outlet temperature of the boiler was stable around the set point.

### *Insufficient flow temperatures under load – Boiler control*

It is important to ensure that sequencing of generation equipment is done correctly to avoid the risk of insufficient generation in response to changing demand. Incorrect or poor sequencing can lead to unstable flow temperatures, which ultimately can impact heat delivery to residents.

It was observed during a load test of the same boiler-led system mentioned above that the network flow temperature stability did not improve during the application of load, and that the flow temperature was consistently below the set point during the load test despite all 3no. boiler modules being enabled. Evidence of this performance can be seen in Figure 4. This was determined to be caused by the poor outlet temperature control on the boilers failing to respond to the system demand.

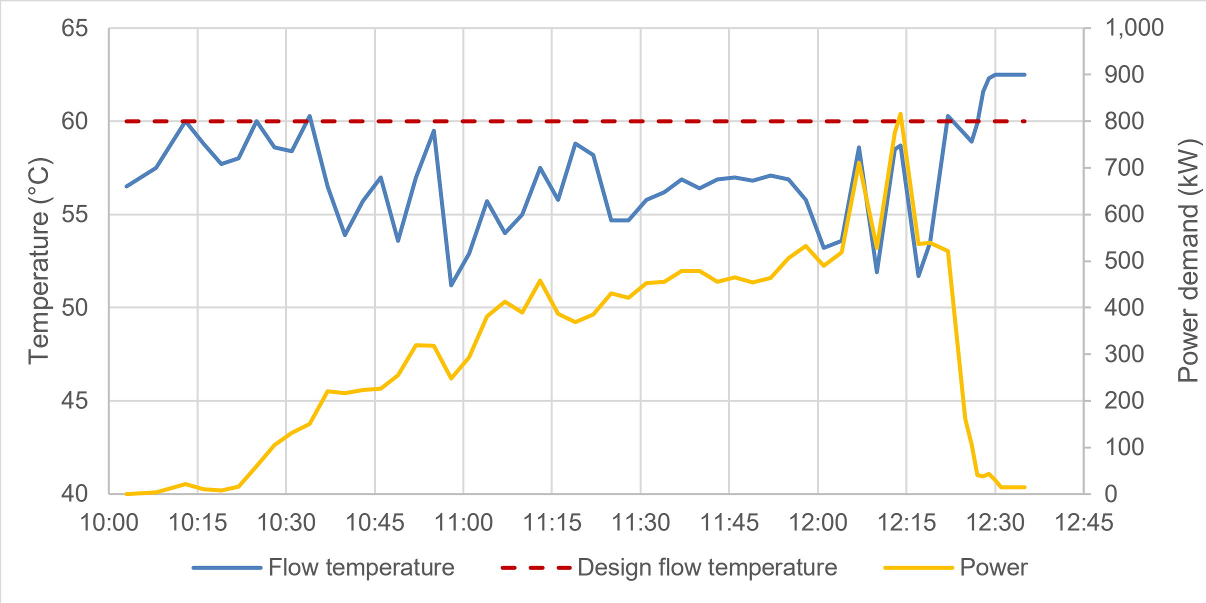


**Figure 4: Unstable flow temperature during the application of load on a boiler-led system.**

It was recommended that the boiler manufacturer improve the start-up and operational temperature stability via the internal boiler controls to ensure a consistent outlet temperature was achieved during varying demands. The results of this work can be seen from block level heat meter data of the handed over system in Figure 5. Flow temperature is consistently maintained just above the set point, enabling consistent delivery of heat to residents.

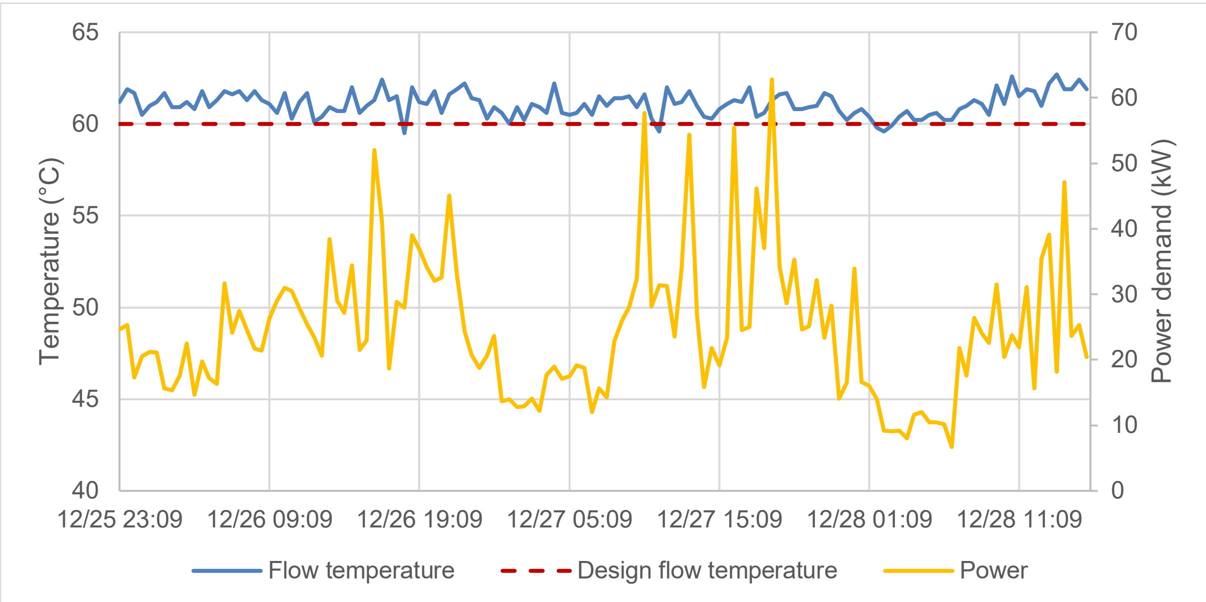


**Figure 5: Stable flow temperature from a block level meter during operation of a boiler-led system**

### *Inability to supply peak load – blocked strainers*

It is essential that even flow occurs through all online boilers. If there is a significant variation in flow, the boilers will not operate at consistent firing outputs. If that variation is large enough, the flow through some boilers could exceed their maximum flow rate, resulting in outlet temperature instability and reduced effective maximum heat output from the boilers.

It was observed during a load test that the flow rates through one bank of boilers was c. 50% higher than the other. This led to modules in one bank exceeding their rated output and operating at c. 8 °C below their set point, despite the other modules operating at set point the plant room flow temperature fell c. 4 °C below set point, as can be seen in Figure 6.

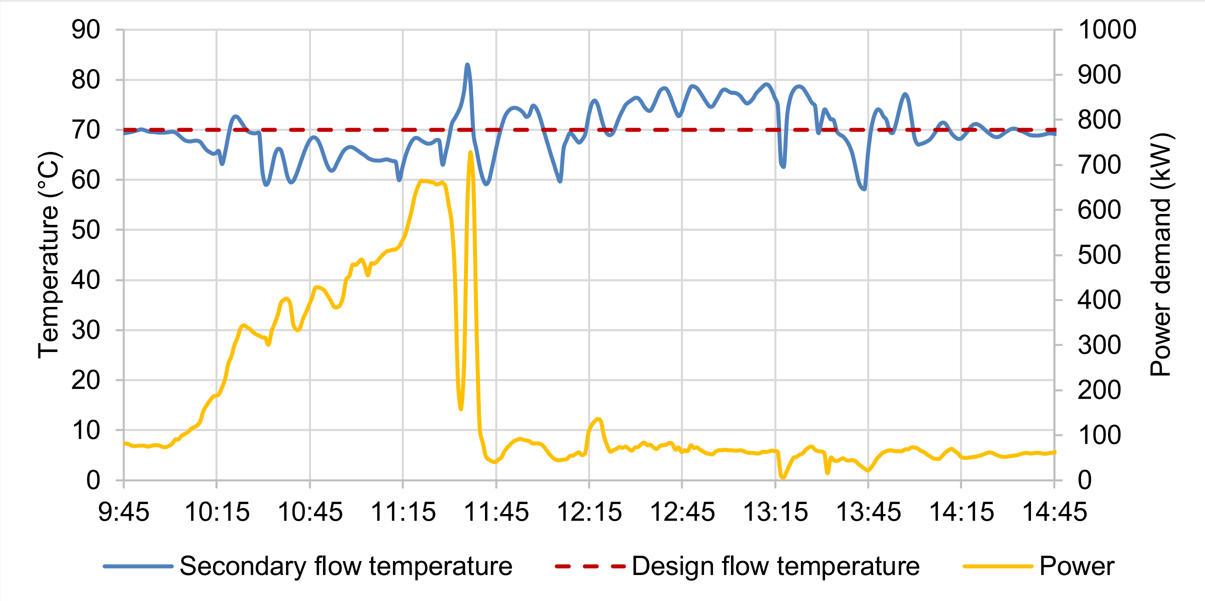


**Figure 6: Inability to maintain flow temperature under load**

Investigation of possible causes of flow restriction to the boiler modules identified a blocked strainer. The boiler modules had not been correctly rotating and the high run hours in the low flow rate boilers had contributed to the increased build up of debris.

After cleaning the blocked strainer and updating the changeover procedure, the boilers were able to maintain the design flow temperature set point under load and sequence as expected by the design.

### *Inability to supply peak load – boiler sequencing and valve control*

It was observed during a load test of a CHP and boiler-led system that the plant room was not able to consistently supply any loads exceeding a third of the expected peak load. During the load test both the CHP and the boilers failed to supply heat to the system, as can be seen from the inconsistent flow temperature shown in Figure 7. It should be noted that no additional load was applied after 14:50, and load was steadily removed from 15:10. The flow instability witnessed in the plant room led to instantaneous loads of up to 850 kW being measured despite the lower system load.

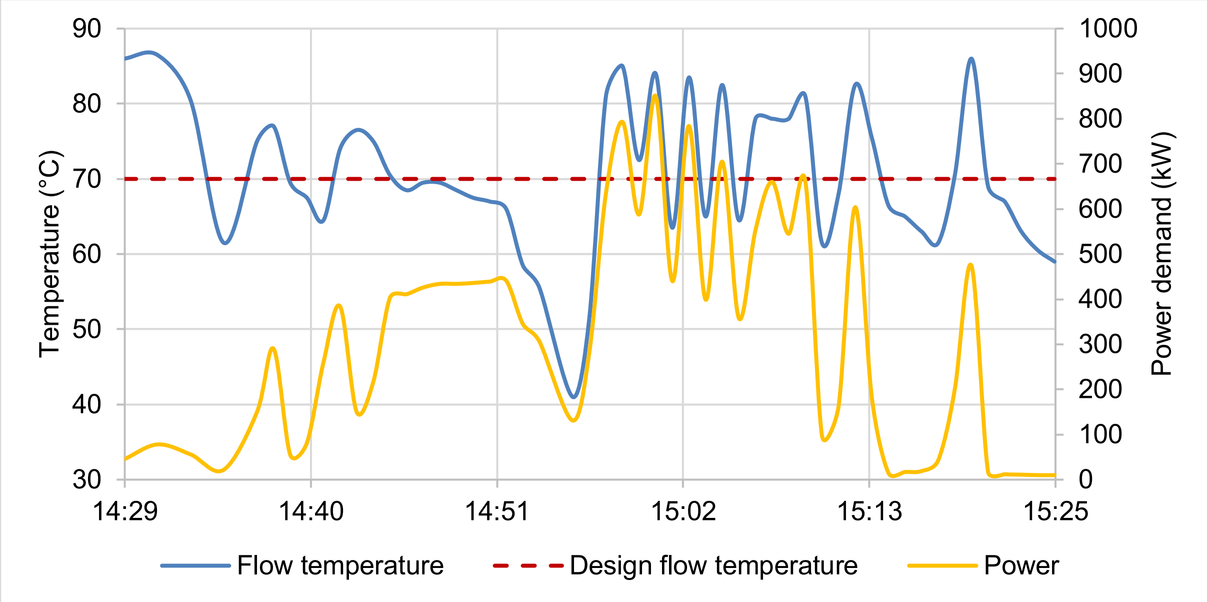


**Figure 7: Inconsistent flow temperature during a load test**

Investigation of these issues identified that the CHP control valves closed at 14:31, contrary to the signals output by the BMS. Furthermore, although the lead boiler module began firing to maintain the rising load, once the load exceeded the demand of a single boiler module and sequencing of an additional module was expected, no additional boiler modules were enabled. The lead boiler module then disabled itself at 14:50, when the BMS was unable to re-enable the lead boiler module. Whilst the CHP was manually re-enabled, it was not sufficient to maintain the high system load.

It was proposed that BMS control and wiring to the CHP valves was reviewed to ensure flow valves remained open when desired by the BMS. In addition to this the internal boiler sequencing methodology was reviewed by the manufacturer, where a software issue had restricted the system’s ability to sequence more than one boiler.

Implementation of these works, as well as further works to tune control valve settings and controls logic based on follow-up load tests, have enabled the system to operate the CHP in accordance with the design intent and to effectively sequence the boilers in response to peak loads.

### *Inability to supply peak load – boiler back-end valves and valve control*

Two load tests were performed back-to-back on a CHP and boiler-led system where previous issues with low pressure faults during boiler start-up had led to the contractor permanently opening one boiler back-end valve. During these tests considerable issues with supplying the design flow temperature to the network was observed, as can be seen in Figure 8.

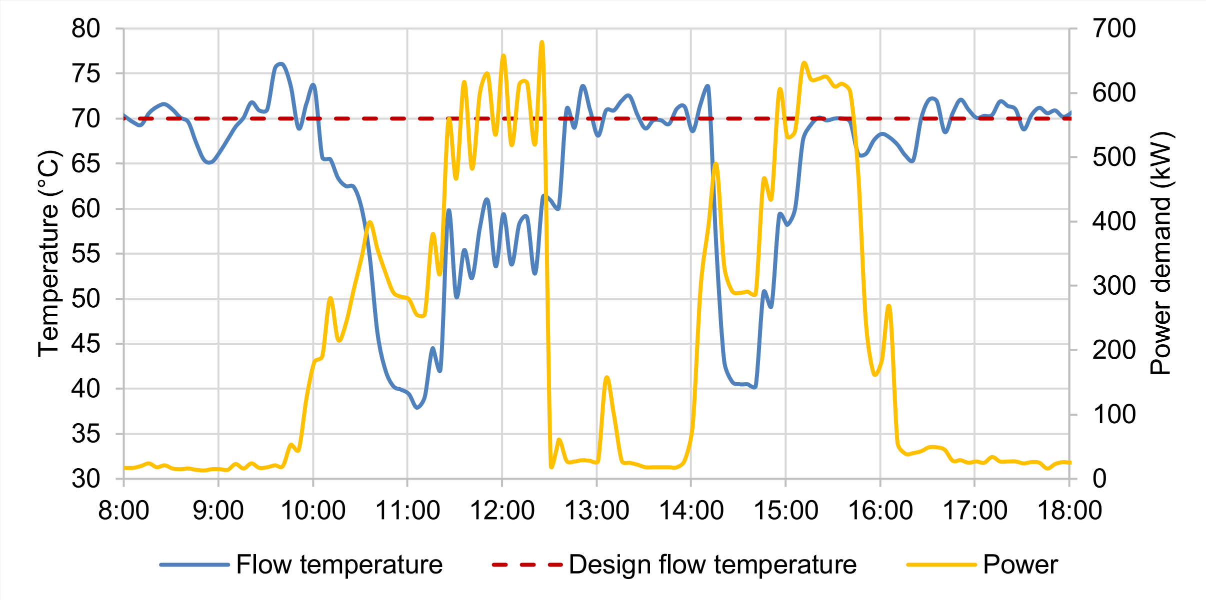


**Figure 8: Unstable flow temperatures during back-to-back load tests**

During the first load test, the thermal store initially discharged as expected to maintain the system flow temperature. However, the thermal store was quickly found to be unable to provide the system load, despite the thermal store not being completely discharged. As the thermal store was still charged, the BMS did not call for the boilers to fire, and the system could not meet the required load. Investigation determined that the thermal store discharge PICV had been programmed with a maximum flow rate, restricting the speed at which the thermal store was able to discharge and rendering it incapable of meeting the network demand. Furthermore, this issue was being compounded by the flow temperature dilution caused by the open boiler back-end valve. An labelled indicative schematic of the plant room hydraulic layout is shown in Figure 9.

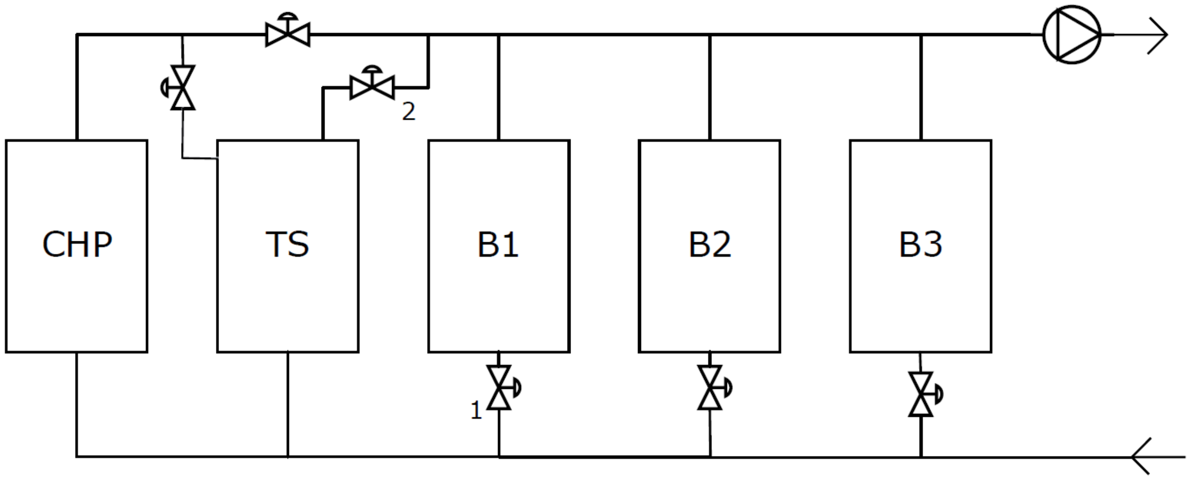


**Figure 9: A simplified plant room schematic. [1] Open boiler back-end valve. [2] Flow restricted PICV**

This issue persisted through the second load test until the thermal store was discharged. Once the thermal store was discharged the BMS was able to enable the boilers, which were able to consistently maintain the flow temperature set point under load. However, it was observed that the system enabled all six boilers at once, causing high cycling and instability as load was decreased.

It was recommended that the PICV flow restriction was removed, and the boiler back-end valve closed when not in use; closure of the back-end valve meant additional boiler expansion vessels were required to address the low-pressure faults during start up. It was also recommended that the boiler sequencing methodology be reviewed, to ensure only the required number of boiler modules were enabled for any given load.

Implementation of these works enabled the CHP to act effectively as the lead heat source through the thermal store and enabled the boilers to sequence effectively to stabilise the flow temperature during higher loads.

### *Unstable differential pressure delivery – pump control*

Pump sequencing control loops can cause instability in index run differential pressure if not properly tuned, leading to inconsistent delivery of heat to dwellings.

During a load test, there were 2no. pumps operating in duty/assist. As the load was gradually decreased from peak load to low load the assist pump was observed cycling on and off, as is shown in Figure 9. The pump cycling caused instability in the top of riser index run differential pressure, varying from 0.2-1.35 bar during this period, as can be seen in Figure 10.

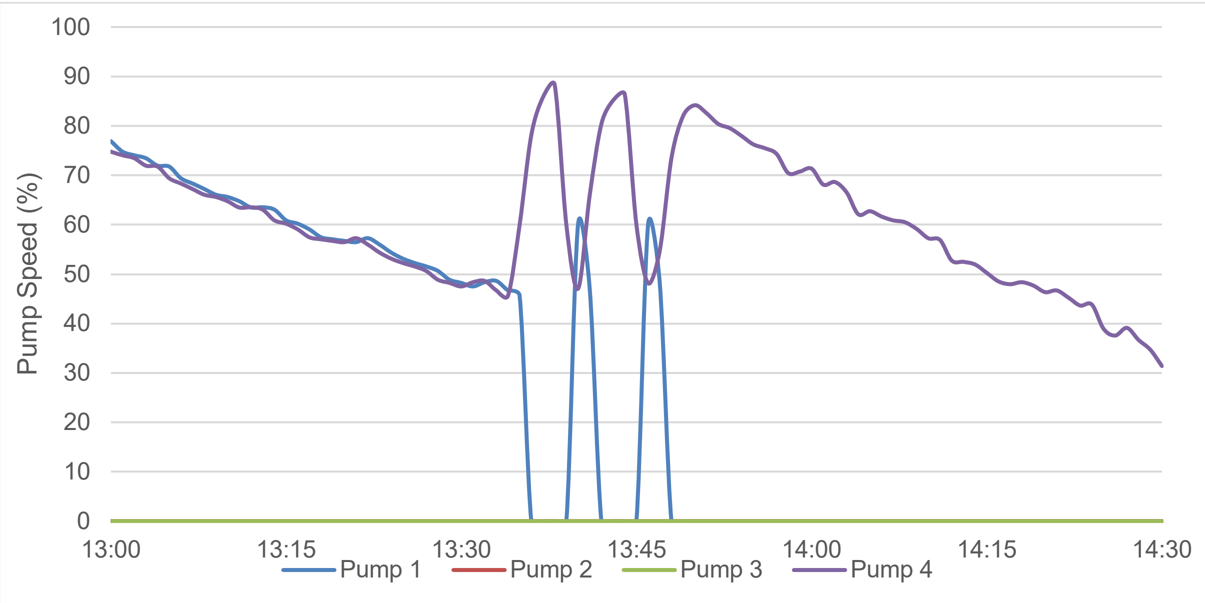


**Figure 10: Network circulation pump speed during decreasing system load**

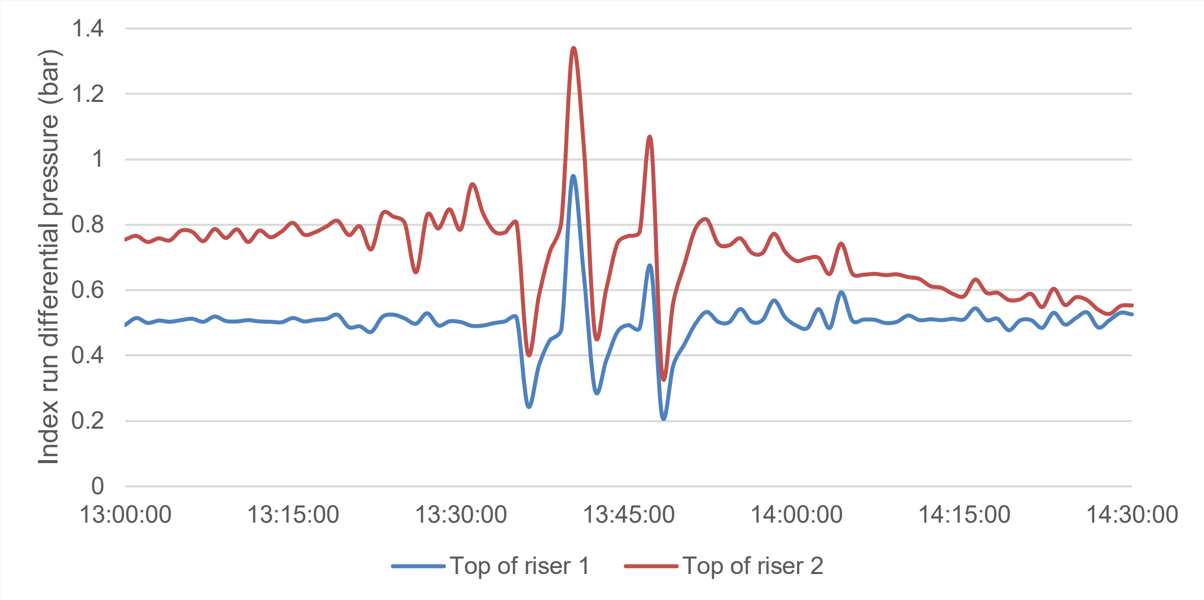


**Figure 11: Index run differential pressure during decreasing load**

Investigation of the BMS revealed that the pump assist disable point was set at 45% pump speed, causing the duty pump to instantly be required to run at 90% speed, leading to demand for the assist pump to enable. This behaviour can be confirmed in Figure 9.

It was recommended that the pump assist disable point was reduced from 45% to 35% to prevent the pumps from cycling as load decreases and to maintain a stable index run differential pressure.

## *Poor return temperature performance/excessive flow rates*

Incomplete or poor commissioning of terminal units and bypasses left open will lead to excessive return temperatures even when there is no load on the system.

Prior to a load test commencing, return temperatures of 60-65 °C were observed, as per Figure 11. These temperatures were above the return temperatures expected by the system design.

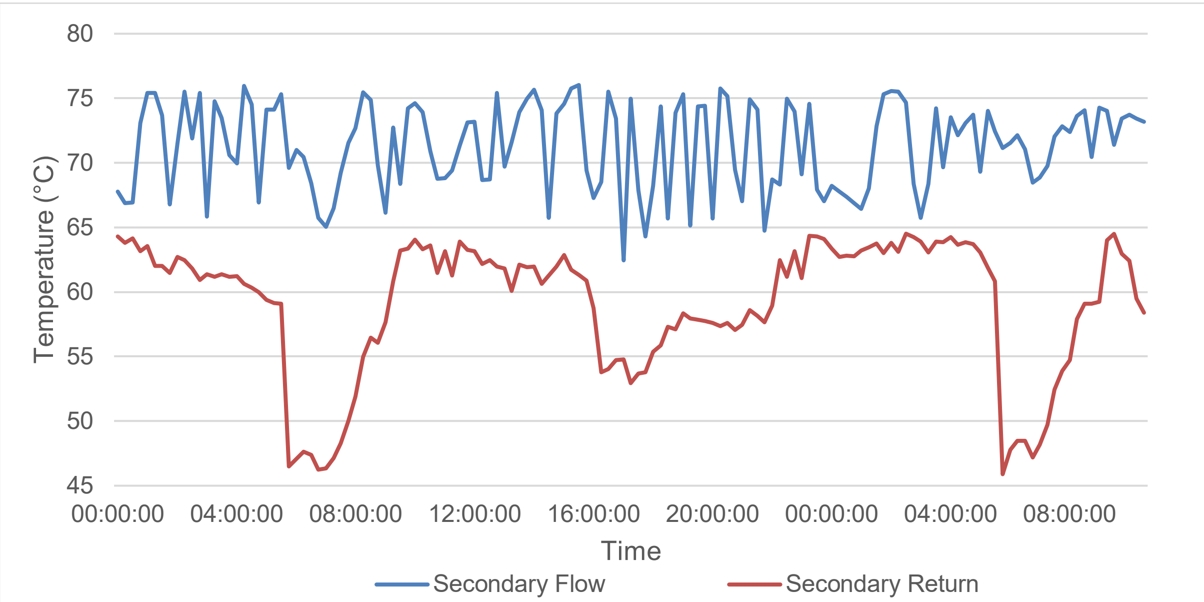


**Figure 12: Elevated secondary return temperatures**

It was identified that these high return temperatures were occurring due to incomplete commissioning of some parts of the network and open network bypasses. It was recommended that HIU commissioning was reviewed and completed, and that the network was reviewed for open bypasses, any that were found were to be closed in order to reduce the primary and secondary return temperatures.

Once this work had been completed, a second load test confirmed that the secondary return temperature had been reduced, as per Figure 12, leading to more efficient network performance and reduced heat losses.

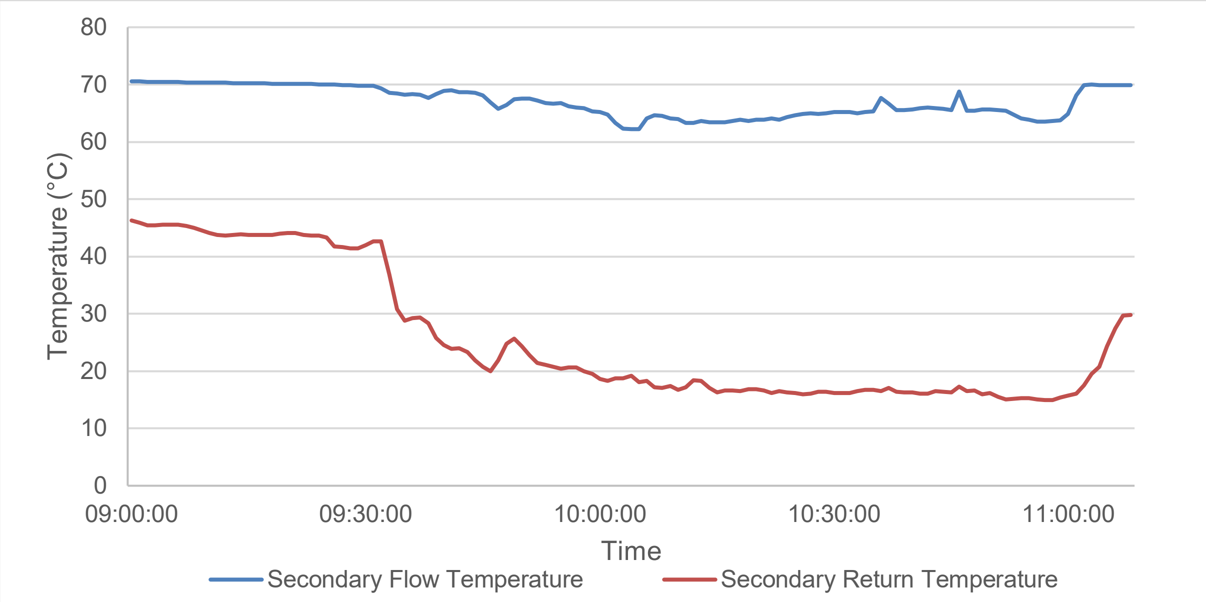


**Figure 13: Reduced secondary return temperatures after open bypasses were closed and commissioning completed**

## Conclusions

It has been determined that typical industry commissioning practices fall short of the “bigger picture” approach required to ensure that systems perform well after occupation. A heat load test methodology has been developed and has been outlined in this paper. Experience has shown that the application of this methodology consistently identifies potential future performance issues, enabling them to be addressed prior to system handover and occupation, more easily and at significantly lower cost than after occupation.

Even well commissioned systems can have unexpected performance issues during operation. A heating load test provides a vital opportunity to determine and address these issues in a low risk scenario.

It is essential that a heating load test is performed on all LTHW systems prior to handover and occupation. This process must be a collaborative process with buy in from all project parties to ensure all potential issues can be identified and resolved. This collaborative process should include:

- A load test methodology included in commissioning method statements
- The mechanical contractor undertake their own load test to verify that the DesOps has been executed and to identify faults
- An independent party witness a separate load test prior to acceptance of plant handover
- Access to 1-minute BMS data on key parameters during the load test(s)

By following this process LTHW systems can be handed over with confidence in their long-term performance after occupation. However, performance monitoring should not stop at handover; ongoing performance check ups and regular maintenance/recommissioning of HIUs and plant room equipment are essential in ensuring that the high performance at handover continues throughout the life of a building.

Whilst the examples of load tests detailed above were all performed on boiler-or CHP-led heat networks, the same testing process is strongly recommended for heat pump-led systems as they are delivered. The principle issues identified in this paper are likely to also occur on heat pump-led systems, performing a building-level heat load test will enable these issues to be identified and addressed.

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