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Analysis of Thermostat Design for Vertical Fan Coil Units Within Modern Window-Wall Condominium Suites

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ANALYSIS OF THERMOSTAT DESIGN FOR VERTICAL FAN COIL UNITS WITHIN MODERN WINDOW-WALL CONDOMINIUM SUITES

By

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Abstract

The aim for this research is to identify the issues with poor thermostat designs in a window-wall condominium suite during cooling season, and to investigate how low-cost changes in the design can improve occupant comfort, reduce energy consumption, and increase terminal equipment service life. Temperature logging and fan coil operation monitoring procedures were carried out during the peak cooling season in a sample condominium suite located in Toronto, Ontario. Data was collected and analyzed presenting the effects of thermostat installation in proximity of an exterior window-wall and supply air diffuser, and system durability concerns of implementing a proportional-based algorithm via pulse width modulation. Several design changes have been proposed that can be implemented at negligible cost during construction design and are expected to lead to comfort and system improvements during the cooling season.

Acknowledgement

I would like to express my appreciation to my supervisor Dr. Zaiyi Liao who provided guidance and direction not only for this thesis work but throughout this program. His vast knowledge, ideas, positive outlook and sincere passion for the industry has made these past three years stimulating. Thank you to my second reader Dr. Russell Richman for your help and suggestions in finalizing this research.

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Nomenclature

°C Degrees Celsius

m^2 Square Meter

1. Introduction

Thermostats play a vital role in providing occupant comfort by controlling the most energy intensive systems in buildings, those for heating and cooling. Existing research has focused on the performance of specific space conditioning equipment [Jiang et al., 2011]. However, the thermostat controlling these systems and its placement relative to environmental influences has received much less attention.

This research aims to understand the effects of poor thermostat design within a window-wall condominium that negatively impacts system performance, occupant comfort and terminal equipment service life during cooling season. The analysis and discussion in this research identifies how control interference from solar loads, poor performing building envelopes, and relative location of supply diffusers with respect to the thermostat, affect space conditioning systems in modern condominium suites during the cooling season.

Thermostats that implement proportional algorithm control via pulse width modulation activate space conditioning systems on a pre-established number of cycles per hour, regardless of the heating or cooling loads in the space. When properly commissioned, proportional controls ensure more consistent space temperatures, but the system is then susceptible to unnecessary short cycling of the fan motor and hydronic valves. The increased frequency of operating the equipment subsequently decreases the equipment service life and increases lifecycle costs.

In combination, the noted deficiencies above create an environment where the space conditioning equipment is jeopardized in terms of energy performance during the cooling season and system lifecycle costs. Several low-cost changes in the design can improve overall occupant comfort and reduce energy consumption during the cooling season, and increase service life expectancy of the terminal space conditioning equipment.

2. Background

Existing research reviewed on thermostats for residential buildings focused on several areas including occupant comfort, and energy efficiency practices such as set-point scheduling, thermostat usability, and occupant usage behaviour [Aragon et al., 2011-1] [Aragon et al., 2011-2] [CMHC, 2005] [Friedman, 2004] [Han et al., 2010] [Lilkendey et al., 2004]. Locating existing research specific to implications from poor thermostat placement in modern condominium suites relative to environmental influences that impact system performance and occupant comfort proved difficult during literature review. This is mostly due to existing research focusing on typical residential homes where centralized systems dominate, and the thermostats are typically within the building core zones and not exposed to unsteady environmental factors as within a modern window-wall condominium suite.

Existing research discusses the effects of thermostat control on occupant comfort, which should account for both thermal comfort and acoustic comfort [ASHRAE, 2010] [ESP, 2008] [Firth et al., 2010] [Friedman, 2004] [Lilkendey et al., 2004]. The prior is a well researched area of occupant comfort and discusses that thermal discomfort situations can arise from several factors: improper system capacity, lack of appropriate zoning, improper control, varying space usage, varying solar load, changes in occupancy, changes to the space envelopes, drafts and diffuser performance [Friedman, 2004].

If one thermostat cannot represent the serviced space, then there will be thermal comfort deficiencies. Similarly, if there is significant temperature gradient within a space, whether that is a vertical or horizontal gradient, then thermostat placement will dictate the degree of thermal discomfort within the zone. Within modern window-wall condominiums, a large temperature gradient can be expected given the solar load on the large spans of glass and heat loss through such glass.

Research on temperature gradient or stratification within a space were reviewed, but did not present any discussions on horizontal stratification, which is felt to be a significant concern in window-wall condominium suites as outlined above. In a stratified environment, temperature shown by the thermostat may fail to represent the air temperature in the occupied space of the service zone. Further research begins to discuss how these spatial variations in temperature may lead to substantial energy wastage and inefficiencies in delivery, as the thermostat needs to be set higher or lower than desired to heat or cool portions of a zone that are distant from it [Matthews, 2010]. However, as stated previously, the available data and research in this area is unfortunately scarce setting the path for future research studies.

Further research published provides incremental operational costs for increasing and decreasing thermostat set-points during the heating and cooling seasons [ESP, 2008] [CMHC, 2005]. Although, this is geared toward central forced-air heating and cooling within single-family residences, the costs associated with increasing or decreasing the set-points can begin to compliment the concerns in this research paper. Placing thermostats close to window-walls, and ignoring the large degree of horizontal temperature gradient, is expected to lead to over-use of space conditioning systems increasing energy consumption and subsequently higher operational costs.

An often overlooked form of occupant comfort is that of acoustic comfort. One area where this has been addressed is in schools and the attempts to reduce inherent noise in operating space conditioning systems [Lilkendey et al., 2004]. Types of noise can be classified into several categories in relation to space conditioning operation, but the focus of the literature review is on small decentralized systems relatable to fan coil units for condominiums. Specifically for the fan coil unit, airborne noise would originate from the ON/OFF sequencing of the hydronic valve and the supply fan operation. The airborne noise is transmitted into the occupant space causing discomfort; therefore, steps must be taken to reduce the frequency of fan coil operation. This supports the discussion above in regards to reducing the space conditioning equipment operation by taking into account the environmental influences, relative positioning of the thermostat within a window-wall condominium suite, and the control logic of the thermostat itself.

Although the results of the initial literature review did not provide specific research into optimized design and placement of thermostats within window-wall condominium suites, there was brief discussion relating to overcoming installation constraints. A specific discussion on the promise of wireless thermostat controls for space conditioning was reviewed [Wills, 2004]. The paper discusses how wireless controls for space conditioning systems can essentially be mounted anywhere within the range of its receiver. Therefore, in cases where running wiring is prohibitively expensive, such as concrete areas, or simply prohibitive, such as glass or marble walls, or surfaces that cannot be disturbed, optimized thermostat installation can be achieved without installation constraints.

For this research project, the first step in understanding the current issues with thermostat design and placement is to understand the basic control terminology and theory. As discussed in an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) technical paper, there are several components within a controlled process, with each functioning to successfully control a given process [Rosandich, 1997]. The paper provides a concise overview of the basic control terminology and theory to be applied to thermostatic control within a space and was reviewed extensively. Using *Figure 1*, the paper discusses each component of the feedback loop, which can then be easily related to a thermostatic control system for space conditioning in a residential building.

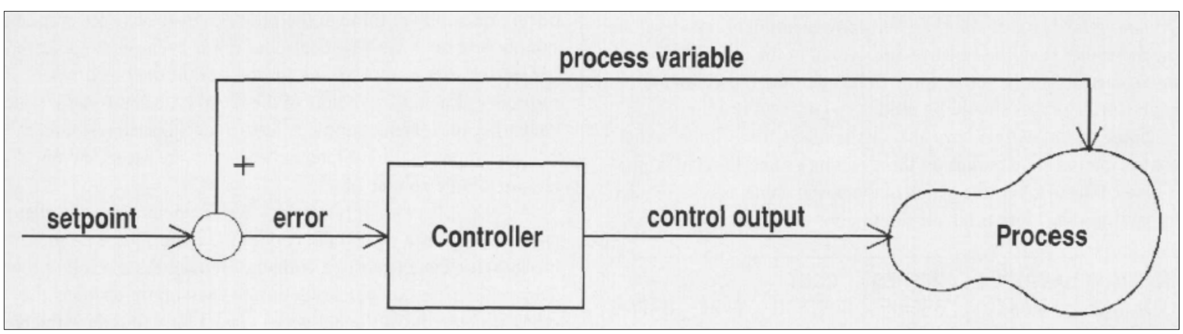


Figure 1: Closed-Loop Feedback Control Schematic [Rosandich, 1997]

A *process controller* is a device that measures the value of the variable being controlled and tries to maintain it at a desirable value by adjusting the *output device*, with the input that is measured and controlled being the *process variable* [Rosandich, 1997]. In the case of the thermostatic control system, the process controller is the thermostat and the process variable would be the space temperature. The desirable value for the process variable is the *set-point*, which is the temperature set on the thermostat by the occupant within a space [Rosandich, 1997].

Controllers change the process variable by adjusting the control output, which is essentially cycling the space conditioning equipment ON and OFF, as necessary, in attempt to meet and maintain the set-point. An *error signal* (e) is created by the controller through relating the process variable (PV) and set-point (SP) at any given time interval (t), as depicted in the formula below, and uses the value of the error signal to determine the control output necessary to maintain the process variable at the setpoint [Rosandich, 1997].

$$e(t) = PV(t) - SP$$

There are two types of control algorithms applicable for a space controlled thermostatically. The first is an ON/OFF controller, which is the simplest variation of control. The ON/OFF controller will turn the output device ON or OFF depending on the value of the calculated error signal at any given time. A *deadband* is incorporated within the controller to avoid frequent ON and OFF cycling of the output device as the process variable approaches the set-point [Rosandich, 1997].

As depicted in *Figure 2*, the controller remains in the current state until the error signal has increased beyond the set deadband, and will then reverse to the opposite state and vice versa. An ON/OFF controller is typical with most residential thermostats used within central forced-air space conditioning systems [Rosandich, 1997]. However, due to the nature of deadband, the process variable controlled by an ON/OFF controller will always cycle back and forth around the set-point.

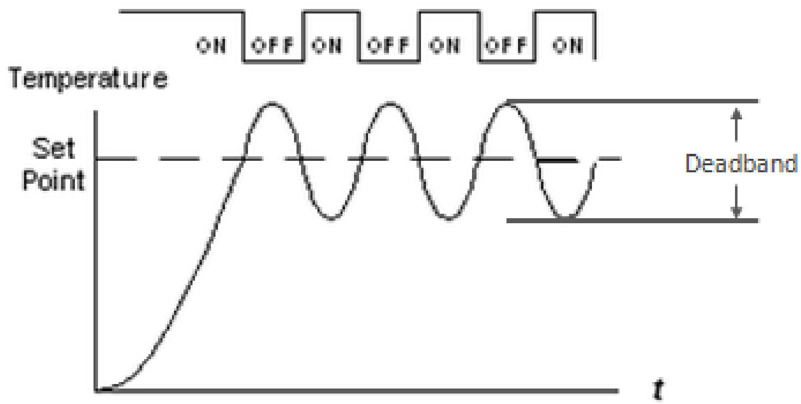


Figure 2: ON/OFF Controller Response (Adapted from [Unitronics, 2002])

The second type is a continuous controller, which is most commonly found in spaces that require accurate and consistent thermal control [Rosandich, 1997]. A continuous controller effectively controls the space conditioning system output like a dimmer, gradually increasing and decreasing output to ensure an extremely constant room temperature. The advantage of using a continuous controller is that it will eliminate the ups and downs in the process variable as experienced with an ON/OFF controller. Within the family of continuous controllers, there are three main types as described below.

Proportional (P) controllers adjust the control output proportionally to the magnitude of the error signal [Rosandich, 1997]. Therefore, a large error generates a large control output, and a small error generates a small control output. However, using a proportional controller alone will result in a steady-state error as shown within *Figure 3* below.

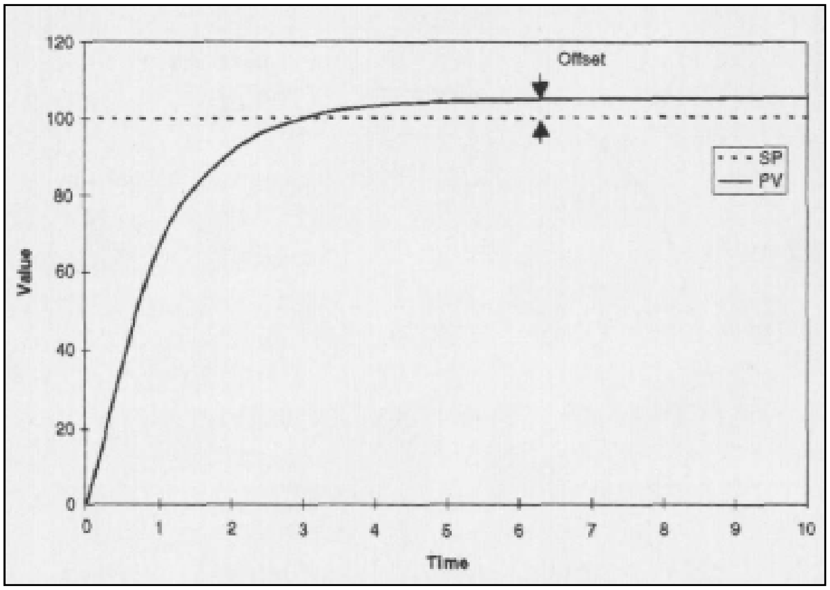


Figure 3: Proportional Controller Response [Rosandich, 1997]

Proportional-Integral (P+I) controllers have the added integral logic to solve the steady-state error concerns with standalone proportional controllers [Rosandich, 1997]. Integral action essentially acts on what has occurred in the past to reduce the current error. Therefore, if the process variable being controlled is stable, integral action will guarantee that the steady-state error eventually becomes zero as shown in *Figure 4* below.

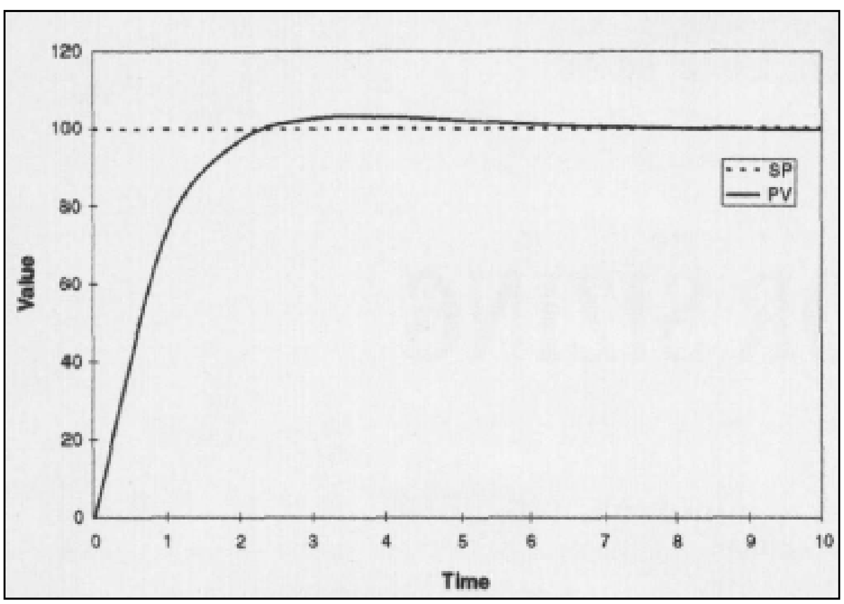


Figure 4: Proportional-Integral Controller Response [Rosandich, 1997]

Proportional-Integral-Derivative (P+I+D) controllers take on derivative logic to improve system response with sluggish processes such as space conditioning. Derivative actions reacts to the rate of change or slope of the error signal over time and effectively used to predict future error magnitudes and compensate the control output to reduce overshoot, anticipating that the process is soon to reach the set-point.

3. Objective and Intent of Research

The research objective is to identify how control interference from solar loads, poor performing building envelopes, and relative location of supply diffusers with respect to the thermostat, affect space conditioning systems in modern condominium suites during the cooling season. Specifically, temperature gradients in the cooling season from solar load and poor performing window-wall facades will influence thermostat readings and prematurely activate space conditioning regardless of acceptable average temperatures within the space. Further, discharged supply air adjacent to a thermostat will bias space temperature feedback and prematurely de-activate the fan coil inhibiting desired temperature setpoint from being achieved. This is believed to unnecessarily increase energy consumption and operational costs during the cooling season. The research also aims to identify system durability concerns of operating a thermostat using pulse width modulation to implement a proportional-based control algorithm, which activates space conditioning systems on a pre-established cycle per hour frequency regardless of the space cooling load. The intent for the research analysis and discussion is to lead to a conceptual design for improving cooling season conditions within a typical window-wall condominium suite. This is important because it will help address peak demand and energy conservation concerns, a sector that Ontario has heavily invested, and applicable to a building sector that has seen significant growth over the past decade.

4. Methodology

A series of temperature logging and fan coil operation monitoring procedures were carried out during the peak cooling season in a sample condominium suite located in

Toronto, Ontario. Data was collected and analysed to identify the effects of thermostat installation in proximity of an exterior window-wall and supply air diffuser, and system durability concerns of implementing a proportional-based algorithm via pulse width modulation.

Recorded temperature data was analyzed by comparing the horizontal temperature gradient profile, which is a plot of recorded temperature versus distance from the exterior window-wall, for various times of the day with and without space conditioning active. The graphical comparison was used to identify and analyze the effects of thermostat installation in proximity of an exterior window-wall and supply air diffuser in the cooling season.

Recorded fan coil ON/OFF sequencing was overlaid on the logged space temperature data for several small time segments to examine their correlation. Specifically, the data was examined to understand how fan coil operation is affected during the periods of higher solar heat gain in mid-afternoon and how adjacent supply air affects the fan coil operation relative to setpoint.

4.1. Sampled Condominium Suite Details

The condominium suite sampled for analysis is located on the fourth floor of a twenty-eight storey multi-residential building with approximately 40 [m^2] of conditioned interior floor area and a single exterior window-wall facing West. The residential building was constructed in 2005 and is located in Toronto, Ontario. The building's elevation and fourth floor layout is provided below in *Figures 5* and *6*.

Figure 5: West Elevation of Condominium Suite

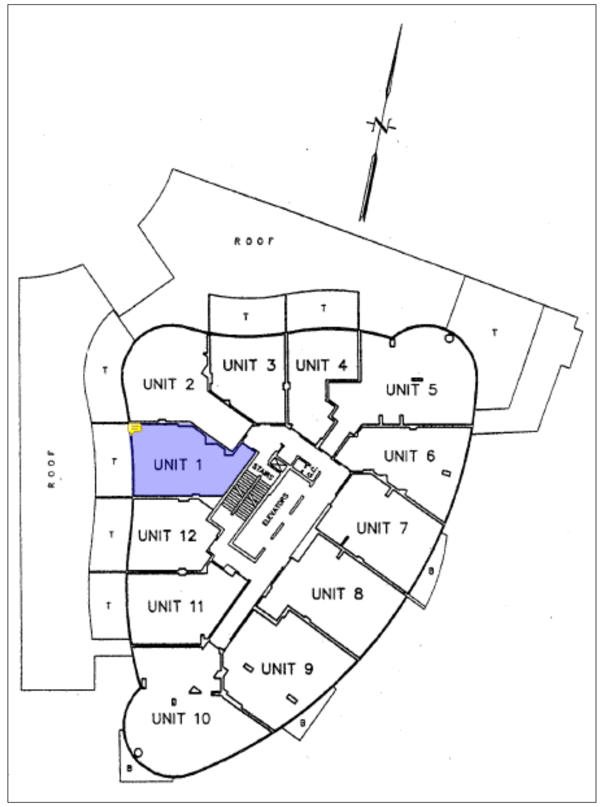


Figure 6: Fourth-Floor Layout of Condominium

The exposed walls of the building are of modern window-wall construction and have an estimated window-to-wall ratio of 70%. The window-wall glazing comprised typical double pane insulated glass units (IGUs), assumed to have low-emissivity glazing treatment and thermally-broken aluminum framing. A detailed analysis of the facade thermal performance is not the focus of this research; however, industry experts have recognized that the effective thermal performance of such wall constructions are poor [Kesik, 2011].

Central heating and cooling is provided in the condominium suite by a single 2-pipe vertical fan coil unit and controlled by a digital non-programmable thermostat with manual three-speed fan control (*Figure 7)*. As shown in *Figure 8* below, the thermostat is located directly below the supply diffuser of the fan coil unit and in close proximity to the exterior window-wall. It is uncertain to the extent at which other suites in the studied condominium have similar thermostat locations.

Figure 7: Honeywell Thermostat

Figure 8: Fan Coil Unit Location in Sampled Suite

Fresh air for the suite is provided by a centralized make-up air (MUA) system pressurizing the common corridor with conditioned air, which infiltrates into the condominium suite through designed perimeter gaps around the entrance door. The supply water to the fan coil unit and central MUA is maintained by the central heating plant and cooling plant.

4.1. Fan Coil Conditioning System

In general, a fan coil is a space conditioning system that houses an air filter, a centrifugal fan, heating and cooling coils, and operates by drawing air through an opening in the unit, across the coils and then supplies the conditioned air back to the space (*Figure 9*).

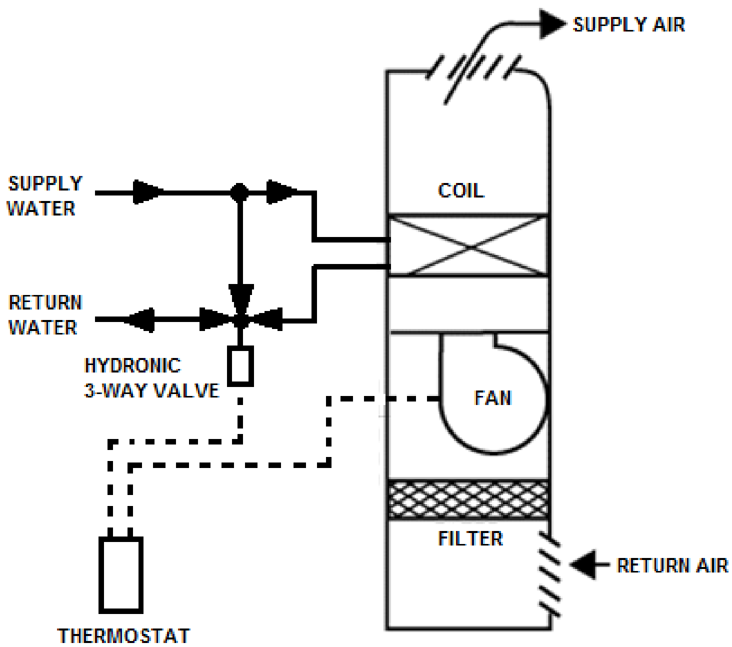


Figure 9: Two-Pipe Heating/Cooling Fan Coil (Adapted from [Honeywell, 1997])

Fan coil units are more economical for use in residential buildings than other central HVAC systems. However, they produce significant noise as the fan and hydronic valve are within the same space. Unit configurations are numerous including horizontal (ceiling mounted), or vertical (floor mounted) as within the sampled condominium suite.

A two-pipe fan coil system consists of fan coil units with single coils, which are connected to two pipes (one supply pipe and one return pipe) that either provide hot water or chilled water throughout the building. A building with a two -pipe system is either entirely in a heating mode or entirely in a cooling mode. It is not possible to cool some rooms while heating others. In the Spring and Fall it is not uncommon to have alternating hot and cold spells, or cold mornings with warm afternoons. A 2-pipe system then inflicts significant thermal discomfort due to these temperature swings.

4.2. Fan Coil Thermostat

The thermostat in the studied condominium suite was a Honeywell T6574B, which controls the centrifugal fan and hydronic valve in relation to the space temperature and desired setpoint. The T6584B thermostat has ON/OFF control output. However, this output is regulated by a proportional-integral (P+I) algorithm. The P+I analog output is converted to a digital ON/OFF signal through pulse width modulation (PWM). Therefore, the fan coil is operated based on the duty ratio, μ, as determined by the PWM conversion from the P+I controller output (*Figure 10*).

$$\text{Duty Ratio, } \mu = \frac{\tau_{ON}}{\tau_{ON} + \tau_{OFF}} = \frac{\tau_{ON}}{\tau_o}$$

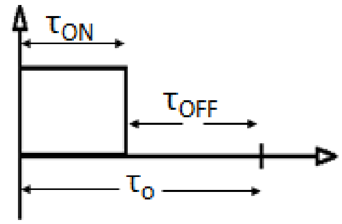


Figure 10: Duty Ratio Calculation for Pulse Width Modulation

The thermostat is programmed to operate with (4) cycles per hour for cooling (τ_o = 15 minutes) and (8) cycles per hour for heating (τ_o = 7.5 minutes), and operates with a proportional band of 1.6 [°C] [Honeywell, 2005]. As the error between the space temperature and setpoint increases so will the duty ratio, and therefore, the fan coil remains ON for a larger portion of the complete cycle, τ_o. Also important to note, in cooling mode the user setpoint will be positioned at the bottom of the proportional band, so the setpoint will effectively be the temperature where the cooling switches off. In heating mode the user setpoint will be positioned at the top of the proportional band, and this will be the temperature where the heating switches off. This is presented schematically in *Figure 11* below.

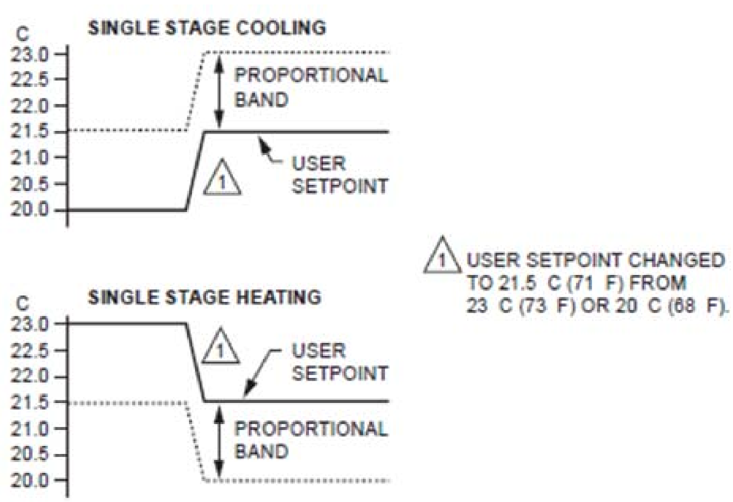


Figure 11: Single-Stage Cooling and Heating Control [Honeywell, 2005]

4.3. Data Loggers and Analysis Software

Temperature data within the sampled condominium suite was obtained using (9) Onset HOBO® U12-012 data loggers. Fan coil ON/OFF operation was obtained using (1) Onset HOBO® U12 4-External Channel Data Logger paired with (1) Onset CTV-D 0-200A split-core AC current transformer. Data was downloaded using HOBOware® Pro Version 3.1.1 software, and then imported to Microsoft Excel .csv format for analysis.

5. Monitoring Procedure and Approach

5.1. Temperature Monitoring

Three temperature logging intervals were undertaken to present the effects of poor thermostat designs in proximity of the exterior window-wall and supply air diffuser of a typical condominium suite during the cooling season. The first monitoring period was carried for a single day, and was set to understand the horizontal temperature gradient that exists within the sampled condominium suite when no space cooling system was active. The second and third monitoring periods were carried each for five days, and were dedicated towards analysing the same spatial temperature gradient with an active space cooling system. The control setpoint was adjusted slightly from the second and third monitoring period to witness any effects and understand the system's capability of meeting various set points.

In order to establish the horizontal temperature gradient within the condominium suite during the cooling season, temperature loggers were placed within the space as depicted in *Figure 9* below. Nine data loggers were used in total, with a single unit for outdoor temperature, seven units placed within the suite itself, and a final logger monitoring the common corridor. One of the interior loggers was located directly beside the thermostat so that the temperatures at the thermostat location could be understood. The remaining interior loggers were placed to ensure adequate coverage of major spaces in the suite. All loggers were located approximately at five feet from the floor, which was on plane with the thermostat. Monitoring positions remained consistent throughout the three monitoring intervals.

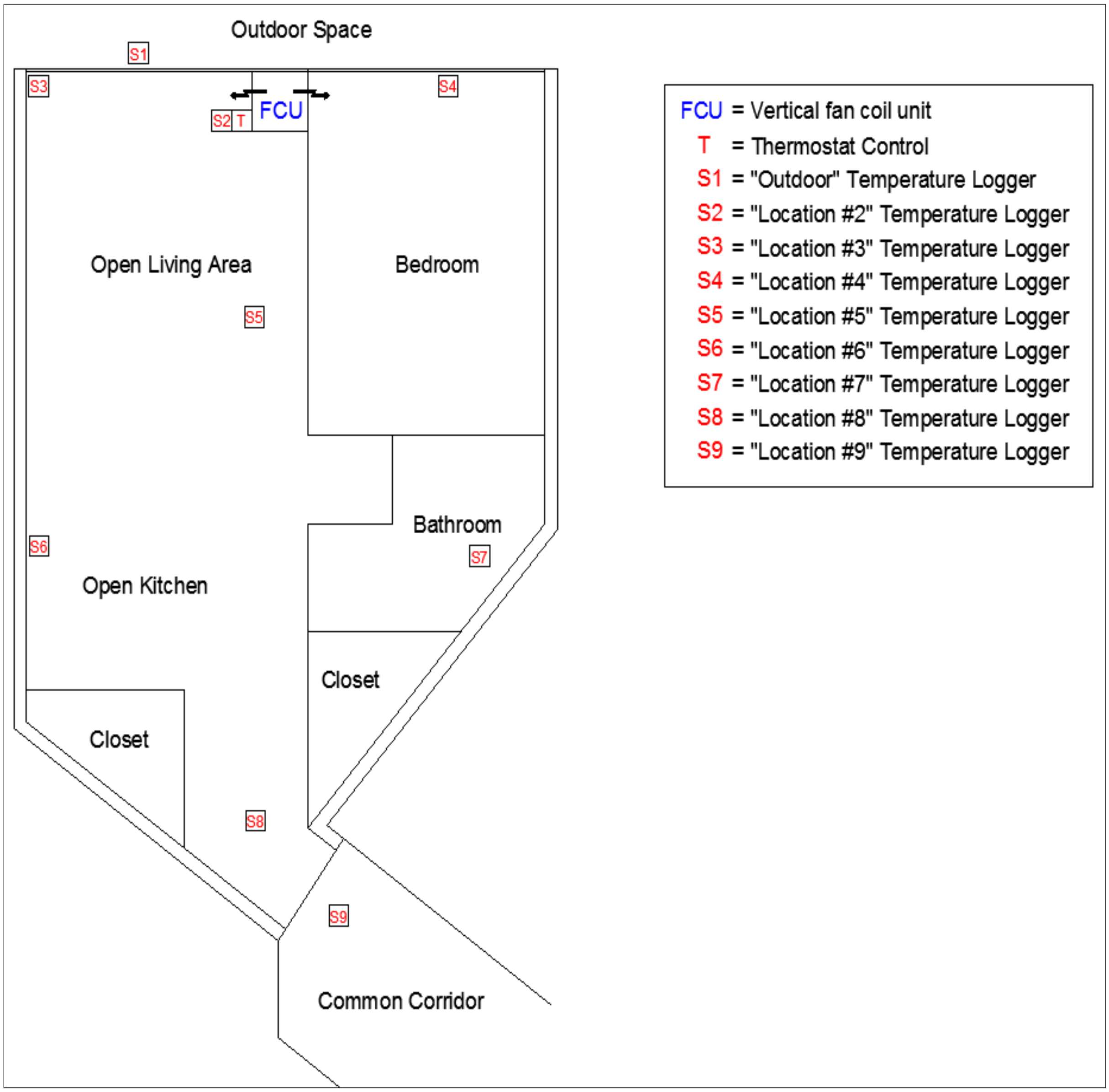


Figure 12: Temperature Sensor Layout

5.2. Fan Coil Operation Monitoring

Simultaneous to the second and third temperature monitoring intervals, the ON/OFF cycling of the fan coil itself was also monitored. A data logger designed to log low-voltage ON/OFF pulses, was used to monitor when the thermostat calls for fan coil operation and was also capable of monitoring the duration of each activation period. The resulting data was then analyzed with the temperature data collected on identical time stamps to analyze the system performance.

5.3. Monitoring Conditions and Intervals

The timing of this research led to the monitoring intervals occurring in late July, which falls within the peak cooling season for Toronto, Ontario. During this time the 2-pipe fan coil was operating in cooling mode receiving chilled water from the central chiller plant of the property. Supply air entering the space from the fan coil ranged from 14 – 16°C over the monitoring periods, and was measured twice per interval day in the morning and early evening.

Throughout the monitoring periods, the suite was unoccupied between the hours of 9:00 AM and 5:00 PM, and inactive occupancy during the overnight periods from 11:00 PM to 6:00 AM. During all occupied hours, there were only two adult occupants in the space. All interior doors were left open except for the bathroom door which was periodically closed during shower and toilet use. Showering occurred in the morning and later evenings on most days, and cooking appliances were used between 7:00 PM to 8:00 PM daily. All window blinds were left open throughout the day, so solar loads were unobstructed entering the space.

Table 1 below outlines the monitoring periods used to acquire sufficient temperature data within the sampled condominium suite, and were logged using set five minute intervals.

Table 1: Periods for Temperature Logging

Temperature Monitoring Period		Active Space Conditioning	Thermostat Setpoint
Start Date & Time	End Date & Time		
07/21/12 6:00 PM	07/22/12 7:00 AM	No	N/A
07/22/12 3:30 PM	07/27/12 4:00 PM	Yes	22 °C
07/27/12 4:15 PM	08/01/12 6:00 PM	Yes	23 °C

Similarly, *Table 2* below outlines the measurement periods used to acquire the fan coil operation data to cover the temperature measurement intervals with active space conditioning. The data was acquired on set five second intervals to provide a high resolution of the ON/OFF fan coil cycling.

Table 2: Periods for Fan Coil Operation Logging

Temperature Monitoring Period		Active Space Conditioning	Thermostat Setpoint
Start Date & Time	End Date & Time		
07/22/12 8:00 PM	07/25/12 5:55PM	Yes	22 °C
07/25/12 6:00 PM	07/27/12 4:00 PM	Yes	22 °C
07/27/12 4:05 PM	07/30/12 4:20 AM	Yes	23 °C
07/30/12 7:25 AM	08/01/12 6:05 PM	Yes	23 °C

The monitoring periods contained several incomplete calendar days as they were typically begun in the early evening and time was taken in between periods to download data and reset the loggers. It was decided that only complete calendar days from each measurement period were to be used for analysis. These specific calendar days are outlined in *Table 3* below.

Table 3: Full Calendar Day Periods for Analysis

Analysis Day	Active Space Conditioning	Thermostat Setpoint	Temperature Logged	Fan Coil Operation Logged
7/22/12	No	N/A	Yes	N/A
7/23/12	Yes	22 °C	Yes	Yes
7/24/12	Yes	22 °C	Yes	Yes
7/26/12	Yes	22 °C	Yes	Yes
7/28/12	Yes	23 °C	Yes	Yes
7/29/12	Yes	23 °C	Yes	Yes
7/31/12	Yes	23 °C	Yes	Yes

6. Data Analysis

The temperature profiles acquired during each of the three monitoring intervals were plotted to visualize the horizontal temperature gradient that exists in the sampled condominium suite with and without space cooling active. Each full calendar day was plotted and all full scale plots are available for reference in Appendix I.

The data presented consistent results across each specified interval and supported the set research goals at the onset of the project. The consistent results allowed for a single day with and a single day without space cooling to be used for analysis purposes. The plotted data chosen for analysis has been examined in full detail below.

6.1. Temperature Data with No Space Cooling

With no space cooling active, the first monitoring interval provided a clear picture to how the indoor space temperature was affected by external conditions. As presented in *Figure 13*, there is correlation between the external temperature profile with that in the suite, and specifically those loggers placed along the external window-wall facade. A slight delay in the peak indoor temperatures relative to the external peak is observed and can be expected given the minimal thermal mass of the window-wall. Interesting to note, as the temperatures fall during the overnight period, those within the suite remain in steady-state condition with an appreciable offset from the external levels.

The outdoor temperature sensor recorded temperatures as high as 50 [°C] in the mid-afternoon. Environment Canada's National Climate Data and Information Archive recorded a peak outdoor temperature for Toronto of 24.6 [°C] during this same period [Environment Canada, 2012]. Therefore, the recorded temperatures are not a direct indication of the ambient temperatures alone, but are significantly elevated from direct solar radiation during this period with the West exposure of the suite. As well, to protect the sensor from wetting, it was enclosed within a small plastic bag that will have increased the temperature readings further due to a greenhouse effect. Nonetheless, it provided a clear indication of the peak solar load cast upon the exposed window-wall facade. The outdoor sensor was shaded for the remaining intervals to avoid direct sunlight and the exaggerated temperature readings.

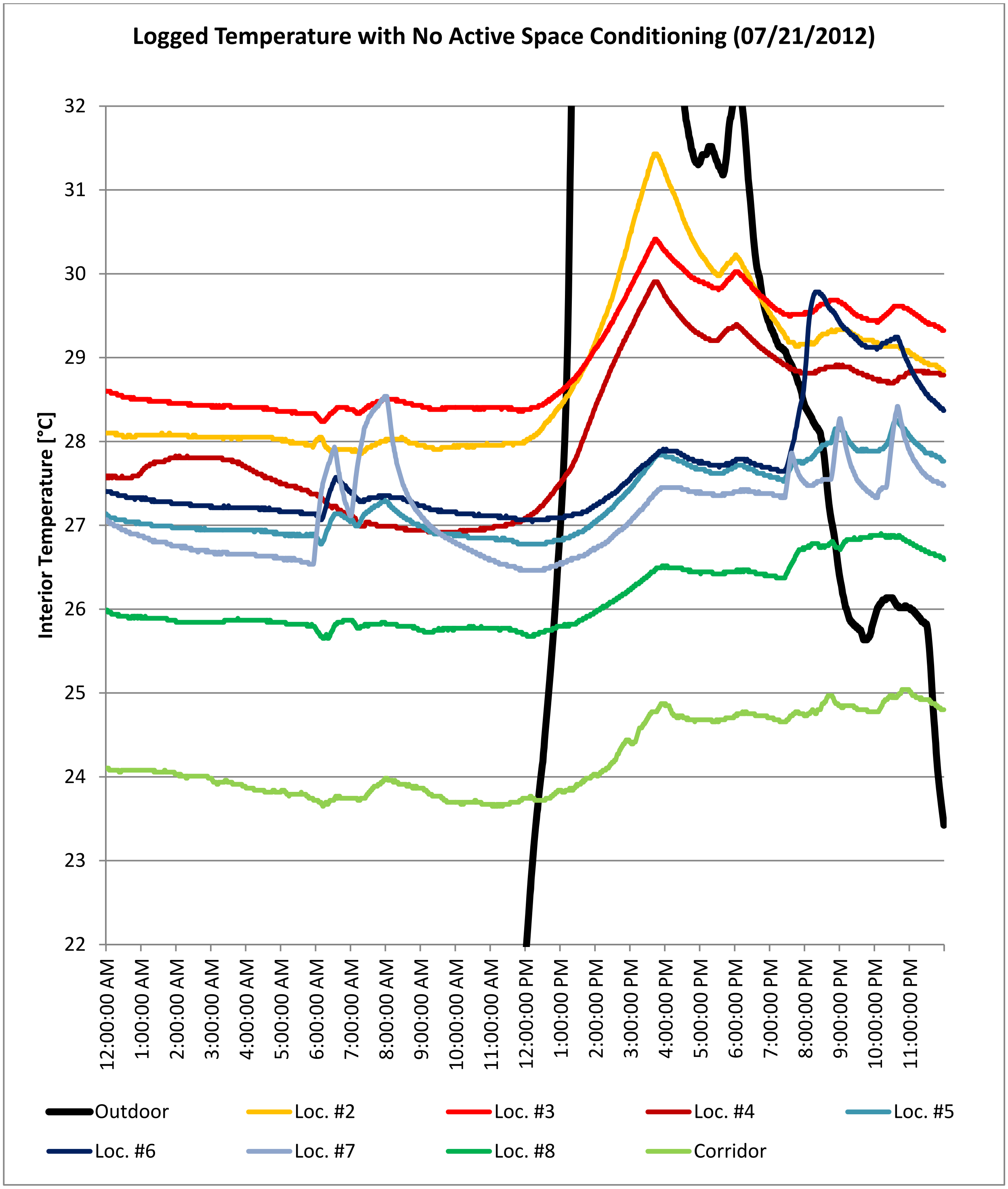


Figure 13: Temperature Profile with No Active Space Conditioning

Data retrieved from the sensor at Sensor Location #2 best represents the space temperatures recorded by the thermostat, as this sensor was mounted directly beside the wall-mounted controller. The data clearly indicates that the thermostat location is significantly influenced by the solar load penetrating the window-wall facade and is not representative of the average space temperature of the suite. In cooling season conditions, this will inherently increase the error calculated by the thermostat relative to the desired space temperature set-point leading to system efficiency concerns. Further, all three temperature loggers along the perimeter window-wall (Sensor Locations 2, 3 & 4) will have slightly elevated temperatures due to sol-air temperature effects from their exposure to direct solar radiation entering the suite in the mid-afternoon and early evening periods [Handergord, 1995].

The plotted data exposes the significant horizontal temperature gradient that exists within the space, with the highest temperatures along the window-wall perimeter (Sensor Locations 2, 3 & 4) and the lowest temperatures in the location closest to the common corridor (Sensor Location 8). It should be noted that the central corridor MUA unit was in constant operation during this logging interval. The temperature data within the corridor typically ranged between 24 [°C] and 25 [°C] during this period. Since the corridor is constantly pressurized by the active MUA unit, conditioned air infiltrates into the condominium suite through designed perimeter gaps around the entrance door. This process will have slightly biased the logged temperature data at Sensor Location #8, as it was positioned close to the front door. Nonetheless, a significant horizontal temperature gradient exists within the condominium suite with no active space conditioning.

6.2. Temperature Data with Active Space Cooling

Having visualized the space temperature profile with no active space cooling first allowed for better understanding of how the space cooling system and controls performed in the space. As presented in *Figure 14*, the horizontal temperature gradient has become inverted with the space cooling system active. The lowest space temperatures were now along the window-wall perimeter (Sensor Locations 2, 3 & 4) and the highest temperatures in the location closest to the common corridor (Sensor Location 8).

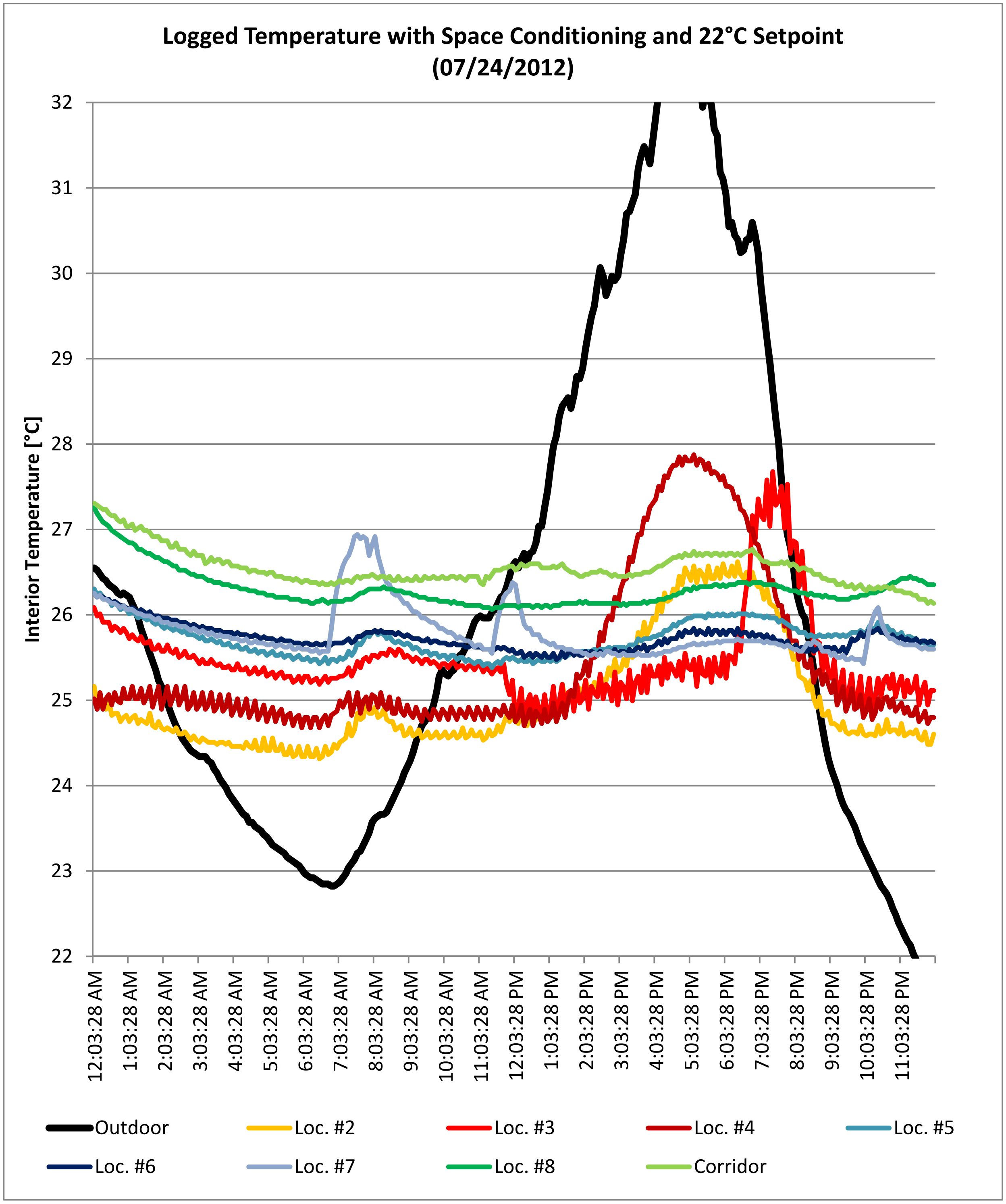


Figure 14: Temperature Profile with Space Conditioning and 22°C Setpoint

It is apparent that the desired setpoint was never recorded by the temperature loggers, and so assumed to never be satisfied in the space. As outlined in Section 4.2, under cooling conditions the P+I control action is designed to power OFF the fan coil when it reaches the setpoint. With the fixed setpoint of 22 [°C] during this measurement interval, the space temperature should have then fluctuated from 22 [°C] to 23.6 [°C], which is the width of the proportional band. Of specific note, the temperature loggers were set to acquire data on five minute intervals, so the plotted temperature may not be the absolute minimum temperatures since the last data point was recorded. However, it can be concluded with certainty based on the plotted data that the temperature setpoint is not reached in the space.

Given the placement of the thermostat directly below the fan coil supply air duct, the rush of conditioned air will mislead the thermostat to thinking the setpoint has been achieved, and prematurely deactivate the fan coil. This effect is understood to hinder the system from achieving the desired setpoint in the space. However, the consequence from the premature deactivation is in fact minimized with the PWM output of the thermostat because it is pre-programmed to only operate on four cycles per hour. So the short cycling will not have an effect on the system energy efficiency, but will affect thermal comfort for occupants that are expecting a specific indoor temperature.

For the three loggers positioned close to the fan coil, the immediate effect of the conditioned supply air can be observed with the sharp fluctuations in space temperatures. This effect begins to diminish as the distance between the fan coil increases. Interestingly, the temperatures increase just as sharply when the fan coil powers OFF. This pattern shows that the conditions in these spaces are heavily influenced by sol-air temperature effects and poor thermal performance of the window-wall. In addition, the immediate temperature increase negates the cooling just delivered to the space and will prove achieving the desired setpoint difficult given the nature of PWM thermostat output.

As outlined in Section 5.2, the fan coil operation was also logged during the final two temperature monitoring intervals. *Figure 15* and *Figure 16* present the fan coil ON/OFF sequencing overlaid on the logged temperature data over a small time segment to show the consistent correlation of the sharp, but brief, temperature fluctuations and the fan coil activation. As expected with PWM control output, the ON-time duration of the fan coil operation does increase during the periods of higher solar heat gain in mid-afternoon. However, the actual space temperature continues to show a persistent error from the desired setpoint and this error continues to increase under increased solar load.

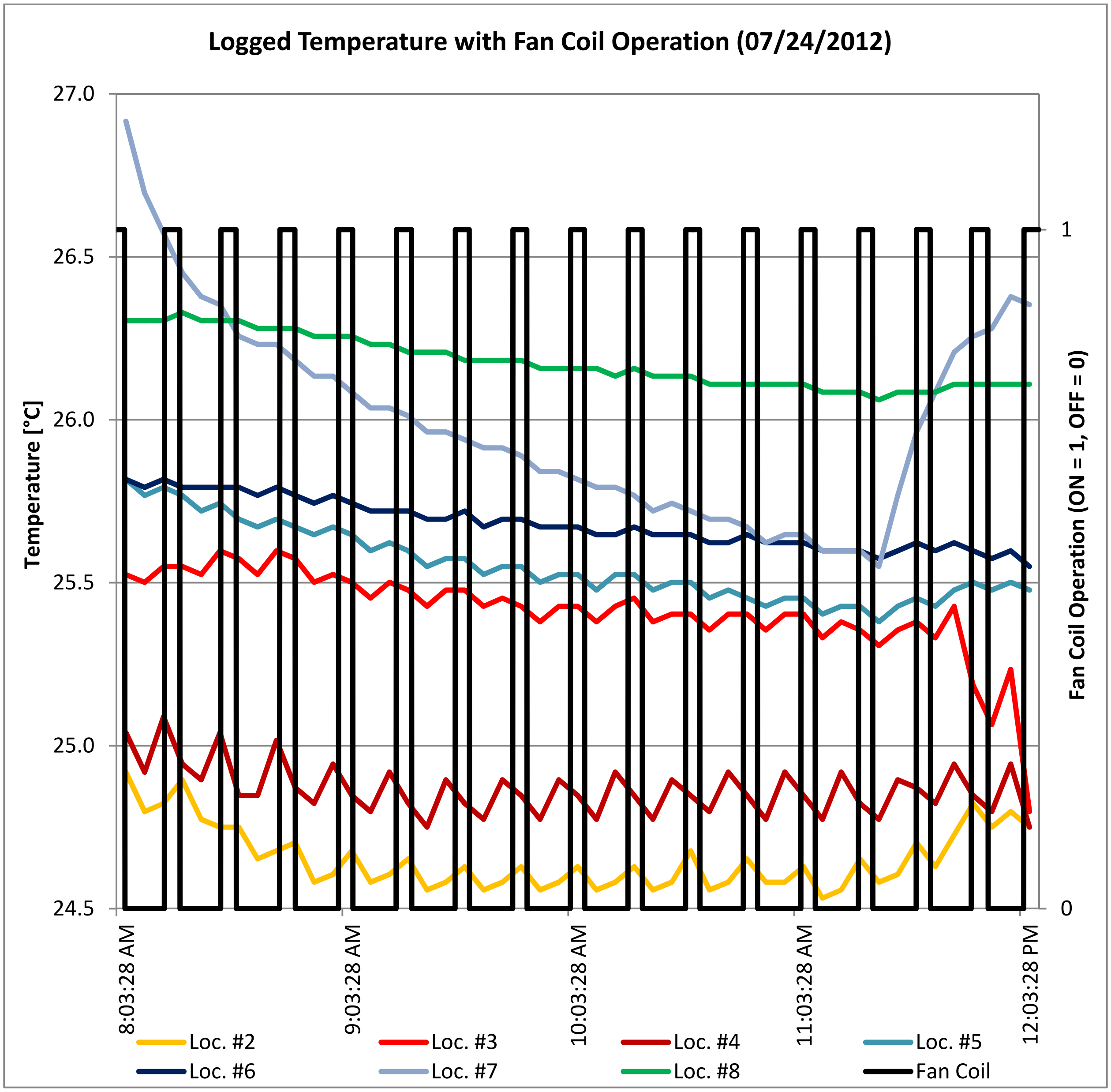


Figure 15: Temperature Profile with Fan Coil Operation at Night

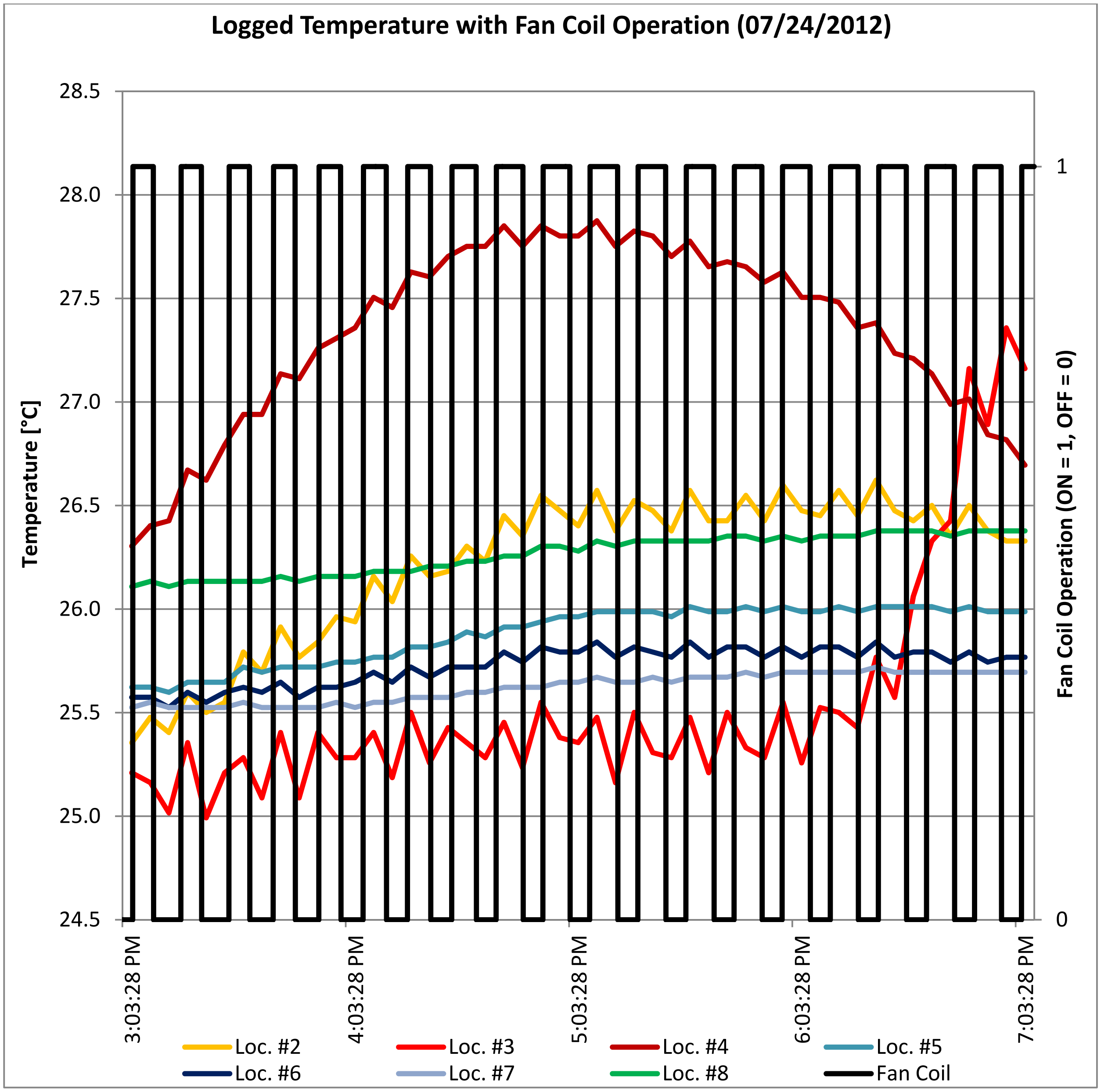


Figure 16: Temperature Profile with Fan Coil Operation with High Solar Load

This pattern would suggest that the fan coil cooling capacity is undersized, and is further complemented by its inability to meet the desired setpoint. However, a contributing factor to consider is the position of the fan coil unit along the external window-wall. Having observed the high temperature loading in this immediate area, the fan coil performance will be compromised by having to draw return air from this space. Additionally, it has already been discussed how the conditioned supply air is immediately tempered by the harsh conditions in this immediate area. However, a complete analysis of the fan coil capacity and heat loss within the sampled suite was not part of the research project scope.

The persistent error during the steady-state conditions during the overnight period is an indication that the P+I controller has not been properly commissioned as the system does not correct the steady-state error in space temperature relative to setpoint. Therefore, it could be said that the integral factor of the control, which is responsible for eliminating this error, should be increased.

6.3. Internal Load Factors

It was readily apparent in the temperature profiles collected that space temperatures in several zones were directly affected by internal loads within the condominium suite. The effects of a high lighting density and cooking loads within the kitchen were observed in sharp spikes in logged temperatures during meal times. As well, the effects from a high lighting density and shower use within the washroom resulted in sharp temperature increases within the space. The elevated temperatures resulting from the internal loads from showering and cooking could not be immediately overcome by the cooling system. Nonetheless, the internal loads elevate the cooling demand in the space. On the other hand, during the heating season the internal loads continue to elevate space temperatures but will reduce the heating demand the space.

Due to these effects, the temperature gradient analysis was held to periods of inactivity within these spaces to ensure a steady-state environment had been reached. With the condominium unoccupied from 9:00 AM to 5:00 PM each day, and inactivity during the overnight periods, temperature gradient analysis was confined to early morning and mid-afternoon periods.

6.4. Occupant Comfort Concerns

As discussed in the literature review, occupant comfort analysis and discussions should include both thermal comfort and acoustic comfort effects. The space temperature profiles and fan coil activation data presented have been used to support the qualitative discussion that occupant comfort is marginalized within the sampled condominium suite. Thermal comfort and acoustic comfort are affected from the designed fan coil location along the perimeter window-wall and the thermostat's PMW control output.

6.4.1. Thermal Comfort

The scope of this research project did not include a detailed analysis on thermal comfort within the sampled condominium suite, although the data collected may assist future research in this area. Nonetheless, the acquired temperature profiles in the space do allow for the qualitative statement that thermal comfort is not maintained at a reasonable level within the space. Further, the current fan coil and thermostat placement within the suite will not allow for thermal comfort levels to be significantly improved.

ASHRAE recommends the ideal indoor space temperature to be between approximately 20 [°C] and 24 [°C] during the heating season, and approximately 23 [°C] and 26 [°C] during the cooling season [ASHRAE, 2010]. These seasonal conditions are based on an approximate 50% relative humidity level. Additionally, the temperature should fluctuate by no more than 1.7 [°C] within the controlled space [ASHRAE, 2010].

Given the thermostat accessibility, it is understood that the average space temperature in the suite could be moderately increased and decreased to fall within the range of acceptable temperatures recommended by ASHRAE. However, the thermal comfort concern rests in the large temperature gradient existing in the space when the conditioning system is active. The acquired temperature data displays an average gradient of 1.6 [°C], and is recorded to be as high as 2.7 [°C] under high solar load. So, simply walking from one end of the condominium suite to the other inflicts an average temperature range on the cusp of ASHRAE's recommendation. Considering the controlled space is very small, this further supports the thermal comfort concerns.

The main cause of this stratification is believed to originate from having the fan coil located along the perimeter window-wall, and poor supply air distribution within the suite. The conditioned air supplied along the perimeter window-wall cannot overcome the solar loads and poor thermal properties in the immediate space, thus increasing conditioned air temperatures prior to mixing within the core areas that would help moderate the temperature gradient severity. As well, having the thermostat located in an extreme perimeter zone of the controlled space further inflicts the degree of thermal discomfort.

6.4.2. Acoustic Comfort

An often overlooked form of occupant comfort is that of acoustic comfort. Specifically for the fan coil unit, airborne noise originates from the ON/OFF sequencing of the hydronic valve and the supply fan activation. The airborne noise is transmitted into the occupant space and can be considered disturbing when a quite environment is desired. As with thermal comfort, the scope of this research project is not to present an analytical discussion of acoustic levels within the suite. Rather, the aim is to present achievable options to reduce acoustic discomfort by addressing the fan coil and thermostat themselves.

Airborne noise from the fan coil unit could obviously be decreased through better quality construction and the use of noise dampening insulation materials within the metal cabinet. Keeping the fan coil construction out of this discussion, simply reducing the ON/OFF cycling of the fan coil unit would reduce the frequency of airborne noise within the space. The thermostat in the studied condominium operates the fan coil on a fixed quantity of cycles per hour due to the PMW conversion of the analog P+I controller output. The fixed frequency of cycles occurs regardless of conditioning demand within the space. There simply needs to be demand, no matter the magnitude. Subsequently this control logic has no means of minimizing the frequency of airborne noise, and actually guarantees it regardless of the conditioning demand in the space.

6.5. PWM Control Output Concerns

As presented in *Figure 15* and *Figure 16*, each fan coil ON cycle provides a minimal effect on the overall space temperatures within the suite. On average, each cycle would reduce space temperature by approximately 0.25 [°C]. In fact, this degree of temperature drop was only confined to the three monitored zones in the direct path of the supply air. As you moved further from the fan coil, the effect of each cycle was hardly evident. Additionally, each fan coil cycle ON-time ranged from 5-10 minutes depending on the cooling demand in the space. With having the four set cycles occurring every hour during the cooling season, the space cooling system is operating 50% of the time. Considering the minimal space temperature improvement observed from each of these cycles, the overall system effectiveness can be considered poor.

The thermostat is designed to power OFF the fan coil once it has reached the desired setpoint, as outlined in Section 4.2. Further, the premise of the P+I control logic is to maintain temperatures closer to this desired setpoint. However, implementing P+I control logic via PMW has clearly been shown to not support that claim in the studied space. As previously discussed, it is believed that the thermostat receives biased temperature feedback due to interference from the supply air duct located above the thermostat. Relocating the thermostat away from the supply air discharge duct would help resolve this interference and help reduce thermal comfort concerns as the fan coil would continue to operate until the space temperature successfully met the desired setpoint.

It can be further stated implementing P+I control action through PWM is not a proper choice for spaces that have high temperature fluctuations over time, as the temperature profile in the condominium suite has presented. Rather, it is better suited for spaces that are not prone to large temperature swings throughout the day, and those that require a small degree of consistent temperature trimming. Additionally, having the set cycle per hour algorithm will increase hydronic valve and fan motor cycling. Subsequently, this will result in shorter service life of the system components while not effectively contributing to occupant comfort.

6.6. Energy Efficiency Concerns

Within a stratified environment, temperature feedback to the thermostat may fail to represent the average temperature in the occupiable space. Having a biased location for the thermostat in such a stratified environment will lead to wasted energy and inefficiencies in delivery. It can be expected that the thermostat setpoint will be adjusted in an attempt to condition the occupiable zones that are distant from the controller. This will subsequently increase energy consumption and operation costs.

To support the energy efficiency concerns in the sampled condominium, temperature values were plotted against their corresponding distance from the exterior window-wall. This is used to present what has been termed the temperature gradient profile. Two points in time were chosen for this analysis, one in the early morning and one during high exterior solar load in mid-afternoon. These times represent two extremes for the space during the cooling season, and also reflect low suite activity periods to avoid internal load interference.

Since several data loggers were positioned at similar distances from the exterior window-wall, an average temperature value was taken and used as the temperature data point for that specific distance. Four distance points were chosen, which divided the suite and sufficiently allowed the analysis to take shape. *Figure 17* and *Figure 18* below provide the temperature gradient profile for 3:00 A.M. and 3:30 P.M. respectively. Each figure also outlines the sensor locations taken into consideration when establishing the average temperature data points.

With no space conditioning active, both times of day have temperature gradient profiles as one would expect. The highest temperatures are along the exterior window-wall and subsequently decrease approaching the corridor temperature. It is also apparent that during the mid-afternoon period, the solar load inflicts a much steeper profile approaching the exterior window-wall. With active space conditioning during the early morning period, the temperature gradient profile has become completely inverted from the non-conditioned case. Thus, the lowest temperatures are now along the perimeter and increases as the distance from the window-wall increases. This is understandable as the perimeter space houses the fan coil unit and the thermostat. However, during the mid-afternoon period, the profile is altered as the fan coil is unable to cool the space sufficiently. Subsequently, the perimeter space exhibits slightly warmer temperatures than the core space.

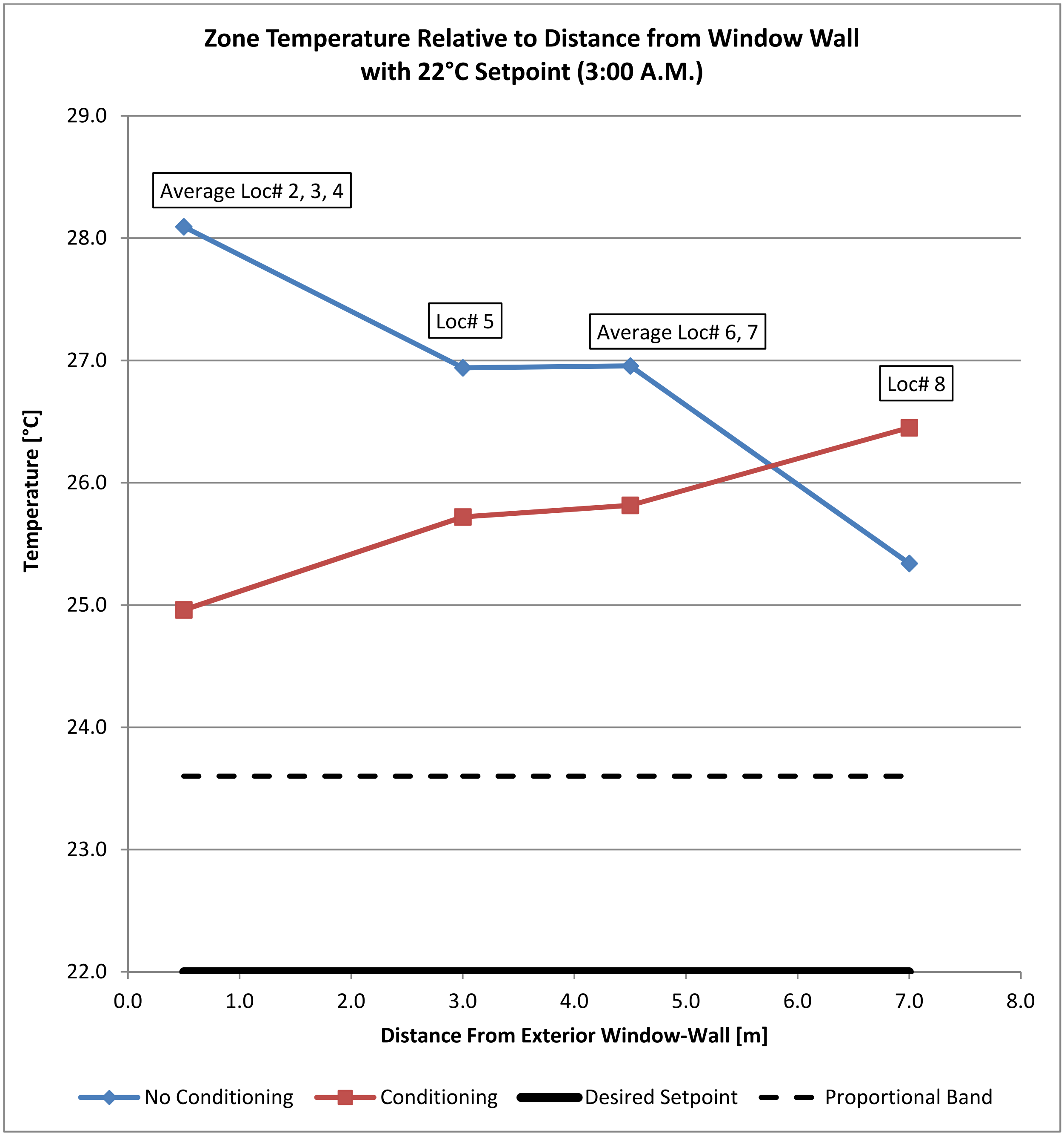


Figure 17: Temperature Profile Gradient at Night

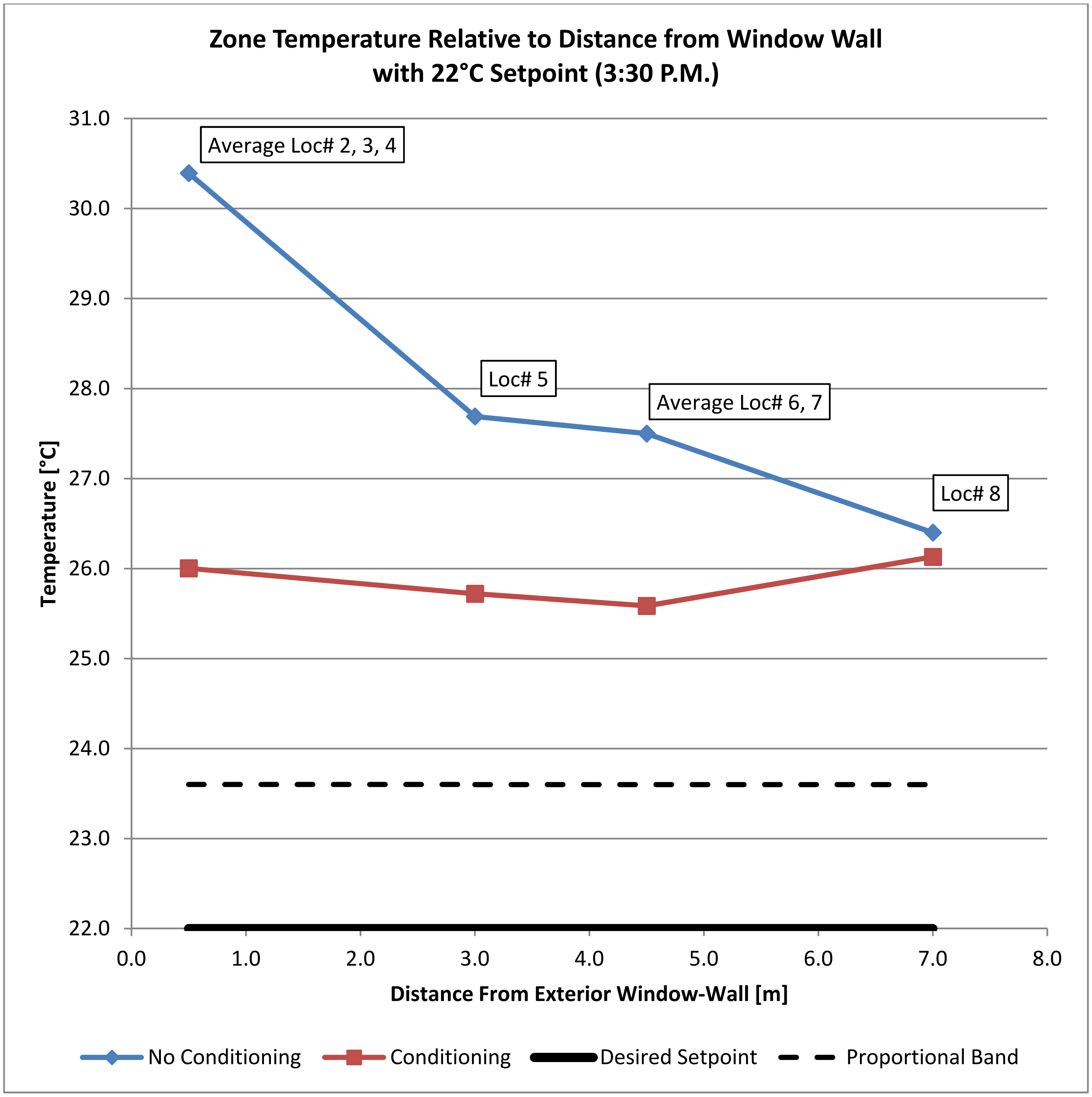


Figure 18: Temperature Profile Gradient with High Solar Load

The most important observation to draw from this analysis is that the two data points in the core zone of the suite consistently show a flattened temperature gradient regardless of whether the space conditioning is active and degree of exterior solar load. Since it is generally known that core zones have little influence by exterior conditions, this result could have been expected. Nonetheless, this core space of the suite will be visited later in this paper as the ideal location for the thermostat and the fan coil system itself.

Looking at the relative temperatures, with and without space conditioning, it is clear that the fan coil does successfully decrease space temperatures along the perimeter zone. However, the fan coil operation offers marginal improvement for the core zone, which can be considered the liveable space of the suite. *Figure 19* and *Figure 20* present how the fan coil system is providing approximately twice the effort required to reduce space temperatures in this liveable space.

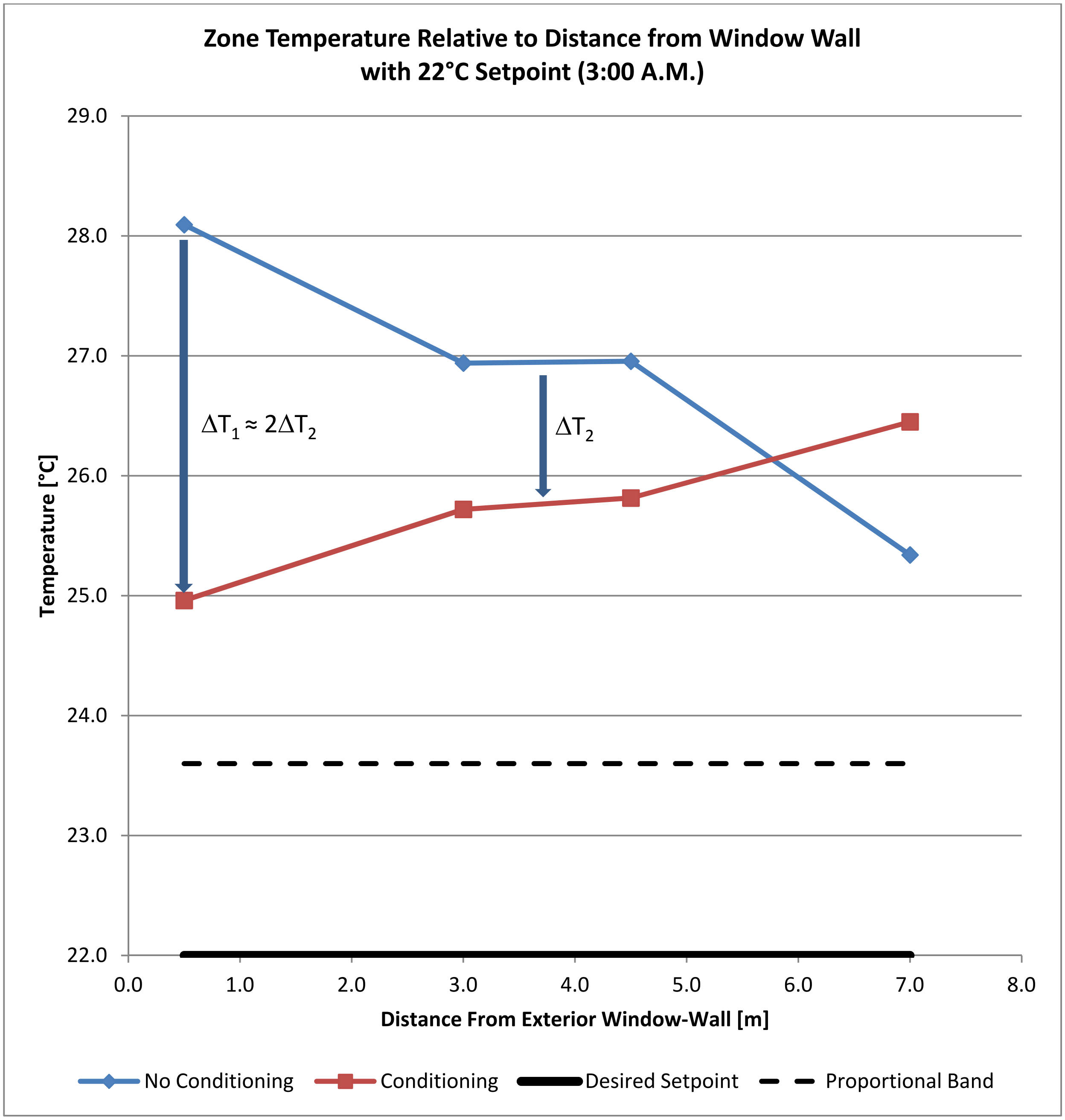


Figure 19: Relative Temperature Decrease Due to Space Conditioning at Night

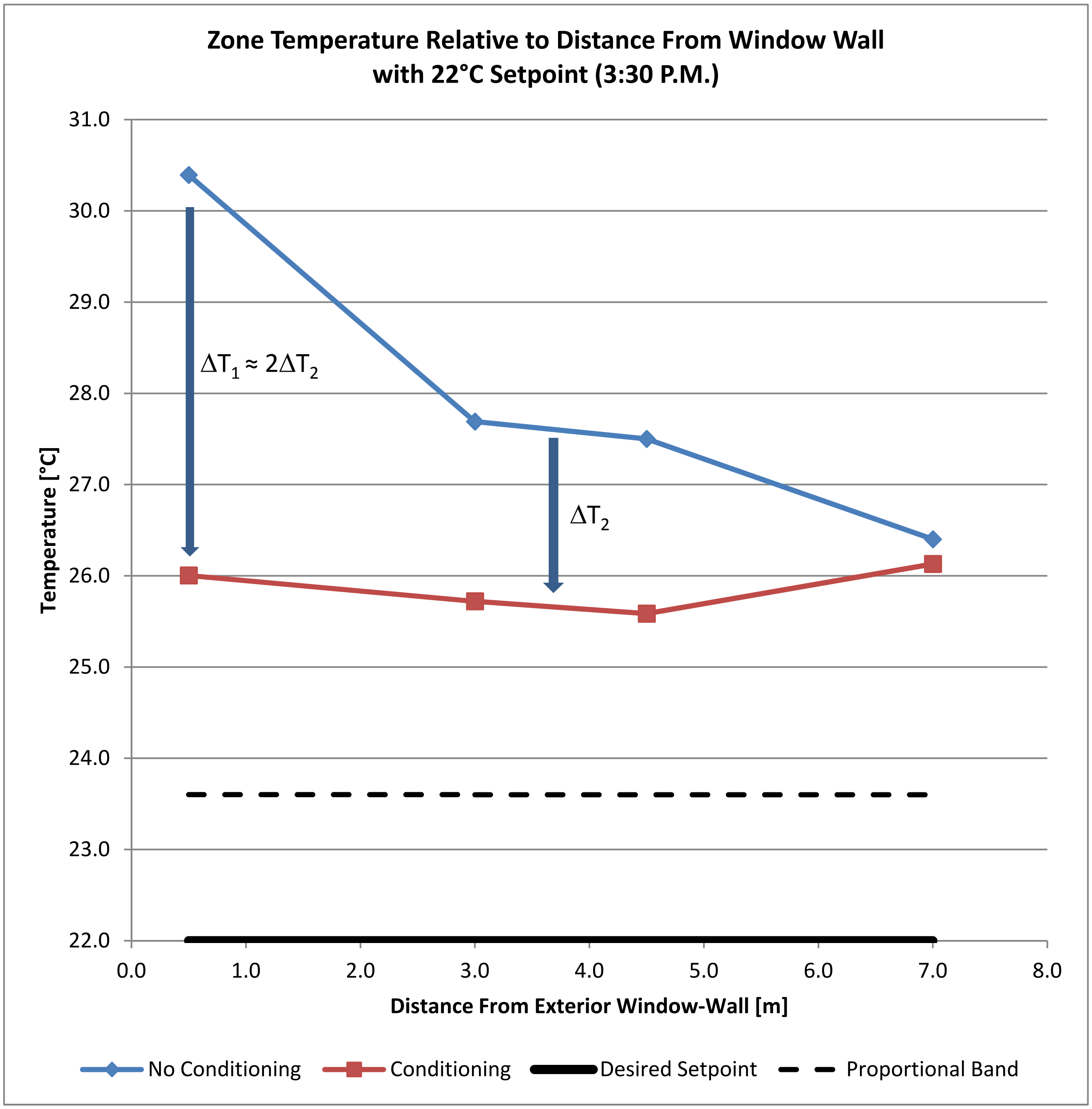


Figure 20: Relative Temperature Decrease Due to Space Conditioning with High Solar Load

Given these profiles, the assumption can be then be made that a typical occupant would further reduce the control setpoint to overcome the gradient and allow for thermal comfort in the core zone of the suite. This undoubtedly leads to an increased load on the conditioning system, and subsequently increased energy consumption in the space. *Figure 21* presents an approximate 50% increase in fan coil cooling load due to the high temperatures within the perimeter zone relative to the core zone of the suite.

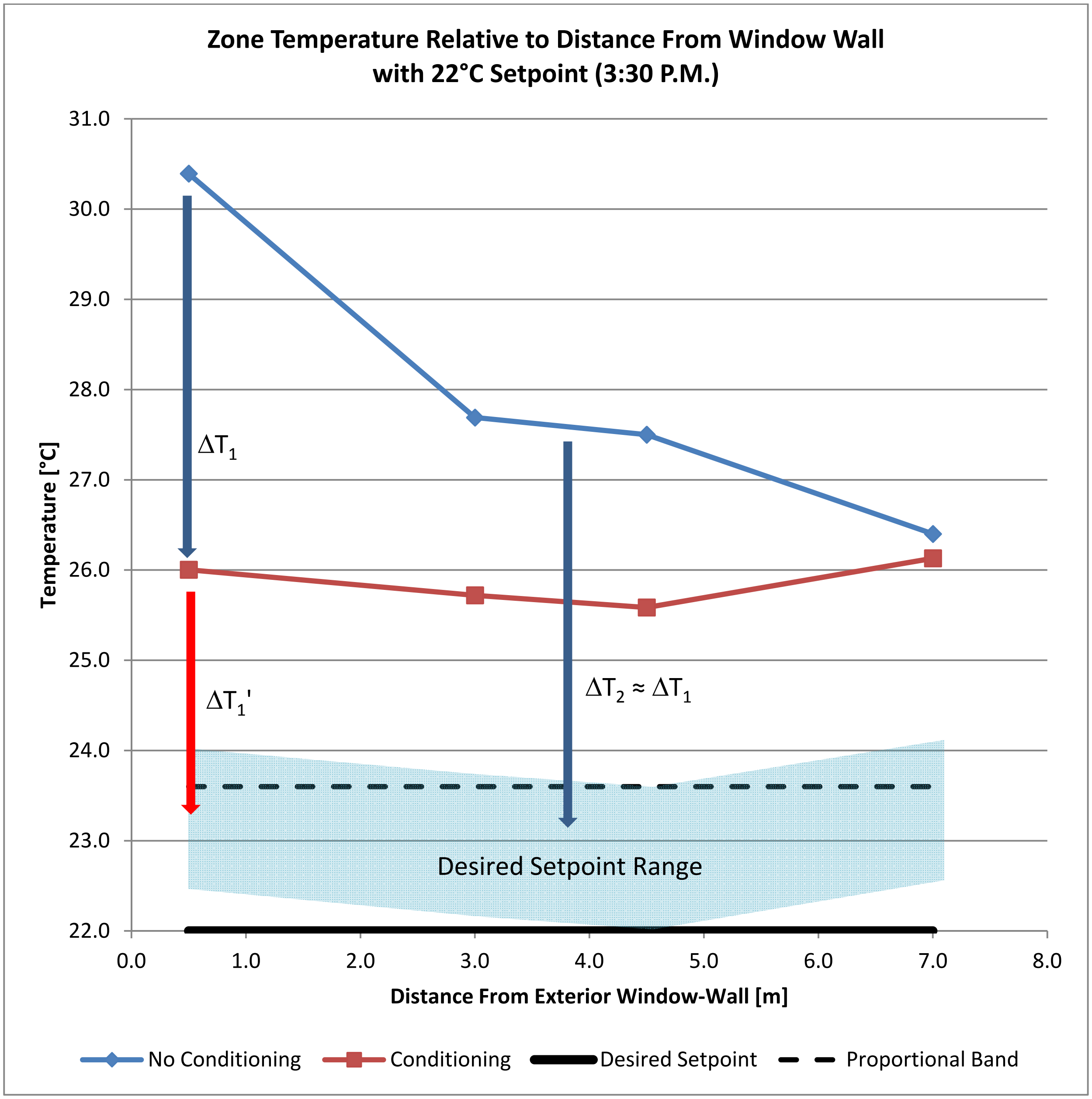


Figure 21: Impact from Thermostat Adjustment to Overcome Temperature Gradient

It can be understood that with the PWM control output, the previously mentioned short-cycling of the fan coil due to supply air interference will actually reduce energy consumption. Since the fan coil has prematurely powered OFF and it being confined to operate on a fixed number of cycles per hour, its energy consumption is limited.

However, the ability to meet desired thermal comfort within the space is also limited. So it can be expected that occupants will reduce the control setpoint further until comfort levels have been achieved in the liveable space. As presented above in *Figure 21*, this will negatively impact the energy consumption of the system and therefore provide poor overall system performance.

7. Discussion

It has been shown that placing the thermostats close to window-walls within condominium suites and ignoring the large degree of horizontal temperature gradient will lead to over-use of space conditioning systems. Additionally, it has been shown that using PWM to implement proportional-based control logic can lead to acoustic discomfort concerns and ultimately decrease terminal equipment service life. Therefore, the studied thermostat design leads to an environment where the space conditioning equipment is jeopardized in terms of system performance and lifecycle costs.

Improvement measures for such designs are available, and can be implemented to improve occupant comfort, system service life, and overall system efficiency. The proposed improvement measures are outlined below. It is expected that each measure improves areas of concern presented in this research paper, but a collaborative effort from all measures is required to address all concerns and provide the optimized design for the space.

Although not discussed in detail in this research paper, improving the thermal performance of the building envelope will improve thermal comfort and temperature consistency in a confined space in both the heating and cooling seasons [Handegord, 1995]. Further, improving the solar heat gain resistance and effective thermal resistance of the window-wall construction would reduce the sharp increases in space temperatures from solar loading that was predominant in the studied space during the cooling season analyzed [Handegord, 1995].

The timing of this research refrained from analysis occurring in the studied suite under heating conditions. Toronto is considered a heating dominated climate, and therefore consideration should be provided to what effect the identified issues with the thermostat design in cooling season would translate to during the heating season. Due to the poor thermal performance of the window-wall construction, the temperature gradient is expected to remain in the space. However, when unconditioned, the exterior window-wall perimeter will suffer from low temperatures rather than high temperatures as logged during the cooling season. However, it is believed that the gradient will remain relatively constant throughout the day and not to experience sharp fluctuations from solar loading as was observed during the cooling season. The negative effects of implementing the P+I control logic through PWM will remain unchanged during the heating season. However, the number of complete cycles is programmed to increase to eight in heating mode versus the six analysed when in cooling mode. This is expected to lead to an increased level of acoustic discomfort as the fan coil will be cycled on an increased frequency per hour.

7.1. Optimized Thermostat Placement

The analysis and discussion presented in this paper have shown that the existing thermostat placement is not ideal, and can be relocated to improve thermal comfort and system efficiency. Referring to the manufacturer guidelines for installation of the sampled thermostat, there are specific guidelines recommended during installation. The applicable clauses from the guidelines are provided below verbatim from the manufacturer installation documentation [Honeywell, 2005]. All applicable recommendations are violated by the existing thermostat location in the sampled suite.

Do not mount device where it can be affected by:

- *Drafts or dead spots behind doors or in corners*
- *Hot or cold air from ducts*
- *Radiant heat from the sun or appliances*
- *Unheated (uncooled) areas such as an outside wall behind the thermostat*

Following these manufacturer recommendations during the installation will have the thermostat optimally located within the core space of the suite. A core space location will not only ensure these manufacturer guidelines are followed, it will minimize direct solar loading to avoid biased space temperature readings by the controller. Further, relocating the existing thermostat to core space of the suite will ensure the desired setpoint is achieved within the livable space.

However, as presented in *Figure 21* the energy consumed by the fan coil is expected to increase as it is forced to overcome the high temperatures along the perimeter space of the suite to reduce the space temperatures in the core space to setpoint. Additionally, the thermal and acoustic comfort concerns within the space are expected to remain as the biased location of the fan coil system in the suite still inflicts a large temperature gradient, and the existing proportional-based control logic is still in operation. It is clear that additional improvement measures in these areas are required. Nonetheless, relocating the thermostat away from the exterior window-wall and into the core space of the suite is a key redesign measure recommended.

7.2. Thermostat Control Logic Revision

Minimizing acoustic comfort concerns for occupants in the space could be obtained through a better choice of thermostat control logic implementation coupled with relocating the thermostat away from the supply air duct to eliminate short-cycling. Opting for a thermostat with simple ON/OFF control logic and an appropriate deadband selection would reduce the number of ON/OFF cycles inflicted on the fan coil unit, subsequently reducing acoustic comfort concerns. Given that the existing controller cycles the fan coil on a fixed number of cycles per hour regardless of magnitude of conditioning load, the control deadband feature in a simple ON/OFF thermostat will reduce cycles to times when temperatures are at the limit of desired comfort and therefore only at required times. The temperatures within the core space of the suite have been shown to be more stable than those along the perimeter space, and therefore following the first design improvement measure of relocating the thermostat to the core space is expected to further minimize fan coil cycling in maintaining the desired setpoint.

An appropriate deadband value is subject to debate and will be dependent on personal occupant comfort in the space. Increasing the deadband will reduce the frequency of fan coil cycles in the space and lead to improved acoustic comfort in the space and increased service life of the fan coil system. However, a large temperature deadband will also increase the risk of thermal discomfort as the space temperature is allowed to float within a wider range prior to fan coil activation. Therefore, revising the thermostat control logic to a simple ON/OFF algorithm can reduce acoustic discomfort and extend system component service life, but will require further system design changes to help minimize thermal discomfort in the space.

7.3. Fan Coil Supply and Return Air Redistribution

Building upon the design improvement measures discussed above, to complete the optimized design by improving both energy efficiency and thermal comfort in the space, the supply and return air must be redistributed away from the perimeter and into the core space of the suite. This will eliminate the need for the fan coil to overcome the harsh environment within the immediate perimeter zone to meet desired setpoint in the livable space of the suite. As well, return air will be closer to the average space temperature and not the extreme temperatures along the exterior window-wall.

Relocating both the supply air duct and thermostat within the core space of the suite will provide a significant improvement to existing conditions, but will also then be susceptible to control feedback interference as outlined with the existing design. This can best be overcome by utilizing the available thermostat option of having the temperature sensor mounted within the return air duct. This will ensure complete isolation from any direct supply air interference in the small condominium suite and also provide a much better average temperature to complete the control feedback loop. Subsequently, combining all measures presented the fan coil will only be cycled when the average livable space temperatures call for conditioning, and ensure that desired setpoint is achieved in the livable space of the suite.

7.4. Expected Temperature Gradient Profile

It is obviously difficult to predict exactly how the proposed improvement measures will perform in the sampled condominium suite, and subsequently those of similar design. Nonetheless, the revised thermostat placement and control logic will ensure that the desired setpoint will be reached in the livable space of the suite. The perimeter zones of a given suite are still expected to fluctuate as they are directly influenced by the exterior conditions and the corridor MUA operation respectively. However, the overall temperature gradient within the suite will now pivot relative to the core livable space of the suite rather than the extreme perimeter space. This will result in improved thermal comfort by reducing the overall temperature gradient across the space.

Figure 22 presents the expected temperature profile resulting during the cooling season from the implementation of the above design measures for the sampled condominium suite. Under cooling conditions, it is obvious that increasing the desired setpoint will result in more energy efficient system operation. This is no different than the existing system design. However, the proposed design measures will ensure a more balanced temperature gradient within the suite. This eliminates the need to over-condition the extreme conditions in the perimeter space, which will increase the fan coil system efficiency and decrease system loading. These effects are expected to improve the system energy efficiency regardless of desired setpoint within the space.

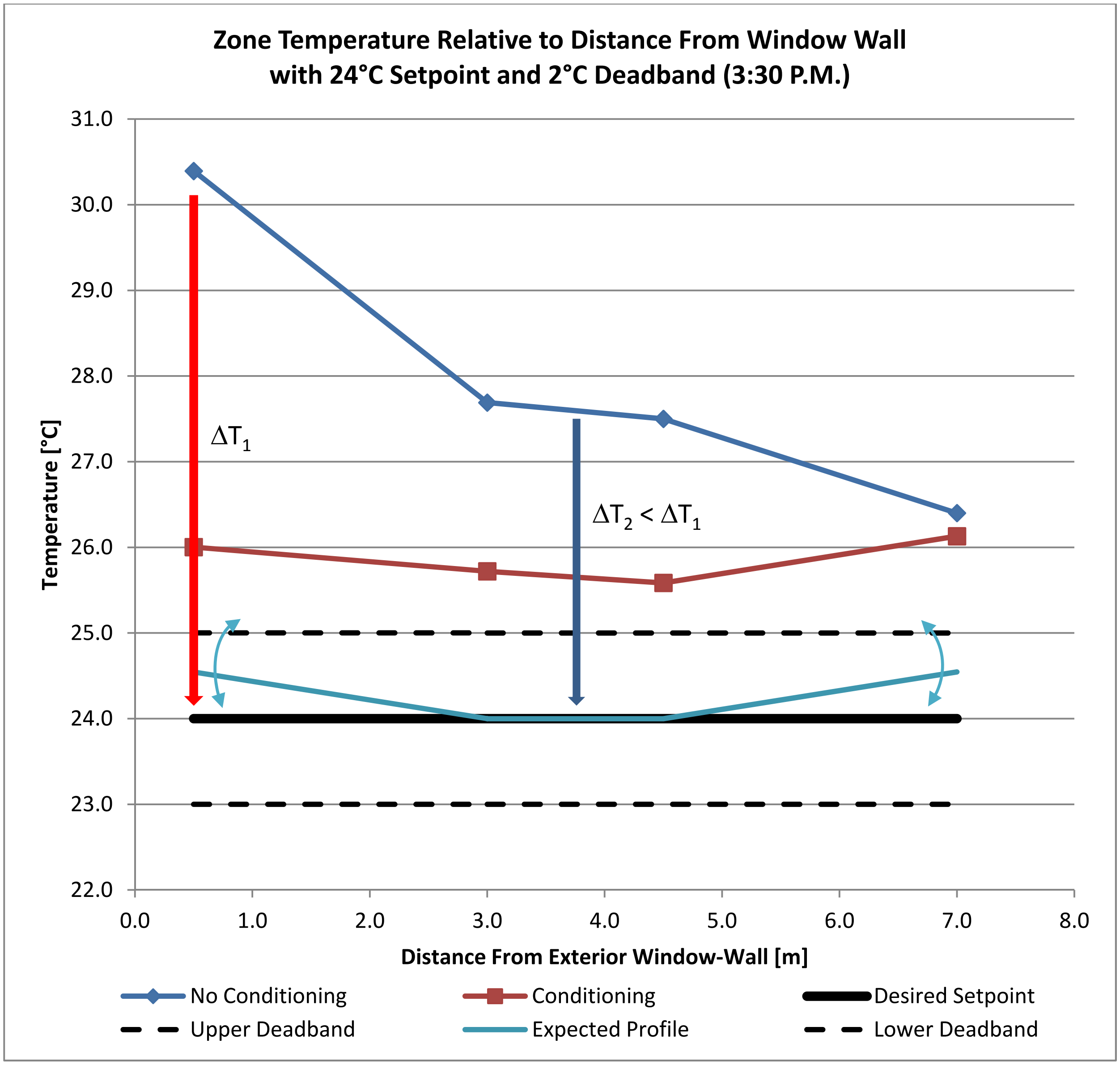


Figure 22: Optimized Temperature Profile Expected Under Proposed Design Change

The high-level calculation below estimates that the revised temperature gradient profile resulting from the proposed improvement measures will decrease energy associated with cooling air in the space by approximately 27% from the existing conditions. This energy reduction is associated with the lower initial air temperature existing in the core space of the suite relative to the perimeter space along the exterior window-wall.

$$Q = m_{air} C_p \Delta T = (T_{SETPOINT} - T_{INITIAL})$$

Where, Q = energy required to raise/lower air temperature in a space
m_{air} = mass of air in space
C_p = specific heat capacity of air
$\Delta T_{SETPOINT}$ = final desired temperature of air in space
$\Delta T_{INITIAL}$ = initial temperature of air in space

Therefore, Q is directly proportional to ΔT

So, for any two initial temperatures of air, $T_{INITIAL}$ and $T'_{INITIAL}$, the relative energy required to lower the temperature to a constant final desired temperature, $T_{SETPOINT}$, can be expressed as a fraction of the existing conditions.

Therefore,

$$\frac{Q'}{Q} = \frac{\Delta T'}{\Delta T} = \frac{(T_{SETPOINT} - T'_{INITIAL})}{(T_{SETPOINT} - T_{INITIAL})} = \frac{(22^{\circ}C - 27.5^{\circ}C)}{(22^{\circ}C - 30.5^{\circ}C)} = \frac{-5.5^{\circ}C}{-7.5^{\circ}C} \approx 73\ \%$$

So, the proposed improvement measures are expected to reduce energy consumption by approximately 27%.

8. Conclusion

It is understood that those designing and developing modern condominiums are focused on reducing costs upfront and often overlook simple measures to improve system performance and service life in the future. This research paper has identified issues with poor thermostat designs in a window-wall condominium suite during cooling season, and proposed system changes that can improve occupant comfort, reduce energy consumption, and increase terminal equipment service life. Further, the proposed measures can be implemented at negligible cost and no appreciable loss of aesthetic value to the interior design. This calls for specific guidelines for the control instruments of energy consuming systems and how they interact with their immediate environment and the systems they ultimately control.

9. Limitations

One major limitation of this study is that heating season measurements were not taken due to the timing of this research project. As outlined in the research paper, it is expected that similar results will be acquired during the heating season with some moderation in the extreme temperatures occurring along the perimeter zones of the condominium suite. However, heating season effects should be fully analyzed prior to any major system changes and as such, further research is required.

Additional limitations are recognized with the data acquired from a single condominium suite, and not from a group of suites representing a variety of exposures and interior floor space layouts. Developing a holistic design approach should include a wide selection of sampled suites and as such, further testing is required.

10. Future Studies

Future work can be pursued in addressing the limitations in the current research as highlighted above. Following similar methodology developed in this research project for the four annual seasons in a wide variety of modern condominium suites will allow for the development of specific guidelines for optimized placement of thermostats and fan coil air distribution. These guidelines will ensure increased occupant comfort, increased service life of space conditioning equipment, and decreased energy consumption based on the site specific characteristics of a given building design.

In Ontario, the importance of designing efficient buildings is important considering the significant growth in high-rise residential development and focus finding sources of energy and demand reduction. The purpose of this suggested future study would provide achievable guidelines for improving an overlooked facet of space conditioning design in modern window-wall condominiums.

List of References

Aragon, C., Meier, A., Peffer, T., Perry, D., Pritoni, M. (2011). *How people use thermostats in homes - A review*. Energy and Environment, 46:2529–2541, 2011.

Aragon, C., Meier, A., Peffer, T., Perry, D., Pritoni, M. (2011). *Usability of residential thermostats: Preliminary investigations*. Energy and Environment, 46:1891–1898, 2011.

ASHRAE Handbook (2005). *Fundamentals volume of the ASHRAE Handbook.* Atlanta, GA, USA.

ASHRAE Standard 55 (2010). *Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA, USA.

Canada Mortgage and Housing Corporation (CMHC) (2005). *Effects of Thermostat Setting on Energy Consumption*. Retrieved December 22, 2012, from CMHC website: www.cmhc-schl.gc.ca/odpub/pdf/63816.pdf

Darwish, M., Moukalled, F., Verma, S. (2010). *The use of CFD for predicting and optimizing the performance of air conditioning equipment*. International Journal of Heat and Mass Transfer, 54 (2011) 549–563.

Dexing, S., Jili, Z., Tianyi, Z. (2010). *Experimental study on a duty ratio fuzzy control method for fan-coil units*. Building and Environment, 46:527-534, 2011.

Energy Solutions Professionals (ESP) (2008). *Maintaining Comfort While Optimizing Energy Efficiency*. Retrieved February 11, 2012, from ESP website: http://www.energyesp.com/downloads/Impact%20of%20Adjusting%20Temperatures%20Handout%20-%20Generic.pdf

Environment Canada (2012). National Climate Data and Information Archive. Retrieved January 13, 2013, from website: http://climate.weatheroffice.gc.ca/climateData/hourlydata_e.html?Prov=ON&StationID=4003&Year=2012&Month=7&Day=21&timeframe=1

Firth, S.K., Gentry, M.I., Lomas, K.J., Shipworth, D.T., Shipworth M., Wright, A.J. (2010). *Central Heating Thermostat Settings and Timing: Building Demographics*. Building Research and Information, 38(1):50-69, 2010.

Friedman, G. (2004). *Too Hot, Too Cold: Diagnosing Occupant Complaints.* ASHRAE Journal, 1:S157-S163, 2004.

Han, S.H., Moon, J.W. (2010). *Thermostat strategies impact on energy consumption in residential buildings.* Energy and Buildings, 43:338–346, 2011.

Handegord, G., O.P., Hutcheon, N. B. (1995). *Building Science for a Cold Climate*. Natural Research Council of Canada, 1995. Printed in Canada.

Honeywell (1997). *Engineering Manual of Automatic Controls: Individual Room Control Applications*. Retrieved September 14, 2012, from Honeywell website: http://www.buildingcontrolworkbench.com/Portals/1/GrayBook/Gircauec.htm

Honeywell (2005). *T6570, T8570 Series Digital Fan-Coil Thermostats*. Retrieved February 11, 2012, from Honeywell website: https://customer.honeywell.com/resources/techlit/.../95c-10897.pdf

Itard, L., Santin, O. G., Visscher, H. (2009). *The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock*. Energy and Buildings, 41 (2009) 1223–1232

Keith, D., Love, J., Montanya, E.C. (2009). *Integrated Design and UFAD*. ASHRAE Journal, 7:S30-S40, 2009.

Kesik, T. (2011). *The Glass Condo Conundrum*. University of Toronto White Paper, November 10, 2011. Retrieved December 22, 2012, from website: http://www.cbc.ca/toronto/features/condos/pdf/condo_conundrum.pdf

Kohler, J. T., Lewis, D. C. (2009), *Two Pipe and Four Pipe Fan Coil Systems*. Retrieved September 14, 2012, from website: http://www.kohlerandlewis.com/WebPage/Technotespipe.html

Lilkendey, R.M., Siebein, G.W. (2004). *Acoustical Case Study of HVAC System in Schools.* ASHRAE Journal, 5:35-47, 2004.

Jiang, W., Liu, B., Wang, W., Zhang, J. (2011). *Energy performance comparison of heating and air-conditioning systems for multi-family residential buildings*. HVAC&R Research, 17(3):309-322, 2011.

Matthews, H.S., Meyers, R.J., Williams, E.D. (2010). *Scoping the potential of monitoring and control technologies to reduce energy use in homes*. Energy and Buildings, 42:563–569, 2010.

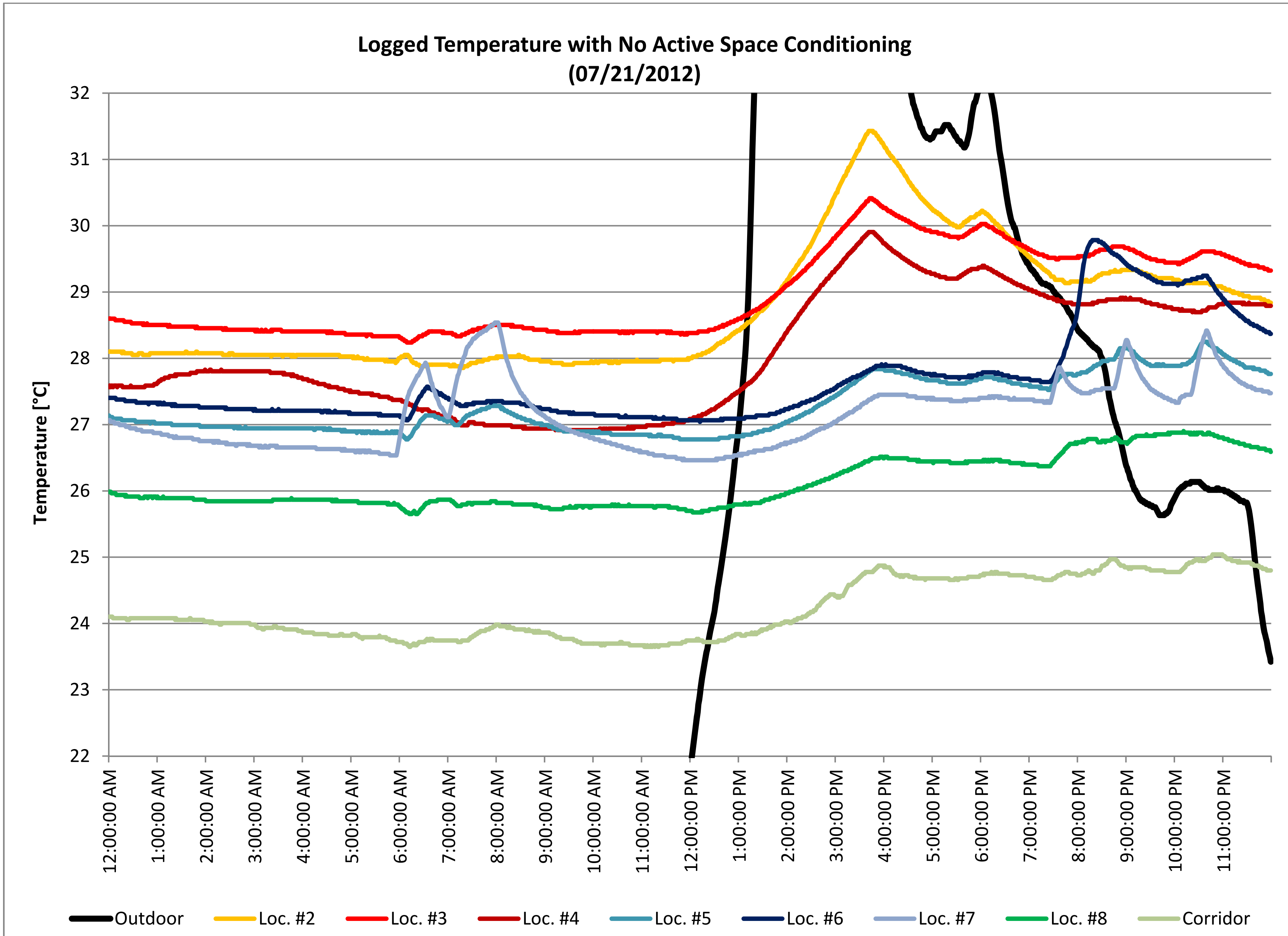
Naidu, T., Rieger, C. (2010). *Advanced control strategies for heating, ventilation, air-conditioning, and refrigeration systems — An overview: Part I: Hard control*. HVAC&R Research, 17(1):2–21, 2011.

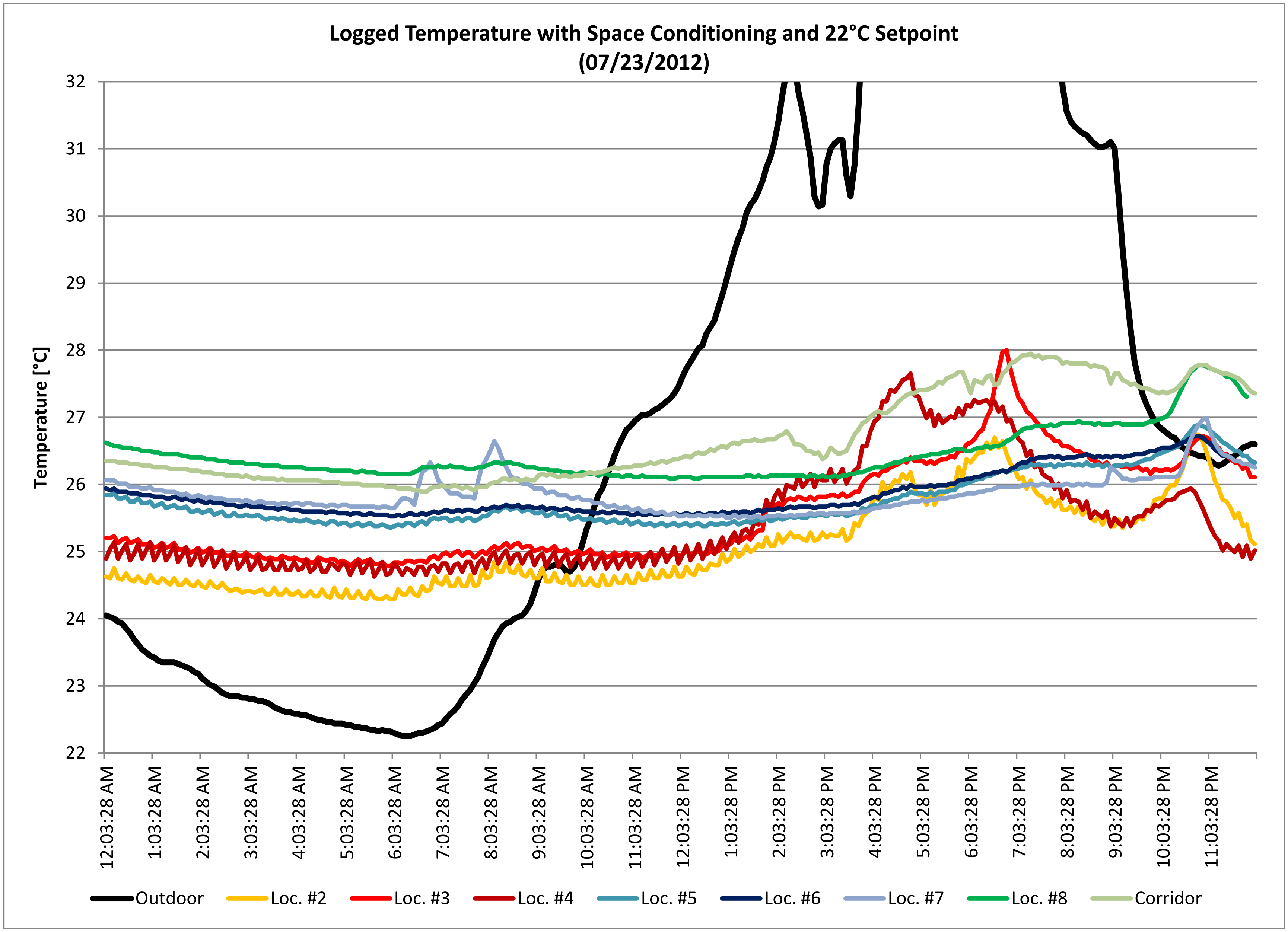
Rosandich, R. (1997). *Understanding Controllers and Control Terminology.* ASHRAE Journal, 9:22-25, 1997.

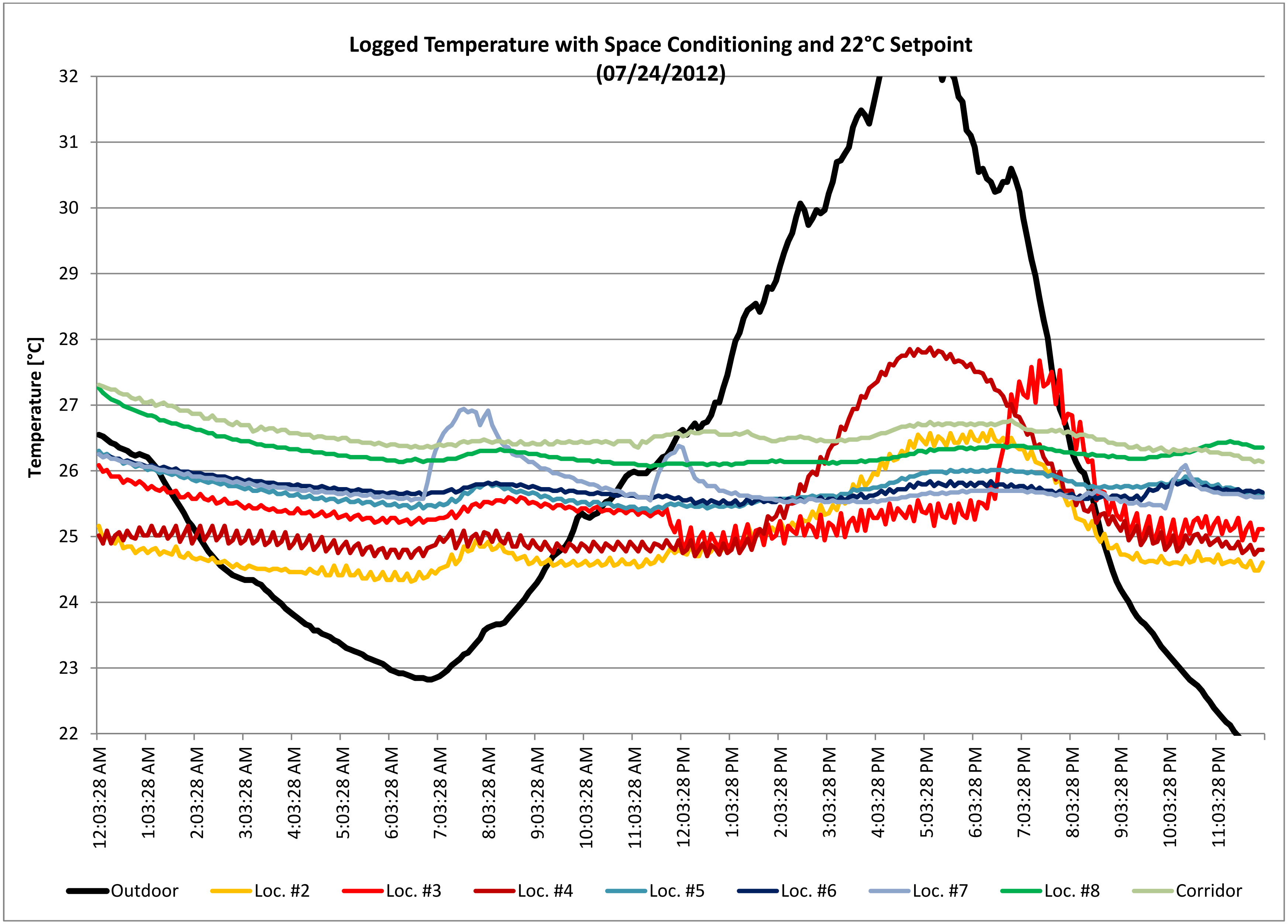
Unitronics (2002). *PID Function*. Retrieved December 18, 2012, from Unitronics website: http://www.unitronics.com/KnowledgeBase/U90Ladder/PID/PID_Function.htm

Wills, J. 2004. *Will HVAC Controls Go Wireless*. ASHRAE Journal, 7:46-52, (2004).

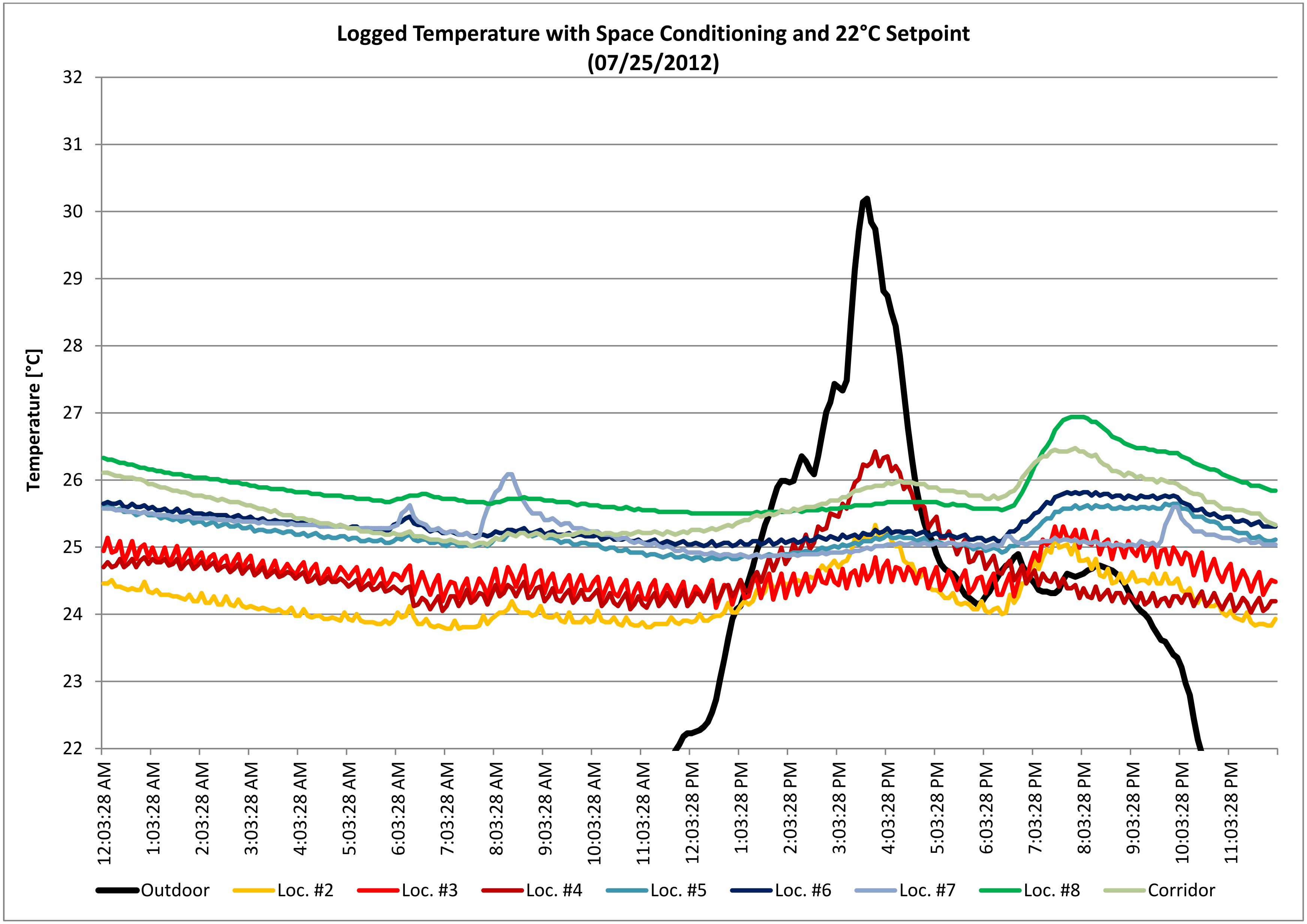
Appendix I: Temperature Profiles Collected from the Studied Condominium Suite

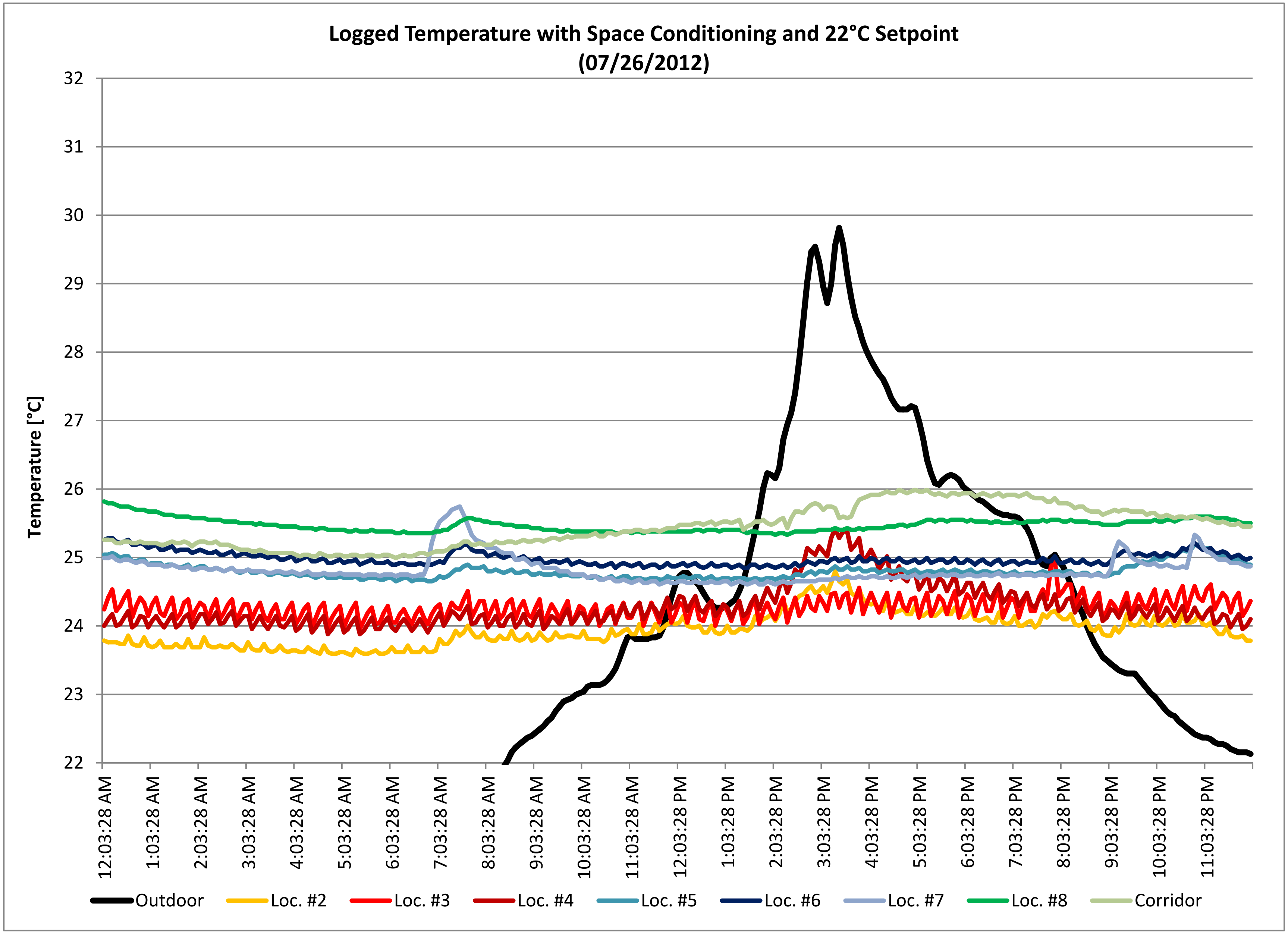

Logged Temperature with No Active Space Conditioning
(07/21/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:00:00 AM
1:00:00 AM
2:00:00 AM
3:00:00 AM
4:00:00 AM
5:00:00 AM
6:00:00 AM
7:00:00 AM
8:00:00 AM
9:00:00 AM
10:00:00 AM
11:00:00 AM
12:00:00 PM
1:00:00 PM
2:00:00 PM
3:00:00 PM
4:00:00 PM
5:00:00 PM
6:00:00 PM
7:00:00 PM
8:00:00 PM
9:00:00 PM
10:00:00 PM
11:00:00 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor

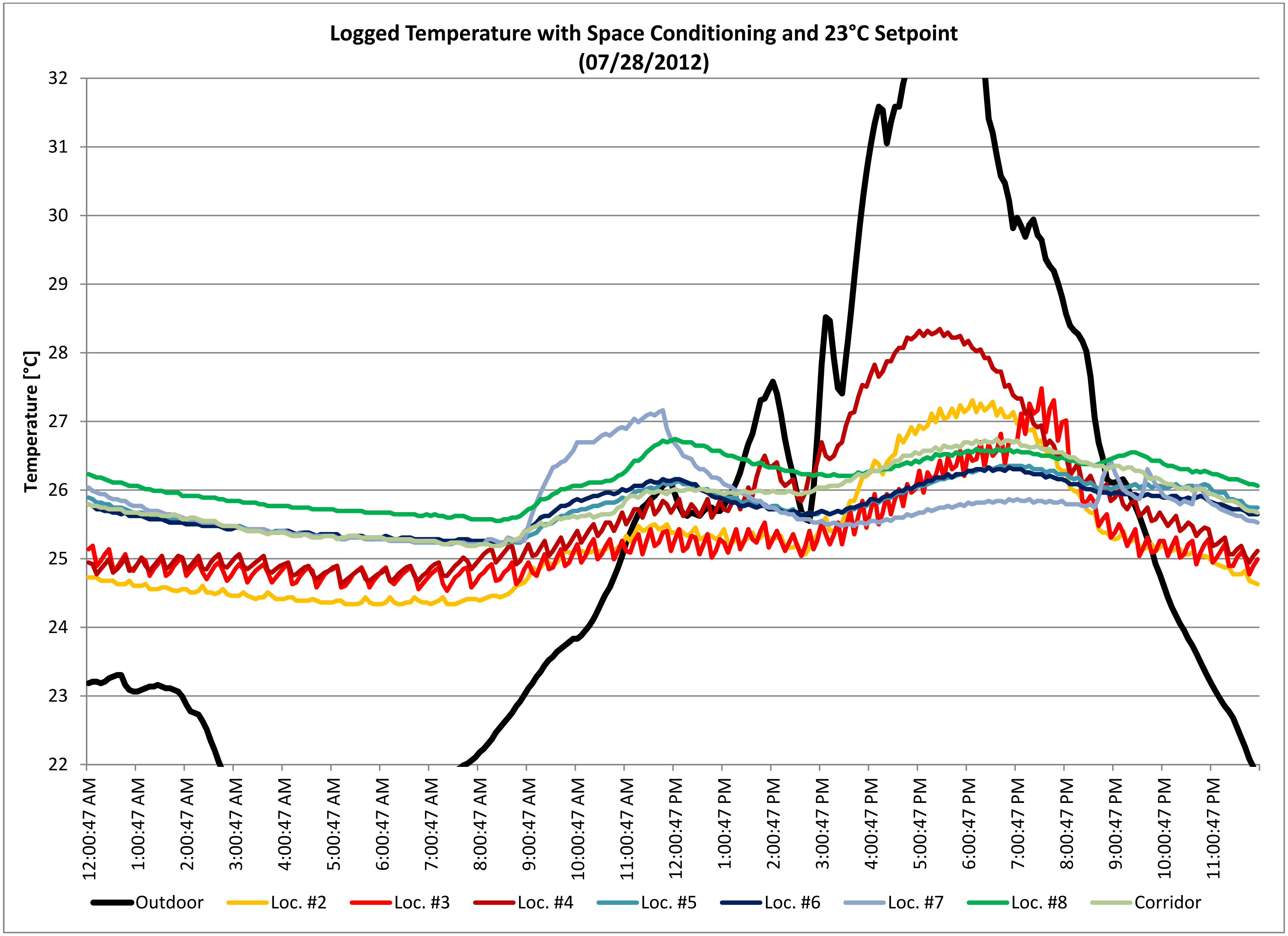

Logged Temperature with Space Conditioning and 22°C Setpoint
(07/23/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:03:28 AM
1:03:28 AM
2:03:28 AM
3:03:28 AM
4:03:28 AM
5:03:28 AM
6:03:28 AM
7:03:28 AM
8:03:28 AM
9:03:28 AM
10:03:28 AM
11:03:28 AM
12:03:28 PM
1:03:28 PM
2:03:28 PM
3:03:28 PM
4:03:28 PM
5:03:28 PM
6:03:28 PM
7:03:28 PM
8:03:28 PM
9:03:28 PM
10:03:28 PM
11:03:28 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor

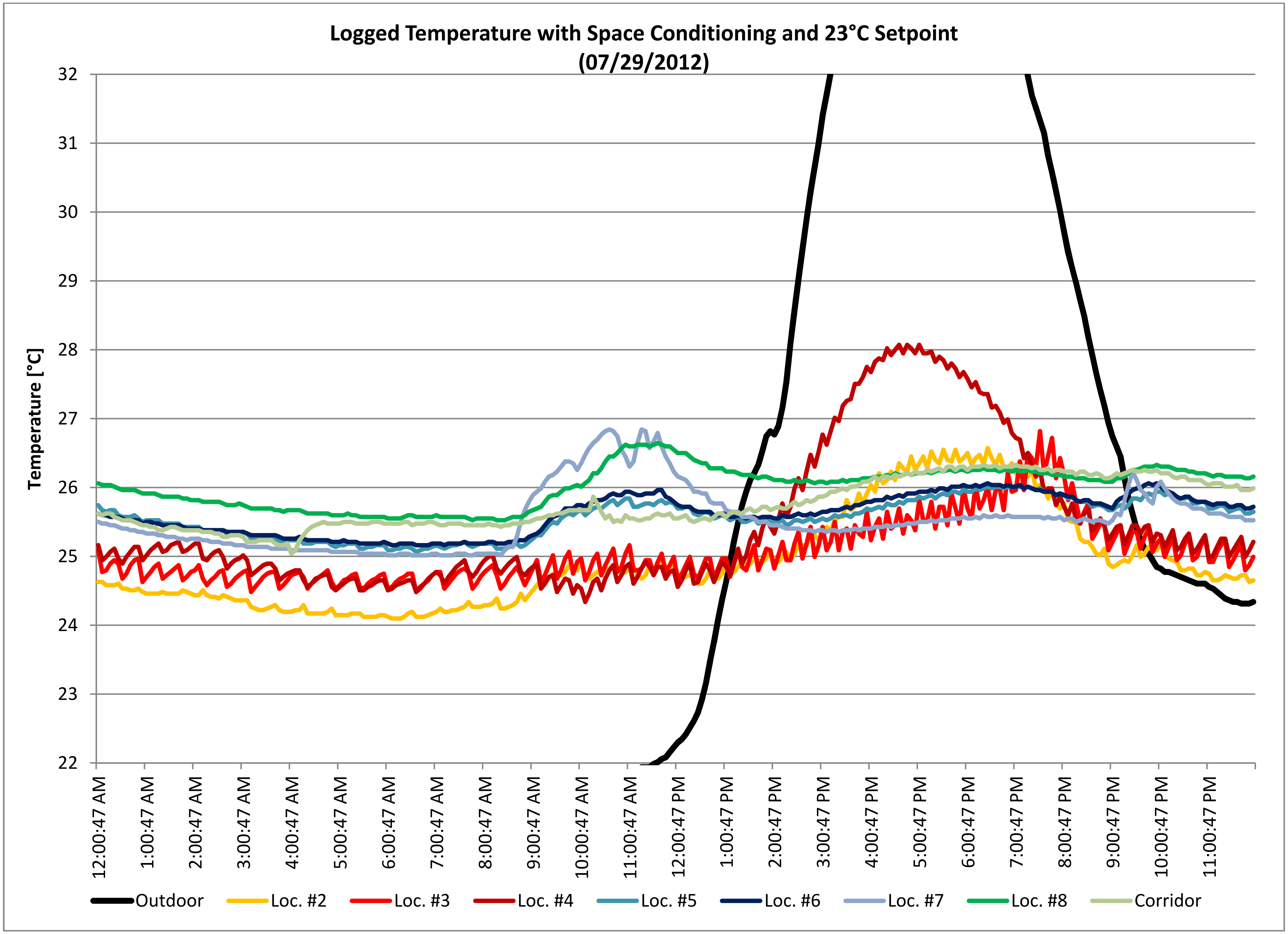


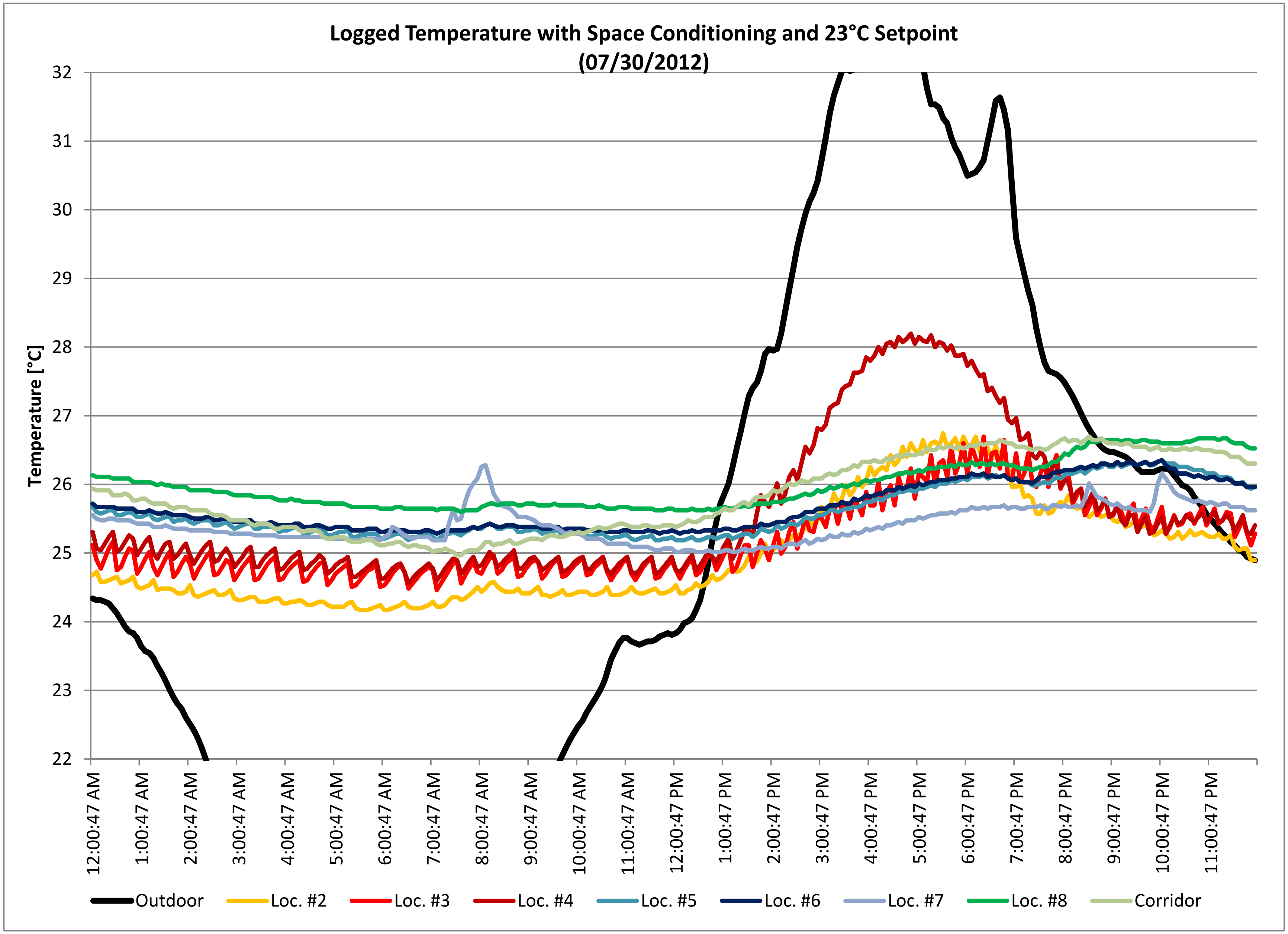
Logged Temperature with Space Conditioning and 22°C Setpoint
(07/24/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:03:28 AM
1:03:28 AM
2:03:28 AM
3:03:28 AM
4:03:28 AM
5:03:28 AM
6:03:28 AM
7:03:28 AM
8:03:28 AM
9:03:28 AM
10:03:28 AM
11:03:28 AM
12:03:28 PM
1:03:28 PM
2:03:28 PM
3:03:28 PM
4:03:28 PM
5:03:28 PM
6:03:28 PM
7:03:28 PM
8:03:28 PM
9:03:28 PM
10:03:28 PM
11:03:28 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor

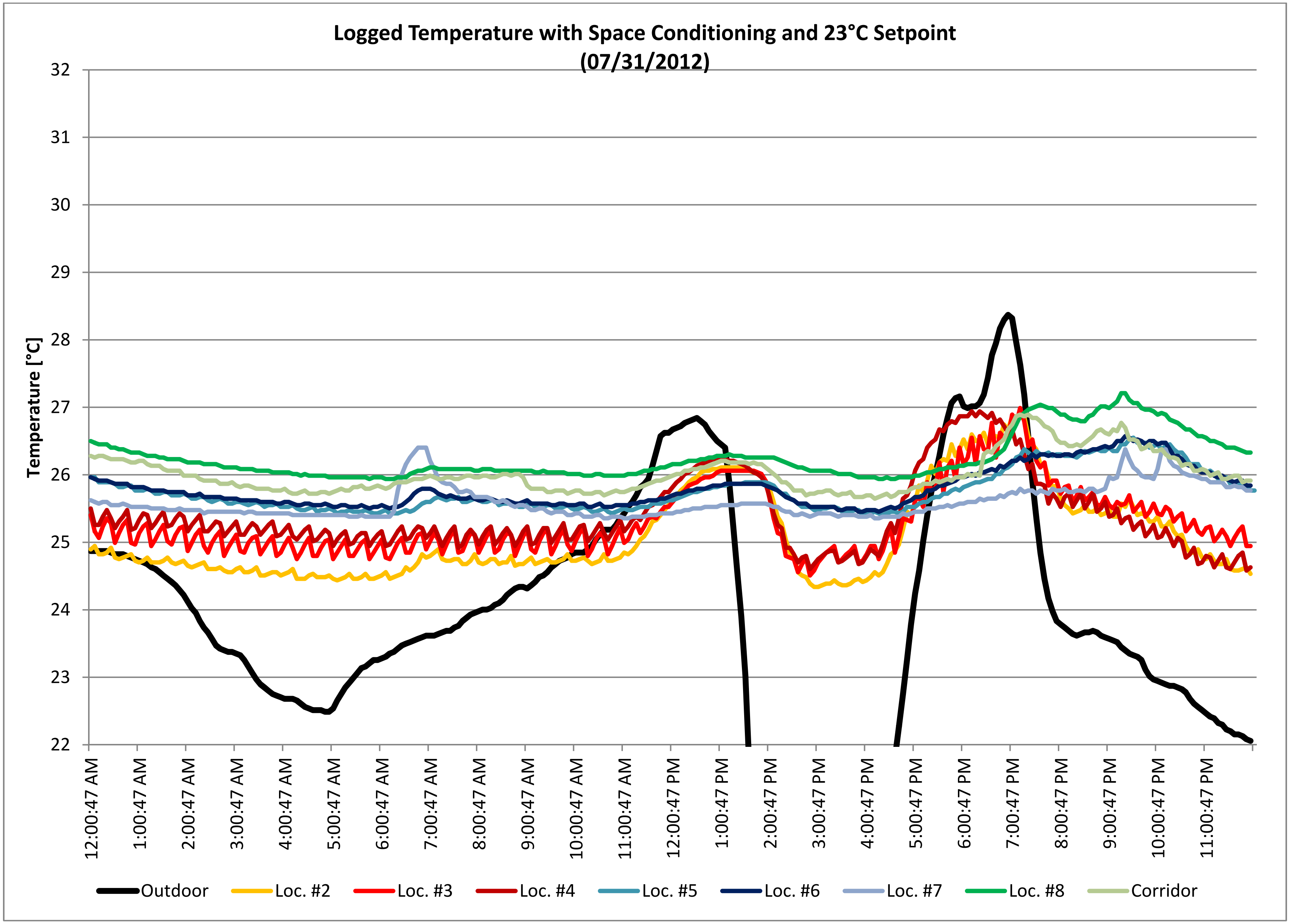

Logged Temperature with Space Conditioning and 22°C Setpoint
(07/25/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:03:28 AM
1:03:28 AM
2:03:28 AM
3:03:28 AM
4:03:28 AM
5:03:28 AM
6:03:28 AM
7:03:28 AM
8:03:28 AM
9:03:28 AM
10:03:28 AM
11:03:28 AM
12:03:28 PM
1:03:28 PM
2:03:28 PM
3:03:28 PM
4:03:28 PM
5:03:28 PM
6:03:28 PM
7:03:28 PM
8:03:28 PM
9:03:28 PM
10:03:28 PM
11:03:28 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor


Logged Temperature with Space Conditioning and 22°C Setpoint
(07/26/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:03:28 AM
1:03:28 AM
2:03:28 AM
3:03:28 AM
4:03:28 AM
5:03:28 AM
6:03:28 AM
7:03:28 AM
8:03:28 AM
9:03:28 AM
10:03:28 AM
11:03:28 AM
12:03:28 PM
1:03:28 PM
2:03:28 PM
3:03:28 PM
4:03:28 PM
5:03:28 PM
6:03:28 PM
7:03:28 PM
8:03:28 PM
9:03:28 PM
10:03:28 PM
11:03:28 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor


Logged Temperature with Space Conditioning and 23°C Setpoint
(07/28/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:00:47 AM
1:00:47 AM
2:00:47 AM
3:00:47 AM
4:00:47 AM
5:00:47 AM
6:00:47 AM
7:00:47 AM
8:00:47 AM
9:00:47 AM
10:00:47 AM
11:00:47 AM
12:00:47 PM
1:00:47 PM
2:00:47 PM
3:00:47 PM
4:00:47 PM
5:00:47 PM
6:00:47 PM
7:00:47 PM
8:00:47 PM
9:00:47 PM
10:00:47 PM
11:00:47 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor


Logged Temperature with Space Conditioning and 23°C Setpoint
(07/29/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:00:47 AM
1:00:47 AM
2:00:47 AM
3:00:47 AM
4:00:47 AM
5:00:47 AM
6:00:47 AM
7:00:47 AM
8:00:47 AM
9:00:47 AM
10:00:47 AM
11:00:47 AM
12:00:47 PM
1:00:47 PM
2:00:47 PM
3:00:47 PM
4:00:47 PM
5:00:47 PM
6:00:47 PM
7:00:47 PM
8:00:47 PM
9:00:47 PM
10:00:47 PM
11:00:47 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor


Logged Temperature with Space Conditioning and 23°C Setpoint
(07/30/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:00:47 AM
1:00:47 AM
2:00:47 AM
3:00:47 AM
4:00:47 AM
5:00:47 AM
6:00:47 AM
7:00:47 AM
8:00:47 AM
9:00:47 AM
10:00:47 AM
11:00:47 AM
12:00:47 PM
1:00:47 PM
2:00:47 PM
3:00:47 PM
4:00:47 PM
5:00:47 PM
6:00:47 PM
7:00:47 PM
8:00:47 PM
9:00:47 PM
10:00:47 PM
11:00:47 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor


Logged Temperature with Space Conditioning and 23°C Setpoint
(07/31/2012)
Temperature [°C]
32
31
30
29
28
27
26
25
24
23
22
12:00:47 AM
1:00:47 AM
2:00:47 AM
3:00:47 AM
4:00:47 AM
5:00:47 AM
6:00:47 AM
7:00:47 AM
8:00:47 AM
9:00:47 AM
10:00:47 AM
11:00:47 AM
12:00:47 PM
1:00:47 PM
2:00:47 PM
3:00:47 PM
4:00:47 PM
5:00:47 PM
6:00:47 PM
7:00:47 PM
8:00:47 PM
9:00:47 PM
10:00:47 PM
11:00:47 PM
Outdoor
Loc. #2
Loc. #3
Loc. #4
Loc. #5
Loc. #6
Loc. #7
Loc. #8
Corridor

Appendix II: HOBO® U12 Temp/RH/Light/External Data Logger

HOBO® U12 Temp/RH/Light/
External Data Logger
(Part # U12-012)

Thank you for purchasing a HOBO data logger. With proper care, it will give you years of accurate and reliable measurements.

The HOBO U12 Temperature/Relative Humidity/Light/External Data Logger is a four-channel logger with 12-bit resolution and can record up to 43,000 measurements or events. The external channel accepts a variety of sensors, including temperature, and split-core AC current sensors as well as 4-20 mA and voltage input cables (sold separately). The logger uses a direct USB interface for launching and data readout by a computer.

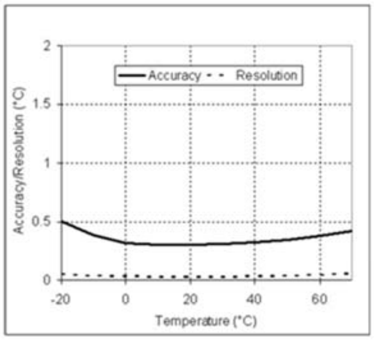
An Onset software starter kit is required for logger operation. Visit www.onsetcomp.com for compatible software.

Inside this package:

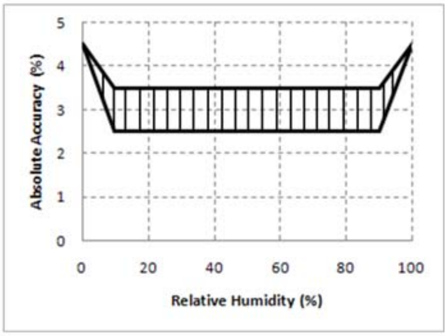
- HOBO U12 Temp/RH/
  Light/External Data Logger
- Mounting kit with magnet, hook and loop tape, tie-wrap mount, tie wrap, and two screws.

Specifications

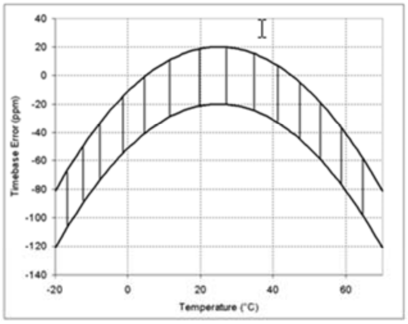
Measurement range	Temperature: -20° to 70°C (-4° to 158°F) RH: 5% to 95% RH Light intensity: 1 to 3000 footcandles (lumens/ft^2) typical; maximum value varies from 1500 to 4500 footcandles (lumens/ft^2) External input channel (see sensor manual): 0 to 2.5 DC Volts
Accuracy	Temperature: ± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F), see Plot A RH: +/- 2.5% from 10% to 90% RH (typical), to a maximum of +/- 3.5%. See Plot B. Light intensity: Designed for indoor measurement of relative light levels, see Plot D for light wavelength response External input channel (see sensor manual): ± 2 mV ± 2.5% of absolute reading
Resolution	Temperature: 0.03°C at 25°C (0.05°F at 77°F), see Plot A RH: 0.03% RH
Drift	Temperature: 0.1°C/year (0.2°F/year) RH: <1% per year typical; RH hysteresis 1%
Response time in airflow of 1 m/s (2.2 mph)	Temperature: 6 minutes, typical to 90% RH: 1 minute, typical to 90%
Time accuracy	± 1 minute per month at 25°C (77°F), see Plot C
Operating temperature	Logging: -20° to 70°C (-4° to 158°F) Launch/readout: 0° to 50°C (32° to 122°F), per USB specification
Battery life	1 year typical use
Memory	64K bytes (43,000 12-bit measurements)
Weight	46 g (1.6 oz)
Dimensions	58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).



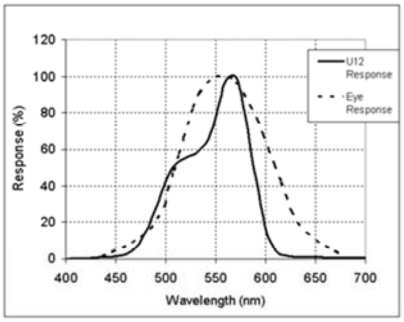
Plot A



Plot B



Plot C

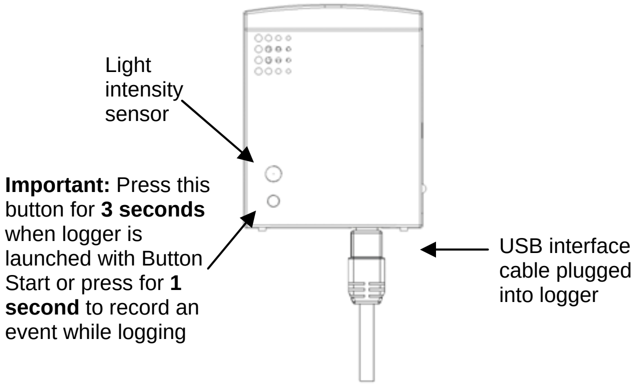


Plot D

Connecting the logger

The U-Family logger requires an Onset-supplied USB interface cable to connect to the computer. If possible, avoid connecting at temperatures below 0°C (32°F) or above 50°C (122°F).

1. Plug the large end of the USB interface cable into a USB port on the computer.
2. Plug the small end of the USB interface cable into the bottom of the logger as shown in the following diagram.



If the logger has never been connected to the computer before, it may take a few seconds for the new hardware to be detected. Use the logger software to launch and read out the logger.

Important: If you configure the logger to start with a button start, be sure to press and hold down the button on the front of the logger for at least three seconds when you want to begin logging.

If using an external sensor, be sure to plug it into the side of the logger before logging begins. Also select the correct sensor and activate the external channel in the logger software when configuring the launch.

Important: If you select an external channel, but do not plug the probe in, false data will be recorded for that channel.

You can read out the logger while it continues to log, stop it manually with the software, or let it record data until the memory is full.

Refer to the software user’s guide for complete details on launching, reading out, and viewing data from the logger.

Sample and event logging

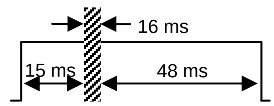
The logger can record two types of data: samples and events. Samples are the sensor measurements recorded at each logging interval (for example, the temperature every minute). Events are independent occurrences triggered by a logger activity. Examples of events recorded asynchronously during deployment include when the logger is connected to the host, when the battery is low, the end of a data file once the logger is stopped, and button pushes.

Press the button on the front of the logger for one second to record an event. Both a button up and down event will be recorded. This is useful if you want to mark the datafile at a particular point. For example, if the logger is located in an incubator, you might press the button each time the door is opened.

The logger stores 64K of data, and can record up to 43,000 samples and events combined.

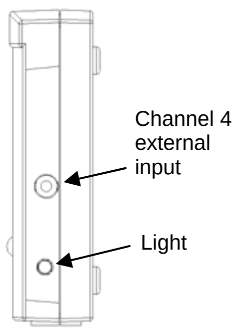
Using external sensors

The external input channel has a switched 2.5 V output. This signal can be used to power a sensor directly or it can also be used to trigger an external circuit. An external sensor should draw no more than 4 mA total when powered. The switched 2.5 V output turns on about 15 ms before the external channel is measured and stays powered for 48 ms after it is measured, as shown in the following diagram. The striped bar shows the 16 ms period during which the logger samples the input signal.



Operation

A light (LED) on the side of the logger confirms logger operation.



The following table explains when the logger blinks during logger operation.

When:	**The light:**
The logger is logging	Blinks once every one to four seconds (the shorter the logging interval, the faster the light blinks); blinks when logging a sample
The logger is awaiting a start because it was launched in Start At Interval, Delayed Start, or Button Start mode	Blinks once every eight seconds until launch begins
The button on the logger is being pushed for a Button Start launch	Blinks once every second while pressing the button and then flashes rapidly once you release the button. The light then reverts to a blinking pattern based on the logging interval

Using the RH sensor

In order to take humidity measurements, the temperature sensor must be used in conjunction with the RH sensor.

Conditions outside the recommended range may offset the RH signal. Vapors may also affect the RH sensor. The diffusion of chemicals into the sensor may cause a shift in both offset and sensitivity. High levels of pollutants may cause permanent damage to the sensor.

Upon returning to normal conditions, the RH sensor will slowly return towards calibration state by itself. However, prolonged exposure to extreme conditions may accelerate aging and eventually lead to a permanent shift. To recondition the sensor, do the following:

1. Remove the battery
2. Warm 24 hours 80–90°C (176–194°F) at < 5% RH
3. Re-hydrate 48 hours 20–30°C (70–90°F) at 75–95% RH

Protecting the logger

The logger can be permanently damaged by corrosion if it gets wet. Protect it from condensation. If it gets wet, remove the battery immediately and dry the circuit board with a hair dryer before reinstalling the battery. Do not let the board get too hot. You should be able to comfortably hold the board in your hand while drying.

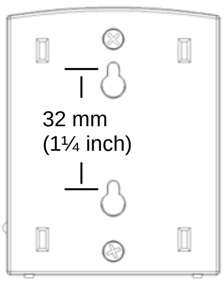
Note! Static electricity may cause the logger to stop logging. To avoid electrostatic discharge, transport the logger in an anti-static bag, and ground yourself by touching an unpainted metal surface before handling the logger. For more information about electrostatic discharge, visit http://www.onsetcomp.com/Support/support.html.

Mounting

There are four ways to mount the logger using the materials in the mounting kit included with the logger.

- Use the hook and loop tape to affix the logger to a surface.
- Attach the magnet and then place the logger on a magnetic surface.
- Use the tie wrap and tie wrap mount to tie the logger to an object.
- Fasten the logger to a surface with the two Phillips-head screws.

The back of the logger has two inserts for the screws, 32 mm (1¼ inches) apart.



Battery

The logger requires one 3-Volt CR-2032 lithium battery. Expected battery life varies based on the temperature and the frequency at which the logger is recording data (the logging interval). A new battery will typically last one year with logging intervals greater than one minute. Deployments in extremely cold or hot temperatures or logging intervals faster than one minute may significantly reduce battery life.

To replace the battery:

1. Disconnect the logger from the computer.
2. Unscrew the logger case.
3. Lift the circuit board and carefully push the battery out with a small blunt instrument, or pull it out with your fingernail.
4. Insert a new battery, positive side facing up.
5. Carefully realign the logger case and re-fasten the screws.

⚠ **WARNING:** Do not cut open, incinerate, heat above 85°C (185°F), or recharge the lithium battery. The battery may explode if the logger is exposed to extreme heat or conditions that could damage or destroy the battery case. Do not dispose of the logger or battery in fire. Do not expose the contents of the battery to water. Dispose of the battery according to local regulations for lithium batteries.

Part #: MAN-U12-012, Doc #: 7661-C

Appendix III: HOBO® U12 4-External Channel Data Logger

HOBO® U12 4-External Channel Data Logger (Part # U12-006)

Inside this package:

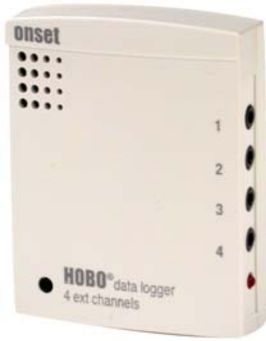
- HOBO U12 4-External Channel Data Logger
- Mounting kit with magnet, hook and loop tape, tie-wrap mount, tie wrap, and two screws.

Doc # 13125-B,
MAN-U12006-web
Onset Computer Corporation

Thank you for purchasing a HOBO data logger. With proper care, it will give you years of accurate and reliable measurements.

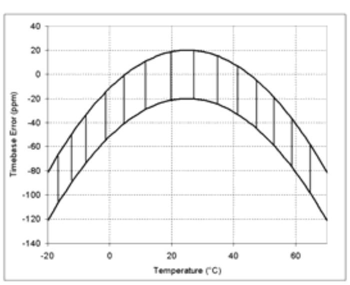
The HOBO U12 4-External Channel data logger has a 12-bit resolution and can record up to 43,000 measurements or events. The four external channels accept a wide range of Onset and third-party sensors/transducers with a 0-2.5 VDC output, including external temperature, AC current, pressure, air velocity, and kW sensors. Specifications for Onset sensors can be found at www.onsetcomp.com or by contacting your Onset Authorized Dealer. For 0-5 VDC, 0-10 VDC, or 4-20mA output, use optional Onset Part No. CABLE-ADAP5, CABLE-ADAP10, or CABLE-4-20mA respectively.

The logger uses a direct USB interface for launching and data readout by a computer. Onset software is required for logger operation. Visit www.onsetcomp.com for details.



Specifications

Measurement range	External input channels (see sensor manual): 0 to 2.5 VDC; 0 to 5 VDC (with CABLE-ADAP5) and 0 to 10 VDC (with CABLE-ADAP10)
Accuracy (logger only)	± 2 mV ± 2.5% of absolute reading ± 2 mV ± 1% of reading for logger-powered sensors
Resolution	0.6 mV
Time accuracy	± 1 minute per month at 25°C (77°F), see Plot A
Operating range	-20 to 70°C (-4° to 158°F)
Operating temperature	Logging: -20° to 70°C (-4° to 158°F) Launch/readout: 0° to 50°C (32° to 122°F), per USB specification
Humidity range	0 to 95% RH, non-condensing
Battery life	1 year typical use (see "Battery" details on next page)
Memory	64K bytes (43,000 12-bit measurements)
Weight	46 g (1.6 oz)
Dimensions	58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).



Plot A

4-20mA input cable

This cable (part number CABLE-4-20mA) measures current from 0 to 20.1 mA. Do not expose to current above 20 mA or to negative current. Do not cut off the end of the gray cable where it connects to the blue and yellow wires, as it contains the precision resistor required for current measurement.

Voltage input cable

The logger's external inputs can accept the voltage input cable (Onset part number CABLE-2.5-STEREO), which allows a voltage to be recorded. The input line must not be exposed to signals below 0 V or above 2.5 V.

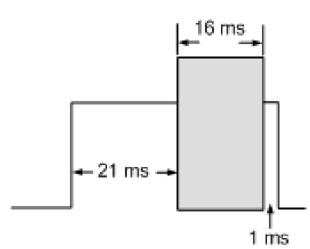
Voltage Input Cable Connections

Wire	Connection
Red	Switched 2.5 V output
White	Voltage input
Black	Ground

Switched 2.5 V output

The external input channels have a switched 2.5 V output. This signal can be used to power a sensor directly, or it can be used to trigger an external circuit. External sensors should draw no more than 4 mA total when powered.

The switched 2.5 V output turns on about 21 ms before the external channels are measured and stays powered for 1 ms after the external channels are measured, as shown in the diagram. The striped area shows the 16 ms period during



which the logger samples the input signals.

When using multiple voltage and/or current inputs, the (-) from your current source(s) and the 0 V line of your voltage source(s) are tied together at the logger. If these lines are at different voltage potentials, this may cause inaccurate readings or even damage your logger. Keep in mind that these lines may also be tied to earth ground through your PC interface cable when connected to your computer. Special precautions may be necessary if any of your voltage or current source common lines are not tied to earth ground. Input isolators may be needed in industrial environments to prevent errors caused by ground loops.

CAUTION: Analog channel input cannot exceed 2.5 VDC. For sensor outputs up to 10 VDC, use appropriate voltage adapter cable.

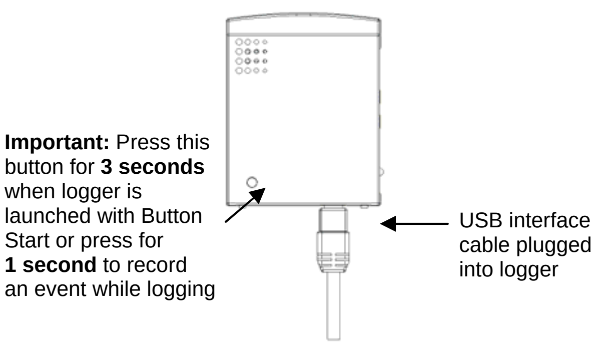
Other external sensors

Onset has a range of external temperature sensors, AC current sensors, and cables for incorporating other sensors that are compatible with the U12 4-External Channel Data Logger. Measurement specifications for using Onset temperature and AC current sensors with this logger are provided in the sensor manuals. Visit www.onsetcomp.com for details on compatible sensors.

Connecting the logger

The U-Family logger requires an Onset-supplied USB interface cable to connect to the computer. If possible, avoid connecting at temperatures below 0°C (32°F) or above 50°C (122°F).

1. Plug the large end of the USB interface cable into a USB port on the computer.
2. Plug the small end of the USB interface cable into the bottom of the logger, as shown in the following diagram.



If the logger has never been connected to the computer before, it may take a few seconds for the new hardware to be detected. Use the logger software to launch and read out the logger.

Important: If you configure the logger to start with a button start, be sure to press and hold down the button on the front of the logger for at least three seconds when you want to begin logging data.

Be sure to plug the external sensors into the side of the logger before logging begins. Also select the correct sensors and activate the external channels in the logger software when configuring the launch. **Important: If you select an external channel, but do not plug the probe in, false data will be recorded for that channel.**

You can read out the logger while it continues to log, stop it manually with the software, or let it record data until the memory is full.

Refer to the software user's guide for complete details on launching, reading out, and viewing data from the logger.

Protecting the logger

The logger can be permanently damaged by corrosion if it gets wet. Protect it from condensation. If it gets wet, remove the battery immediately and dry the circuit board with a hair dryer before reinstalling the battery. Do not let the board get too hot. You should be able to comfortably hold the board in your hand while drying.

Note! Static electricity may cause the logger to stop logging. To avoid electrostatic discharge, transport the logger in an anti-static bag, and ground yourself by touching an unpainted metal surface before handling the logger. For more information about electrostatic discharge, visit our website at http://www.onsetcomp.com/Support/support.html.

Sample and event logging

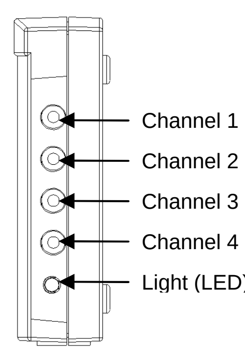
The logger can record two types of data: samples and events. Samples are the sensor measurements recorded at each logging interval (for example, the temperature every minute). Events are independent occurrences triggered by a logger activity. Examples of events recorded asynchronously during deployment include when the logger is connected to the host, when the battery is low, the end of a data file once the logger is stopped, and button pushes.

Press and hold down the button on the front of the logger for at least one second to record an event. Both a button up and down event will be recorded. This is useful if you want to mark the datafile at a particular point. For example, if the logger is located in an incubator, you might press the button each time the door is opened.

The logger stores 64K of data, and can record up to 43,000 samples and events combined.

Operation

A light (LED) on the side of the logger confirms logger operation.



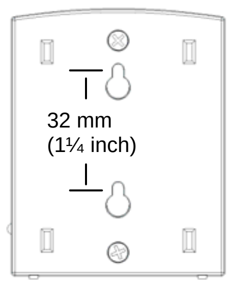
The following table explains when the logger blinks during logger operation:

When:	The light:
The logger is logging	Blinks once every one to four seconds (the shorter the logging interval, the faster the light blinks); blinks when logging a sample
The logger is awaiting a start because it was launched in Start At Interval, Delayed Start, or Button Start mode	Blinks once every eight seconds until launch begins
The button on the logger is being pushed for a Button Start launch	Blinks once every second while pressing the button and then flashes rapidly once you release the button. The light then reverts to a blinking pattern based on the logging interval

Mounting

There are four ways to mount the logger using the materials in the mounting kit included with the logger:

- Use the hook and loop tape to affix the logger to a surface.
- Attach the magnet, then place the logger on a magnetic surface.
- Use the tie wrap and tie wrap mount to tie the logger to an object.
- Fasten the logger to a surface with the two Phillips-head screws. The back of the logger has two inserts for the screws, 32 mm (1¼ inches) apart.



Battery

The logger requires one 3-Volt CR-2032 lithium battery. Expected battery life varies based on the temperature and the frequency at which the logger is recording data (the logging interval). A new battery will typically last one year with logging intervals greater than one minute. Deployments in extremely cold or hot temperatures or logging intervals faster than one minute may significantly reduce battery life. Onset recommends that you install a fresh battery before every deployment if temperatures below 0°C (32°F) are expected.

To replace the battery:

1. Disconnect the logger from the computer.
2. Unscrew the logger case.
3. Lift the circuit board and carefully push the battery out with a small blunt instrument, or pull it out with your fingernail.
4. Insert a new battery, positive side facing up.
5. Carefully realign the logger case and re-fasten the screws.

WARNING: Do not cut open, incinerate, heat above 85°C (185°F), or recharge the lithium battery. The battery may explode if the logger is exposed to extreme heat or conditions that could damage or destroy the battery case. Do not dispose of the logger or battery in fire. Do not expose the contents of the battery to water. Dispose of the battery according to local regulations for lithium batteries.

Appendix IV: Onset CTV-D 0-200A split-core AC current transformer

Onset Computer Corporation
470 MacArthur Blvd., Bourne, MA 02532
Mailing: PO Box 3450, Pocasset, MA 02559-3450
Tel: 508-759-9500, 1-800-564-4377 Fax: 508-759-9100
loggerhelp@onsetcomp.com www.onsetcomp.com

6225-E MAN-CTV

Split-core AC Current Transformer (CTV)

(AC Amperage to DC Voltage Transducer)

Doc. #: 6225-E Part #: MAN-CTV

For use with HOBO® U12 series data loggers and HOBO data nodes

		Dimensions			
Part Number	**Current Range**	Window Size	Length	Width	Height
CTV-A	0-20 AMPS AC	28 x 20 mm (1.1 x 0.8 in.)	79 mm (3.1 in.)	71 mm (2.8 in.)	36 mm (1.4 in.)
CTV-B	0-50 AMPS AC	28 x 20 mm (1.1 x 0.8 in.)	79 mm (3.1 in.)	71 mm (2.8 in.)	36 mm (1.4 in.)
CTV-C	0-100 AMPS AC	28 x 20 mm (1.1 x 0.8 in.)	79 mm (3.1 in.)	71 mm (2.8 in.)	36 mm (1.4 in.)
CTV-D	0-200 AMPS AC	39 x 32 mm (1.54 x 1.26 in.)	100 mm (3.92 in.)	120 mm (4.72 in.)	29 mm (1.14 in.)
CTV-E	0-600 AMPS AC	74 x 62 mm (2.92 x 2.46 in.)	135 mm (5.3 in.)	150 mm (5.91 in.)	28 mm (1.12 in.)

Specifications:

- Accuracy with U12: ±4.5% of full scale (includes logger accuracy)
- Accuracy with ZW: +/-4.0% of full scale (includes data node accuracy)
- Response time (from 10% to 90% of amplitude):
  - CTV-A approx. 440 milliseconds
  - CTV-B approx. 200 milliseconds
  - CTV-C approx. 100 milliseconds
  - CTV-D approx. 450 milliseconds
  - CTV-E approx. 490 milliseconds
- Input Current: AC current, sine wave, single phase 50 Hz or 60 Hz, load power factor 0.5 to 1.0 lead or lag
- Output: 0-2.5 VDC
- Voltage rating: 600 VAC.
- Temperature rating
  - CTV-A, -B, -C: -15° to +60°C (+5° to +140°F),
  - CTV-D, -E: -15°: to +40°C (+5° to +104°F)
- Construction: Molded plastic housing for indoor use per UL508
- Cable: 1.8 m (6 ft.), compatible with U12 family external inputs
- CE The CE Marking identifies this product as complying with all relevant directives in the European Union (EU)

Notice

- This product is not intended for life or safety applications.
- Do not install this product in hazardous or classified locations.
- The installer is responsible for conformance to all applicable codes.
- Mount this product inside a suitable fire and electrical enclosure.

DANGER

HAZARD OF ELECTRIC SHOCK, EXPLOSION, OR ARC FLASH

Failure to follow these instructions will result in death or serious injury.

- Follow safe electrical work practices.
- See NFPA 70E in the USA, or applicable local codes.
- This equipment must only be installed and serviced by qualified electrical personnel.
- Read, understand and follow the instructions before installing this product.
- Turn off all power supplying equipment before working on or inside the equipment.
- Use a properly rated voltage sensing device to confirm power is off.
- DO NOT DEPEND ON THIS PRODUCT FOR VOLTAGE INDICATION
- Specification Note: For CE compliance, conductor shall be insulated according to IEC 61010-1:2001, Installation Category III or equivalent. The product design provides for basic insulation only.

Using the CTV with the HOBO logger or data node

1. Insert the 2.5 mm plug of the CTV into an external input (black 2.5 mm jack) of a U12 series data logger or a ZW series data node.
2. To start the U12 logger, go to the Launch function within HOBOware® software. Use HOBOnode Manager within HOBOware for the data node. For more details on software, please refer to the software manual.
3. Select the correct AC current range in Software.

   The current range of the CTV is provided on the CTV label. Failure to select the correct range will result in inaccurate data.

   Do not exceed the AC current rating of the CTV
4. In the software for the U12 logger, be sure to enable the appropriate channel and select the range within the **Channels and Sensors** selection window. For ZW data nodes, select the sensor type (-A, -B, etc.) in the Configure Sensor pane that matches the Current Transformer model number.

Installation

- The I-bar can be hinged open in order to install the CTV around an individual wire carrying a single phase.

  1) Rotate the I-bar open (on the CTV-D and -E units, press in the I-bar tabs to open, 2) place the wire in the CTV window, 3) snap the I-bar closed.
- The I-bar on the CTV-D and CTV-E units is fully removable for easy installation. Make sure the I-bar is replaced in the proper orientation to ensure correct readings. The contacts on the unit and I-bar are marked with matching notations.
- The CTV-A, -B, and -C units are provided with a snap-on mounting plate which can be removed from the CTV and mounted separately. Mount the plate under the wire you want to monitor and, once the cable is installed into the CTV, snap the CTV/wire assembly onto the mounting plate.
- You can remove the CTV from the plate by opening the CTV and sliding it off the plate or gently rocking the CTV slightly and pulling up at the same time.