Technology Strategy Board
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**TSB FILE REFERENCE 450107** **Building performance evaluation follow-on project**

# FINAL REPORT
# Woodland Trust Concrete Radiator Performance Analysis

**TABLE OF CONTENTS** **Page**




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*The project reported here is part of the Technology Strategy Board's Building Performance Evaluation programme. Acknowledgement is made of the financial support provided by that programme. Specific results and their interpretation remain the responsibility of the project team. Full details of the Technology Strategy Board's BPE programme can be found at https://connect.innovateuk.org/web/building-performance-evaluation.*

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**FINAL REPORT Woodland Trust Concrete Radiator Performance Analysis**
**EXECUTIVE SUMMARY**

1 BACKGROUND

The walls, roof and floors of the naturally-ventilated three-storey Woodland Trust Headquarters in Grantham are all made of cross-laminated timber. To add thermal capacity and structural stiffness, "concrete radiators" are bolted to the undersides of the structural timber ceilings, covering about 60% of the exposed area. In mild weather, the concrete stores excess heat and reduces the need for pre-heating the next day. In warm weather, the Building Management System (BMS) opens motorised top-hung windows on all floors, to remove excess heat overnight as necessary.

In the first two years of operation (2011-2012), the summers were relatively cool, but the offices had a tendency to overheat. To find out why, the Technology Strategy Board sponsored a detailed investigation of the operation of night cooling: monitoring temperatures and heat flows; and with some static and time-lapse infra-red thermography. This has helped to improve performance and control at the Woodland Trust, and understanding of heat storage and night cooling generally.

2 REASONS FOR THE INITIAL UNDERPERFORMANCE

There were four principal causes of the initial underperformance at the Woodland Trust:

- Restrictions on window opening, both from the insurers and a Health and Safety policy whish went beyond regulatory requirements in an office space.
- Incorrect BMS temperature measurements. 1). The outdoor sensor was influenced by indirect solar gains, so was relocated to a better shaded and ventilated position; and 2). the internal temperature average included rooms not night cooled, so the control point was re-programmed.
- It could feel too cold early in the morning, because furniture and other lightweight elements were at a much lower temperature than the concrete. The windows are therefore now closed two hours before occupancy, to allow internal temperatures to come into a better balance.
- An over-complicated control strategy. This was simplified to essentially four decisions, each with settings that could be adjusted easily by facilities management (FM), using the BMS:
  1). *Does the weather demand night cooling?* The FM can decide whether to enable it or not.
  2). *For what period each day should night cooling be enabled?* The FM selects a programme.
  3). *Is the office hot enough at the end of the day to justify night cooling?* Select the temperature.
  4). *Is the office getting too cold during the night cooling?* Select the cut-off temperature.

3 MONITORING RESULTS

In addition to identifying and rectifying the problems above, the monitoring also showed that:

- Heat passed into and out of the concrete radiators 3.5 times as fast as into the timber.
- Heat transfer through the sides of the concrete radiators added about 20% to their effective area.
- On mild days, the average rate of heat absorption was about 5 $W/m^2$, raising the temperature of the concrete by 1°C. On warm days, the figure doubled. Much higher rates occurred if windows were opened on very hot days, but it might have been more comfortable to keep them shut.
- In hot weather, night ventilation removed heat at typically 5-8 $W/m^2$, so weekend cooling was essential to restore indoor temperatures for the following week.
- When the windows were open, there was little stratification within the three floors of offices and the changes in concrete radiator temperature were similar for all locations.

4 CONCLUSIONS FOR FUTURE DESIGNS

- The concrete radiators have achieved their objective: increasing thermal capacity and lowering peak temperatures. However, the effect is relatively small, so they are not a panacea, but a component of a low-energy strategy that also minimises unwanted internal and solar gains.
- Care needs taking in design, commissioning and fine tuning of night ventilation systems. Simple and straightforward proposals may prove to be best, and some user intervention useful.
- Take care in positioning outdoor temperature sensors. Good locations can be difficult to find.
- Concrete is slow to cool, so night cooling process can make lightweight elements including furniture too chilly the next morning. To maximise heat removal whilst avoiding comfort complaints, a rest period between night ventilation an initial occupancy will often be beneficial.
- Try to ensure that night ventilation facilities are secure against activities of vandals.

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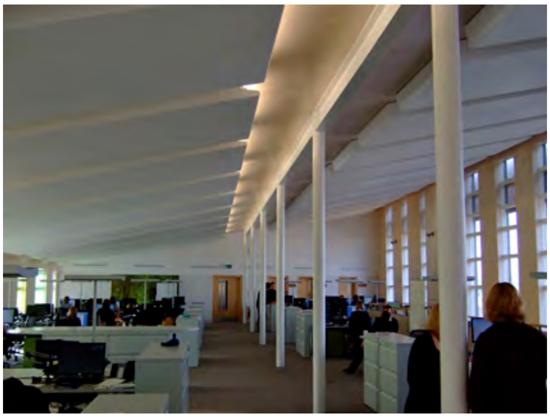
# 1 INTRODUCTION



## 1.1 BACKGROUND

The Woodland Trust Headquarters in Grantham contains three floors of naturally-ventilated north-south facing open-plan offices of cross-laminated timber construction, connected vertically by an atrium against the north facade and a stairwell and light well to the south-west. While the cross-laminated timber has substantial thermal capacity, it exchanges heat relatively slowly, which had caused overheating in an earlier timber building known to Max Fordham. The design team therefore used "concrete radiators", bolted to the undersides of the roof and ceilings, to provide added thermal capacity, response and structural stiffness. The result is illustrated in this photograph of the second floor. The BMS is programmed to open motorised top-hung windows on all floors to remove excess heat overnight as necessary. The concrete radiators then help to reduce peak air and radiant temperatures the following day. Appendix A shows the floor plans and Appendix B the locations of the motorised windows.

## 1.2 THE FOLLOW-ON PROJECT

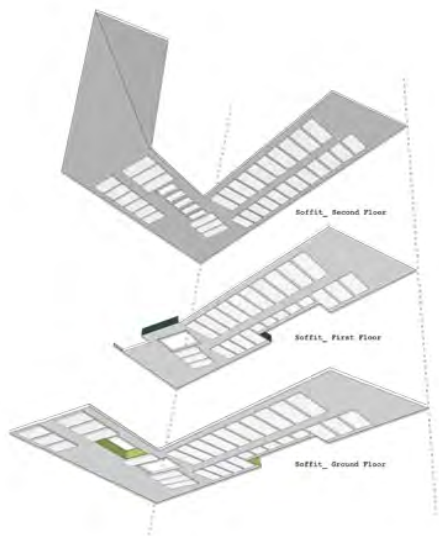
Although the summers of 2011 and 2012 were cool, occupants reported that the building could get hot. Contributory causes were restrictions on window opening owing to health, safety, security and insurance requirements, and a need to re-examine the control strategy. The team undertaking the Building Performance Evaluation for the Technology Strategy Board (TSB) obtained follow-on funding from TSB to help understand how the night cooling was working, improve its performance if possible, and capture lessons to assist future designs, control systems and operations.

## 1.3 OUTLINE OF THE WORK UNDERTAKEN

The work included a period of preliminary monitoring over the weekend 21-23 September 2012 using temperature data logging, heat flux sensing and infra-red thermography, see Appendix D. The preliminary findings led to a number of changes in both monitoring and control strategies:

- Infra-red thermography showed that all the concrete radiators in the building were behaving similarly, so the heat flux monitoring strategy was changed from measurements in four widely separated locations to more comprehensive monitoring of two nearby concrete radiators, with associated air, surface and globe temperature sensing.
- Automatic ventilation was found to have been held off because the outdoor temperature sensor, though in a shaded position, could read very high, owing to convection currents resulting from solar gains onto the west wall. The sensor was relocated to the dustbin compound.
- Change to the BMS control strategy, user interface, and operating practices. These included:
  - Removing the interlock between heating and night cooling. Instead independent night cooling programmes were provided for weekdays (Mon-Thu) and weekends (Fri-Sun). These were configured to allow the facilities managers to make simple changes to time schedules, the extent of window opening, and to the high and low limit temperatures.
  - Closing the automated windows at 6 AM on weekdays, to allow indoor temperatures to begin to come to equilibrium before the office opened. Otherwise, night ventilation could leave furniture and other lightweight items too cool at the start of the working day.
  - Changing the temperature used to control the night ventilation to the average of the open plan offices only. Originally, meeting room temperatures were also included in the average.
  - Additional facilities to control heating and daytime ventilation were also added at the end of the monitoring period, to help improve conditions both in winter and summer, and make it easier for facilities managers to adjust settings and time programmes.

1.4 CONCRETE RADIATOR ARRANGEMENT




The figure to the right shows the arrangement of the concrete radiators on the ceilings, seen from below. The second floor ceiling/roof is at the top and the ground floor ceiling at the bottom. The roof of the second floor slopes down to the left, covering the high-ceilinged Project Space on the first floor and finally the ground floor wing of meeting rooms etc.. North is the long facade to the right, with notches in the ceilings of the ground and first floors to accommodate the atrium.

1.5 HEAT FLUX MONITORING

Heat flux and associated monitoring was undertaken by Archimetrics to a brief prepared by Max Fordham (the building's environmental designers) and William Bordass Associates. The equipment was installed over the weekend 10-12 May 2013. Information was then downloaded by the Woodland Trust and emailed for review at approximately fortnightly intervals. These revealed problems with one, and then two, heat flux sensors losing thermal contact. These were repaired and the whole installation thoroughly checked on 10 July. Everything then worked satisfactorily for the remainder of the project, apart from the failure of the outdoor logger at the very end of September.

## 2 MAIN FINDINGS

2.1 IMPROVED CONTROL OF NIGHT VENTILATION

Feedback from the preliminary tests suggested that alterations to control and management would increase the benefits of night ventilation. The following changes were undertaken:

- Simpler BMS initiation of night cooling, opening windows by a set amount (typically 20% for security) at a scheduled time (8 PM was initially selected, and not changed), if the average indoor temperature was above a set level (23°C selected, and not changed). This proved more robust and effective than the previous regime, which undertook more complicated checks of indoor and outdoor temperatures; and included interlocks with the heating system.
- Simplified termination of night cooling, to keep the average indoor temperature above a pre-set value (18°C, and not yet changed) and with a fixed stop at 6 AM. With the office opening at 7.30 and most people arriving between 8 and 9, closing windows at 6 gave time for heat stored in the concrete radiators and timber panels to warm up more thermally responsive items, including air, floors and furniture, which could get chilled overnight. If windows stayed open until 8 or 9 AM, people could complain that the building was too cold when they came in, and consequently stop night cooling being used, even though there was an excess of stored heat.
- Separate weekday (Sunday night to Friday morning) and weekend programmes. In cooler weather, one night's ventilation was sufficient to dissipate any excess heat stored from the previous week. However, if this happened on a Friday night and the weather then turned cooler, the building might have lost too much heat by Monday morning. In May and June, cooling was therefore programmed to operate on Sunday night only. This ceased to be adequate in early July, when cooling was enabled for every weekend night until the end of the monitoring period.

The changes performed relatively well, but there is scope for further simple improvements, in particular extending the weekend cooling periods to say 10 AM, lowering the minimum night cooling temperature (to 17 or even 16°C), and considering opening some windows further, particularly those that face south and east into the secure courtyard.

## 2.2 OUTDOOR TEMPERATURE SENSOR RELOCATION

For both day and night ventilation, the BMS was originally programmed to compare outdoor and indoor temperatures, to determine whether cool air was available from outside. The outdoor temperature sensor was originally installed on the west facade, in the shade of the escape stair. However, when sun fell onto this wall, the lightweight timber rainscreen cladding, heated rapidly, creating convection currents which could reach the sensor. On one sunny afternoon, we measured an air temperature at the sensor position fully 8°C higher than in the car park. Thinking it was (or had been) very hot outside, the BMS often kept windows shut unnecessarily, day and night. The sensor was therefore moved to a better-shaded and ventilated position in the dustbin compound.

Outside temperature was not used to control night ventilation during the monitored period: internal temperatures and the enabling 8 PM – 6 PM time programme were found sufficient.

## 2.3 OTHER CONTROL CHANGES

Scope was also identified to improve daytime ventilation, in particular with finer control over window opening. The windows were originally programmed to operate all together, and in coarse notches, so the environment tended to swing from stuffy to draughty, particularly in cooler weather. Changes were programmed by the BMS contractor in May 2013, but did not work as intended, so daytime ventilation control remained coarse over the summer. Further changes were made on the BMS visit in September, putting more adjustment of control settings in the hands of the operator.

## 2.4 HEAT TRANSFER

Since the windows were not designed specifically to scrub the concrete radiators with incoming air, heat transfer to and from the concrete radiators was similar throughout the building. This made heat transfer rates modest but more uniform and predictable. Heat flux monitoring revealed that under normal conditions, heat was absorbed by the concrete radiators at a rates of typically 5 Watts per square metre on a normal working day, raising their core temperature by about 1°C. The average rate of daytime heat transfer rose to typically 7-10 $W/m^2$ on hot days. Occasionally much higher values were recorded, for example averaging over 20 $W/m^2$ during the day on the very hot 1 August when windows were opened, probably unwisely, letting much warmer air in. Night ventilation removed heat at similar average rates (5-8 $W/m^2$) in the hotter weather, while in May and June a typical figure was 10 $W/m^2$, and in the cooler parts of September as high as 15 $W/m^2$. Heat transfer to the exposed cross-laminated timber ceilings followed a similar pattern, but with just under 30% of the magnitude. The thermal capacity of the timber is large, so it retained heat for long periods.

Heat was absorbed into the sides of the concrete radiators at about 80% of the rate of transfer into the soffit, and emitted at about 75% of the rate. This extended the effective heat absorption area of a concrete radiator into a margin of some 200 mm beyond its plan area in each direction.

## 2.5 IMPLICATIONS FOR FUTURE DESIGNS

The findings should interest people considering thermal mass and night ventilation, using concrete radiators or by more conventional means. They reveal:

- The order of magnitude of thermal storage available.
- The need to select good, well shaded and ventilated locations for outdoor temperature sensors, away from other sources of heat. In the author's experience, this can be difficult on many sites.
- Insurance and Health & Safety difficulties regarding the extent of window opening at night, even after it had all been discussed in detail during design and construction.
- The need for careful review and fine tuning, for control strategies to work as intended.
- The opportunities for simpler control strategies, and for helping operators to make simple but useful changes including enabling time programmes and trigger temperatures.

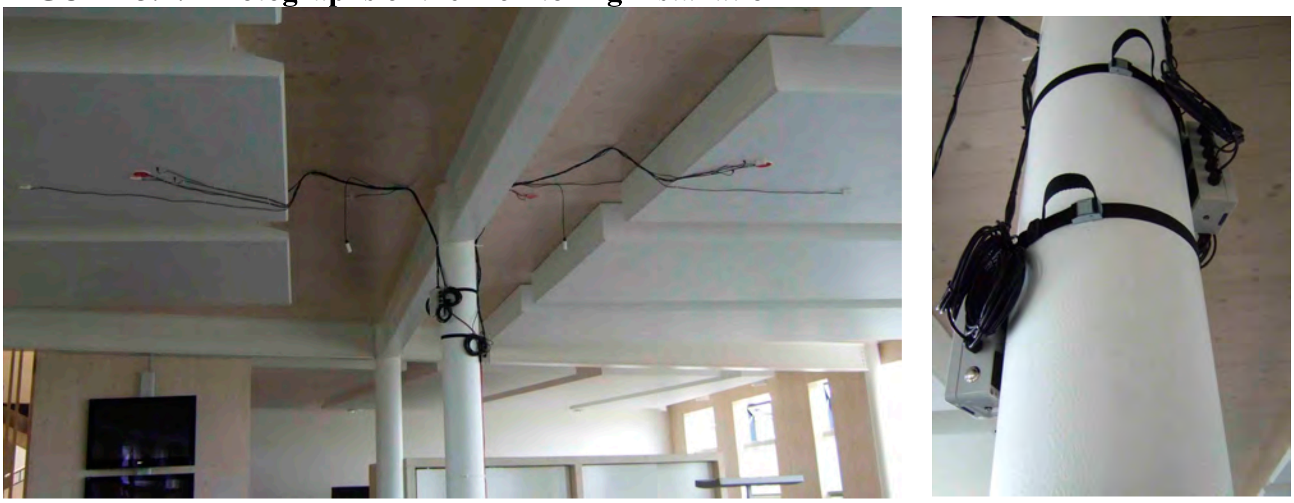
It should be noted that the beneficial cooling effects were modest, confirming that thermal mass needs to be used as a complement to, not a substitute for, designing and operating a building to minimise heat gains. At  the Woodland Trust, this included using “thin client” computer equipment, to minimise heat gains in the offices areas by concentrating its computing the server room.

## 3 DATA LOGGING INSTALLATION *(see Appendix C for locations)*

3.1 The installation consisted of five self-contained data loggers with SD memory cards:

- LOGGER 1 monitored heat flux sensors on the face of a concrete radiator on the north side of the first floor and on the adjacent timber; air and embedded mass temperature sensors nearby; and air in the void between concrete and the timber soffit. Surface temperatures of the concrete radiator were also recorded, for the 80 mm thick main area and the 250 mm reinforcing ribs.
- LOGGER 2 monitored a similar arrangement on the south side of the first floor, but with one heat flux sensor on the bottom of the radiator (as with Logger 1) and the other on its side.
- LOGGER 3 monitored eight air temperature sensors, suspended in a vertical line at intervals in the south-west corner of the atrium on the north side of the building, to measure stratification.
- LOGGER 4 monitored globe and air temperature sensors at about 1.3 m above floor level (the head height of a seated person) just to the north of the first floor corridor. The sensors were paired: one pair over the filing cabinet to measure general conditions; and the other nearer the workstations and more influenced by radiation from computer screens, task lights and people.
- LOGGER 5 was mounted in a north-facing position in the dustbin compound. Outside air temperature was measured by a shielded aspirated sensor at the bottom, while an exposed globe temperature sensor on a cable above it gave an indication of solar radiation gains and night sky radiation losses. This logger was battery powered, with PV-powered aspirator fan.

**FIGURE 3.1: Photographs of the monitoring installation**



*LEFT: Concrete radiator monitoring at the west end of the first floor. Logger 1 monitored the North panel (right) Logger 2 the South panel (left). RIGHT: Loggers 1 and 2 strapped to the column head.*

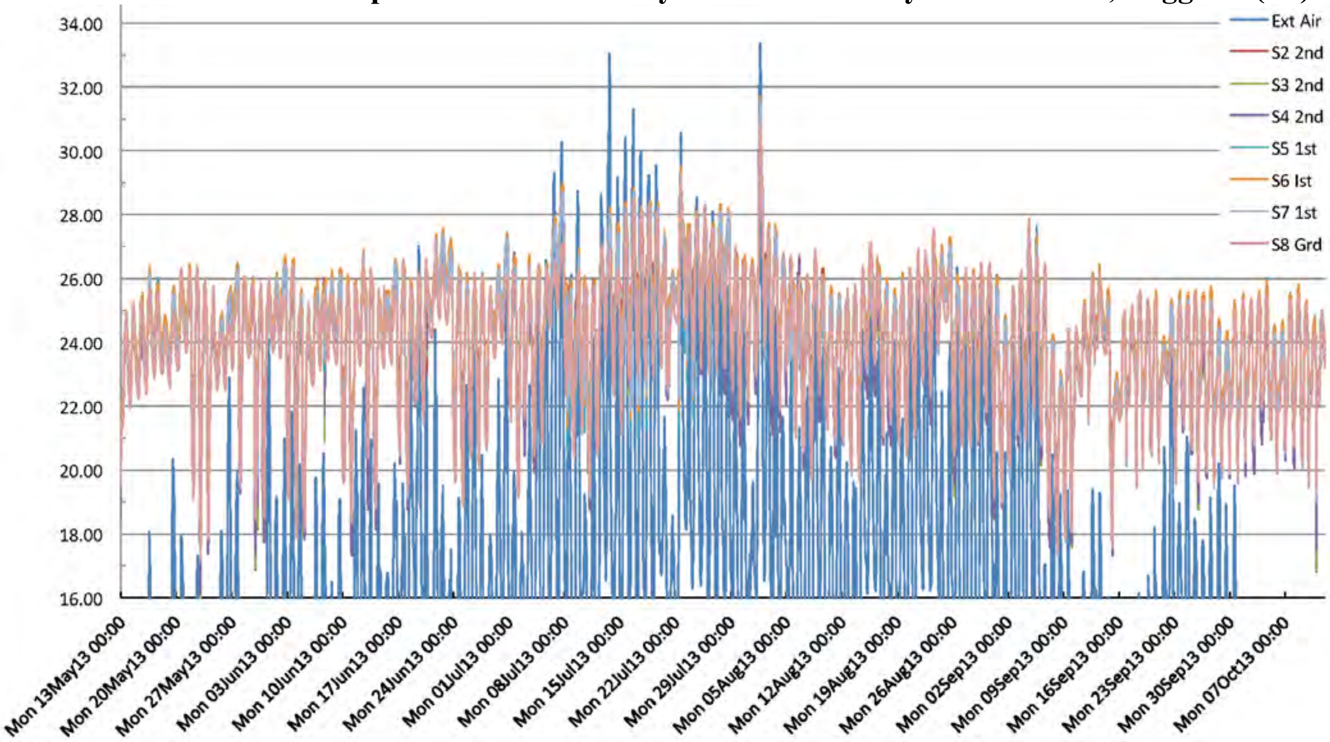
*LEFT: Logger 3, with cable to the vertical array of sensors above. Low voltage power cable below. CENTRE: Globe temperature sensor for Logger 4. RIGHT: Outdoor Logger 5 with globe sensor above.*

# 4 AIR TEMPERATURES

## 4.1 AIR TEMPERATURES GENERALLY

Figure 4.1 below shows temperatures monitored by the vertical array of sensors in the SE corner of the atrium which links all three floors of offices in the middle of the north external wall. Outdoor air temperatures are also shown, in blue. During occupied hours (weekdays 7.30 AM-6.30 PM), office temperatures tended to be within the band 22-26°C, peaking between 3 and 5 PM. Periods of night cooling are readily apparent from the deep temperature drops, typically towards or below 20°C. In the morning, temperatures rose quickly after the windows were closed, either at 6 AM or when average internal temperature measured by the BMS fell below 18°C[1]. This permitted night ventilation in milder weather, without making the offices too cold at the start of the working day.

**FIGURE 4.1: Air temperatures recorded by the vertical array in the atrium, Logger 3 (°C)**



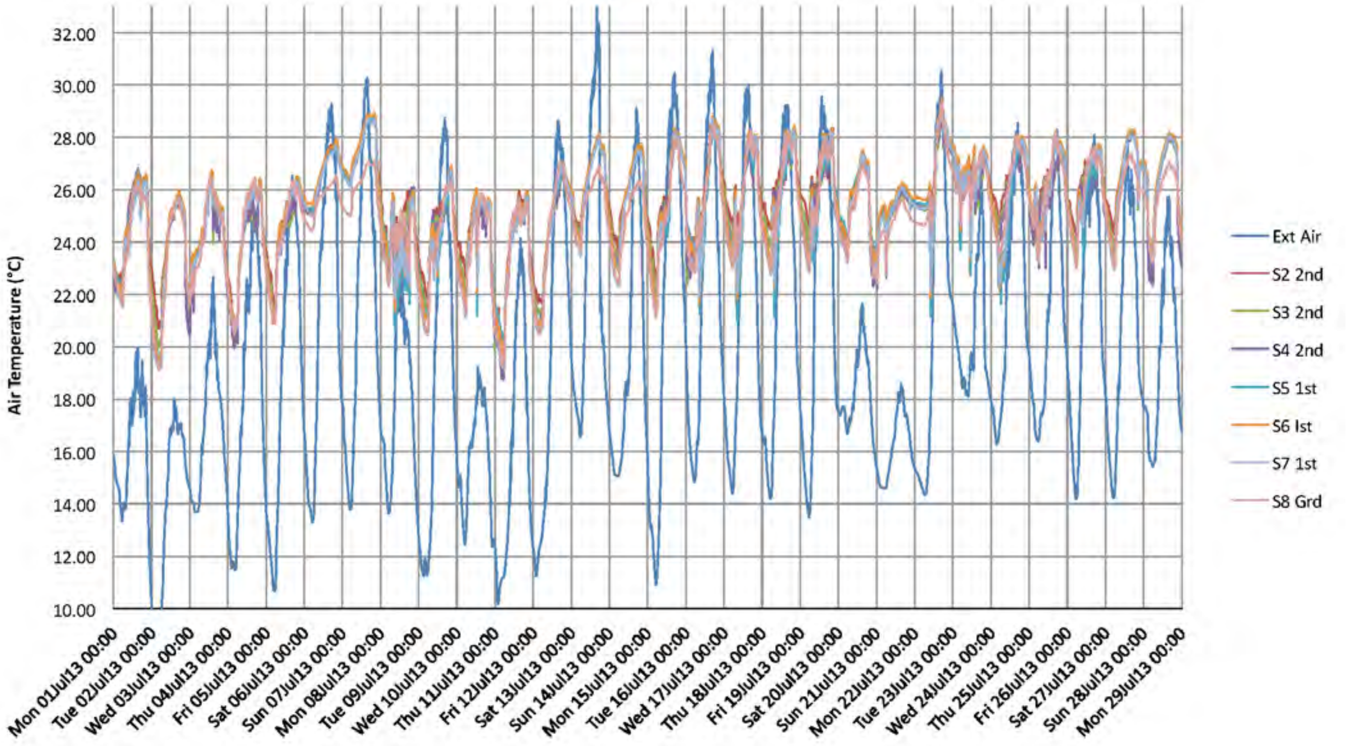

## 4.2 OVERVIEW OF ATRIUM AIR TEMPERATURES IN MAY AND JUNE 2013

Working from left to right in Figure 4.1, by relevant weeks:

- **13-19 May**. The offices started the period relatively cool, as there had been too much outside air ventilation from 10-12 May, while the monitoring equipment was being installed and tested. For the rest of the week, the weather was relatively cold, with no need for night cooling.
- **20-26 May**. Automatic ventilation first operated on the nights of 21-23 May. This successfully lowered afternoon temperatures, as seen by the successively declining peaks, although external temperatures were rising. Weekend night cooling was programmed for Sunday 26 May only: in the event, it did not operate, as by then the indoor temperature had fallen below 23°C. If night ventilation had been used on the Friday, the offices might have become over-cooled.
- **27 May to 16 June** continued similarly, with ventilation automatically operating as required on some nights between Sunday and Thursday, depending on the temperature reached.
- **17-23 June**. The hottest week so far. External peak temperatures exceeded indoor ones on 20 June; and a relatively warm night on Thursday 21 June restricted night cooling. Temperatures stayed high over the weekend, which remained sunny, although the air had turned cooler. Sunday night ventilation was still adequate to restore the situation for the following week.
- **24-30 June**. Similar to previous weeks, with night ventilation largely stopping temperatures climbing from Monday to Friday, and Sunday night ventilation sufficient for the weekend.

[1] For the monitoring period, the mean air temperature calculated by the BMS included not just the offices, but some meeting rooms that did not receive automatic night ventilation, though some do have daytime mechanical ventilation. In September 2013 the BMS was modified for night cooling, to average mean temperatures in the open plan office areas only.

**FIGURE 4.2: Air temperatures recorded by the vertical array in the atrium from 1-24 July**

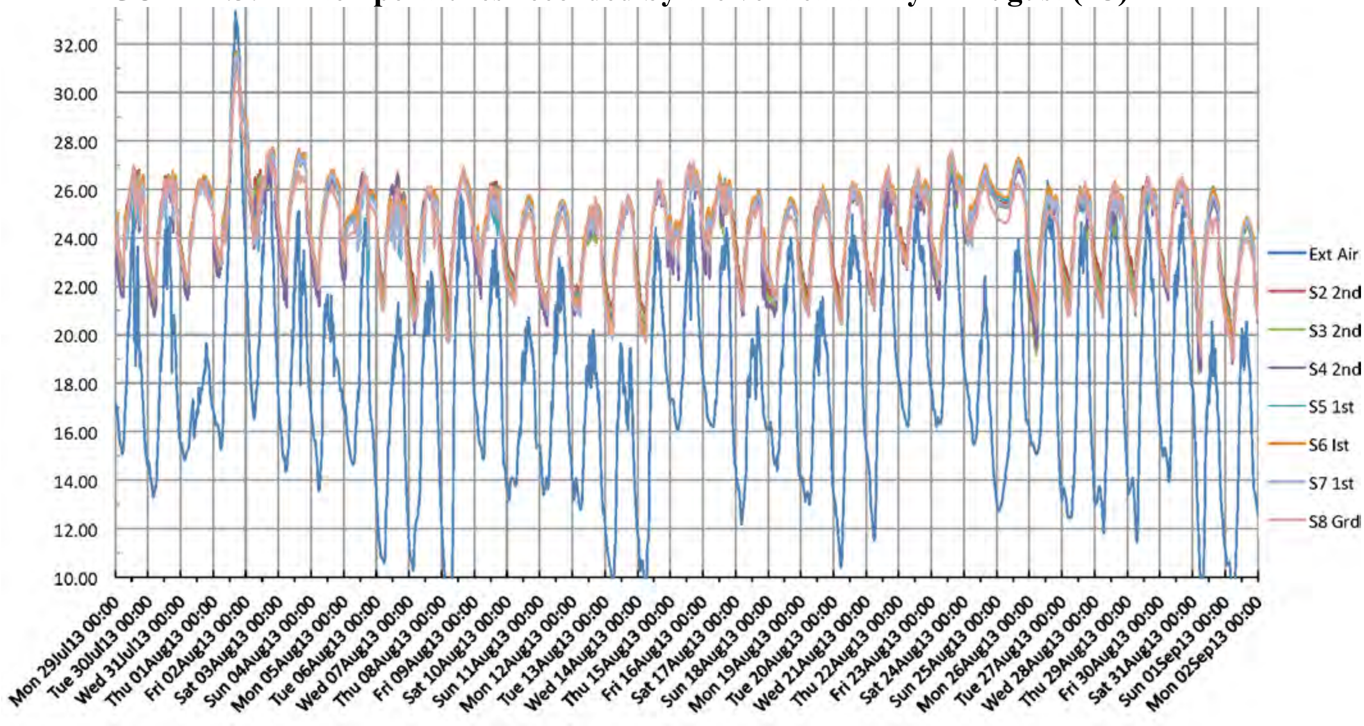



4.3 AIR TEMPERATURES IN JULY 2013

Figure 4.1 shows that July was the warmest month in the monitored period. This led to two weeks of relatively high internal peak temperatures. Figure 4.2 shows the data for July only. By week:

- **1-7 July**. The weather turned hot and sultry on Wednesday 3 July, peaking at just over 30°C on Sunday 7 July. Since night ventilation was not enabled on the Friday and Saturday, peak indoor temperatures on Sunday 7th became very high, approaching 29°C on the top floor. Sunday night ventilation improved the situation, but only to 25.5°C when the building was first occupied. For the rest of the summer, night ventilation was enabled for Friday and Saturday nights too.
- **8-14 July**. In spite of the heat accumulated over the weekend, peak temperatures on Monday 8th were no higher than in previous weeks, because the outside air temperature was lower (20.7°C average during the occupied period). Many windows were also opened manually during the occupied period, as is discernible from the much noisier traces in the middle of the day. Tuesday 9th was warmer, but internal temperatures were contained.
- At the end of this week, outdoor temperatures began to rise. So did indoor temperatures, although the peak office temperature was 5°C less than the 33°C peak outside. Ventilation was now operating on all three weekend nights: however, the cooling effect on Saturday and Sunday night was relatively small, owing to relatively high night-time temperatures.
- **15-21 July**. The hottest week. From Monday to Friday, outside temperatures peaked at between 29 and 30°C and only fell to 14-15°C at night. Night ventilation tended to maintain indoor air temperatures typically in the 24-26°C range in the morning, sometimes into the early afternoon. After that, temperatures tended to rise more rapidly - probably because many windows were opened manually by occupants or management - causing late afternoon peaks around 28°C.
- *RECOMMENDATION: In hot weather, consider starting night cooling periods at say 6.30 PM; and extending them to 10 AM on Saturday and Sunday mornings. Also consider opening the motorised windows further, if only on the courtyard facades where there is greater security.*
- **22-28 July**. Apart from Monday 22 July, external temperatures did not reach the 30°C+ peaks of the previous week. However, outdoor temperatures remained relatively high overnight, limiting the potential for night cooling. The building also started this week hot because, for some reason, night cooling did not operate on Sunday 21 July (although on the Friday and Saturday it had). So peak internal temperatures were in the region of 28°C.

**FIGURE 4.3: Air temperatures recorded by the vertical array in August (°C)**

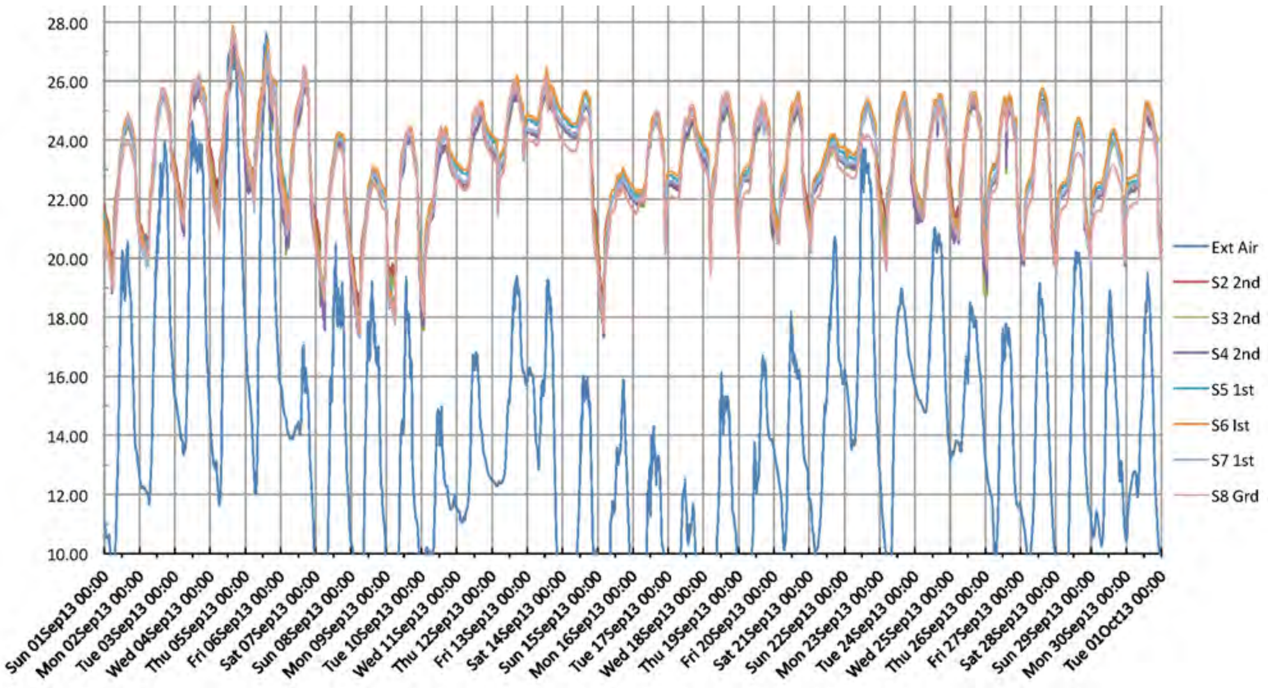



4.4 AIR TEMPERATURES IN AUGUST 2013

It is clear from figure 4.1 that, apart from the very hot Thursday 1 August, internal and external peak temperatures this month were lower than in July. Figure 4.3 above gives more detail:

- **As a general rule**, night cooling operated from 8 PM to 6 AM, lowering night-time indoor air temperatures to between 20-22°C, and giving indoor air temperatures of typically 23-24°C at 9 AM. On warmer days, internal air temperatures rose to about 26°C in the morning, and flattened off in the afternoon, assisted by some window opening, which noisiness in the traces indicates.
- **On 1 August**, the peak external air temperature was the highest recorded during the project. In spite of this, internal air temperatures showed signs of flattening off by noon. In the afternoon, indoor temperatures then surged, as many windows were opened. The office temperature would have stayed lower had the windows been kept shut: however, when interviewed afterwards, occupants said they preferred the air movement (though not necessarily on that particularly day). Night ventilation was not able to dissipate all the extra heat from 1 August, so Friday 2 August was relatively warm too.
- **Over the following weekend**, the building did not cool well, owing to relatively high overnight temperatures and a premature early stop to night ventilation on 5 August, for unknown reasons.
- **For much of the rest of the month,** internal temperatures were similar to those in June, even though external temperatures were often higher. Contributing reasons were the 3-day availability of weekend night ventilation and more window opening during the day.
- **Over the bank holiday weekend**, 24-26 August, night cooling did not operate on the 24th, owing to the BMS holiday time schedule.

**FIGURE 4.4: Air temperatures recorded by the vertical array in September (°C)**




## 4.5 AIR TEMPERATURES IN SEPTEMBER

Figure 4.4 shows air temperatures for the whole of September. By week:

- **1-8 September**. The first week was very warm, similar to that of 19 August. External and internal temperatures rose to 27°C on the Thursday and Friday. However, three nights of weekend ventilation were able to restore temperatures by Monday morning.
- **9-15 September**. Although the week was much cooler, indoor temperatures rose progressively from day to day. The charts reveals that night ventilation seldom operated, or only for short periods (e.g. the downward spike at 4 AM on 12 September), perhaps because the average room temperature measured by the BMS did not trigger night cooling; or the low limit temperature of 18°C was reached. Until 16 September, the trigger temperature average included meeting rooms, some of which some tended to be colder than the open plan offices in cooler weather, while others benefited from air-conditioning when it was warmer.
- Night cooling did however operate on Sunday 15 September, lowering the office temperature to 21°C at 8 AM on Monday 16$^{th}$.
- **16-22 September**. Brief periods of night cooling occurred every day including Friday, but not Saturday when presumably the building was cool enough. However after a warm and sunny Sunday, the ventilation operated overnight.
- **22-29 September**. Although warmer than the previous week, variable amounts of night cooling helped to maintain internal temperatures during the occupied period within a similar range to the previous week – 22 to 25°C. The experience from these two weeks suggests that the changes made to the BMS on 16 September were successfully improving the precision of night cooling control.

# 5 STRATIFICATION

## 5.1 OVERVIEW

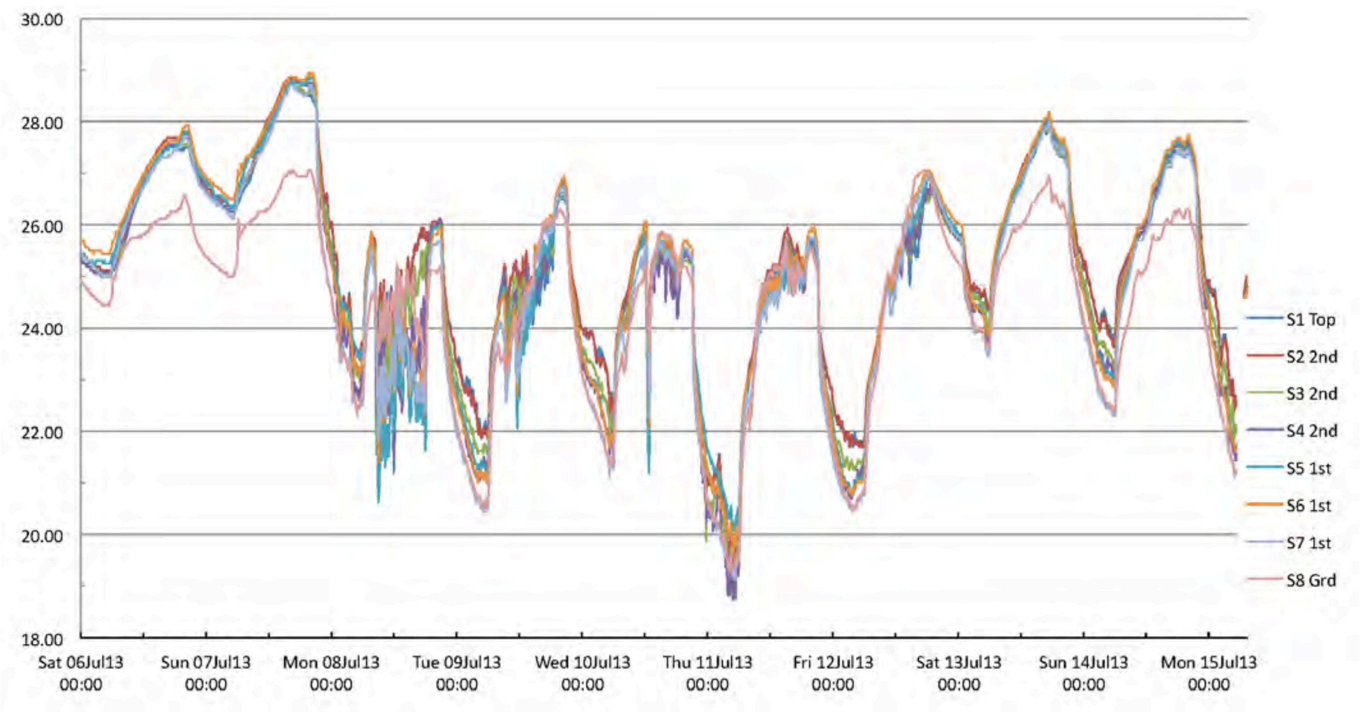
Table 4.1 below shows the maximum, minimum and averaged temperatures for all eight sensors for the entire monitored period. Overall:

- The average temperatures on all floors were very similar.
- The first floor was marginally warmer, perhaps owing to additional heat from the Information Services Department. Spot checks during the main project revealed a similar tendency.
- The ground floor was slightly colder, as might be expected. A particular influence was incoming air from the automatic front doors.
- Peak temperatures were similar on the 1st and 2nd floors but lower on the ground floor.
- From May to August, stratification was most noticeable during unoccupied warm sunny periods, when all windows were closed, particularly during the day at weekends. Temperatures were more uniform when the windows were open, individually or automatically.
- Temperatures at all heights on the first and second floors were very similar.
- However, the coldest temperatures could occur on the second floor, and at high level on the first floor (sensor S5), probably because there were more windows and motorised openings at high level on the north facade, admitting cooler air, particularly if winds had a northerly component.

**TABLE 4.1: Mean, maximum and minimum air temperatures from the vertical array**

| | *Second floor* | | | | *First Floor* | | | *Ground* | ***Averages per floor*** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sensor number** | **1** *Top* | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **2nd** | **1st** | **Grd** |
| Average °C | 24.2 | 24.3 | 24.1 | 24.0 | 24.3 | 24.4 | 24.1 | 23.9 | 24.1 | 24.3 | 23.9 |
| Maximum °C | 31.2 | 31.4 | 31.3 | 31.4 | 31.6 | 31.9 | 31.6 | 31.7 | 31.4 | 31.6 | 30.7 |
| Minimum °C | 16.5 | 16.4 | 16.0 | 16.1 | 17.7 | 17.6 | 17.1 | 17.3 | 16.3 | 17.5 | 17.3 |

**FIGURE 4.5: Air temperatures recorded by the vertical array from 6-15 July 2013 (°C)**
*NOTE: At the time, window control during the day was coarse, so its operation can be identified by ragged traces when it happened, here particularly on 8 and 9 July. Although the BMS was altered in May 2013 give the facilities manager more fine control, this did not initially work as intended. This situation was not fully rectified until the BMS visit on 16 September.*



5.2 STRATIFICATION IN HOT WEATHER

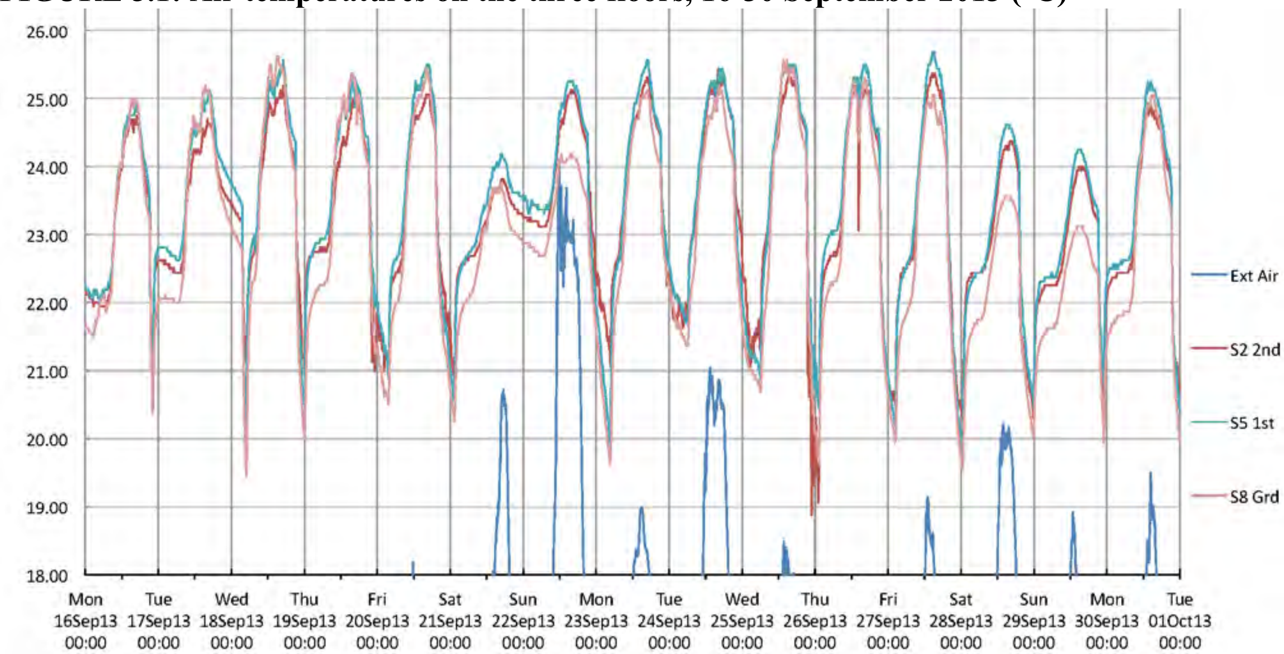
Figure 4.5 above is an expanded version of Figure 4.1 for the hot period 6-15 July. Night ventilation was programmed to come on at 8 PM, if the average indoor temperature was above a value set by the operator (23°C was initially chosen, and not changed); and to operate until 6 AM unless the average indoor temperature fell below another set value (set at 18°C). In fact:

- It did not operate on the nights of Friday 5 and Saturday 6 July. This was as programmed.
- It did operate for the full programmed period 20:00 to 06:00 on all the other nights.
- The automatic windows were also over-ridden Open on occasions during the working day from Mon to Wed 8-10 July, to help recover from the overheating the previous weekend.

In terms of temperature stratification, Figure 4.5 indicates:

- Mostly small temperature differences between vertical locations on the first and second floors.
- During hot unoccupied weekends, a tendency of the ground floor to stay 1°C or so cooler than the others, particularly on 6-7 July, when night ventilation did not operate.
- Ground floor temperatures tending to be lower during the troughs of night cooling, though not consistently so.
- Less tendency to stratify during the working week, when some windows were opened by staff.
- Varying situations during periods of automated window opening, whether by night or by day, depending on outside temperature, wind speed and direction.

**FIGURE 5.1: Air temperatures on the three floors, 16-30 September 2013 (°C)**




5.3 STRATIFICATION IN COOLER WEATHER

Figure 5.1 above shows selected second, first and ground floor temperatures from the atrium array in the last two weeks of September, on an expanded scale for clarity. This reveals:

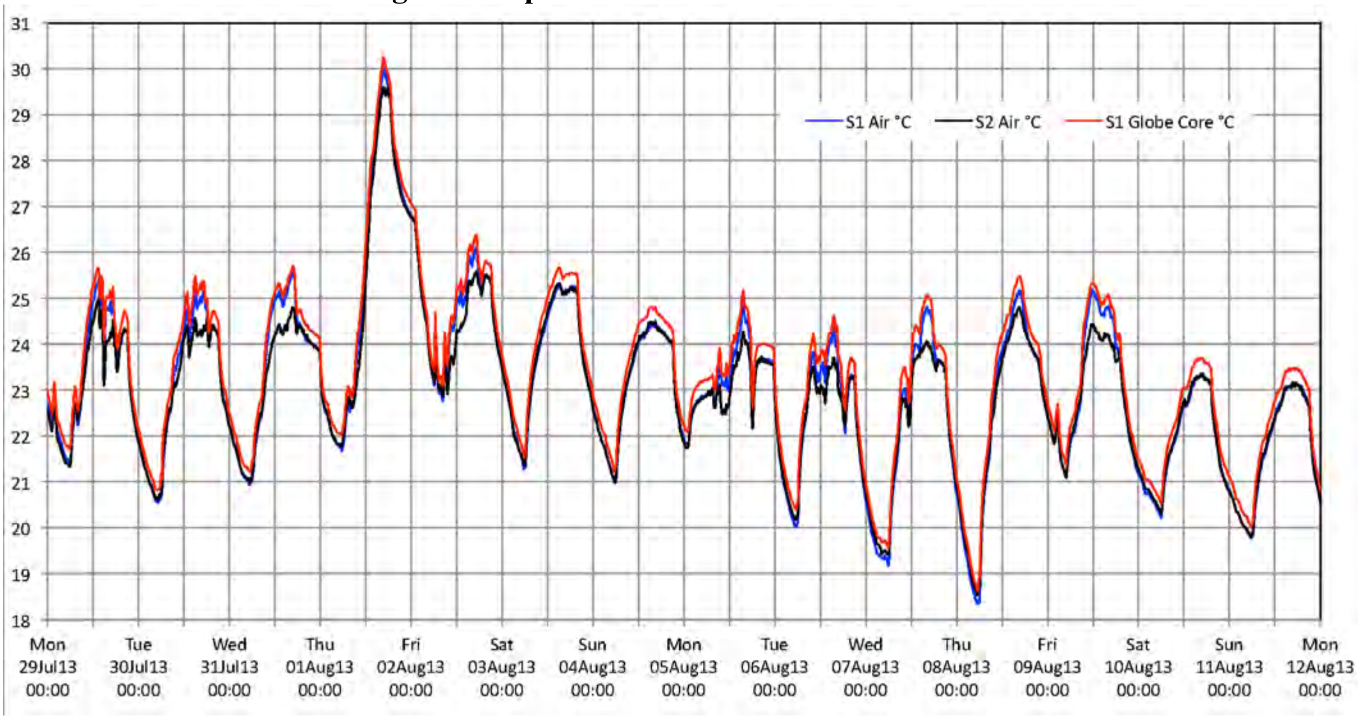
- Much shorter periods of night cooling, shown by the downward spikes around midnight.
- A tendency for the ground floor to get colder overnight, particularly after night cooling, and at weekends. However, on weekdays, the ground and upper floor temperatures were often similar, with the ground floor occasionally hotter, particularly during the first week.
- A tendency for the first floor to be hotter generally.
- Variable behaviour on the second floor, often with lower daytime peaks; and usually with lower minima during periods of night ventilation, presumably owing to the large number of ventilation openings on the second floor north facade, relatively close to the sensor array.
- However, once windows were shut, the second floor temperature tended to rise more rapidly.

Over the period 9 September-11 October, mean air temperatures were 23.0, 23.4 and 23.2°C on the ground, first and second floors respectively.

## 6 AIR AND RADIANT TEMPERATURES AT DESK LEVEL

6.1 The concrete radiators were intended not just to store excess heat (for removal by night ventilation or to carry forward to the following day, depending on season) but to improve the radiant temperatures experienced by occupants. To explore this effect, Logger 4 monitored air and globe temperature sensors on the first floor, mounted at the head height of a seated person. One pair of sensors (S1) were at a workstation position, where they were also exposed to some convection and radiation from computers, screens, occupants and task lighting. The other pair (S2) were above a filing cabinet (see Figure 3.1) and came under fewer of these influences.

**FIGURE 6.1: Air and globe temperatures at workstation level on the first floor north**




6.2 Figure 6.1 above shows an extract of the data for the period 29 July to 11 August, a typical warm summer period, apart from the exceptionally hot 1 August. This indicates:

- Generally higher air temperatures at the workstation position (S1 air, blue) during working days than at the filing cabinet (S2 air, black), owing to heat from local occupancy and equipment.
- Similar air temperatures at both positions during unoccupied periods, nights and weekends.
- Marginally lower air (and globe) temperatures at the workstation at the trough of the night cooling period, presumably owing to the higher thermal capacity of the filing cabinet.
- The globe temperature at the workstation (red trace) was nearly always above air temperatures.
- The globe temperature at the filing cabinet is not shown here, as it makes the traces too difficult to read. During occupied hours, it tended to be typically 0.5°C lower than the workstation globe temperature. Outside occupied hours, the two globe temperatures were usually similar.

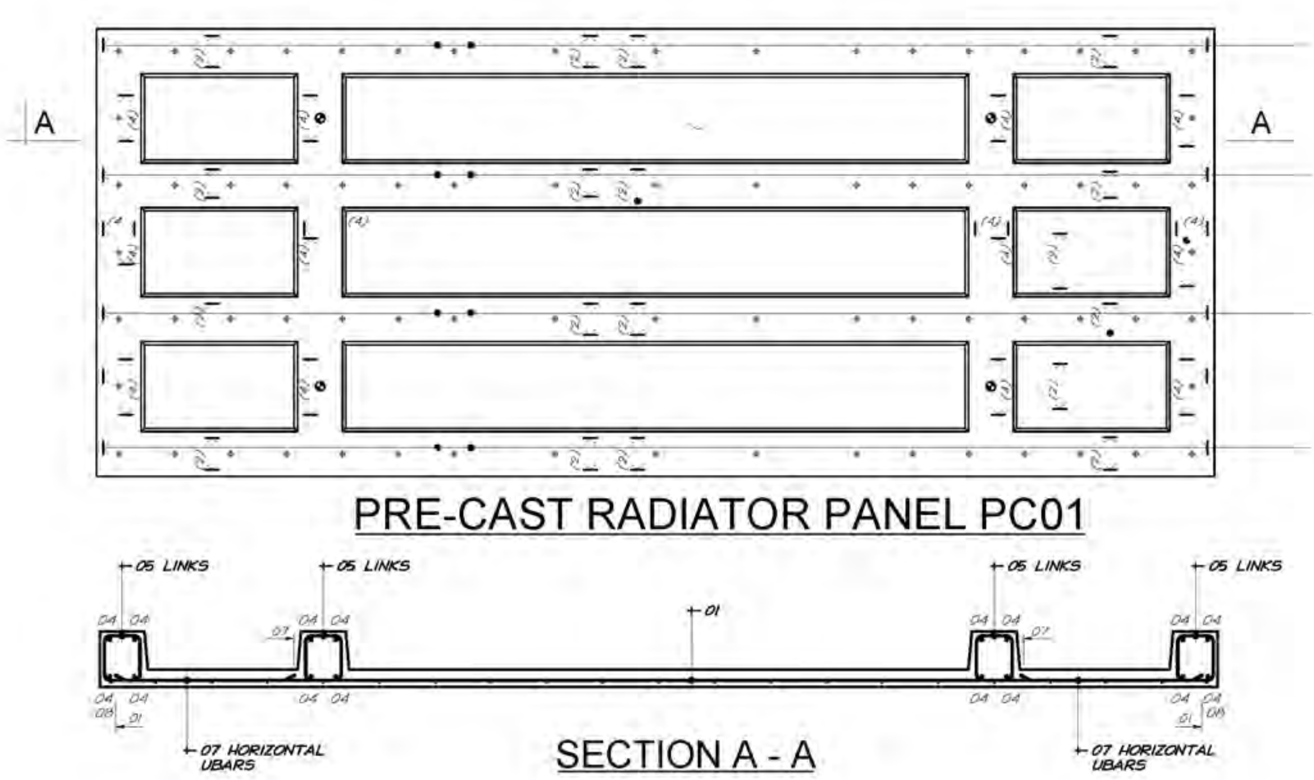
6.3 On 1 August (see figures 4.1 and 4.3), many windows were opened manually, leading to very rapid warming when the day became exceptionally hot. Even then, recorded globe temperatures remained a little above indoor air temperatures. However, the peak internal air temperature of 29.5°C was 3.5°C below that recorded outside, so the thermal capacity was bringing significant benefits.

6.4 Overall, the air and globe temperatures were too closely coupled to be able to deduce from the globe and air temperatures alone what radiant temperature benefits to occupant comfort came from the surfaces of the concrete radiators being cooler on hot afternoons. Over the entire monitored period, globe temperatures at the workstation position averaged 0.4°C above the local air temperature; and at the filing cabinet 0.2°C. This makes physical sense, as there would need to be a net loss of heat from fabric to air for there to be an overall cooling effect.

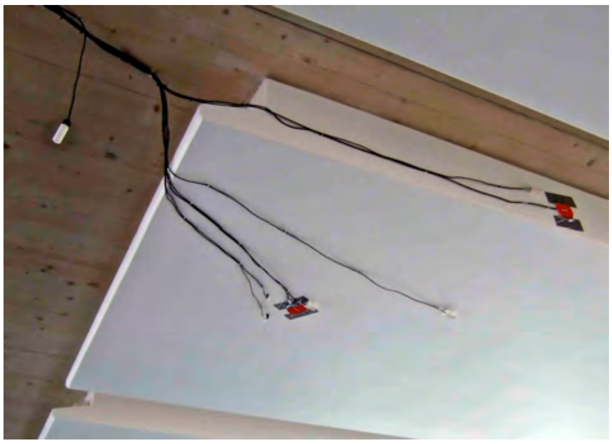
# 7 CONCRETE RADIATOR AND HEAT FLUX MONITORING

7.1 Figure 7.1 below shows the construction of a typical concrete radiator, 2 metres wide x 5 metres long by 250 mm deep at the 200 mm wide ribs and 80 mm deep in between.

**FIGURE 7.1: Typical concrete radiator plan and section**



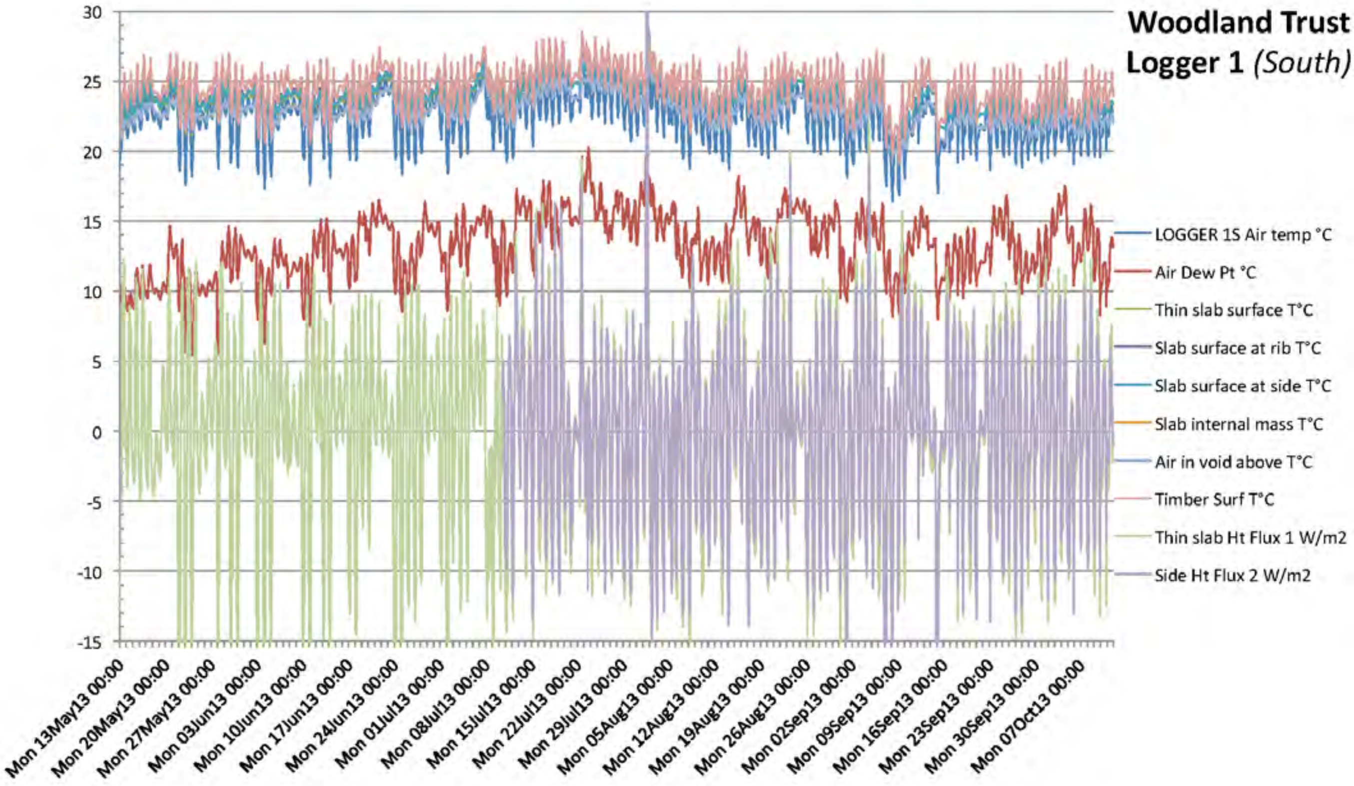

7.2 INSTALLATION



The photo to the right shows the sensors attached to the second concrete radiator towards the south on entry to the first floor offices from the main (west) stair. These were monitored by Logger 1. The projecting rim at the left (northern) edge of the concrete conceals a fluorescent tube that provides ambient lighting to the central corridor of the first floor offices as necessary. The concrete radiators on the north side do not have the lamp and lip.

- The white suspended cylinder to the top left is an open-ended tube that contained the local air temperature sensor.
- The red discs are Hukseflux heat flux sensors.
  - The first (HF1, centre left) was attached to the bottom of the concrete radiator, in the centre of the lowest 80 mm thick cell of the structure.
  - The second (HF2, top right) was attached to the side, to help identify the contribution of this surface to stabilising indoor temperatures.
- Immediately adjacent to the left of HF1 was a sensor that measured the surface temperature of the thin concrete slab in its vicinity.
- A second surface temperature sensor can be seen further to the right, above one of the 200 mm wide x 250 mm deep ribs that stiffen the concrete radiators.
- A further sensor (not visible here) recorded the surface temperature of the timber soffit.
- Just to the left of HF1, two drilled holes contained temperature sensors. The first measured the temperature in the void between the thin slab and the soffit of the 180 mm thick timber ceiling, which (stiffened by the concrete radiators) forms the structural floor to the second floor. The second was embedded 50 mm into the thin concrete, to measure its core temperature.

**FIGURE 7.2: Concrete Radiator temperature and heat flux monitoring – first floor south**




7.3 DATA FROM LOGGER 1, SOUTH SIDE

Figure 7.2 above summarises the Logger 1 data for the entire period. The traces at the top show:

- In dark blue, the indoor air temperature near the lower surface of the concrete radiator. Periods of night cooling are clearly revealed by rapid temperature drops, often to 20°C or less.
- In light red, surface temperatures of the timber soffit of the structural floor/ceiling. Peak timber temperature tends to be significantly higher than the concrete radiator surface: averaging 0.8°C more than the underside of its 100 mm deep slab, and 0.7°C more than the radiator's edge.
- In pale blue, the air temperature in the void between the ribs of the concrete radiator and the soffit of the cross-laminated timber ceiling panel. This tended to follow the office air temperature, but with a smaller amplitude and a time lag of about 6 hours. Its average temperature over the whole period was 22.8°C, the same as the surface of the rib.
- The timber soffit tended to be warmer than the concrete radiator, by 0.7°C on average. There appear to be three reasons for this initially surprising result:
  1. The large thermal capacity (estimated at 39 W.h/$m^2$) and relatively low thermal conductivity of the cross-laminated timber, causing heat to be retained for long periods.
  2. Heat from the ambient lighting, which was programmed ON from 7 to 9 AM and from 4 to 6.30 PM on working days. The effect was most noticeable during the afternoon ON period, when it caused spikes of typically 1.5°C. Heat from the lights was also retained in the southern edge of the concrete radiator for up to 12 hours, as revealed by infra-red photos.
  3. Heat passing up from the concrete radiators, keeping the floor void above the ceiling warm.
  4. A relatively enclosed situation, sheltered by the downstand beam and the edges of the concrete radiators, reducing air movement and opportunities for radiative heat loss.
- The mean surface temperatures of the thin main section, the rib and the side of the concrete radiator were all similar, averaging 23.6°C in the thin section, 23.8°C at the ribs and 23.7°C at the sides over the whole period, as against an mean air temperature of 22.65°C. Not surprisingly, the temperature of the ribs varies more slowly owing to their higher thermal mass, as was apparent from the infra-red photographs taken in the September 2012 test period.
- The slab mass temperature was also recorded, in the centre of one of the 100 mm deep sections. This averaged 23.8°C, similar to the surface temperature of the ribs and the air in the voids.

## 7.4 HEAT FLUX RESULTS, LOGGER 1, SOUTH SIDE

The green trace at the bottom of Figure 7.2 shows the heat flux through the thin (80 mm deep) soffit of the concrete radiator panel. The lilac trace shows heat flux through the side of the panel: this sensor lost thermal contact a few days after installation, so readings do not start until 10 July.

- Values above zero indicate heat passing into the concrete radiator, normally during the day.
- Values below zero show heat coming out, normally at nights.
- At weekends, low internal heat gains make the inward heat flux smaller, so the traces show a 5:2 cyclic pattern, particularly when night ventilation was only operated on Sundays.

## 7.5 SENSOR HF1, LOGGER 1, BOTTOM OF CONCRETE RADIATOR

The green trace shows that, on working days, heat absorption by the 80 mm thick underside of the concrete radiator typically peaked at rates of between 5 and 12 $W/m^2$, apart from the occasional really hot afternoon when windows were opened wide, when it could rise to 20-30 $W/m^2$ or more.

- At night, when windows were closed, as in early May, heat was lost much more slowly.
- However during night ventilation, heat transfer rates were usually faster than during the day, unless it was exceptionally warm outside.
- Dividing the heat flux by the temperature difference between the adjacent surface temperature sensor and the air temperature below the concrete radiator (and applying a fixed offset correction to minimise the variance of the results), produced a heat transfer coefficient averaging 7.5 $W/m^2K$, very similar to the result from preliminary tests in 2012.
- A small net outward heat flux through HF1 was recorded, averaging 0.3 $W/m^2$ in the period 11 July to 11 October. This may represent heat that entered through other surfaces including the floor above and the side of the concrete radiator exposed to the ambient light fitting.

## 7.6 SENSOR HF2, LOGGER 1, SIDE OF CONCRETE RADIATOR

The lilac trace shows heat flux through the vertical side of the concrete radiator. This varied in a very similar way to heat flux through the soffit, but with a smaller amplitude, giving an average heat transfer coefficient 25% smaller, at 5.5 $W/m^2K$. Reasons include lower air speeds over the surface and a larger solid angle of warm radiant surfaces, including the timber ceiling and the side of the adjacent concrete radiator. There was also a small net heat loss over the period, 0.2 $W/m^2$.

## 7.7 CONCRETE RADIATOR MONITORING – NORTH SIDE, LOGGER 2

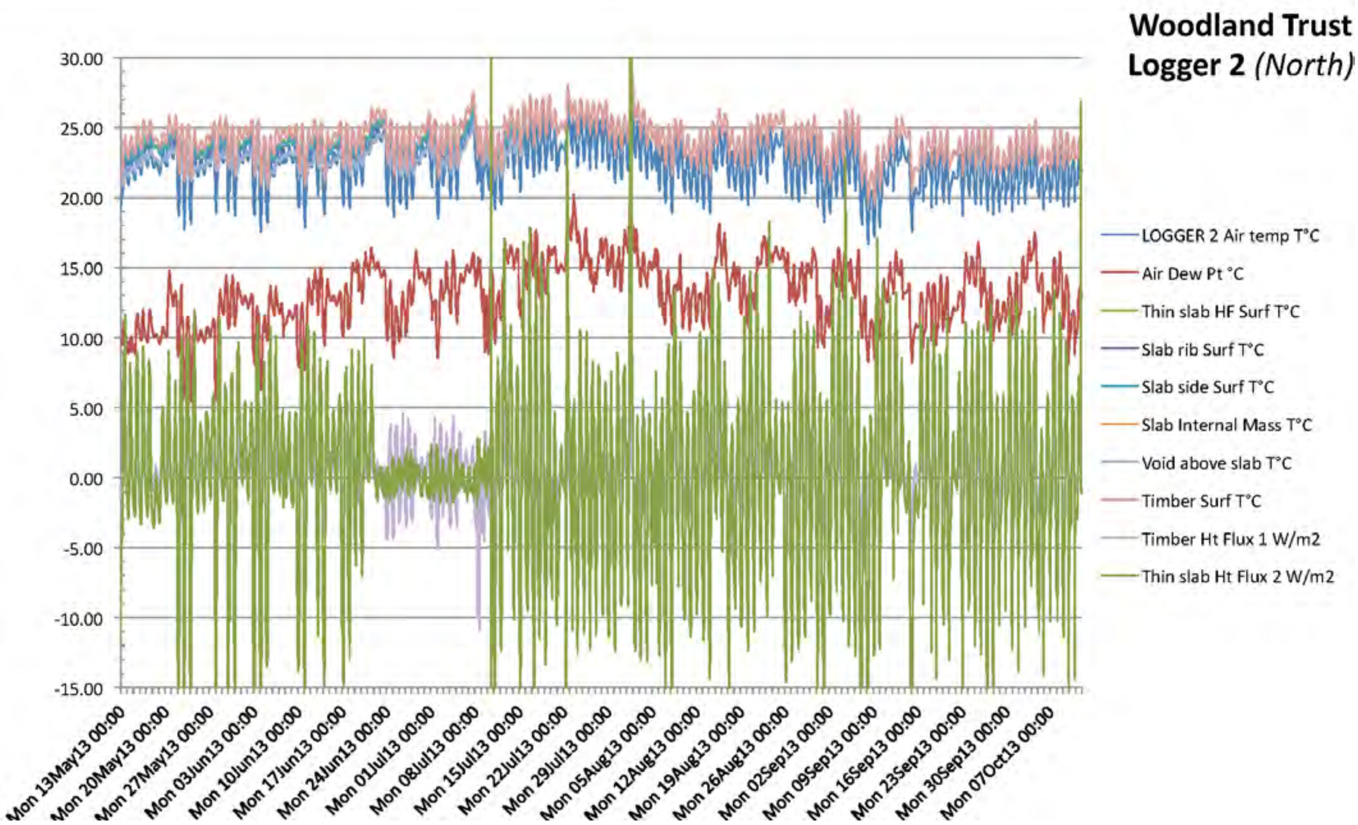
The monitoring arrangement on the north side was almost a mirror image of that on the south, apart from the second heat flux sensor being fitted to the surface of the timber ceiling: it can just be seen in Figure 3.1, to the right of the central beam. The main heat flux sensor, fitted to the underside of the concrete radiator, became detached on 21 June and was re-fixed on 10 July.

Recorded surface and air temperatures were similar to those from Logger 1 (South), see Figure 7.3, but about 0.2°C lower on average. This reflects additional heat on the south side from the ambient light fittings and the extra electronic equipment in the Information Services Department.

Over the monitored period as a whole:

- The mean heat flux coefficient to the underside of the concrete was 8.5 $W/m^2K$.
- There was a small net inward heat flux to the underside of the concrete, 0.1 $W/m^2$, which is probably indistinguishable from zero. *[The higher value on the south side is thought to represent heat from the ambient lighting passing in through the side of the concrete radiator and out through the bottom].*
- The pattern of heat flux through the timber soffit was similar to the concrete, but with 28% of the amplitude on average.
- On some days, the rate of heat transfer could fluctuate significantly, presumably the result of fluctuating air speeds under windy conditions.

**FIGURE 7.3: Concrete Radiator temperature and heat flux monitoring – first floor south**




7.8 PERIODS OF HEAT ABSORPTION AND RELEASE

Every weekday, as the offices began to be occupied, heat started to go into the concrete radiators.

- For both concrete radiators monitored, the direction of heat flux typically changed over at 8 AM (± 1 hour). Similarly, at about 8 PM, heat started to come out of the concrete.
- When night ventilation was operating, the heat flux changeover times were similar, as the windows were programmed to open at 8 PM and close at 6 AM, unless the air got too cold.
- On those Saturdays and Sundays when the windows did not operate, changeover times depended on heat stored, inside-outside temperature differences and solar gains. For example:
  - On Saturday 18 May, heat went in for less than an hour (2.45 to 3.30 PM); however,
  - on the Sunday, the concrete was cooler, and absorbed heat from 8.50 AM to 9.50 PM.

  The following week was the first of weekday night ventilation, making the concrete relatively cooler on the Friday. As a result, more heat went in over the weekend: on Saturday 25 May, between 9.20 AM and 10.30 PM; and on Sunday from 8.10 AM until just after midnight.

7.9 OVERALL EFFECT OF THE CONCRETE RADIATORS

To estimate the overall daily effect of the concrete radiators, we sorted the daily heat flux into:

- The period between 8 AM and 8 PM, accepting only positive values (heat flow into the slab).
- The period between 8 PM and 8 AM, accepting only negative values.

We then calculated the daily average heat flux into and out of the concrete for these two periods. The filtering process means that some calculated values differ slightly from those mentioned earlier.

Figures 7.4 and 7.5 show the results for the entire monitoring period. Each day runs from 8 AM to 8 AM, so, for example, the period called "13 May" finishes at 8 AM on 14 May.

- In both charts, heat passing into the thin (100 mm) soffits of the concrete radiators during the day is shown in red, while the heat passing out at night in the same locations is shown in blue.
- In Figure 7.4, the thin black and lilac traces show heat flux through the side of the radiator.
- In Figure 7.5, the same coloured traces show heat flux into the timber panel.
- The missing traces before 10 July indicate when sensors lost good thermal contact.

**FIGURE 7.4: Logger 1: South panel daily 12-hour heat absorption and night removal** *(W/m²)*

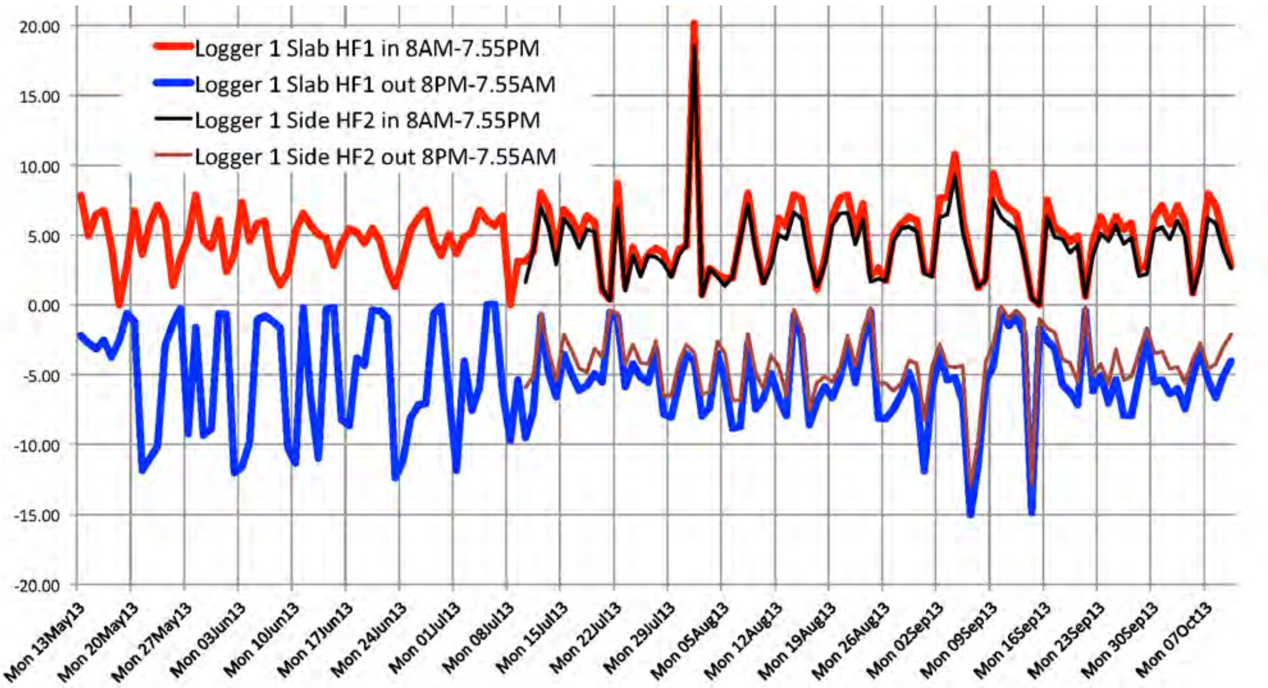
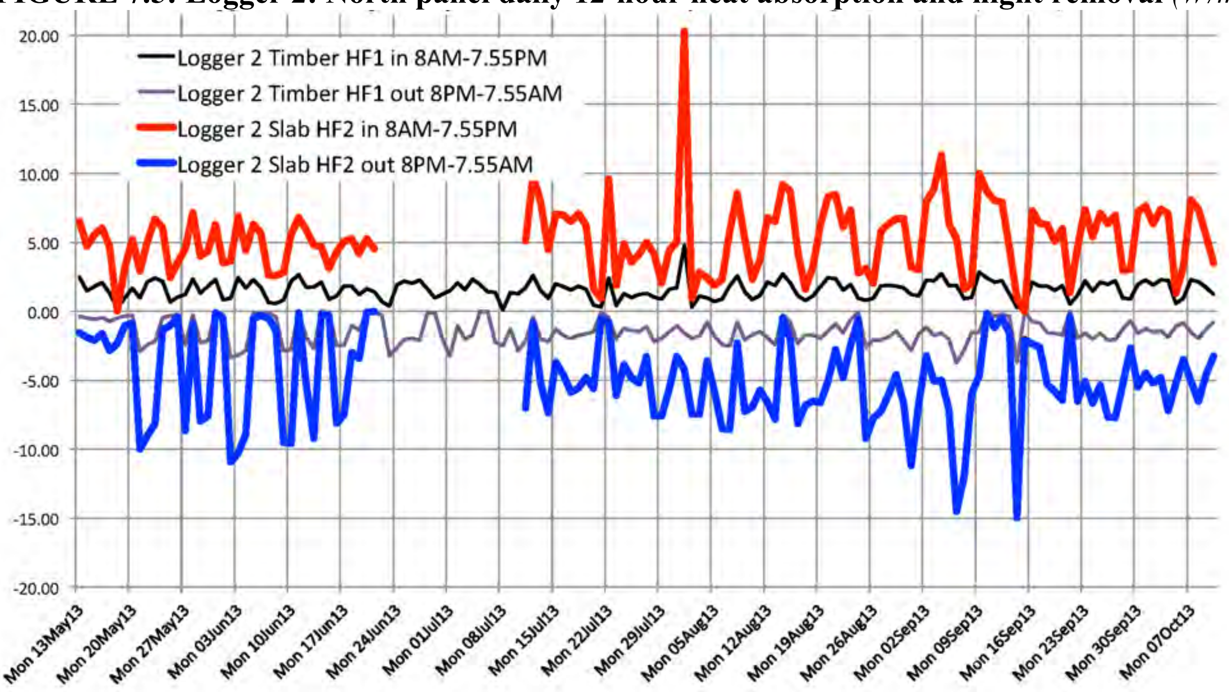



**FIGURE 7.5: Logger 2: North panel daily 12-hour heat absorption and night removal** *(W/m²)*




7.10 12-HOUR HEAT FLUX

Figures 7.4 and 7.5 confirm that heat transfer through the bottom of the concrete radiators was much the same in both locations. The pattern of heat flux through the side was similar, but typically 20% less in magnitude. Heat flow through the timber was also similar, but with 28% of the amplitude. Some key figures are summarised in Table 7.1 below.

**TABLE 7.1: Average daily heat flux for the thirteen weeks 12 July to 10 October**

| AVERAGE HEAT FLUX | Underside of North slab (100 mm) | | | Underside of South slab (100 mm) | | | Side of South slab | | | Timber Soffit North side | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W/m2 | Heat In 8AM to 8PM | Heat Out 8PMto 8AM | *Diff* | Heat In 8AM to 8PM | Heat Out 8P to 8AM | *Diff* | Heat In 8A to 8PM | Heat Out 8P to 8AM | *Diff* | Heat In 8AM to 8PM | Heat Out 8PM to 8AM | *Diff* |
| Sunday | 2.9 | -5.2 | *-2.3* | 2.6 | -4.8 | *-2.2* | 2.1 | -3.7 | -1.6 | 0.9 | -1.4 | *-0.5* |
| Monday | 6.4 | -5.0 | *1.4* | 6.1 | -5.1 | *1.0* | 5.0 | -3.7 | 1.3 | 1.9 | -1.5 | *0.4* |
| Tuesday | 6.2 | -5.4 | *0.8* | 5.5 | -5.7 | *-0.2* | 4.7 | -4.3 | 0.5 | 1.8 | -1.6 | *0.1* |
| Wednesday | 7.0 | -4.4 | *2.6* | 6.1 | -4.8 | *1.4* | 5.3 | -3.5 | 1.9 | 2.0 | -1.4 | *0.6* |
| Thursday | 7.5 | -4.4 | *3.1* | 6.8 | -4.8 | *2.0* | 5.9 | -3.5 | 2.4 | 2.0 | -1.3 | *0.7* |
| Friday | 5.7 | -6.2 | *-0.4* | 4.9 | -6.5 | *-1.5* | 4.3 | -4.9 | -0.6 | 1.6 | -1.7 | *-0.1* |
| Saturday | 2.7 | -6.5 | *-3.8* | 2.1 | -6.5 | *-4.4* | 1.9 | -5.1 | -3.2 | 0.9 | -1.7 | *-0.8* |
| | | • | | | | | | | | | | |
| 7-day week | 5.5 | -5.3 | *0.2* | 4.9 | -5.4 | *-0.6* | 4.2 | -4.1 | 0.1 | 1.6 | -1.5 | *0.1* |
| Mon-Fri | 6.6 | -5.1 | *1.5* | 5.9 | -5.4 | *0.5* | 5.0 | -4.0 | 1.1 | 1.9 | -1.5 | *0.4* |
| Sat & Sun | 2.8 | -5.9 | *-3.1* | 2.4 | -5.6 | *-3.3* | 2.0 | -4.4 | -2.4 | 0.9 | -1.5 | *-0.6* |

7.11 DAILY HEAT FLUX

Table 7.1 summarises the results of a day-by-day analysis during the period 12 July to 10 October, when all heat flux sensors were recording consistently and night cooling was available every day. Average values are shown by day, for the whole week, and for weekdays and weekends.

- For the week as a whole, heat gains and losses were more or less in balance in all four positions, apart from a net loss through the soffit of the concrete radiator on the south side. This is thought to reflect its slightly higher temperature, and the effect of the ambient lighting.
- However, there tended to be a build-up of heat over the week, which was then lost over the weekend, particularly on Saturday, when the concrete tended to be hotter.
- The larger heat build-up on Wednesday and Thursday also reflects the two hottest days of the period, Thu 1 August and Wed-Thu 4-5 September, which both stored much more heat during the day, and were able to exhaust less. Omitting these days removes much of the anomaly.

7.12 HEAT FLUX RATIOS

The ratios between heat fluxes are informative, with variation between weekdays and weekends:

- Comparing the undersides of the South and North concrete radiators, the radiator to the south appears to absorb heat more slowly during the day and give it out faster at night. This probably reflects its being slightly warmer, and the direct heat gains from the ambient lighting.
- The vertical side of the South concrete radiator absorbs heat about 15% more slowly than the bottom, but gives it out 25% more slowly, probably because the solid angle of cooler radiant surfaces is less. The contribution of the sides of the concrete radiators helps to increase their effective area beyond that of their plan area alone.
- On average, the timber soffit emits and absorbs heat at just under 30% of the rate through the underside of the North radiator. The emission rate at weekends is slightly lower (26%), which may not be significant but may also reflect the smaller solid angle of colder surfaces "seen" by the side of the concrete radiator, two of which face the sides of adjacent radiators and all of which have a warm timber ceiling above.

7.13 HEAT STORAGE OVERALL

The concrete radiators typically absorb 5 to 6 W/m$^2$ average on a weekday, which equates to 60-70 W.h/m$^2$ total over the 12-hour period 8 AM to 8 PM. Much of this stored heat was removed daily by night cooling, but over a hot week the concrete radiators could increase in temperature by 1-2°C, which is equivalent to 50-100 W.h/m$^2$.

# 8 DISCUSSION AND CONCLUSIONS

## 8.1 HEAT ABSORPTION DURING THE DAY

The concrete radiators made a useful contribution to stabilising temperatures in the open-plan offices. They absorbed an average of 5 to 6 Watts per square metre on a typical working day, making 50-60 Watt-hours in all between 8 AM and 6 PM. With a thermal capacity estimated at 57 W.h/m$^2$K, this would raise the average temperature of the concrete by about 1°C, similar to the observed values. The vertical sides of the concrete radiators absorbed heat at about 80% of the rate through the bottom. This suggests that designers could conservatively regard the effective area of a concrete radiator as the plan area, plus a perimeter strip of about two-thirds the depth. The concrete radiators here are 2000 mm wide and 250 mm deep, within a 2400 mm wide module, so could be regarded thermally as continuous strip without the gaps; and an extra 400 mm in length. The building's cross-laminated timber structure also has a large thermal capacity, estimated at 39 W.h/m$^2$K in the floors and 31 W.h/m$^2$K in the walls. However, owing to its better insulating properties, the measured heat transfer rate into the timber soffit was 28% of that into the concrete.

## 8.2 HEAT REMOVAL AT NIGHT

At the Woodland Trust, most of the heat stored during the day could be removed the following night if the windows were opened. In warmer weather, there was a tendency for temperatures to creep up over the week: however, the surplus could normally be removed over the weekend, with no occupancy heat gains and three opportunities for night ventilation (Friday to Sunday nights). To start with, night ventilation was activated on Sunday nights only, so that heat was not let out on Friday night that might have been welcome on Monday morning. However, once the weather turned warmer, it was essential for night cooling to be available on all three nights if necessary. This approach continued to be successful until the monitoring ceased in October.

## 8.3 UPWARD HEAT TRANSFER

The monitoring concentrated on temperatures and heat flux rates via the underside of the concrete radiators. However, heat is also transferred from the upper side, to or from the void of the floor above, albeit through 200 mm of cross-laminated timber with a conductance of about 0.55 W/m$^2$K. Heat flux monitoring suggested heat transfer was well balanced through the underside, with little nett upward heat loss or gain. However, the concrete radiators are likely to have kept the floor void above warmer than it would have been otherwise; and the cross-laminated timber ceilings between the concrete radiators were usually slightly warmer than the concrete and cooled little overnight. Future projects should consider monitoring temperatures and heat transfer rates to the floor above.

## 8.4 STRATIFICATION

As discussed in Section 5, there tended to be relatively little stratification between floors, apart from warm unoccupied sunny periods, when the windows were closed. Indeed, the first floor could often be slightly warmer. Stratification was reduced by the relatively low levels of internal and solar gains, the large window opening area on the top floor north, and the ability of air to move relatively freely between floors between the northern atrium, the stairs, and the light well over reception.

## 8.5 UNIFORMITY OF CONCRETE RADIATOR TEMPERATURES

With the low levels of stratification and a night ventilation system that was not designed to scrub the concrete radiators with air (though this was considered at the outline proposals stage), infra-red thermographic checks indicated that the temperatures of all the concrete radiators were similar. This was first identified in the preliminary tests in September 2012 (see the appendices to Appendix D) and confirmed by subsequent checks in 2013. Upward offsets from average temperatures tended to occur where the concrete radiator was above a source of heat, particularly kitchen and copying equipment, ambient lighting, and any task lights that were on for extended periods. Downward offsets tended to be in the vicinity of windows opened manually. The ceiling of the Project Space (above Reception) also tended to be cooler after night ventilation, owing to better cross-ventilation here than elsewhere, owing to a shallower plan and no central beam.

8.6 EXTENT OF WINDOW OPENING

The motorised windows were initially intended to open by up to 100% of their travel for night ventilation. This was agreed with the Woodland Trust's insurers during design and construction. Unfortunately, some vandalism occurred after the building was completed; and although the windows were not affected, only 20% opening was permitted. The photo to the right shows part of the north facade with the lower window approximately 20% open and the upper window full open. The reduced night ventilation was a mixed blessing: lower air volumes and velocities reduced the cooling effect, but may have helped to keep the temperatures of the concrete radiators relatively uniform and the control simple.

8.7 CONTROL STRATEGY

The original control strategy operated night ventilation depending on internal temperature, the history of internal and external temperatures the previous day, and whether the heating had operated the previous 24 hours. In practice, night ventilation did not always operate when it would have been useful. Frequently night cooling was not activated because the outside air temperature sensor read very high in sunny weather, owing to heat rising off the cladding on the west elevation. On other occasions, if the windows had been left open all night, the building could feel too cold at the beginning of the working day, even though an excess of stored heat still remained to be exhausted.

As a result, the control strategy was much simplified. In particular:

- The outside temperature sensor was moved to a more representative position.
- The decision whether to enable night ventilation was transferred to the facilities manager, together with new weekday and weekend night ventilation time programmes, and average room temperature settings for automatic activation (23°C), subject to not letting average indoor temperatures fall below another set temperature (18°C) during the night cooling period.
- Closing the windows two hours before occupancy to allow temperatures to equilibrate, with residual heat from the concrete radiators and cross-laminated timber allowing the air and low thermal capacity items of furniture and fabric to warm up before people arrived.

The changes were broadly successful, though not without initial problems. In particular, a hidden heating interlock stopped windows opening automatically and had to be over-ridden manually. Final BMS changes were made on 16 September, when the heating and night cooling programmes were completely separated, leaving decisions about which to operate to the facilities manager. At the same time, the temperature used to activate and stop night cooling was based on the average from the open plan offices only. The success of these changes was confirmed by the steadier temperature ranges achieved in the ensuing period in relation to those in May and June. Changes have also been made to improve fine control over window opening during the day.

8.8 EFFECT ON COMFORT

Occupants and management confirm that the control changes have improved summertime conditions, though no formal survey has been done. Temperatures during the occupied period were relatively high, typically in the range 22-26°C, but the facilities manager reports that anything much cooler leads to complaints. While the thermal capacity moderates the afternoon peaks, occupants sometimes preferred to open the windows to get more air movement. However, this could be counter-productive on really hot days, particularly so on 1 August.

8.9 SCOPE FOR FURTHER IMPROVEMENTS

Now the night cooling system is working reliably, there is scope to improve its performance further, in particular adjusting temperatures for initiating and particularly for stopping night cooling, and extending the night cooling period on Saturday and Sunday mornings to about 10 AM. It may also be possible to obtain agreement from the insurers to open the windows on the south and east elevations further at night, as these face onto a secure courtyard.

# APPENDICES

A FLOOR PLANS

B ELEVATIONS SHOWING MOTORISED WINDOWS

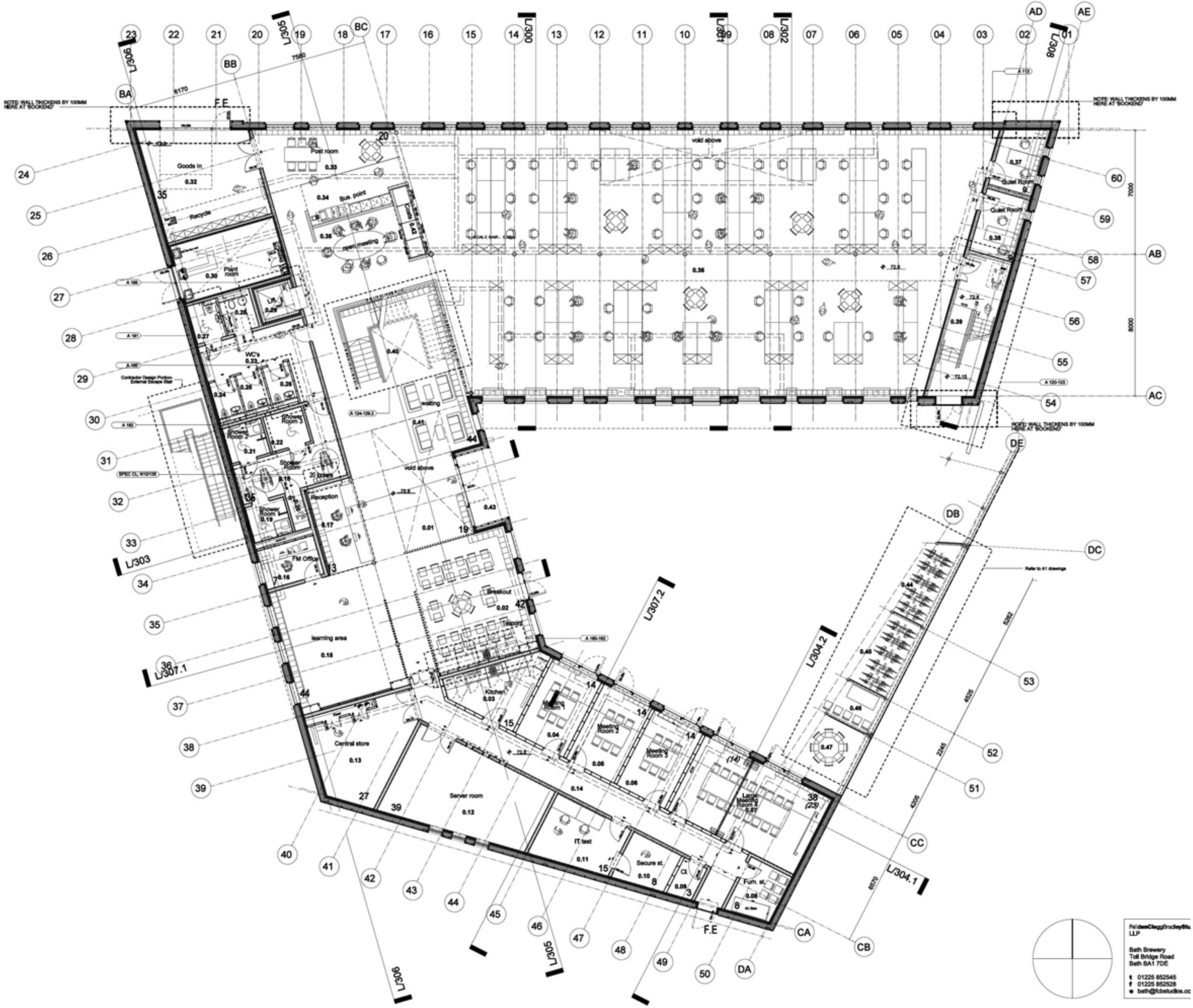
C LOGGER INSTALLATION DRAWING

D REPORT OF PRELIMINARY MONITORING, SEPTEMBER 2012

The project reported here is part of the Technology Strategy Board's Building Performance Evaluation programme and acknowledgement is made of the financial support provided by that programme. Specific results and their interpretation remain the responsibility of the project team. Full details of the Technology Strategy Board's BPE programme can be found at https://connect.innovateuk.org/web/building-performance-evaluation.

# APPENDIX A

# FLOOR PLANS



NOTE: WALL THICKENS BY 100MM HERE AT 'BOOKEND'
F.E
Goods In
Post room
Recycle
Plant room
Bus. point
open meeting
void above
Quiet Room
WC's
Shower Room
waiting
Reception
FM Office
Breakout
Teapoint
learning area
Kitchen
Meeting Room 1
Meeting Room 2
Meeting Room 3
Large Meeting Room 4
Central store
Server room
IT test
Secure st.
Furn. st.
Refer to A1 drawings
Contractor Design Portion - External Escape Stair
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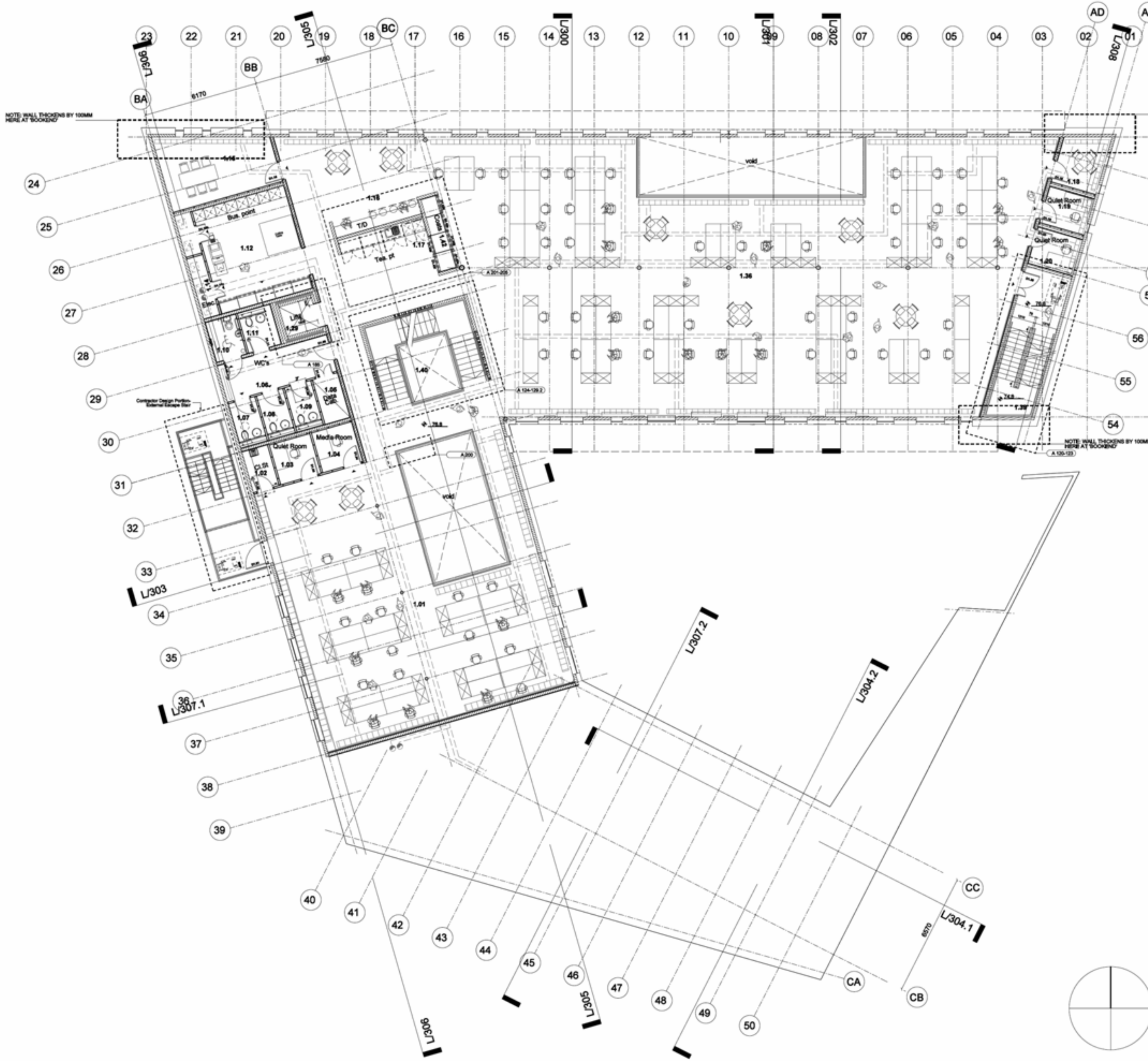



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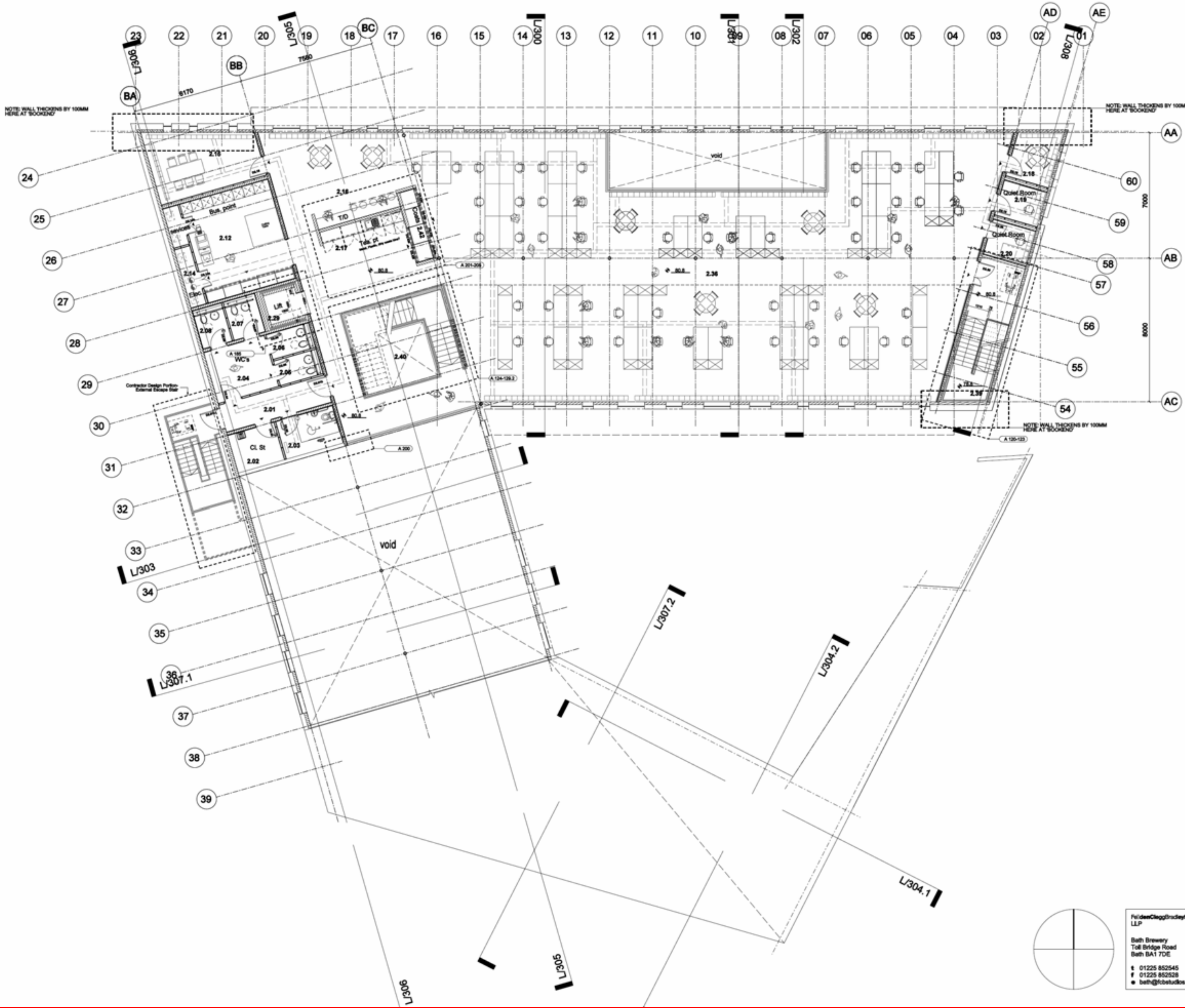


FeildenCleggBradleyStudios
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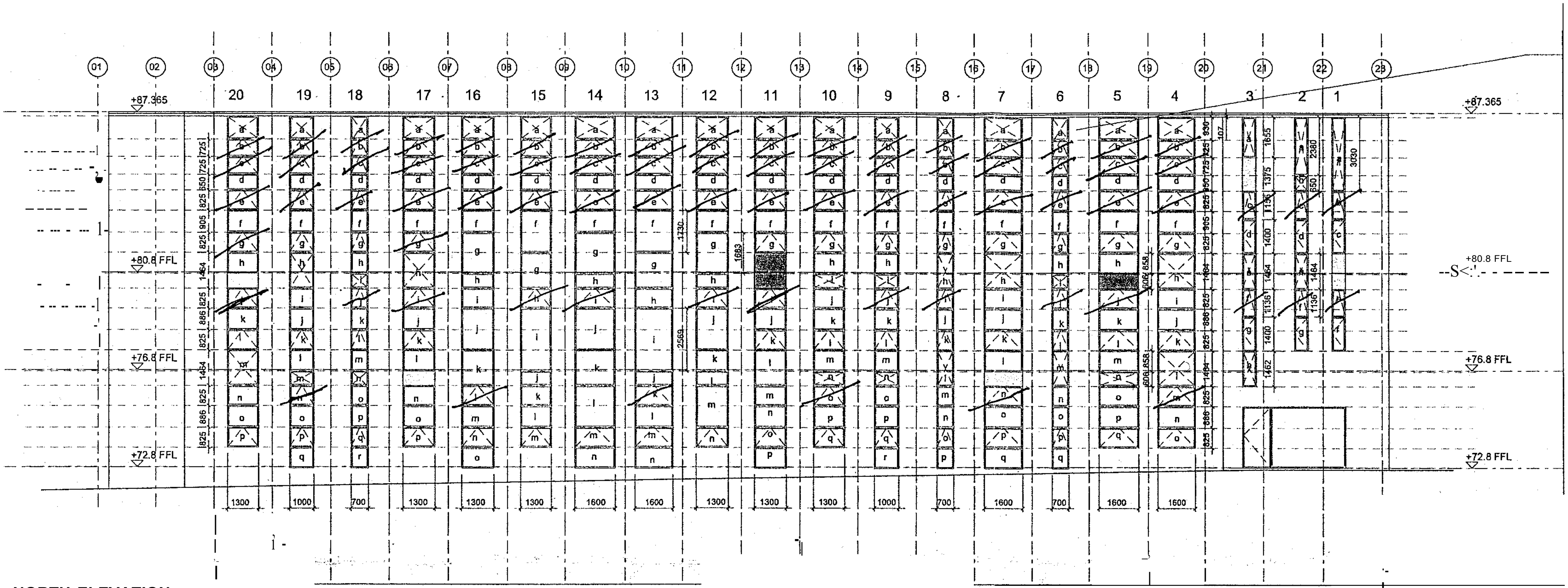
Toll Bridge Road
Bath BA1 7DE

t 01225 852545
f 01225 852528
e bath@fcbstudios.com

# APPENDIX B

# ELEVATIONS
with motorised windows



**NORTH ELEVATION**
Motorised windows
shown struck through

# APPENDIX C

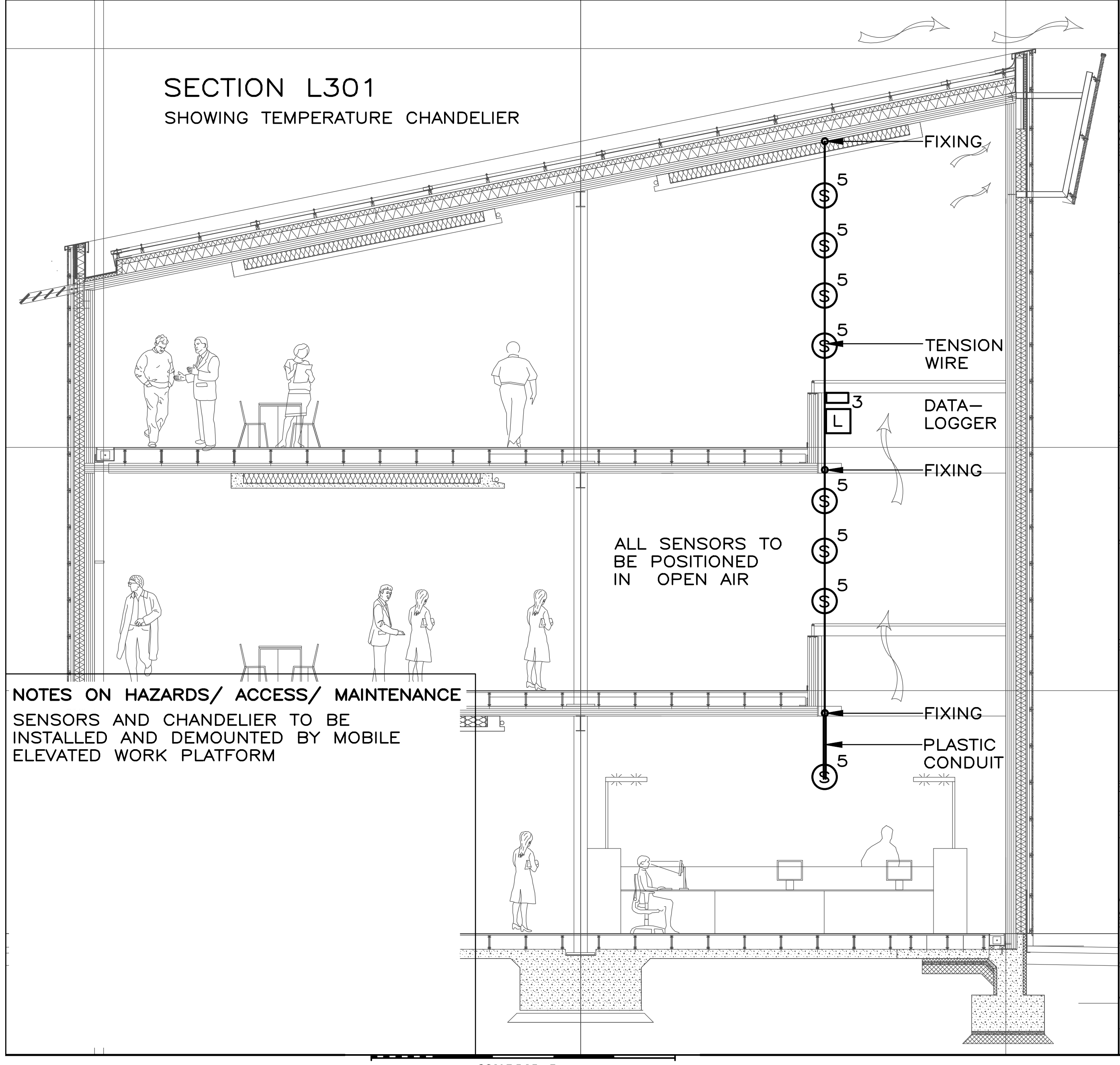
# LOGGER INSTALLATION DRAWING

## POINTS LIST

| REF | APPLICATION | DESCRIPTION/TYPE | NO OFF. | NOTES / ACCESSORIES |
|---|---|---|---|---|
| S1 | HEAT FLUX | MASS SENSOR | 4 | C/W 1 NO. DATALOGGER PER LOCATION |
| S2 | SURFACE TEMPERATURE | SURFACE TEMPERATURE SENSOR | 8 | 4 NO. PER S1 DATALOGGER |
| S3 | AIR TEMPERATURE AND RH | INTERNAL AIR TEMPERATURE AND RH SENSORS | 4 | 1 NO. PER S1 DATALOGGER |
| S4 | AIR TEMPERATURE AND RH | EXTERNAL AIR TEMPERATURE AND RH SENSORS | 1 | C/W DATALOGGER. EXTERNAL IP RATED. SECURE, SHADED LOCATION TBA. |
| S5 | AIR TEMPERATURE | CHANDELIER AIR TEMPERATURE SENSOR | 8 | C/W 1 NO. DATALOGGER FOR ALL SENSORS |
| S6 | INNER SLAB TEMPERATURE | MASS SENSOR | 2 | 6MM HOLE FOR ACCESS TO INSIDE SLAB |
| S7 | MEAN RADIANT TEMPERATURE | GLOBE THERMOMETER | 3 | |

## DATA LOGGERS

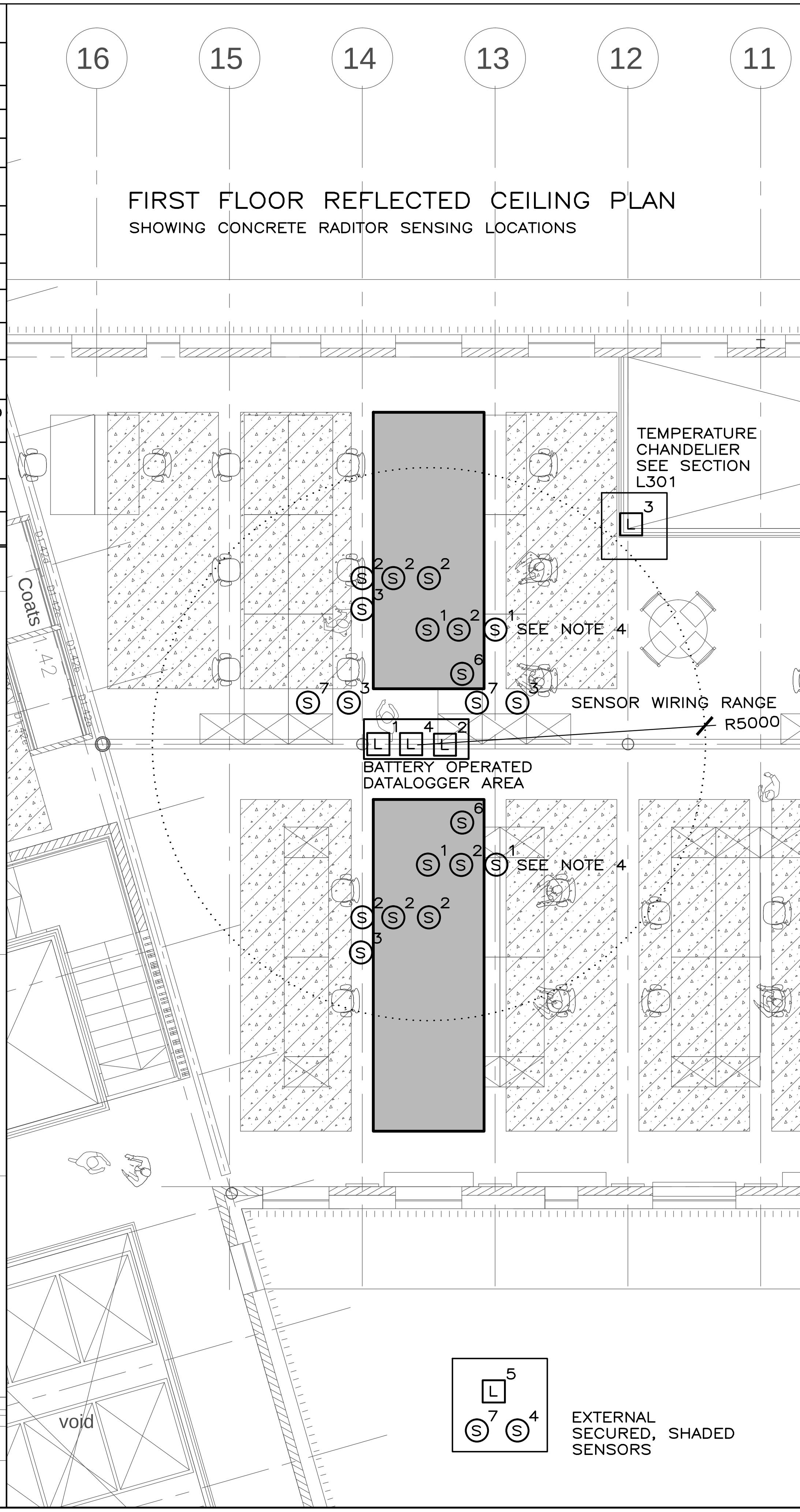
| REF. | DESCRIPTION | S1 | S2 | S3 | S4 | S5 | S6 | S7 | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| L1 | ARCHIMETRICS CUSTOM DATA LOGGERS | 2 | 4 | 1 | 0 | 0 | 1 | 0 | 3NO. S2 ASSOCIATED TO PANEL, 1NO. S2 ASSOCIATED TO HEAT FLUX. |
| L2 | | 2 | 4 | 1 | 0 | 0 | 1 | 0 | 3NO. S2 ASSOCIATED TO PANEL, 1NO. S2 ASSOCIATED TO HEAT FLUX. |
| L3 | | 0 | 0 | 0 | 0 | 8 | 0 | 0 | TEMPERATURE SENSOR CHANDELIER |
| L4 | | 0 | 0 | 2 | 0 | 0 | 0 | 2 | SPACED MAX. 2M FROM DATA LOGGER |
| L5 | | 0 | 0 | 0 | 1 | 0 | 0 | 1 | EXTERNAL LOGGER |




**NOTES ON HAZARDS/ ACCESS/ MAINTENANCE**

SENSORS AND CHANDELIER TO BE INSTALLED AND DEMOUNTED BY MOBILE ELEVATED WORK PLATFORM

SCALE BAR : 5 m



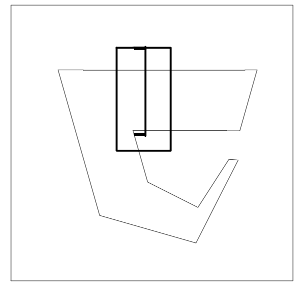

NOTES:

1. PRINCIPLE GOAL
   ESTIMATE A CHARACTERISTIC MEAN HEAT TRANSFER CO-EFFICIENT (W/(m².K)) FOR THE CONCRETE RADIATORS.
2. FINAL SENSOR LOCATIONS TO BE AGREED WITH FACILITIES MANAGMENT.
3. ALL SENSING EQUIPMENT TO BE SECURELY FIXED TO AVOID SECURITY ALARM TRIGGERING FROM AIR MOVEMENT INTERACTION.
4. WOOD OR SIDE FIXING FOR 2ND HEAT FLUX TBA.

LEGEND:

S^x SENSOR (x DENOTES TYPE. REFER TO POINTS LIST)

L^x LOGGER (x DENOTES TYPE. REFER TO POINTS LIST)



| rev | date | description | eng |
|---|---|---|---|
| A | 25/02/13 | FOR COSTING<br>WBA and Archimetrics comments incorporated | BP |
| * | 21/02/13 | FOR COSTING | PJB |

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Registered Office 42-43 Gloucester Crescent London NW1 7PE


architect
**FEILDEN CLEGG BRADLEY STUDIOS**

job title
**WT CONCRETE RADIATOR PERFORMANCE ANALYSIS**

| project leader | date | scale (at A3) |
|---|---|---|
| PJB | FEB 2013 | 1:100 |

drawing title
**THERMAL PERFORMANCE MONITORING STRATEGY DETAIL**

| job no | dwg no | rev |
|---|---|---|
| 4646 | N[35]420 | / A |

# APPENDIX D

# PRELIMINARY REPORT SEPTEMBER 2012

**TSB FILE REFERENCE 450028**
**Building performance evaluation of the Woodland Trust head office, Grantham**

**REPORT ON WEEKEND MONITORING OF NIGHT COOLING, 21-23 SEP 2012**

# 1 INTRODUCTION, SUMMARY AND CONCLUSIONS

## 1.1 THE BUILDING

The external walls, upper floors and roof at the Woodland Trust's naturally-ventilated offices are made of cross-laminated timber. To add thermal capacity and structural stiffness, "concrete radiators" are bolted to the undersides of the roof and ceilings, as shown in **Figure 1.1** to the right. The BMS is programmed to open motorised windows on all floors to remove any excess heat overnight, providing cooler air and radiant temperatures for the following day.

## 1.2 EXPERIENCE IN USE

Although the summers of 2011 and 2012 were cool, occupants report that the building has a tendency to be hot. There seem to be three reasons for this:

- Restricted opening of the manually-controlled lower windows owing to health & safety.
- Insurance requirements restricting night opening of the automatically-controlled windows.
- A need to re-examine the strategies for automated control of the windows.

The BPE team is therefore seeking to understand and to optimise the effect of night cooling, by:

- As part of the original BPE project, undertaking tests of night cooling performance.
- With funding for the follow-on project, to understand and seek to optimise concrete radiator performance during summer 2013, using heat flux sensors applied to the concrete radiators.

## 1.3 THE WEEKEND MONITORING PROPOSED

In order to minimise physical and perhaps thermal disruption to occupants, the team decided to undertake tests over a weekend that was convenient to the Woodland Trust, WBA, Max Fordham, and Archimetrics (who are undertaking the heat flux and associated monitoring during the follow-on project). The tests would comprise "forced" night cooling over the Friday night, with an opportunity for a second attempt over the Saturday night, and with sufficient time to restore a satisfactory internal environment if necessary on the Sunday. Monitoring was to include:

- Infra-red thermography before-and-after night cooling – see Section 2 and the Appendix.
- Time lapse infra-red thermography – see Section 3.
- Insitu tests of the proposed heat flux sensing equipment – see Section 4.

## 1.4 SUMMARY OF PROGRESS

The overnight session Friday 21 – Saturday 22 September was successful, achieving the intended level of night ventilation; and with all monitoring equipment operating satisfactorily, including heat flux monitoring on the first floor. We therefore decided to do a second run on the Saturday, including a second heat flux monitoring installation on the top floor. This was less satisfactory, as the night ventilation was stopped by the BMS shortly after we left. The cause turned out to be an interlock with the heating, which had been programmed to come on if necessary on Sunday PM if the building had become too cold. A software failure also halted the time lapse IR photography.

## 1.5 CONCLUSIONS

- Infra-red before-and-after measurements showed that the concrete radiators all cooled by a similar amount overnight, with little variation between locations. The summer 2013 monitoring will therefore concentrate on a "typical" concrete radiator, not on spatial variations.
- The heat flux sensors performed well, but the mains wiring of the data loggers could be unsightly and a possible source of unreliability. Battery-powered loggers will be used 2013 to make the installation less intrusive. Downloads will be from removable SD cards.
- The average surface heat transfer coefficient of the monitored concrete radiators was in the region of 7.5 $W/m^2K$. The design assumed an admittance value of 5.5 $W/m^2K$. Although the two values are not directly comparable, this may indicate more thermal stability than predicted.
- Time-lapse infra-red is a promising way to record the geography of night cooling. It also revealed the importance of an equilibration period after cooling, so that furniture and cold spots could warm up. This points the way to more effective night cooling control next summer.

# 2 INFRA-RED SPOT MEASUREMENTS OF CONCRETE RADIATOR TEMPERATURES

## 2.1 APPROACH

On the Friday evening, Saturday morning and evening, and Sunday morning, spot measurements were taken of average surface temperatures at approximately the centres of the top and bottom halves of each concrete radiator. Appendices A to C show the results.

## 2.2 AVERAGE TEMPERATURES

Average temperatures are summarised in Table 2.1 below, which also shows differences from the Friday night temperatures in brackets, *and differences between Saturday night and Sunday morning in italic brackets.* In particular:

- Concrete radiator temperatures on all floors were similar. Perhaps surprisingly those on the second floor were coolest on the Friday. This may be the result of heat losses through the roof.
- Temperatures at the West ends of the offices tend to be slightly higher, because of constant heat gains from printer-copiers and tea points in these areas.
- The concrete radiators in the Project Space cooled most on Friday night. This might be a consequence of higher air circulation velocities in this more open area.
- The ground floor South cooled least on Friday night. This may just be because readings for half the area were overlooked on the Friday night. There may also be an influence of heat gains from electrical equipment in the adjacent store room, particularly the power conditioning unit.
- In spite of room air temperatures during the day normally being lower, the concrete radiator surfaces warmed up on the Saturday, as heat stored deeper down came through to the surface. There may also be a solar gain effect from the roof to the second floor. The effects of this heat redistribution can be seen in the infra-red photographs on the following pages, Figures 3.1 to 3.4 and Figure 4.2. This effect helps the building to recover from any over-cooling.

**TABLE 2.1: MEAN SURFACE TEMPERATURES OF THE CONCRETE RADIATORS**

| Temperatures ( C) | Friday night | Saturday morning | Saturday night | Sunday morning |
|---|---|---|---|---|
| 2nd floor office | 23.0 | 20.2 (-2.8) | 21.1 (-1.9) | 20.6 (-2.4) *(-0.5)* |
| 2nd floor West end | 23.8 | 20.7 (-3.1) | 21.2 (-2.6) | 21.0 (-2.8) *(-0.2)* |
| 1st floor office | 24.0 | 21.1 (-2.9) | 21.3 (-2.7) | 20.9 (-3.1) *(-0.4)* |
| 1st floor West end | 24.4 | 21.1 (-3.3) | 21.4 (-3.0) | 21.0 (-3.4) *(-0.4)* |
| Project Space | 24.1 | 19.2 (-4.9) | 21.4 (-2.7) | 20.9 (-3.2) *(-0.5)* |
| Ground floor office | 23.6 | 20.7 (-2.9) | 21.0 (-2.6) | 20.5 (-2.6) *(-0.5)* |
| Ground floor W end | 23.8 | 20.9 (-2.9) | 20.8 (-3.0) | 20.1 (-3.7) *(-0.7)* |
| Ground floor South | 23.5 | 21.3 (-2.2) | 21.0 (-2.5) | 20.4 (-3.1) *(-0.6)* |

## 2.3 LOCAL VARIATIONS

The detailed measurements, summarised graphically in Appendices A to C for the ground, first and second floors respectively, show that the local variations in concrete radiator surface temperature were small, with maximum-minimum differences in any one area seldom exceeding 0.5 C:

- On the Friday night, lower temperatures tended to be where staff had opened windows during the day, while higher temperatures were above printers, tea points and perimeter lights left on.
- There was rather more cooling on the North side of the offices, probably owing to the greater glazed area to the North and to the wind from the North or North-East at the time. The concrete radiators in the vicinity of the atrium also cooled slightly more, particularly on the upper floors. Care needs to be taken here, as occupants also report downdraughts from the atrium, both from heat losses from the tall windows in cold weather, and from incoming air in warmer weather.

## 2.4 IMPLICATIONS OF THE SPOT MEASUREMENTS

The temperatures of the concrete radiators moved very similarly throughout the building. This suggests that the monitoring of heat flux to be carried out in summer 2013 would be most usefully carried out in detail in a characteristic location, rather than in less detail at a variety of locations. Infra-red spot checks would seem to be a more appropriate way of identifying local variations. In spite of the uniformity, variations in room and concrete radiator surface temperature could well cause local discomfort after night cooling periods. The following approaches may reduce the effect.

- Taking care which windows are opened for night cooling (and during the day), perhaps with less opening in the atrium and the project space. Unfortunately, the wiring may forbid much fine control on a facade, with the only option being to disconnect some of the actuators.
- Stopping the night cooling an hour or two before occupancy (say at 5 AM), to allow radiant and air temperatures to equilibrate, and in particular for the more lightweight elements to warm up.

# 3 TIME LAPSE INFRA-RED THERMOGRAPHY

## 3.1 APPROACH

To investigate the feasibility of time-lapse thermography, we hired a FLIR 640T infra-red camera with 45° wide-angle lens and set it up at the West end of the second floor offices, facing East, with a view of most of the office space and the concrete radiators there.

Pairs of infra-red and visual photographs were taken at 5-minute intervals, starting at 10 PM on Friday 21 September, before the windows were opened at 22:35. The windows were closed at 9:30 AM on the Saturday, while recording continued. At 10:20, the recording interval was reduced to 1 minute and continued throughout the day. Night cooling resumed at 11 PM, but unfortunately the camera ceased to operate at 23:25, even though the memory card was only half full. There appears to have been a software fault, because on the following day the camera would only take still photos, even using a new memory card.

## 3.2 RESULTS

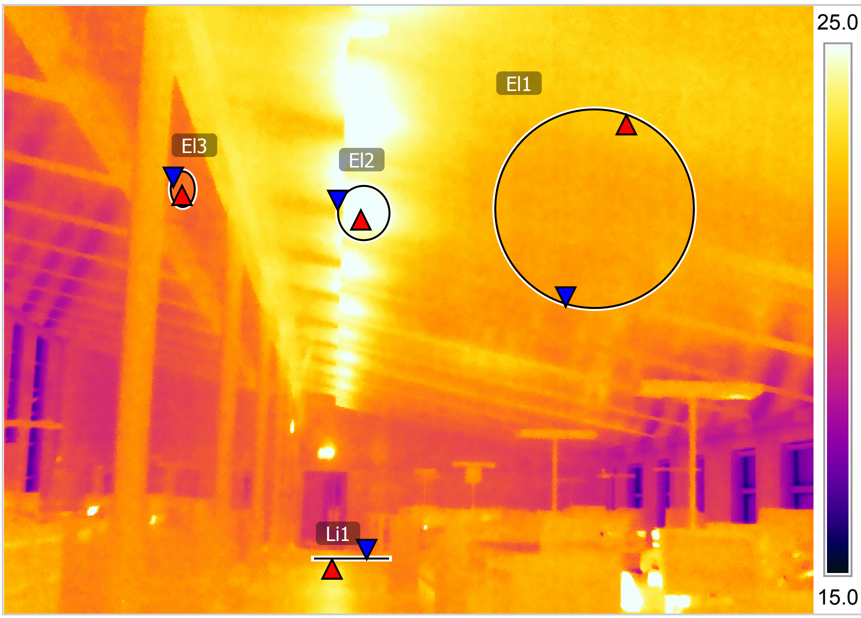
The results were revealing. The main findings are illustrated Figures 3.1 to 3.4 below. A large MPEG file is also available. In Figures 3.1 to 3.3 the range has been set to 15-25 C. It has not been possible to standardise the scale on Figure 3.4, as the camera fault corrupted the index.

**FIGURE 3.1: THE FRIDAY EVENING, AT THE END OF A WEEK'S OCCUPANCY**

| Measurements | | °C |
|---|---|---|
| El1 | Max | 24.1 |
| | Min | 23.7 |
| | Average | 23.9 |
| El2 | Max | 25.9 |
| | Min | 24.1 |
| | Average | 25.2 |
| El3 | Max | 23.7 |
| | Min | 23.5 |
| | Average | 23.6 |
| Li1 | Max | 24.0 |
| | Min | 23.7 |
| | Average | 23.8 |

| Parameters | |
|---|---|
| Emissivity | 0.95 |
| Refl. temp. | 20 °C |

21/09/2012 22:15:52




IR_0055.jpg

*This shows the first floor office after the end of the working week, before the windows were opened for night cooling at about 22:35. The hottest point in the image was the emergency exit sign in the middle, which was separately measured at 26.0 C. The left-hand ends of the concrete radiators to the right (South) were also warmed by the lamps above them. There is some hot office equipment under the desk to the bottom right. Note the reflections in the ceilings from the colder windows.*

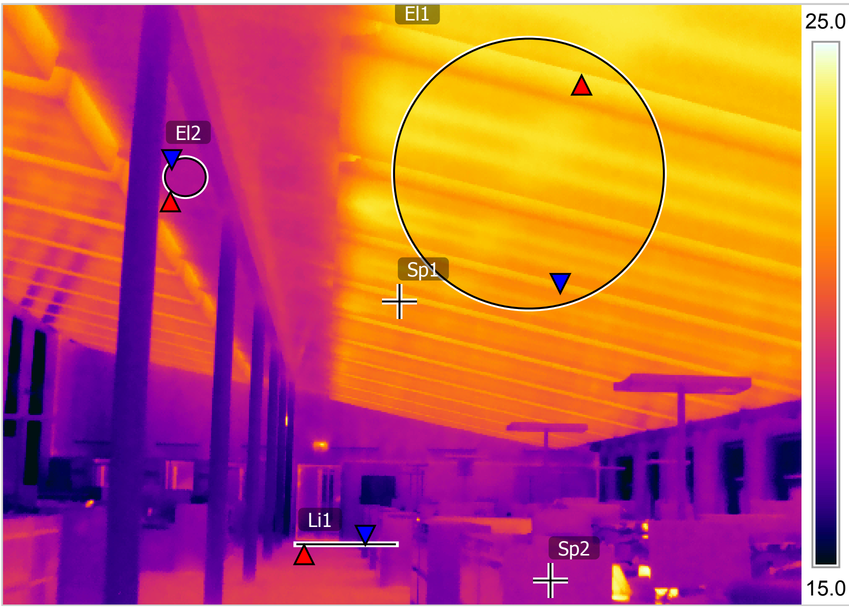
In Figures 3.1 to 3.3, the legends to the left of each photograph show the maximum, minimum and average temperatures in ellipses (El1, El2 and El3) and along lines (Li1). In Figure 3.1 these show that the concrete radiator temperature, El1 23.9 C± 0.2 C, the average timber soffit temperature El3 slightly cooler at 23.6 C. The floor and furniture at the far end of the office, L1 was at a very similar temperature averaging 23.8 C.

**FIGURE 3.2: THE SATURDAY MORNING, AT THE END OF OVERNIGHT COOLING**

| Measurements | | °C |
|---|---|---|
| El1 | Max | 20.9 |
| | Min | 19.4 |
| | Average | 20.1 |
| El2 | Max | 17.7 |
| | Min | 17.5 |
| | Average | 17.6 |
| Sp1 | | 19.4 |
| Sp2 | | 17.6 |
| Li1 | Max | 17.7 |
| | Min | 16.8 |
| | Average | 17.4 |

| Parameters | |
|---|---|
| Emissivity | 0.95 |
| Refl. temp. | 20 °C |

22/09/2012 09:30:51




IR_0325.jpg

*Figure 3.2 was taken just before the windows were closed. The measurements reveal:*

*El1 The mean surface temperature of the concrete radiators has fallen by 3.8 C in relation to the measurements in Figure 3.1. The spread of surface temperature has also widened, from 0.4 to 1.5 C, as is clearly visible, with the thinner parts of the concrete having lost heat fastest and the thicker ones retaining heat, see figure 4.2. The difference is largest for the ribs in the middle of each radiator. The slabs are also thickened around the perimeter, but here they can lose heat in two directions.*

*El2 The surface temperature of the timber ceiling has dropped much more, by 6 C, owing both to its smaller thermal capacity and a loss of heat both to the room and from upper roof surface.*

*Li1 The surface temperature of the floor and the furniture has fallen even more, an average of 6.4 C, owing to their light weight and because incoming cold air will tend to slump to the floor.*

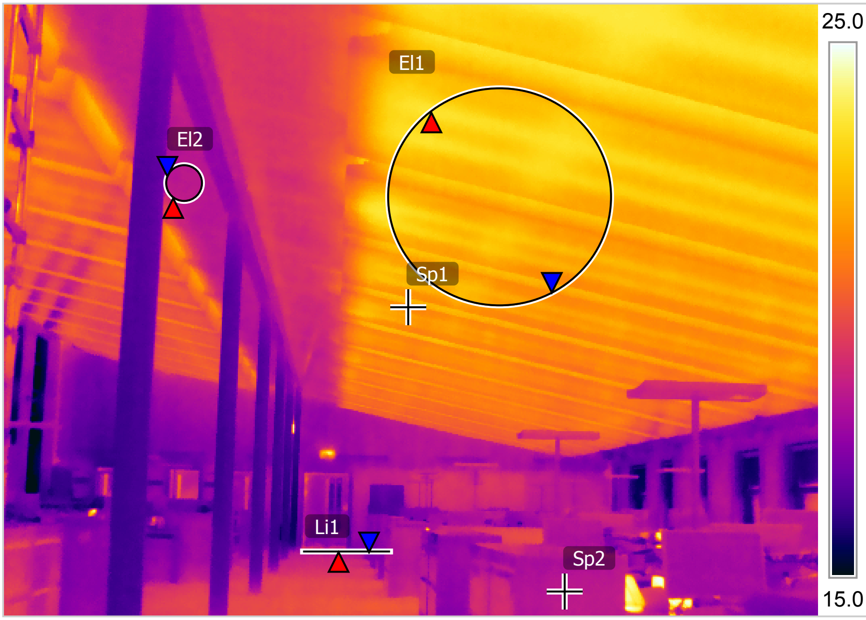
*Note also the cold surfaces of the furniture and East wall, the spot measurement Sp2 showing a filing cabinet surface temperature of 17.6 C. This would be unacceptably cold for occupants.*

## FIGURE 3.3: THE SATURDAY MORNING, 15 MINUTES AFTER WINDOWS CLOSED

| Measurements | | °C |
|---|---|---|
| El1 | Max | 21.1 |
| | Min | 19.8 |
| | Average | 20.4 |
| El2 | Max | 18.4 |
| | Min | 18.1 |
| | Average | 18.3 |
| Sp1 | | 19.9 |
| Sp2 | | 18.3 |
| Li1 | Max | 18.4 |
| | Min | 17.8 |
| | Average | 18.2 |

| Parameters | |
|---|---|
| Emissivity | 0.95 |
| Refl. temp. | 20 °C |

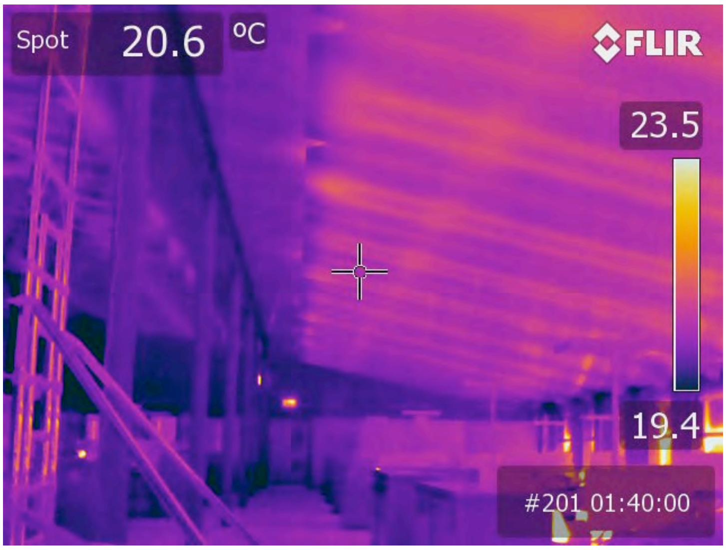
22/09/2012 09:45:50




IR_0331.jpg

*Figure 3.3 shows how much the surface temperatures have risen, in as little as fifteen minutes after the windows were closed. The average surface temperature of the concrete radiators (El1)is up by 0.4 C, the ceiling surface by 0.5 C, and the floor and furniture by 0.7 C.*

## FIGURE 3.4: MIDDAY ON THE SATURDAY




*This photograph show how, at noon on the Saturday, the indoor temperatures have converged substantially.*

*Unfortunately, owing to a corruption of the camera's indexing system, we could not use the manufacturer's software afterwards to standardise the temperature scale here (as done in Figures 3.1 to 3.3), or to add temperature sampling points.*

*However, since the camera was auto-ranging at the time, it confirms a minimum temperature of 19.4 C, while at 09:45 it was 16 C.*

3.3 CONCLUSIONS ON THE USE OF INFRA-RED AND OPTIMISING NIGHT COOLING

The tests revealed the power of infra-red time lapse photography in helping to understand the dynamics of night cooling. Although the cooling regime in the test (ten hours at an average outside temperature of 6 C) was much more severe than would occur on most summer nights, by noon the building had recovered to a reasonable temperature, while the concrete radiator temperatures had fallen by only 3 C in relation to the evening before. Operating a similar regime in the summer might only reduce their temperatures by 1 or 1.5 C, but if this were done daily there would be a useful overall effect. We therefore see the potential for a crude but effective night cooling regime. For example, if the office felt too warm at the end of the day, the management could trigger the night cooling, which would not need any other control (apart from the rain and wind safety protection already fitted), but to stop at say 6 AM, so any cold spots could warm up by natural heat exchange in advance of occupancy.

## 4 HEAT FLUX SENSING

### 4.1 INSTALLATION

After the Woodland Trust's working day had ended on Friday 21 September, Archimetrics temporarily installed heat flux sensors to the ceiling and the underside of the second concrete radiator on the South side of the first floor offices. This position was deemed be reasonably representative, as was later confirmed by the thermographic spot tests summarised in Section 2. Surface temperature sensors were also fitted to the concrete radiators and the adjacent timber ceiling. Internal and external air temperature and RH sensors were also installed. On 22 September, a second installation was fitted in the second floor offices, this time to the right (north) of the central beam, and with heat flux sensors on both on the thin and the thick parts of the concrete radiators. Figure 4.1 below shows the temporary internal installation on the first floor.

**FIGURE 4.1: TEMPORARY HEAT FLUX MONITORING EQUIPMENT**
*Heat flux sensors (red discs) and surface temperature sensors are attached to the undersides of the concrete radiators and cross-laminated timber ceilings with low tack tape. The tubes suspended from the sensors contain air temperature and relative humidity sensors. The data loggers are taped to the flange of the beam on the right, with the mains cable attached to the back of the column with cable ties. For summer 2013, we propose using battery powered loggers to avoid the mains cables.*

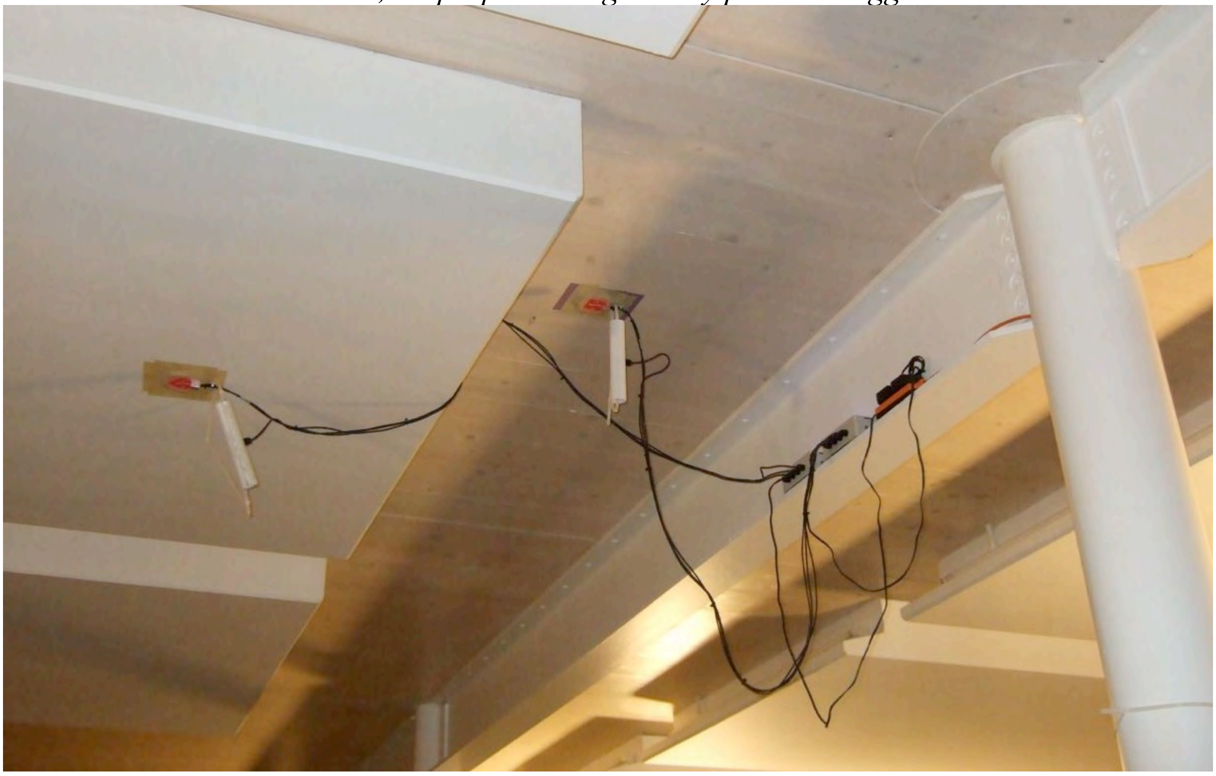
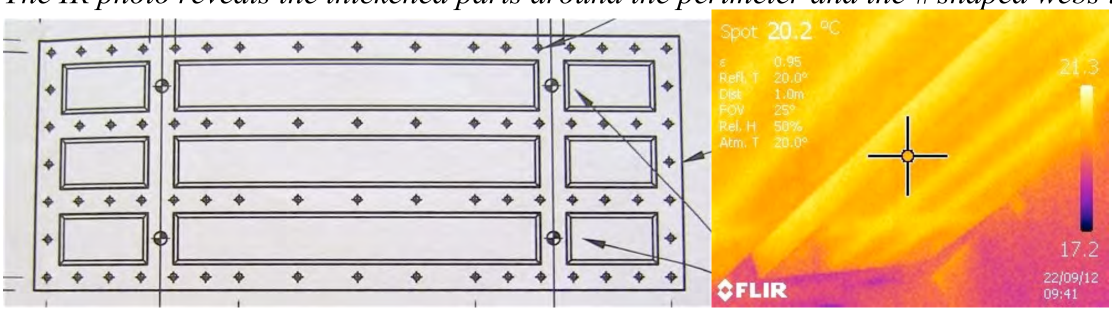


Figure 4.2 - the concrete radiator as designed, and its internal structure, as revealed by thermograph on the Saturday morning *(see also figures 3.2-3.4)*. The effect of the thickened parts is most visible up in the middle, where the ratio of exposed ceiling surface to concrete volume is least.

**FIGURE 4.2: CONFIGURATION OF THE CONCRETE RADIATORS**
*The IR photo reveals the thickened parts around the perimeter and the # shaped webs in the middle.*



## 4.2 RESULTS

Figure 4.3 shows charts of the concrete radiator surface temperature, heat flux, internal air temperature and external (North facade) surface temperature in the first floor position (Figure 4.1).

- The external temperature started at 9 C and fell to 3.2 C at 5:20 GMT before rising to 9 C again.
- The internal temperature fell rapidly when the windows were opened at about 21:35 GMT. Spot measurements suggested that the air in the ground and first floors initially cooled fastest, because incoming cold air tends to slump to the floors, displacing warmer air out at the top.
- At the beginning, the radiator was giving up heat only slowly, at 2.3 W/m$^2$ (a negative sign indicates flow out of the radiator. When the windows opened, the heat flux increased rapidly and for much of the night was in the region of 25 W/m$^2$.
- The average heat transfer coefficient at the concrete radiator surface was about 7.5 W/m$^2$K. Max Fordham's design calculations used an admittance value of 5.5 W/m$^2$K.
- In the small hours, the heat flux was more variable, probably owing to fluctuating air velocity.
- After the windows shut, the internal air temperature rose rapidly towards that of the concrete.

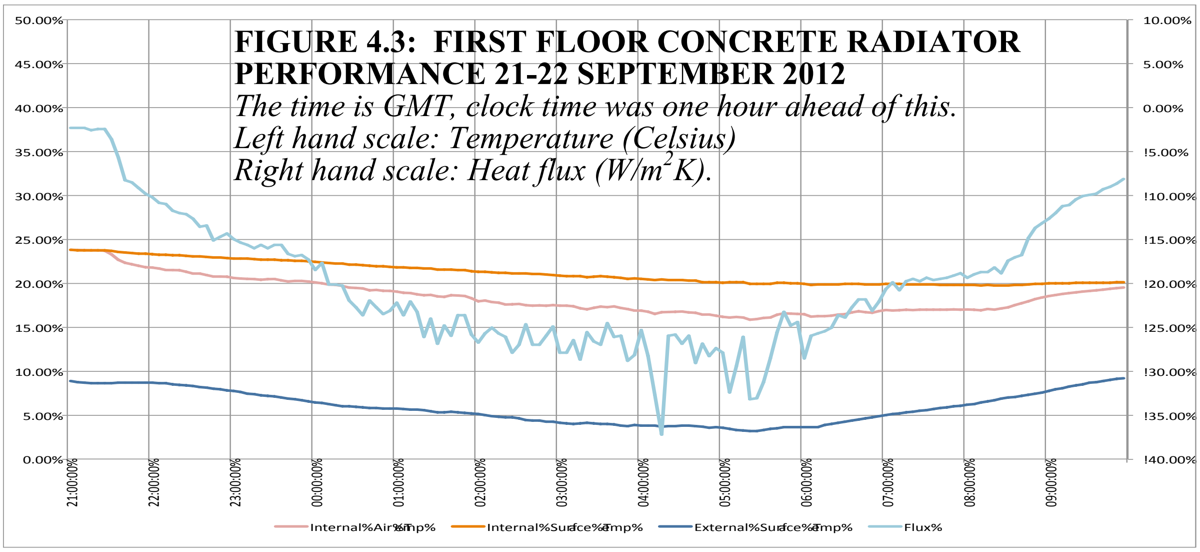



**FIGURE 4.3: FIRST FLOOR CONCRETE RADIATOR PERFORMANCE 21-22 SEPTEMBER 2012**
*The time is GMT, clock time was one hour ahead of this.*
*Left hand scale: Temperature (Celsius)*
*Right hand scale: Heat flux (W/m$^2$K).*

Figure 4.4 shows similar results for the wooden ceiling. Here the surface and air temperatures during the night cooling period had typically only a degree or so between them, and a heat flux rate of 5 to 6 W/m$^2$. The calculated heat transfer coefficient was however similar to that of the concrete. The heat flux also fluctuated less, probably because the ceiling sensor was more sheltered (see Figure 4.2) The external surface temperature sensor here was South-facing. Its temperature increased rapidly as sun shone on the timber cladding in the sheltered NW corner of the courtyard.

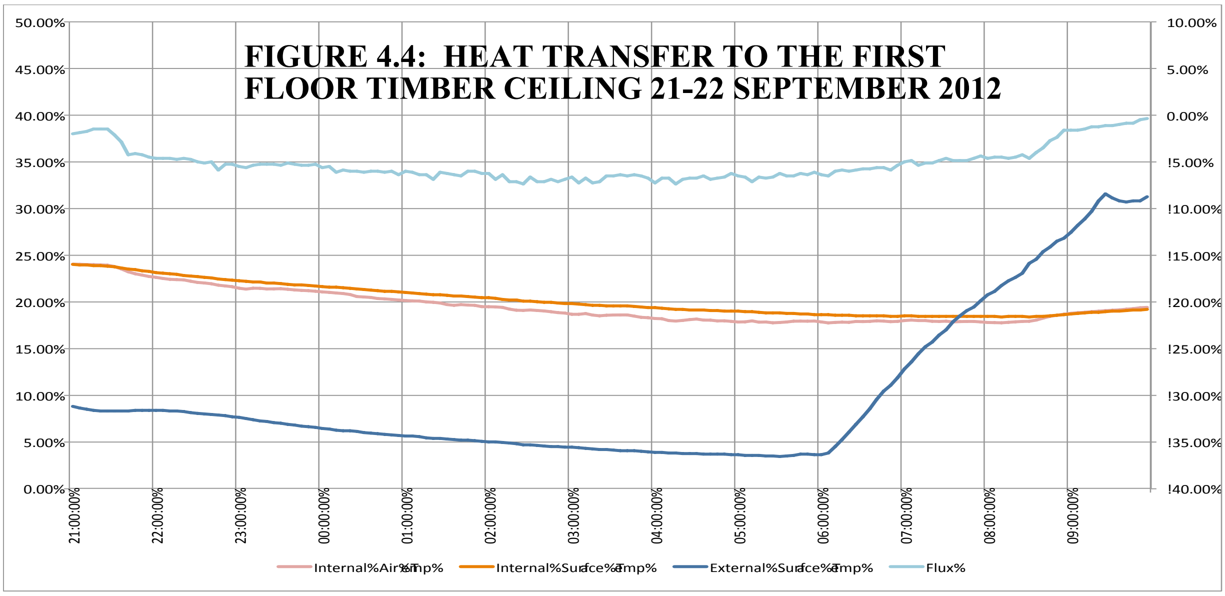



**FIGURE 4.4: HEAT TRANSFER TO THE FIRST FLOOR TIMBER CEILING 21-22 SEPTEMBER 2012**

## 4.3 CONCLUSIONS FROM THE HEAT FLUX MONITORING TESTS

The results have verified the practicality of the heat flux sensing technique, demonstrated potential for using it in Summer 2013 to optimise concrete radiator performance, and helped to inform the final installation in terms of sensor locations and using battery rather than mains power supplies.

**APPENDICES**

Appendices A, B and C are highly schematic floor plans which show the spot temperatures of the concrete radiators on the ground, first and second floors respectively at four time intervals: Friday night before night cooling, Saturday morning after night cooling, Saturday night and Sunday morning.

## WOODLAND TRUST - SPOT IR TEMPERATURES OF CONCRETE RADIATORS — APPENDIX A - GROUND FLOOR

### A1. ORIGINAL - AT THE END OF THE WORKING WEEK ON FRIDAY 21 SEPTEMBER 2012

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average west end* | | | *23.8* | *23.8* | | | | | | | | | | | | *Average main office space* | | | |
| **Floor** | **Ground** | | | **22.9** | **23.1** | **23.1** | **23.3** | **23.6** | **23.3** | **Atrium** | | | | | **23.2** | **23.3** | **23.1** | **23.1** | *23.3* | |
| **Date** | **21Sep12** | | | **23.6** | **23.2** | **23.4** | **23.6** | **23.8** | **23.6** | | | | | | **23.2** | **23.6** | **23.5** | **23.5** | *23.5* | |
| **Time** | **20:45 to 21:00** | | | **24.4** | **24.5** | | | | | | | | | | | | | | | |
| **Instrument** | **Flir 640 Instrotech** | | | **24.2** | **24.2** | | **23.8** | **23.6** | **24.1** | **24.1** | **23.8** | **23.8** | **23.7** | **23.7** | **23.9** | **23.8** | **23.7** | | *23.8* | |
| **Wind** | **Largely north** | | | | | | **23.8** | **23.4** | **23.6** | **23.9** | **23.5** | **23.6** | **23.6** | **23.5** | **23.4** | **23.7** | **23.5** | | *23.6* | |
| | | | | **Rooflight** | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | | | | | *23.3* | *23.6* | *23.6* | *23.7* | *24.0* | *23.7* | *23.7* | *23.7* | *23.6* | *23.4* | *23.6* | *23.5* | *23.3* | *23.6* | |
| | | **missing** | | **23.1** | **23.2** | | | | | | | | | | | | | | | |
| | | **missing** | | **23.7** | **23.5** | | | | | | | | | | | | | | | |
| | | **missing** | | **23.7** | **23.7** | | | | | | | | | | | | | | | |
| *Average south end* | | *###* | *###* | *23.5* | *23.5* | | | | | | | | | | | | | | | |

### A2. AFTER FORCED OVERNIGHT COOLING FROM 22:00 ON 21 SEPTEMBER 2012 TO 09:30 ON SATURDAY 22 SEPTEMBER

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Average Temp drop West end* | | | | *2.9* | *2.9* | | *Average Temperature drop in main office space from 21 SEPTEMBER evening* | | | | | | | | | | | | | |
| | *Average west end* | | | *20.9* | *20.9* | | | | | | | *Average main office space (excluding west end)* | | | | | | | | |
| **Floor** | **Ground** | | | **20.4** | **20.2** | **20.2** | **20.1** | **20.1** | **19.8** | **Atrium** | | | | | **20.0** | **20.3** | **20.2** | **20.4** | *20.1* | *3.1* |
| **Date** | **22Sep12** | | | **21.1** | **21.1** | **20.7** | **20.0** | **20.4** | **20.1** | | | | | | **20.6** | **20.9** | **21.0** | **20.7** | *20.6* | *3.0* |
| **Time** | **09:30 to 09:45** | | | **20.8** | **21.0** | | | | | | | | | | | | | | | |
| **Instrument** | **Flir B200 WBA** | | | **21.1** | **21.3** | | **21.0** | **21.1** | **21.4** | **21.3** | **21.4** | **21.3** | **21.2** | **21.1** | **20.7** | **20.8** | **21.2** | | *21.1* | *2.7* |
| **Wind** | **Largely north** | | | | | | **20.7** | **20.7** | **20.8** | **20.8** | **20.6** | **20.8** | **20.8** | **20.7** | **20.5** | **20.7** | **20.8** | | *20.7* | *2.9* |
| | | | | **Rooflight** | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | | | | | *20.5* | *20.5* | *20.6* | *20.5* | *21.1* | *21.0* | *21.1* | *21.0* | *20.9* | *20.5* | *20.7* | *20.8* | *20.6* | *20.7* | *2.8* |
| | | | | | | *Average temperature drops in main office space from FRIDAY 21 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | | **20.7** | **21.2** | **21.0** | **20.7** | *2.8* | *3.2* | *3.0* | *3.1* | *3.0* | *2.7* | *2.7* | *2.7* | *2.7* | *3.0* | *2.9* | *2.7* | *2.8* | *2.8* | |
| | | **20.7** | **21.0** | **21.3** | **21.1** | | | | | | | | | | | | | | | |
| | | **21.2** | **21.8** | **21.3** | **21.1** | | | | | | | | | | | | | | | |
| *Average south end* | | *20.9* | *21.3* | *21.2* | *21.0* | | | | | | | | | | | | | | | |
| *Ave T drop south end* | | *###* | *###* | *2.3* | *2.5* | | | | | | | | | | | | | | | |

### A3. AFTER EQUILIBRATING FOR THE DAY OF SATURDAY 22 SEPTEMBER

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Average Temp drop West end* | | | | *2.9* | *3.0* | | *Average Temperature drop in main office space from 21 SEPTEMBER evening* | | | | | | | | | | | | | |
| | *Average west end* | | | *20.9* | *20.8* | | | | | | | *Average main office space (excluding west end)* | | | | | | | | |
| **Floor** | **Ground** | | | **20.2** | **20.2** | **20.4** | **20.8** | **20.8** | **20.6** | **Atrium** | | | | | **21.1** | **20.5** | **20.7** | **20.6** | *20.7* | *2.6* |
| **Date** | **22Sep12** | | | **20.9** | **20.8** | **20.6** | **20.9** | **21.1** | **21.0** | | | | | | **21.1** | **21.1** | **21.0** | **20.8** | *21.0* | *2.6* |
| **Time** | **22:10 to 22:20** | | | **21.1** | **21.1** | | | | | | | | | | | | | | | |
| **Instrument** | **Flir B200 WBA** | | | **21.3** | **21.1** | | **21.3** | **21.2** | **21.4** | **21.4** | **21.4** | **21.4** | **21.3** | **21.4** | **21.2** | **21.1** | **21.3** | | *21.3* | *2.5* |
| **Wind** | **Largely north** | | | | | | **20.9** | **21.0** | **21.0** | **21.1** | **21.1** | **21.1** | **21.0** | **21.1** | **20.9** | **20.9** | **21.1** | | *21.0* | *2.6* |
| | | | | **Rooflight** | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | | | | | | *21.0* | *21.0* | *21.0* | *21.3* | *21.3* | *21.3* | *21.2* | *21.3* | *21.1* | *20.9* | *21.0* | | *21.1* | *2.5* |
| | | | | | | | *Average temperature drops in main office space from FRIDAY 21 SEPTEMBER evening* | | | | | | | | | | | | | |
| | | **20.5** | **21.0** | **21.1** | **20.8** | | *2.7* | *2.6* | *2.7* | *2.8* | *2.4* | *2.5* | *2.5* | *2.4* | *2.9* | *2.9* | *2.6* | *3.1* | *2.7* | |
| | | **20.8** | **21.0** | **21.3** | **20.6** | | | | | | | | | | | | | | | |
| | | **21.0** | **21.5** | **21.3** | **20.9** | | | | | | | | | | | | | | | |
| *Average south end* | | *20.8* | *21.2* | *21.2* | *20.8* | | | | | | | | | | | | | | | |
| *Ave T drop south end* | | *###* | *###* | *2.3* | *2.7* | | | | | | | | | | | | | | | |

### A4. THE FOLLOWING MORNING SUNDAY 23 SEPTEMBER- NIGHT COOLING FAILED AFTER 30 MINUTES

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Average Temp drop West end* | | | | *0.7* | *0.7* | | *Average Temperature drop in main office space from 22 SEPTEMBER evening* | | | | | | | | | | | | | |
| | *Average west end* | | | *20.2* | *20.1* | | | | | | | | | | | | *Average main office space* | | | |
| **Floor** | **Ground** | | | **19.8** | **19.8** | **20.0** | **20.1** | **20.1** | **20.0** | **Atrium** | | | | | **20.0** | **20.1** | **19.9** | **19.9** | *20.0* | *0.7* |
| **Date** | **23Sep12** | | | **20.1** | **20.0** | **20.3** | **20.4** | **20.5** | **20.4** | | | | | | **20.3** | **20.4** | **20.2** | **20.2** | *20.3* | *0.6* |
| **Time** | **09:20 to 09:35** | | | **20.0** | **20.3** | | | | | | | | | | | | | | | |
| **Instrument** | **Flir B200 WBA** | | | **20.7** | **20.4** | | **20.7** | **20.8** | **20.9** | **21.0** | **21.0** | **20.8** | **20.9** | **20.9** | **20.9** | **20.8** | **20.8** | | *20.9* | *0.4* |
| **Wind** | **Largely north** | | | | | | **20.3** | **20.4** | **20.5** | **20.5** | **20.5** | **20.5** | **20.5** | **20.5** | **20.4** | **20.4** | **20.3** | | *20.4* | *0.6* |
| | | | | **Rooflight** | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | | | | | | *20.4* | *20.5* | *20.5* | *20.8* | *20.8* | *20.7* | *20.7* | *20.7* | *20.4* | *20.4* | *20.3* | | *20.5* | *0.6* |
| | | **19.9** | **20.3** | **20.5** | **20.2** | | *0.6* | *0.6* | *0.6* | *0.5* | *0.5* | *0.6* | *0.4* | *0.6* | *0.7* | *0.5* | *0.7* | | *0.6* | |
| | | **20.1** | **20.4** | **20.8** | **20.2** | | | | | | | | | | | | | | | |
| | | **20.4** | **20.8** | **20.7** | **20.5** | | | | | | | | | | | | | | | |
| *Average south end* | | *20.1* | *20.5* | *20.7* | *20.3* | | | | | | | | | | | | | | | |
| *Ave T drop south end* | | *0.6* | *0.7* | *0.6* | *0.5* | | | | | | | | | | | | | | | |

## WOODLAND TRUST - SPOT IR TEMPERATURES OF CONCRETE RADIATORS — APPENDIX B - FIRST FLOOR

### B1. ORIGINAL - AT THE END OF THE WORKING WEEK ON FRIDAY 21 SEPTEMBER 2012

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average west end* | | | *24.4* | *24.4* | | | | | | | | | | *Average main office space* | | | | | |
| Floor | First | | | 23.8 | 23.8 | 23.9 | 23.9 | 23.0 | 24.0 | Atrium | | | | | 23.9 | 23.8 | 23.6 | 23.2 | *23.7* | |
| Date | 21Sep12 | | | 24.1 | 24.2 | 24.2 | 24.4 | 24.2 | 24.1 | | | | | | 23.8 | 23.9 | 23.9 | 23.9 | *24.1* | |
| Time | 20:05 to 20:20 | | | 24.9 | 24.9 | | | | | | | | | | | | | | | |
| Instrument | Flir 640 Instrotech | | | 24.7 | 24.7 | | 24.4 | 24.3 | 24.3 | 24.5 | 24.3 | 24.1 | 24.3 | 24.1 | 24.5 | 24.1 | 23.7 | | *24.2* | |
| Wind | Largely north | | | | | | 24.2 | 24.3 | 24.3 | 24.4 | 24.1 | 24.2 | 23.0 | 23.8 | 23.9 | 23.6 | 23.5 | | *24.0* | |
| | | 23.7 | 23.8 | Rooflight | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | 23.7 | 23.7 | | | | *24.2* | *24.0* | *24.2* | *24.5* | *24.2* | *24.2* | *23.7* | *24.0* | *24.0* | *23.9* | *23.7* | | *24.0* | |
| | | 23.9 | 23.7 | | | | | | | | | | | | | | | | | |
| | | 23.9 | 23.9 | 24.0 | 23.7 | | | | | | | | | | | | | | | |
| | | 24.0 | 24.1 | 24.0 | 23.7 | | | | | | | | | | | | | | | |
| | | 24.6 | 24.5 | 24.3 | 24.3 | | | | | | | | | | | | | | | |
| *Average project space* | | *24.2* | *24.2* | *24.1* | *23.9* | | | | | | | | | | | | | | | |

### B2. AFTER FORCED OVERNIGHT COOLING FROM 22:00 ON 21 SEPTEMBER 2012 TO 09:30 ON SATURDAY 22 SEPTEMBER

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average Temp drop West end* | | | *3.4* | *3.2* | *Average Temperature drop in main office space from 21 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | *Average west end* | | | *21.0* | *21.2* | | | | | | | *Average main office space* (excluding west end) | | | | | | | | |
| Floor | First | | | 20.8 | 20.8 | 20.5 | 20.4 | 20.4 | 20.2 | Atrium | | | | | 20.0 | 20.1 | 20.3 | 20.4 | *20.3* | *3.4* |
| Date | 22Sep12 | | | 20.8 | 20.9 | 21.0 | 21.3 | 21.1 | 20.9 | | | | | | 20.9 | 20.8 | 21.0 | 20.8 | *21.0* | *3.1* |
| Time | 11:15 to 11:30 | | | 21.1 | 21.5 | | | | | | | | | | | | | | | |
| Instrument | Flir B200 WBA | | | 21.1 | 21.5 | | 21.4 | 21.3 | 21.4 | 21.4 | 21.4 | 21.4 | 21.4 | 21.4 | 21.4 | 21.2 | 21.1 | | *21.3* | *2.9* |
| Wind | Largely north | | | | | | 21.3 | 21.2 | 21.3 | 21.4 | 21.2 | 21.2 | 21.1 | 21.0 | 21.1 | 20.9 | 20.7 | | *21.1* | *2.8* |
| | | 18.7 | 19.0 | Rooflight | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | 18.9 | 18.9 | | | | *21.1* | *21.0* | *21.0* | *21.4* | *21.3* | *21.3* | *21.3* | *21.2* | *20.9* | *20.8* | *20.8* | | *21.1* | *2.9* |
| | | 19.1 | 19.2 | | | *Average temperature drops in main office space from FRIDAY 21 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | | 19.1 | 19.2 | 19.2 | 19.3 | | *3.1* | *3.0* | *3.2* | *3.1* | *2.9* | *2.9* | *2.4* | *2.8* | *3.2* | *3.1* | *2.9* | | *2.9* | |
| | | 19.3 | 19.3 | 19.1 | 19.2 | | | | | | | | | | | | | | | |
| | | 19.6 | 19.2 | 19.2 | 19.1 | | | | | | | | | | | | | | | |
| *Average project space* | | *19.3* | *19.2* | *19.2* | *19.2* | | | | | | | | | | | | | | | |
| *Ave T drop proj space* | | *4.8* | *4.9* | *4.9* | *4.7* | | | | | | | | | | | | | | | |

### B3. AFTER EQUILIBRATING FOR THE DAY OF SATURDAY 22 SEPTEMBER

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average Temp drop West end* | | | *3.1* | *3.1* | *Average Temperature drop in main office space from 21 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | *Average west end* | | | *21.3* | *21.4* | | | | | | | *Average main office space* (excluding west end) | | | | | | | | |
| Floor | First | | | 20.7 | 21.0 | 21.0 | 20.9 | 21.0 | 20.7 | Atrium | | | | | 20.5 | 20.7 | 20.8 | 20.8 | *20.8* | *2.9* |
| Date | 22Sep12 | | | 21.1 | 21.1 | 21.3 | 21.4 | 21.3 | 21.3 | | | | | | 21.1 | 21.2 | 21.3 | 21.2 | *21.3* | *2.8* |
| Time | 22:20 to 22:30 | | | 21.6 | 21.7 | | | | | | | | | | | | | | | |
| Instrument | Flir B200 WBA | | | 21.7 | 21.6 | | 21.6 | 21.6 | 20.9 | 21.8 | 21.8 | 21.9 | 21.8 | 21.8 | 21.7 | 21.2 | 21.4 | | *21.6* | *2.6* |
| Wind | North-East | | | | | | 21.3 | 21.4 | 21.5 | 21.6 | 21.6 | 21.6 | 21.5 | 21.5 | 21.3 | 21.4 | 21.1 | | *21.4* | *2.5* |
| | | 21.2 | 21.3 | Rooflight | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | 21.2 | 21.3 | | | | *21.3* | *21.3* | *21.1* | *21.7* | *21.7* | *21.8* | *21.7* | *21.7* | *21.2* | *21.1* | *21.2* | | *21.4* | *2.6* |
| | | 21.2 | 21.3 | | | *Average temperature drops in main office space from FRIDAY 21 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | | 21.3 | 21.4 | 21.5 | 21.3 | | *2.9* | *2.6* | *3.1* | *2.8* | *2.5* | *2.4* | *2.0* | *2.3* | *2.9* | *2.9* | *2.6* | | *2.6* | |
| | | 21.4 | 21.6 | 21.5 | 21.3 | | | | | | | | | | | | | | | |
| | | 21.5 | 21.6 | 21.4 | 21.1 | | | | | | | | | | | | | | | |
| *Average project space* | | *21.4* | *21.5* | *21.5* | *21.2* | | | | | | | | | | | | | | | |
| *Ave T drop proj space* | | *2.8* | *2.6* | *2.6* | *2.7* | | | | | | | | | | | | | | | |

### B4. THE FOLLOWING MORNING SUNDAY 23 SEPTEMBER- NIGHT COOLING FAILED AFTER 30 MINUTES

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average Temp drop West end* | | | *0.3* | *0.4* | *Average Temperature drop in main office space from 22 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | *Average west end* | | | *21.0* | *21.0* | | | | | | | | | | *Average main office space* | | | | | |
| Floor | First | | | 20.6 | 20.5 | 20.5 | 20.6 | 20.5 | 20.5 | Atrium | | | | | 20.5 | 20.7 | 20.8 | 20.8 | *20.6* | *0.2* |
| Date | 23Sep12 | | | 20.8 | 20.8 | 20.9 | 21.1 | 20.9 | 20.9 | | | | | | 20.8 | 20.8 | 20.9 | 20.9 | *20.9* | *0.4* |
| Time | 09:40 to 09:55 | | | 21.3 | 21.3 | | | | | | | | | | | | | | | |
| Instrument | Flir B200 WBA | | | 21.4 | 21.2 | | 21.2 | 21.2 | 21.3 | 21.0 | 21.4 | 21.3 | 21.3 | 21.3 | 21.1 | 21.1 | 21.1 | | *21.2* | *0.4* |
| Wind | East | | | | | | 20.8 | 20.8 | 21.0 | 21.4 | 21.1 | 20.9 | 20.7 | 21.0 | 20.8 | 20.6 | 20.6 | | *20.9* | *0.6* |
| | | 20.8 | 20.9 | Rooflight | | *Averages in main office floor:* | | | | | | | | | | | | | | |
| | | 20.8 | 20.9 | | | | *20.9* | *20.9* | *20.9* | *21.2* | *21.3* | *21.1* | *21.0* | *21.2* | *20.8* | *20.8* | *20.9* | | *21.0* | *0.4* |
| | | 20.6 | 20.9 | | | *Average temperature drops in main office space from SATURDAY 22 SEPTEMBER evening* | | | | | | | | | | | | | | |
| | | 20.6 | 20.9 | 21.1 | 20.7 | | *0.4* | *0.5* | *0.2* | *0.5* | *0.5* | *0.6* | *0.6* | *0.5* | *0.3* | *0.3* | *0.3* | | *0.4* | |
| | | 20.9 | 21.0 | 21.0 | 20.8 | | | | | | | | | | | | | | | |
| | | 21.0 | 21.1 | 20.9 | 20.9 | | | | | | | | | | | | | | | |
| *Average project space* | | *20.8* | *21.0* | *21.0* | *20.8* | | | | | | | | | | | | | | | |
| *Ave T drop proj space* | | *0.6* | *0.5* | *0.5* | *0.4* | | | | | | | | | | | | | | | |

**WOODLAND TRUST - SPOT IR TEMPERATURES OF CONCRETE RADIATORS** **APPENDIX C - SECOND FLOOR**

**C1. ORIGINAL - AT THE END OF THE WORKING WEEK ON FRIDAY 21 SEPTEMBER 2012**

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average west end* | *23.9* | *23.7* | ***Average main office space** (excluding west end)* | | | | | | | | | | | | | | |
| Floor | Second | 23.8 | 23.2 | 22.9 | 22.9 | 22.7 | 22.7 | 22.6 | 22.7 | 22.6 | 22.7 | 22.7 | 23.2 | 22.8 | 22.7 | 22.7 | *22.8* | |
| Date | 21Sep12 | 23.6 | 23.6 | 23.1 | 23.2 | 23.0 | 23.1 | 22.9 | 22.9 | 23.0 | 23.1 | 23.0 | 23.1 | 23.1 | 23.1 | 23.0 | *23.0* | |
| Time | 21:05 to 21:20 | 24.0 | 24.0 | | | | | | | | | | | | | | | |
| Instrument | Flir T640 Instrotech | 24.2 | 24.0 | | 23.5 | 23.4 | 23.3 | 23.5 | 23.7 | 23.0 | 23.4 | 23.3 | 23.3 | 23.1 | 23.1 | | *23.3* | |
| Wind | Largely North | 24.0 | 24.0 | | 23.1 | 23.1 | 23.4 | 23.1 | 23.1 | 23.2 | 23.3 | 23.1 | 23.0 | 22.8 | 22.8 | | *23.1* | |
| | *Average temperatures* | *23.9* | *23.8* | | *23.2* | *23.1* | *23.1* | *23.0* | *23.1* | *23.0* | *23.1* | *23.0* | *23.2* | *23.0* | *22.9* | | *23.0* | |

**C2. AFTER FORCED OVERNIGHT COOLING FROM 22:00 ON 21 SEPTEMBER 2012 TO 09:30 ON SATURDAY 22 SEPTEMBER**

*Average Temperature drop in main office space from 21 SEPTEMBER evening*

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average west end* | *20.7* | *20.7* | ***Average main office space** (excluding west end)* | | | | | | | | | | | | | | |
| Floor | Second | 20.1 | 20.2 | 20.3 | 20.2 | 20.2 | 20.2 | 20.0 | 20.0 | 20.0 | 20.0 | 19.9 | 20.2 | 20.1 | 19.9 | 20.1 | *20.1* | 2.7 |
| Date | 22Sep12 | 20.6 | 20.5 | 20.6 | 20.3 | 20.5 | 20.4 | 20.4 | 20.3 | 20.4 | 20.2 | 20.3 | 20.4 | 20.4 | 20.3 | 20.1 | *20.4* | 2.7 |
| Time | 10:55 to 11:05 | 21.0 | 21.0 | | | | | | | | | | | | | | | |
| Instrument | Flir B200 WBA | 21.2 | 21.1 | | Missing | Missing | Missing | Missing | Missing | Missing | Missing | Missing | Missing | Missing | Missing | | ### | #### |
| Wind | Largely North | 20.9 | 20.9 | | | | | | | | | | | | | | ### | #### |
| | *Average temperatures* | *20.8* | *20.7* | | *20.3* | *20.4* | *20.3* | *20.2* | *20.2* | *20.2* | *20.1* | *20.1* | *20.3* | *20.3* | *20.1* | | *20.2* | |
| | *Ave T drop from evening 21 Sep* | *3.2* | *3.0* | | *2.9* | *2.7* | *2.8* | *2.8* | *3.0* | *2.8* | *3.0* | *2.9* | *2.9* | *2.7* | *2.8* | | *2.8* | |

**C3. AFTER EQUILIBRATING FOR THE DAY OF SATURDAY 22 SEPTEMBER**

*Average Temperature drop in main office space from 21 SEPTEMBER evening*

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average west end* | *21.2* | *21.2* | ***Average main office space** (excluding west end)* | | | | | | | | | | | | | | |
| Floor | Second | 20.9 | 21.0 | 20.9 | 20.8 | 20.8 | 20.9 | 20.7 | 20.5 | 20.6 | 20.6 | 20.7 | 20.7 | 20.8 | 20.8 | 20.6 | *20.7* | 2.0 |
| Date | 22Sep12 | 21.2 | 21.2 | 21.1 | 20.8 | 20.8 | 21.1 | 21.0 | 20.9 | 21.0 | 20.7 | 21.0 | 21.0 | 21.0 | 21.0 | 21.0 | *21.0* | 2.1 |
| Time | 22:30 to 22:40 | 21.1 | 21.0 | | | | | | | | | | | | | | | |
| Instrument | Flir B200 WBA | 21.7 | 21.6 | | 21.5 | 21.4 | 21.5 | 21.5 | 21.6 | 21.5 | 21.5 | 21.4 | 21.3 | 21.3 | 21.3 | | *21.4* | 1.9 |
| Wind | North-East | 21.5 | 21.5 | | 21.3 | 21.3 | 21.3 | 21.4 | 21.5 | 21.4 | 21.3 | 21.3 | 21.1 | 21.1 | 21.1 | | *21.3* | 1.8 |
| | *Average temperatures* | *21.3* | *21.3* | | *21.1* | *21.1* | *21.2* | *21.2* | *21.1* | *21.1* | *21.0* | *21.1* | *21.0* | *21.1* | *21.1* | | *21.1* | |
| | *Ave T drop from evening 21 Sep* | *2.6* | *2.5* | | *2.1* | *2.0* | *1.9* | *1.9* | *2.0* | *1.8* | *2.1* | *1.9* | *2.1* | *1.9* | *1.9* | | *2.0* | |

**C4. THE FOLLOWING MORNING SUNDAY 23 SEPTEMBER - NIGHT COOLING FAILED AFTER 30 MINUTES**

*Average Temperature drop in main office space from 22 SEPTEMBER evening*

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Average west end* | *21.0* | *21.0* | ***Average main office space** (excluding west end)* | | | | | | | | | | | | | | |
| Floor | Second | 20.4 | 20.5 | 20.6 | 20.5 | 20.4 | 20.3 | 20.3 | 20.2 | 20.2 | 20.1 | 20.3 | 20.3 | 20.4 | 20.3 | 20.1 | *20.3* | 0.4 |
| Date | 23Sep12 | 20.9 | 20.8 | 20.9 | 20.8 | 20.7 | 20.7 | 20.6 | 20.6 | 20.5 | 20.6 | 20.6 | 20.7 | 20.6 | 20.6 | 20.6 | *20.7* | 0.3 |
| Time | 10:00 to 10:15 | 21.5 | 21.4 | | | | | | | | | | | | | | | |
| Instrument | Flir B200 WBA | 21.2 | 21.1 | | 21.0 | 20.9 | 21.0 | 20.9 | 20.9 | 21.0 | 20.9 | 20.9 | 20.9 | 20.8 | 20.9 | | *20.9* | 0.5 |
| Wind | East | 21.1 | 21.0 | | 20.8 | 20.8 | 20.9 | 20.8 | 20.7 | 20.7 | 20.7 | 20.7 | 20.6 | 20.6 | 20.7 | | *20.7* | 0.6 |
| | *Average temperatures* | *21.0* | *21.0* | | *20.8* | *20.7* | *20.7* | *20.7* | *20.6* | *20.6* | *20.6* | *20.6* | *20.6* | *20.6* | *20.6* | | *20.6* | |
| | *Ave T drop from evening 22 Sep* | *0.3* | *0.3* | *0.0* | *0.3* | *0.4* | *0.5* | *0.5* | *0.5* | *0.5* | *0.4* | *0.5* | *0.4* | *0.4* | *0.4* | *0.0* | *0.4* | |