Overheating in Hot Water- and Steam-Heated Multifamily Buildings

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Overheating in Hot Water- and Steam-Heated Multifamily Buildings

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Office of Energy Efficiency and Renewable Energy

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Definitions

ARIES	Advanced Residential Integrated Energy Solutions Collaborative Building America Team
EMS	Energy management system
T_n	Neutral temperature
T_o	Outdoor temperature

Acknowledgments

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Executive Summary

The Building America program aims to develop and prove technologies that optimize the energy performance of buildings—reducing energy consumption by 30%–50% without compromising occupant comfort. Indoor thermal climate is also an important issue affecting the health and productivity of building occupants. Many steam- and hydronically heated multifamily buildings are reportedly overheated in winter due to poor boiler system controls and uneven heat distribution, which result in heating energy waste and uncomfortable interior conditions. A rigorous study measuring the extent of overheating in these building types and associated building characteristics has not been previously done.

In this project, data have been collected from the archives of companies that provide energy management systems (EMSs) to multifamily buildings in the northeastern United States. EMSs typically include temperature sensors located in apartments networked to a central controller that modulates the heating system. The collected data have been analyzed from more than 100 apartments in 18 buildings where EMSs were already installed to quantify the degree of overheating. For the purposes of this report, overheating is defined as indoor temperatures > 70°F during periods when heating is supplied. This research attempts to answer the question, "What is the magnitude of apartment overheating in multifamily buildings with central hot water or steam heat?" This report provides valuable information to researchers, utility program managers, and building owners interested in controlling heating energy waste and improving resident comfort.

Apartment temperature data were analyzed for deviations from minimum heating requirements and for variations by heating system type, apartment floor level, and ambient conditions. To quantify overheating, temperature data for more than 10% of the apartments in each building were analyzed for deviation from this set point. Information on heating system type, apartment floor level, and ambient conditions was also collected for each building. The data show that overheating is significant in these multifamily buildings with both hot water and steam heating systems.

When EMSs were inactive, average temperatures for all apartments were > 70°F in 15 of the buildings, while the other three buildings had 88% of the apartments > 70°F. Average apartment temperatures ranged from 71.8°F to 81°F with a mean of 76.3°F.

When EMSs were active, average temperatures for all apartments were > 70°F in seven of the buildings, while the other 11 buildings had 67% of the apartments > 70°F. Average apartment temperatures ranged from 70.5°F to 77.3°F with a mean of 74.2°F.

Based on this analysis, the estimated average increase in annual space heating energy costs for these buildings due to overheating is approximately 18.6% when the EMS is off, compared to a baseline average temperature of 70°F all the time.

1 Introduction

To minimize energy consumption and associated greenhouse gas emissions, researchers and practitioners employ various techniques to avoid excess energy consumption in residential and commercial buildings. In the United States, approximately 41% of all energy utilized (approximately 40,000 trillion Btu [11.7 trillion kWh]) is consumed in residential and commercial buildings (U.S. Energy Information Administration/Annual Energy Review 2010).

Of the energy consumed in U.S. buildings, approximately 50% is used for space heating. This energy consumption increases rapidly if a building is overheated. In the Northeast and Midwest, many multifamily buildings are heated by common systems using hot water or steam. According to the 2005 American Housing Survey, there are about 3.2 million occupied hydronically heated, low-rise housing units in the United States (U.S. Census Bureau, 2005). Nearly 90% of these homes are in the Northeast or Midwest, with a large portion being rental units (40%), or occupied by the elderly (24%) (U.S. Census Bureau, 2005). Most hydronically heated residences are older, with only 1% being classified as New Construction (built within the past four years) in the 2005 American Housing Survey data (U.S. Census Bureau, 2005). Typically, residents of these buildings do not pay for heat directly (i.e., heat is not submetered). Heating fuel use for these systems is reputed to be higher than necessary, given the thermal properties of the buildings. Anecdotally, a significant number of apartments are overheated much of the time (the window-as-a-thermostat syndrome) (Urban Green Council, 2010). Overheating results in an estimated increase in annual energy consumption of approximately 1% per °F over the desired temperature in a dwelling for each eight hours of the day (the percentage of energy waste is greater in milder climates than in severe climates) (U.S. Department of Energy, 2012). This savings estimate does not include any increase in energy use associated with the reported opening of windows by residents to temper discomfort caused by overheating. In the United States, controlling space hydronic and steam heating systems typically involves an outdoor reset control algorithm, possibly with different day and night space temperature targets.

The extent of overheating, and the variance of it in different parts of the building and on different days of the heating season, affects the strategy used to combat it. Generally, local laws require apartments to be heated to at least 68°F during the heating season. If overheating is shown to be similar throughout a building, reducing heat at the heating plant is a logical solution. However, most often overheating patterns are more complex, requiring zone- or apartment-specific solutions. Many older multifamily buildings, such as those addressed in this research, were built without effective zone-level controls (e.g., a thermostat and zone valve for each room or dwelling unit). Therefore, one strategy is to reduce the range between the warmest and coldest apartments by making distribution or radiator improvements, and then lowering the entire average building or zone temperature at the heating plant or zone valve.

In order to estimate overheating in multifamily residential and commercial buildings, and to relate optimum indoor temperature to outdoor air temperatures, researchers in the past have performed several theoretical and field studies. Robinson and Haldi (Robinson & Haldi 2008) proposed a mathematical model for predicting overheating risk given a set of measured or simulated environmental conditions based on an analogy between the charging and discharging of human's tolerance to overheating stimuli and that of charge in an electrical capacitor.

EME Group (EME, 1994) performed a study to determine if the installation of large-capacity air vents at the ends of steam mains and risers would economically reduce the temperature gradient between apartments and reduce the amount of space heating energy required. They conducted tests by enabling and disabling air vents biweekly in 10 multifamily buildings in New York City and compared the temperatures of selected apartments and total space heating energy during each venting regime. No difference in energy consumption between "vents on" and "vents off" periods was found. However, there was a reduction in the maximum spread of apartment temperatures.

Many researchers have used an adaptive approach to thermal comfort based on the findings of surveys of thermal comfort conducted in the field (such as those of Humphreys 1978, Humphreys & Nicol 2000, Nicol & Humphreys 2002, de Dear & Brager 2002). Humphreys established a relationship between the indoor temperatures with the outdoor mean effective temperature for naturally ventilated buildings (Humphreys, 1978),

$$\text{Optimum indoor temperature } (^\circ\text{C}) = 18.9 + 0.255 \times (\text{outdoor mean effective temperature}) \quad (1)$$

He also proposed a correlation between the neutral temperatures (T_n) against outdoor mean monthly temperatures (T_o) for air-conditioned buildings:

$$T_n = 23.9 + 29.5(T_o - 22) \times e^{-((To-22)/(24\times\sqrt{2}))2} \qquad (2)$$

where T_o is the outdoor temperature (°C).

Humphreys' equation was revised by Auliciems, who analyzed the data obtained for several other studies which included many other climate zones and more countries and considered only compatible field studies of Humphreys (Auliciems 1981, 1983). Auliciems presented the equation after analyzing the data for naturally ventilated building and air-conditioned buildings, for 53 different studies,

$$T_n = 0.48T_i + 0.14T_o + 9.22 \qquad (3)$$

In addition, Auliciems and de Dear (Auliciems & de Dear, Air conditioning in Australia I: human thermal factors, 1986) presented an equation for all types of buildings,

$$T_n = 17.6 + 0.31T_o \qquad (4)$$

For the purposes of this report, overheating is defined as indoor temperatures > 70°F during periods when heating is supplied. Nicol and Humphreys (2002) collected data in a number of countries and climate zones and found that the typical indoor comfort temperature range is 67.6°–69.8°F for a wide range of outdoor air temperatures (–4°–55°F). Therefore, additional energy spent to raise indoor temperatures above 70°F contributes to overheating buildings.

1.1 Background

At the 2011 expert meeting conducted by the Advanced Residential Integrated Energy Solutions (ARIES) Building America team[1] titled Multifamily Hydronic and Steam Heating Controls and Distribution Retrofits, the subject of how significant a factor overheating is (and how large a potential exists for energy savings by eliminating it) was debated. It was acknowledged that no rigorous analysis of the phenomenon is published (The Levy Partnership, Inc., 2011).

Building energy consumption can be reduced in several ways, including improving boiler control strategy, giving the occupant the ability to modulate the temperature according to need (instead of opening a window), and altering the distribution of heat within the building in ways that better reflect demand. ARIES currently has a project underway in this area.[2] Case studies of multifamily buildings in New York State (Allen, 2011) have shown a pattern of excessive temperatures of 80°–85°F in some apartments, while building-wide averages in the mid-70s°F imply that overheating is typically in only part of the building, for only part of the winter.

1.2 Relevance to Building America's Goals

The motivation to quantify and characterize overheating in multifamily buildings is driven by the desire to reduce overheating. Reducing overheating is relevant to Building America goals because it reduces the space heating energy consumption of the building and increases occupant comfort. Quantifying and characterizing overheating in multifamily buildings will help to reduce it by:

- Proving that the issue exists, if indeed it does, and measuring the savings opportunity
- Identifying the characteristics of multifamily buildings that are most closely associated with overheating
- Developing a baseline measurement for overheating to which improvements can be compared.

1.3 Cost Effectiveness

Because this project does not include the implementation of any retrofits, there is no direct cost analysis for this project. Indirectly, the results of this report can be used to evaluate the most cost-effective approach to retrofitting heating plants and distribution systems in multifamily buildings. Although the data currently available on the topic are largely anecdotal, they are the primary driver of the hydronic heating retrofit market. The determination of statistically relevant information would inform manufacturers and building owners on the best approach to reducing their heating energy expenditure.

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[1] Building America is a U.S. Department of Energy research program focusing on residential energy efficiency.

[2] Hydronic Heating Control Retrofits for Low-Rise Multifamily Buildings

2 Problem Description

For the purposes of this report, overheating is defined as heating to a temperature > 70°F while heating is supplied.[3]

However, it was found that indoor temperatures in many buildings were significantly higher than 70°F while boilers were in operation. Overheating can cause discomfort for residents due to the heat and excessively low humidity levels, which can have negative health consequences. Overheating also results in higher fuel consumption than necessary and increases building fuel expenses. Moreover, if residents find it too hot, they may open windows, which further exacerbates the problem.

Reducing overheating improves occupant comfort. However, different habits and preferences cannot all be accounted for, and some dissatisfaction may occur. Reducing overheating should result in a reduction of energy use, and thus a reduction on the load on the heating system, increasing the equipment's lifetime (Energystar.gov, 2013). Quantitatively understanding the heating patterns in multifamily buildings can assist owners in complying with local minimum heat ordinances and can spur owners to take action to reduce the problem. Furthermore, if it can be proven that a heating plant's output can be reduced as a result of curing overheating problems, then when heating plants are replaced, smaller systems can be installed.

In this report, we address the following research questions: (1) what is the magnitude of apartment overheating in multifamily buildings with central hot water or steam heat; and (2) what drives variation in overheating and by how much, with respect to heating system type and apartment location. Data have also been tabulated separately for periods when the energy management system (EMS) software was actively managing the energy consumption of the building versus when the EMS was only monitoring the temperature. These results are also compared.

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[3] Note that in New York City where the study buildings are located, local law requires multifamily building operators to maintain a minimum daytime (6:00 a.m. to 10:00 p.m.) indoor air temperature of 68°F (when the outside temperature is below 55°F) and a minimum nighttime indoor air temperature of 55°F (when the outside temperature is below 40°F) (NYC Department of Housing Preservation and Development).

3 Research Methods

In order to quantify overheating, data were obtained from the archives of companies that provide EMSs to multifamily buildings in the Northeast. EMSs typically include temperature sensors located in apartments networked to a central controller that modulates the heating system. In all buildings the data were acquired hourly and when boiler status changed. This resulted in a typical sampling rate of one to four temperature measurements per hour. Data were collected for time periods when the EMS control system was disabled and for periods of time when it was enabled. This procedure enabled us to quantify overheating in these buildings when the EMSs were not in operation as well as the effectiveness of the EMSs when they were in operation. Data were collected and analyzed for 18 multifamily buildings for deviations from the 70°F established above as the desired temperature. Data have been analyzed for enough apartments (a minimum of 11%, and an average of 20% per building) so that the data are representative of the entire building. Table 1 shows characteristics of the buildings considered in this study. Figure 1 shows one of the buildings in the study.

Table 1. Building Characteristics

No.	Number of Floors	Total Number of Apartments	Heating System*	Ownership Type
1	3	60	1-pipe steam	Rental
2	3	48	Hot water	Rental
3	4	36	1-pipe steam	Rental
4	4	16	1-pipe steam	Rental
5	4	12	1-pipe steam	Rental
6	4	39	1-pipe steam	Rental
7	5	21	Hot water	Rental
8	5	77	1-pipe steam	Rental
9	5	77	1-pipe steam	Co-op
10	5	202	1-pipe steam	Rental/co-op
11	6	71	Hot water	Rental
12	6	74	1-pipe steam	Rental
13	6	56	Hot water	Rental
14	6	48	1-pipe steam	Rental
15	6	26	1-pipe steam	Rental
16	6	22	1-pipe steam	Rental
17	6	34	1-pipe steam	Rental
18	6	44	1-pipe steam	Rental

* All are single zone with no apartment level controls)

Figure 1. Multifamily building used in the study

Researchers visited each building to collect information on boiler type, heater type, exposures, sensor locations, and other building characteristics. All apartments were heated with radiators (Figure 2).

Figure 2. Typical wireless temperature sensor (left) and radiator (right)

Following is a list of potential uncertainties that could affect the results and how they were addressed in the study:

- **Data are from buildings with EMSs:** Buildings with EMSs may be more efficient (i.e., have less overheating) than buildings without such a system due to the function of the EMS itself. These systems are sometimes run in passive mode after installation to obtain baseline temperature data before actively modulating the heating system, or during periods when the controls are overridden by building staff. Data recorded during these periods have been analyzed separately and compared to the data recorded during active system management.

- **Variance in reset controls settings:** While the indoor temperature averaging and cutoff function of EMSs are not designed to reduce temperature variations within a building, in a steam-heated building, its effect on shortening boiler cycles may reduce steam delivery to distant apartments in some cases. Also, because the EMSs used in these buildings had different outdoor reset control settings than the original outdoor reset boiler controllers, the comparison between EMS on and EMS off includes effects of these different control settings.

- **Sensor location within building:** Most EMSs don't require temperature sensors to be installed in every apartment. The EMS vendors from which the data have been collected typically install sensors in top floor apartments so that the building staff can confirm that all heating risers are operating properly for the full height of the building. However, a number of buildings had sensors on lower floors as well. An analysis of data by floor level shows that average temperature was not a function of floor level during the periods observed in these buildings. This is presented in more detail later in this report. Sensors located in apartments that are a long horizontal distance from the boiler room as well as the overheating of apartments directly above the boiler room could also influence these results.

- **Sensor location within apartment:** The location of the sensor within the apartment should be representative of the overall climate in the apartment. Radiation from windows and proximity to radiators and ovens can influence local temperatures. Data have been collected from buildings where sensors were in a central location distant from these conditions. Sensors were typically installed approximately 5 ft above the floor and at least 10 ft away from any window or kitchen appliances (Figure 2).

- **Local effects:** Opening windows to relieve overheating would depress temperatures and cause overheating to be underestimated, while local solar gain or the use of space heaters or other heat generating devices (electronics) near the sensors would increase apartment temperatures, potentially causing overheating to be overestimated.

- **Sensor calibration:** Best practices would call for commissioning of new EMSs by calibrating each sensor with a hand-held temperature sensor and adding adjustments to each sensor reading prior to factoring that reading into the algorithm that controls boiler operation. Temperature readings in a sample of units in each building (about 10%) were measured to confirm readings were within acceptable limits (± 1°F). In cases where the hand-held sensors varied by more than 1°F from the EMS sensor, the EMS data were adjusted (offset) accordingly.

Table 2 shows the difference between the temperatures measured by the EMS sensors and a handheld temperature sensor (TSI, model 8345) at the same time in various apartments of one building. The difference in temperature (TSI – EMS) for each apartment was added to all temperature data for that location considered in this analysis. In some apartments with EMS sensors, TSI temperature readings could not be made because of lack of access. The EMS readings in those apartments were adjusted by the average difference in temperature readings between the TSI and EMS readings for the other apartments in that building. This approach was used for all buildings.

Table 2. Difference Between TSI and EMS Temperature Readings in One Building

Apartments	1	2	3	4	5	6	Average
TSI Temperature Reading	80.3	85.3	84.3	78.4	77.5	84.7	–
EMS Temperature Reading	79	83	81	76	79	82	–
Delta (TSI – EMS)	1.3	2.3	3.3	2.4	–1.5	2.7	1.75

4 Results and Discussion

A summary of the data for the 18 buildings is provided in Table 3. The number of floors, sensor location by floor, and number of sensors in each building are provided along with average temperatures during periods when the EMS is ON and OFF.

Overheating is significant in nearly every building, even with the use of an EMS. Note that minimum temperatures in few buildings were low but for a short duration, perhaps due to open windows or vacancies. The average temperature was > 70°F in all the buildings when the EMSs were OFF. In 15 of the 18 buildings, average temperatures in all the apartments when EMSs were not in operation ranged from 70.7°F to 87.4°F and in three buildings, average temperatures in more than 88% of apartments ranged from 70.3°F to 85.2°F. Likewise, when the EMSs were on, in seven of 18 buildings, average temperatures in all the apartments were > 70°F, ranging from 70.3°F to 81.1°F. In the remaining 11 buildings, average temperatures in more than 67% of apartments were also > 70°F, ranging from 70.0°F to 81.2°F. The average temperature in overheated apartments was > 75°F in 61% of the buildings when EMSs were off and > 75°F in 33% of the building when EMSs were on.

Table 3. Building Summary Data

Building Number	Number of Floors	Number of Apartments	Sensor Location (by Floor)	Number of Apartments With Sensors	EMS Status	Range of Instantaneous Temperature (°F)	Average Temperature in All Apartments (°F)	Apartments Overheated (> 70°F)	Average Temperature in Overheated Apartments (°F)
1	3	60	1, 3	16	OFF ON	59.0–82.0 53.0–85.0	71.8 72.3	88% 94%	72.3 72.5
2	3	48	3	16	OFF N/A	57.2–90.2 –	76.8 –	100% –	76.8 –
3	4	36	4	5	OFF ON	63.4–87.6 66.0–88.4	78.7 77.3	100% 100%	78.7 77.3
4	4	16	3, 4	12	OFF ON	60.0–91.0 46.0–88.0	73.7 71.3	100% 83%	73.7 72.0
5	4	12	3, 4	3	OFF ON	69.1–87.1 69.1–95.1	75.5 75.8	100% 100%	75.5 76.1
6	4	39	3	9	OFF ON	62.0–84.0 59.0–82.0	72.3 70.5	89% 67%	72.7 71.7
7	5	21	4, 5	5	OFF ON	69.2–83.7 65.7–90.2	75.5 74.6	80% 100%	76.5 74.6
8	6	77	6	9	OFF ON	65.0–84.0 59.0–83.0	76.2 73.6	100% 89%	76.2 74.2
9	5	77	1, 4	12	OFF ON	54.0–86.0 61.0–83.0	77.9 75.0	92% 92%	78.5 75.8

Building Number	Number of Floors	Number of Apartments	Sensor Location (by Floor)	Number of Apartments With Sensors	EMS Status	Range of Instantaneous Temperature (°F)	Average Temperature in All Apartments (°F)	Apartments Overheated (> 70°F)	Average Temperature in Overheated Apartments (°F)
10	5	202	5	20	N/A ON	– 64.8–82.8	– 76.8	– 100%	– 75.2
11	6	71	6	8	OFF ON	65.5–87.5 62.5–93.5	74.3 75.9	100% 100%	74.3 75.9
12	6	74	6	10	N/A ON	– 59.0–83.0	– 72.9	– 80%	– 74.1
13	6	56	6	6	OFF ON	62.1–100 57.0–91.0	77.7 75.1	100% 83%	77.7 76.8
14	6	48	5, 6	12	OFF ON	62.8–94.7 48.8–95.7	81.0 75.1	100% 92%	81.0 75.2
15	6	26	2, 3, 4, 5	10	OFF ON	65.0–88.0 54.0–82.0	76.3 70.6	100% 70%	76.3 72.1
16	6	22	1, 2, 3, 5	13	OFF ON	59.4–89.6 62.8–95.4	79.7 75.1	100% 100%	79.2 75.0
17	6	34	6	11	OFF ON	61.0–87.0 55.0–87.0	76.7 75.4	100% 73%	76.6 73.4
18	6	44	1, 2, 3, 5, 6	15	OFF ON	66.5–86.5 63.3–90.5	77.8 75.8	100% 100%	77.6 74.1

Table 4 shows the time periods from which the temperature data were gathered for each building. The EMSs were turned on and off more than one time in some buildings. Periods of less than two days were excluded. The average temperatures in Table 4 are the averages of the average apartment temperatures within each building. The maximum, minimum, and standard deviations are the averages of those values for all apartments in the respective building.

Table 4. EMS ON/OFF Time Periods by Building

Bldg. No.	EMS Status	Time Periods	No. Days	Average	Max	Min	Std. Dev.
1	ON	10/27/2011 to 04/30/2012	186	72.3	79.4	65.1	2.0
	OFF	10/06/2011 to 10/27/2011	21	71.8	76.3	68.1	1.7
2	ON	–	0	–	–	–	–
	OFF	01/22/12 to 04/30/2012	99	76.8	87.6	65.7	3.1
3	ON	10/02/2011 to 02/09/2012 and 03/12/2012 to 04/30/2012	179	77.3	85.1	68.7	2.5
	OFF	02/09/2012 to 03/12/2012	32	78.7	84.7	68.8	3.0
4	ON	11/17/2011 to 04/21/2012	156	71.3	83.4	60.8	2.8
	OFF	04/22/2012 to 04/28/2012	6	73.7	84.8	60.3	4.7
5	ON	03/02/2012 to 05/04/2012	63	75.8	84.4	66.1	2.8
	OFF	02/26/2012 to 03/02/2012	5	75.5	82.1	70.8	2.5
6	ON	10/31/2011 to 04/30/2012	182	70.5	79.3	62.2	2.1
	OFF	10/21/2011 to 10/31/2011	10	72.3	80.7	65.3	3.7
7	ON	01/31/2012 to 04/30/2012	90	74.6	87.1	67.1	2.3
	OFF	01/28/2012 to 01/30/2012	2	75.5	78.9	72.9	1.5
8	ON	03/24/2012 to 04/30/2012	37	73.5	80.2	67.9	2.0
	OFF	02/11/2012 to 03/19/2012	37	76.2	81.4	68.8	2.4
9	ON	01/25/2011 to 04/23/2011	88	75.0	81.9	68.6	1.9
	OFF	12/19/2010 to 01/25/2011	37	77.9	83.8	71.1	2.3
10	ON	03/05/2012 to 04/18/2012	44	76.8	79.9	69.5	1.9
	OFF	–	–	–	–	–	–
11	ON	03/03/2012 to 04/30/2012	58	75.9	85.9	69.0	2.7
	OFF	02/27/2012 to 03/02/2012	4	74.3	79.2	70.2	1.9
12	ON	12/01/2011 to 03/31/2012	121	72.9	78.8	65.9	1.7
	OFF	–	–	–	–	–	–
13	ON	12/27/2011 to 01/04/2012	8	75.1	84.8	66.8	4.0
	OFF	01/04/2012 to 04/30/2012	117	77.8	94.3	65.7	4.4

Bldg. No.	EMS Status	Time Periods	No. Days	Average	Max	Min	Std. Dev.
14	ON	01/17/2012 to 03/31/2012	74	75.1	81.9	66.6	2.6
	OFF	01/10/2012 to 01/17/2012	7	81.0	87.2	70.6	4.0
15	ON	12/01/2011 to 01/26/2012	56	70.6	77.2	64.2	1.9
	OFF	01/27/2012 to 02/03/2012	7	76.3	82.0	69.6	3.2
16	ON	01/18/2012 to 04/30/2012	103	75.1	85.5	65.9	2.6
	OFF	01/03/2012 to 01/18/2012	15	79.7	86.5	71.4	3.0
17	ON	12/01/2011 to 02/02/2012 and 02/22/2012 to 04/30/2012	131	75.4	83.7	67.4	2.9
	OFF	02/02/2012 to 02/22/2012	20	76.7	84.5	65.9	3.6
18	ON	12/01/2011 to 01/10/2012 and 02/11/2012 to 04/30/2012	119	75.8	83.9	67.8	2.9
	OFF	02/05/2012 to 02/10/2012 and 01/11/2012 to 01/17/2012	11	78.0	82.1	72.5	2.2

Figure 3 through Figure 5 show data from a typical building (building 15) in the study for January and February 2012. The figures show the variations of indoor air temperature, average indoor air temperatures, and the variations of indoor air temperatures as functions of outdoor air temperature. For nearly the entire time and for a wide range of outdoor air temperatures, indoor air temperatures in all apartments were > 70°F. Likewise, the average indoor air temperatures in all apartments for this period were > 70°F.

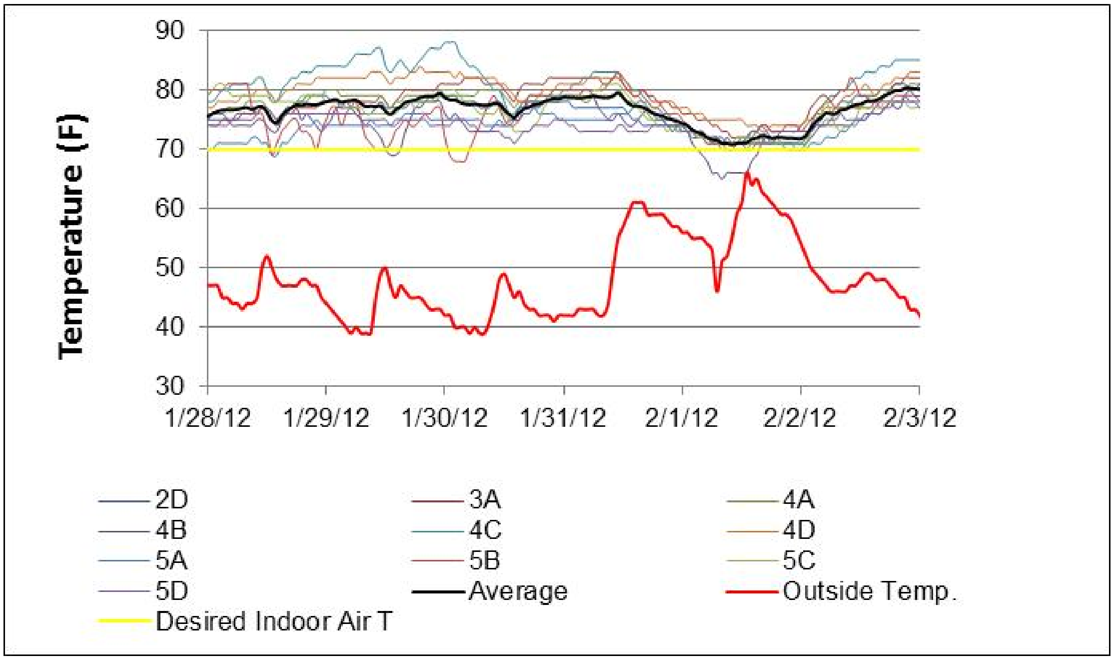


Figure 3. Building 15 indoor air temperatures and outdoor air temperature with EMS off

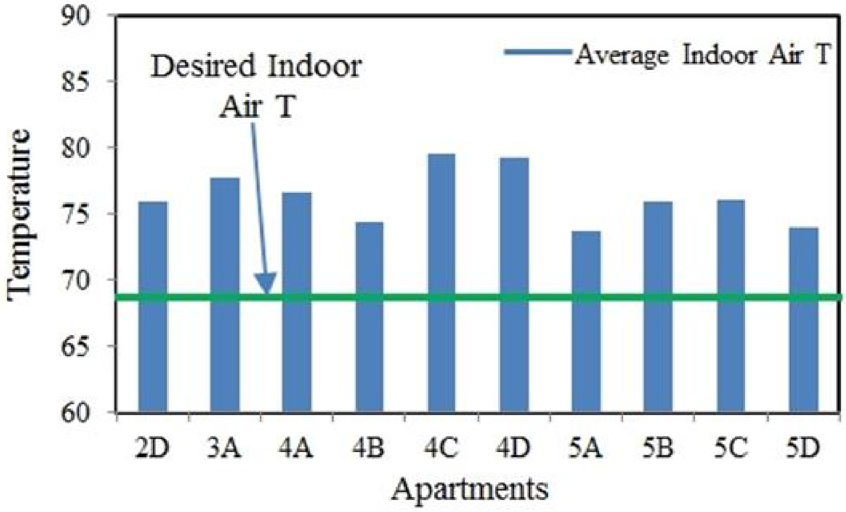


Figure 4. Building 15 average indoor air temperatures during the 2011–2012 heating season

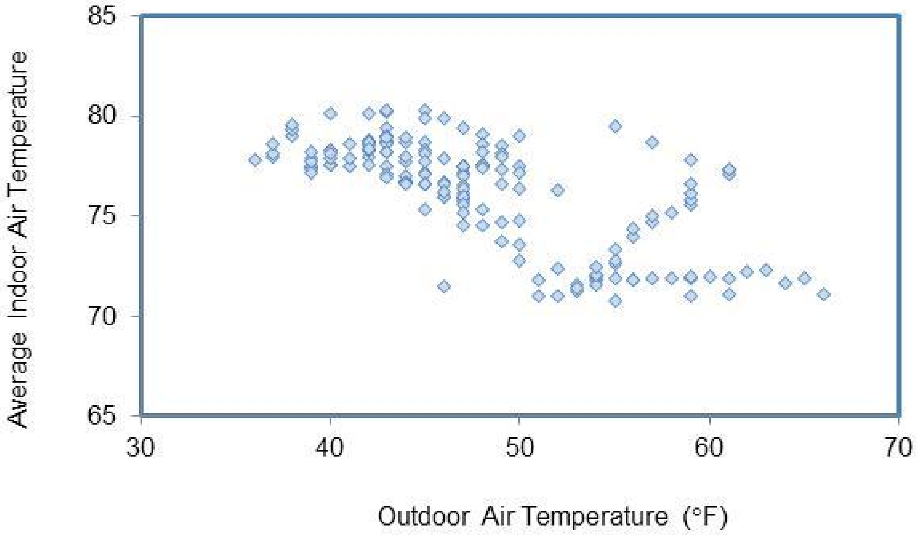


Figure 5. Building 15 indoor air temperature as a function of outdoor air temperature (2010–2011 heating season)

Note that the temperature data presented in Figure 3 and Figure 4 represent temperatures in the buildings for only a portion of the 2011–2012 winter because the EMS was installed partway through the heating season. The green line in Figure 4 shows the desired indoor air temperature of 70°F. As can be seen in Table 3 and Figure 3, average space temperatures in all the buildings were significantly higher than desired space temperatures, especially when the EMSs were disabled.

In this building, the sensors were located in 10 different apartments on various floors. The average temperatures in all the apartments were > 70°F, ranging from 73.8°F to 79.6°F (average of 76.3°F). Apartments located on the fourth floor were overheated the most (Figure 4). The average temperature of the top floor apartments was 75.0°F, which was lower than the average temperature of the entire building.

It can also be seen in Figure 5 that indoor temperature increases as outdoor air temperature decreases. Histograms are presented in the appendix showing the impact of outdoor temperature on the apartment temperatures when the EMSs were off in these buildings (Figure 29 to Figure 45). It can be noted in these graphs that for some buildings the average building temperature increased with increasing outdoor temperature; for some the average building temperature decreased with increasing outdoor temperature; and for others the average building temperature barely changed with increasing outdoor air temperature. This information may be useful in tuning the outdoor reset boiler control parameters for each building.

4.1 Effect of Floor Levels

Temperature variation by floor was examined in four buildings. Figure 4 through Figure 8 show average temperature by apartment for apartments on various floors. In these figures average temperature is not a function of floor level. These were low-rise buildings and therefore stack effect did not play a major role. Based on these results, it is concluded that for buildings in which sensors were located only at the top floors, the average of top floor temperature sensors closely represents the average temperature of the entire building.

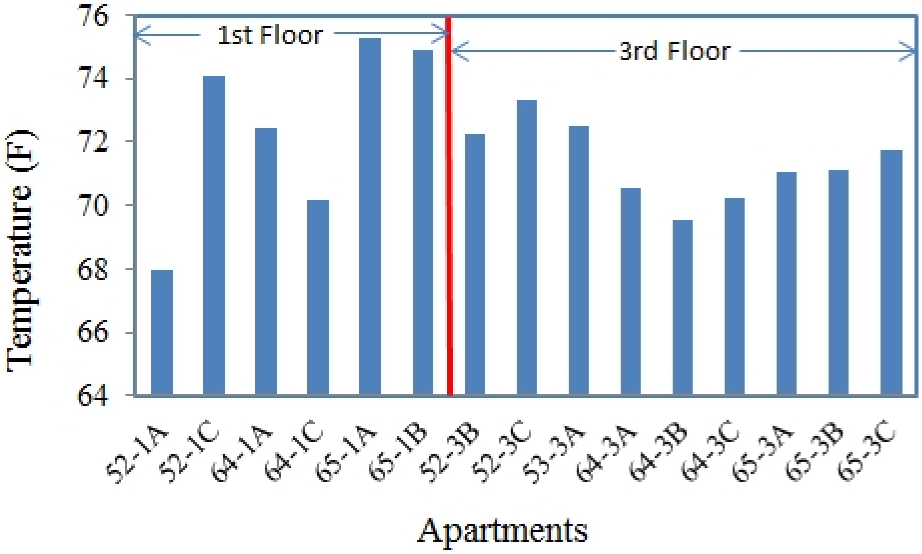


Figure 6. Building 1 average temperatures for apartments on the top and bottom floors of a two-story building

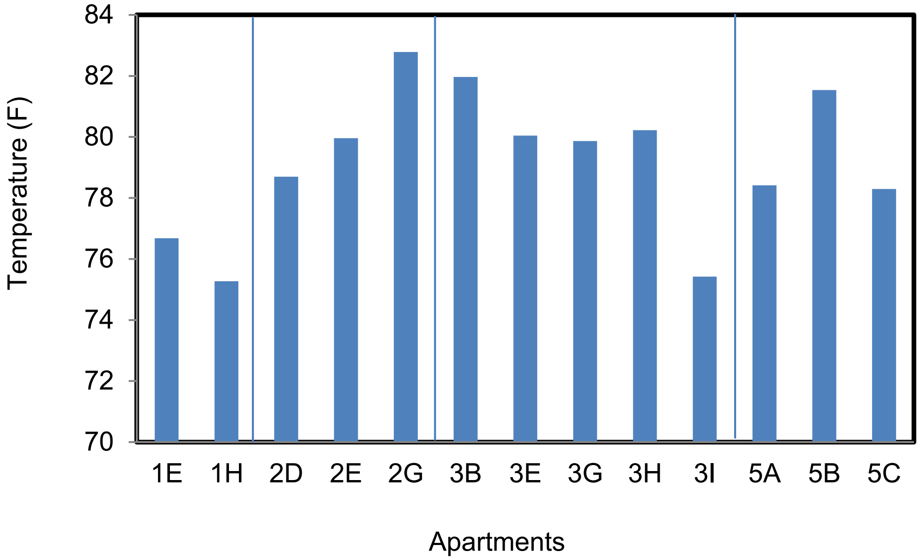


Figure 7. Building 16 average temperatures for apartments on four floors of a six-story building (1st digit is floor number)

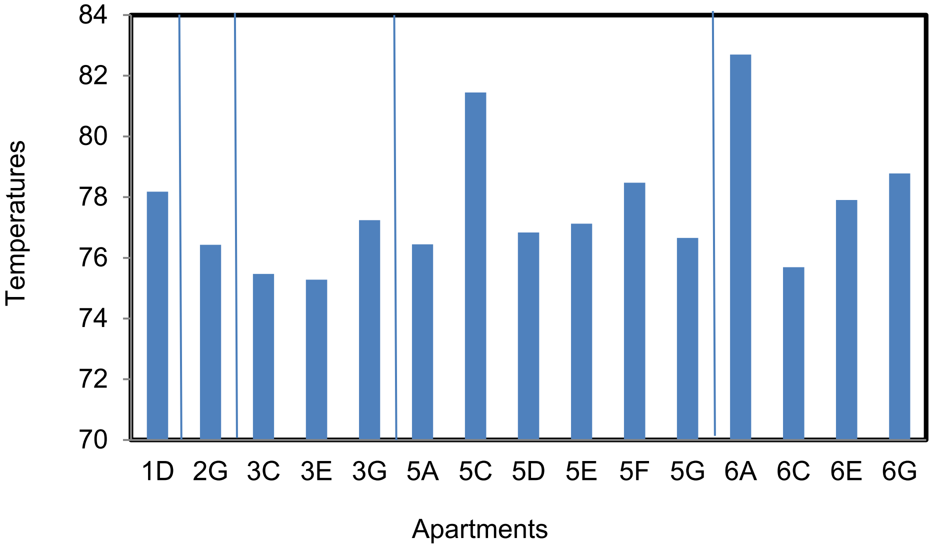


Figure 8. Building 18 average temperatures for apartments on five floors of a six-story building

4.2 Effect of Building Height on Energy Management System Performance

The effectiveness of the EMS appears to increase with the height of the building. Average temperature data were weighted by number of apartments with sensors for steam-heated buildings of four and six floors high that have both EMS off and EMS on data (there was only one such five-story building and one such three-story building). The temperature differences were calculated as follows: average apartment temperature with EMS off minus average apartment temperature with EMS on. The weighted average differences by building floor are shown in Table 5.

Table 5 Weighted Average Differences by Building Floor EMS on Minus EMS Off

Number of Floors	Number of Buildings	Weighted Average Temperature Difference
4	4	1.77
6	6	3.65

4.3 Variation of Indoor Temperature Between Apartments

Figure 3 shows the variations of indoor air temperature in various apartments in building 15 and the outdoor air temperatures. It can be seen that for nearly the entire time and for a wide range of outdoor air temperatures, indoor air temperatures in all apartments were above 70°F. In this building, temperature sensors were located in apartments at four different floors. In all the apartments, indoor air temperatures were > 70°F. The appendix shows similar graphs for all remaining buildings. The pattern is similar: nearly all apartments are heated to > 70°F for nearly the entire time when the EMS is off. However, there is a wide spread of apartment temperatures with the warmest and coolest apartments being separated by about 10°F on average and the coolest apartment being close to 70°F much of the time. This indicates that while there is some room to reduce heating building wide, an individual zone (by apartment or by section of building) is necessary to achieve the full extent of available savings.

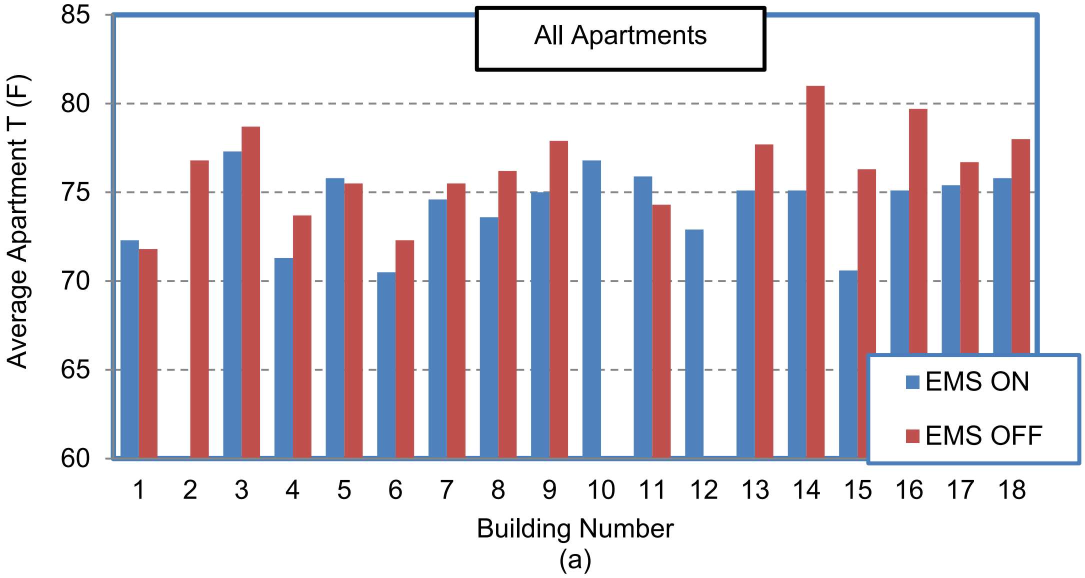
4.4 Effect of Heating System Type

Table 6 shows the effects of different types of heating distribution systems on overheating. Of the 18 buildings, four were heated by hot water and the remainder by one-pipe steam. When the EMSs were off, the average temperature in the hot water-heated buildings was slightly lower than that of the steam buildings. When the EMSs were on, the average temperature in the hot water buildings was nearly 2°F higher than that of the steam buildings. Table 4 includes only the 15 buildings for which both EMS on and EMS off data are available.

Table 6. Variation in Overheating by Heating System Type

Heating Type	Number of Buildings	EMS OFF			EMS ON		
		Range	Average T	Average T in Overheated (> 70°F) Apartments	Range	Average T	Average T in Overheated (> 70°F) Apartments
Hot Water	3	74.3–77.7	75.9	76.3	74.6–75.9	75.2	76.3
Steam	12	71.8–81.0	76.6	76.7	70.5–77.3	74.1	74.7

Figure 9 (a and b) compares the overall average indoor temperature of the buildings and average indoor temperatures of overheated apartments when the EMSs were off and on. As stated, the data were collected for the 2011–2012 winter season except building 9, for which data were collected from the 2010–2011 season.



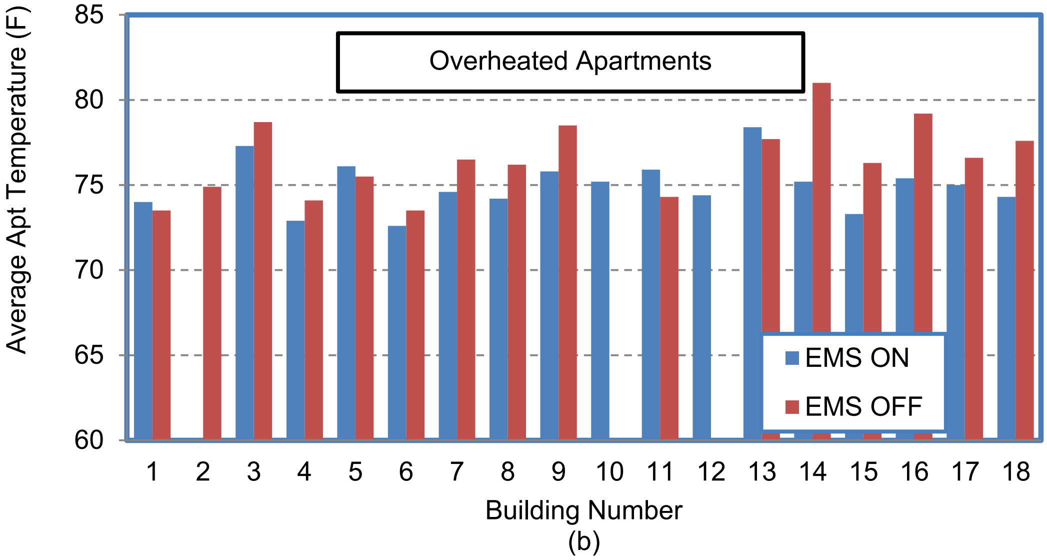


Figure 9. Comparison between the overall average indoor temperature of the buildings and average indoor temperatures of overheated apartments when the EMSs were off and on

Table 6 presents a statistical analysis of the temperature data collected in the buildings. The average lowest temperature of all apartments was 72.6°F when the EMS was off.

Table 7. Statistical Analysis of the Temperature Data

EMS Status		Mean T (°F)	Standard Deviation	Minimum T (°F)	Maximum T (°F)	Range T (°F)
ON	Overall average T in apartments	74.2	2.1	70.5	77.3	6.8
	Average T in the overheating apartments	74.4	1.8	71.7	77.3	5.6
OFF	Overall average T in apartments	76.3	2.5	71.8	81	9.2
	Average T in the overheating apartments	76.5	2.6	72.3	81	8.7

Based on a U.S. Department of Energy report (U.S. Department of Energy, 2012), overheating results in an increase in annual energy consumption of approximately 1% per °F over the desired temperature in a dwelling for each eight hours of the day. In all the buildings studied, the average temperatures were well above 70°F, ranging from 75.2°F to 81.0°F. It was also found that most apartments' average temperature during heating operation was well above 70°F. Average temperature of all the buildings when the EMS system was off was 76.2°F, whereas when the EMS was on, the average temperature of all the buildings was 74.4°F. Based on this analysis, the estimated average increase in annual space heating energy cost for these buildings (when the EMS is inactive) due to overheating is approximately 18.6% based on 70°F target temperature, or 24.6% based on the 68°F legal daytime temperature. In addition, nighttime setback can be used, reducing the legally required temperature to 55°F during the night (in New York City), possibly increasing savings. Saving assumptions will vary with envelope characteristics and climate conditions.

In a year with average winter temperatures, fuel bills for a typical 80–100 unit apartment building can run $50,000–$60,000. Therefore, annual overheating waste for this typical building and overheating profile is approximately $11,160 based on a desired temperature of 70°F, or $14,760 based on the legal limit of 68°F.

5 Conclusion

This study presents an analysis of the data collected from multiple buildings to develop conclusions on the magnitude of apartment overheating for buildings heated by single-zone steam and hot water heating systems. Eighteen sites were selected where EMSs were already installed and the data were analyzed for several apartments in each building.

The primary research question addressed by this report was: What was the observed temperature range above comfort level (70°F) for the 18 buildings measured when the EMS was operating and when it was inactive, and what is the impact of overheating on operational energy consumption?

The answer to this question is that overheating was found in all 18 buildings. In all 18 buildings, average temperature was well above 70°F when the EMSs were not in operation (Table 3). In 15 of the 18 buildings, average temperatures in all the apartments when EMSs were not in operation were 70.7° to 87.4°F and in three buildings, average temperatures in more than 88% of apartments ranged from 70.3°F to 85.2°F. Likewise, when the EMSs were on in seven of 18 buildings, average temperatures in all the apartments were > 70°F, ranging from 70.3°F to 81.1°F. In the remaining 11 buildings, average temperatures in more than 67% of apartments were also > 70°F, ranging from 70.0°F to 81.2°F.

Based on this analysis, estimated average increase in annual energy cost for these buildings due to overheating was approximately 18.6% based on a 70°F target temperature. This does not account for potential under- or overestimating of overheating due to occupants opening windows to relieve overheating or using space heaters to supplement the central heat.

Nearly all apartments were heated to > 70°F for nearly the entire time when the EMSs were off; however, there is a wide variation in temperatures among apartments in the same building. Therefore, to achieve the full potential of possible savings, individual zone or apartment control would be necessary.

A secondary research question was whether apartment floor level or heating system type was correlated to degree of overheating. No correlation was found with these factors.

Another secondary research question was whether EMSs reduced overheating and average apartment temperatures. We found that EMSs did reduce overheating; however, in many buildings average indoor temperatures were still > 70°F for much of the time. EMSs were slightly more successful in reducing average temperatures in steam-heated buildings than in hot water-heated buildings, and in taller buildings compared to shorter buildings.

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Appendix: Variations of Indoor Temperatures

The following graphs show the variation of indoor temperature in various apartments in all the buildings. Note that the data are truncated when the outdoor temperature > 55°F because that is the warm weather boiler shutdown temperature for these buildings.

The histograms show the variation in average indoor temperature with outdoor temperature by building, as well as the range in indoor temperature for each outdoor temperature bin.

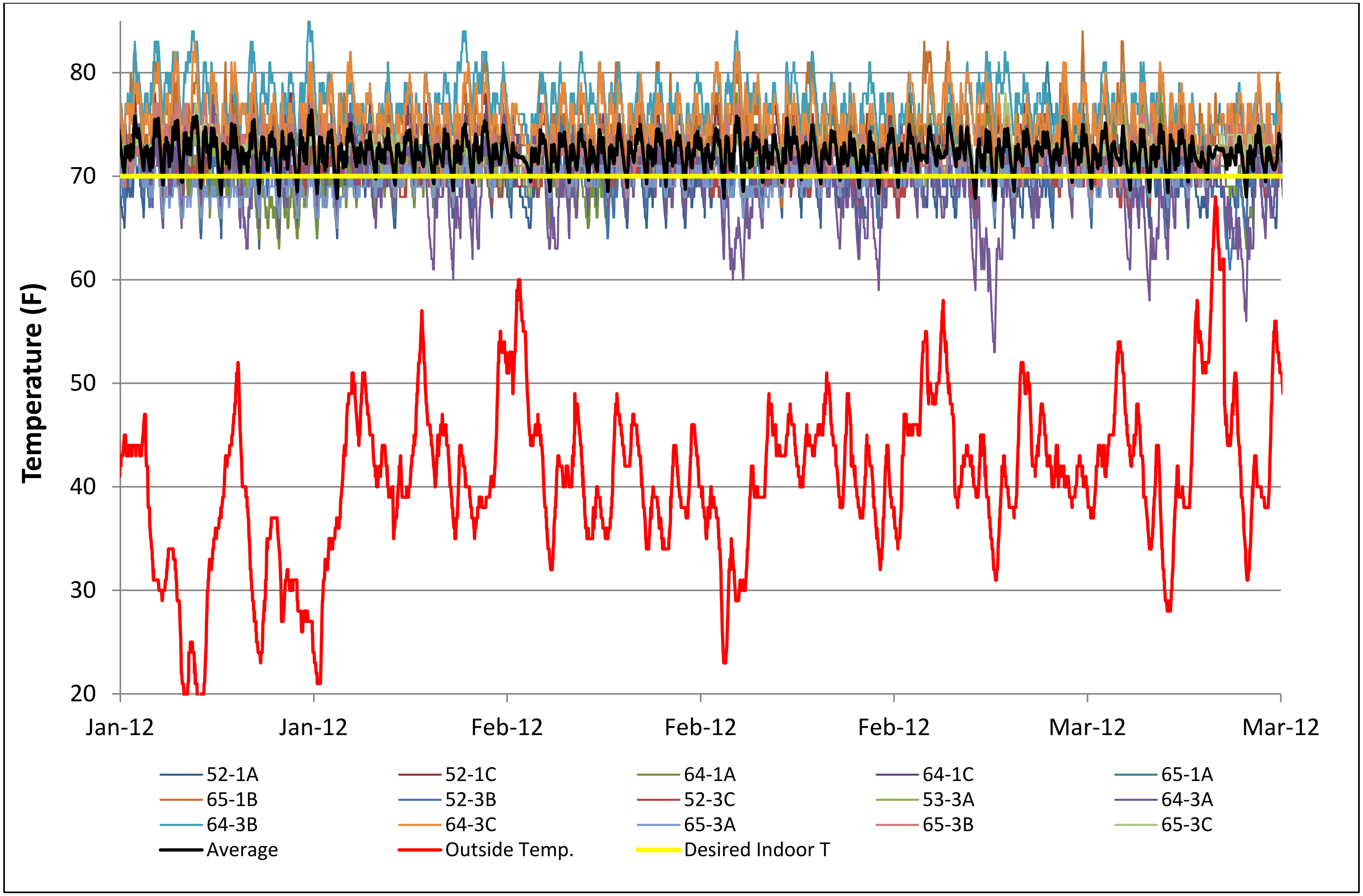


Figure 10. Building 1 temperatures

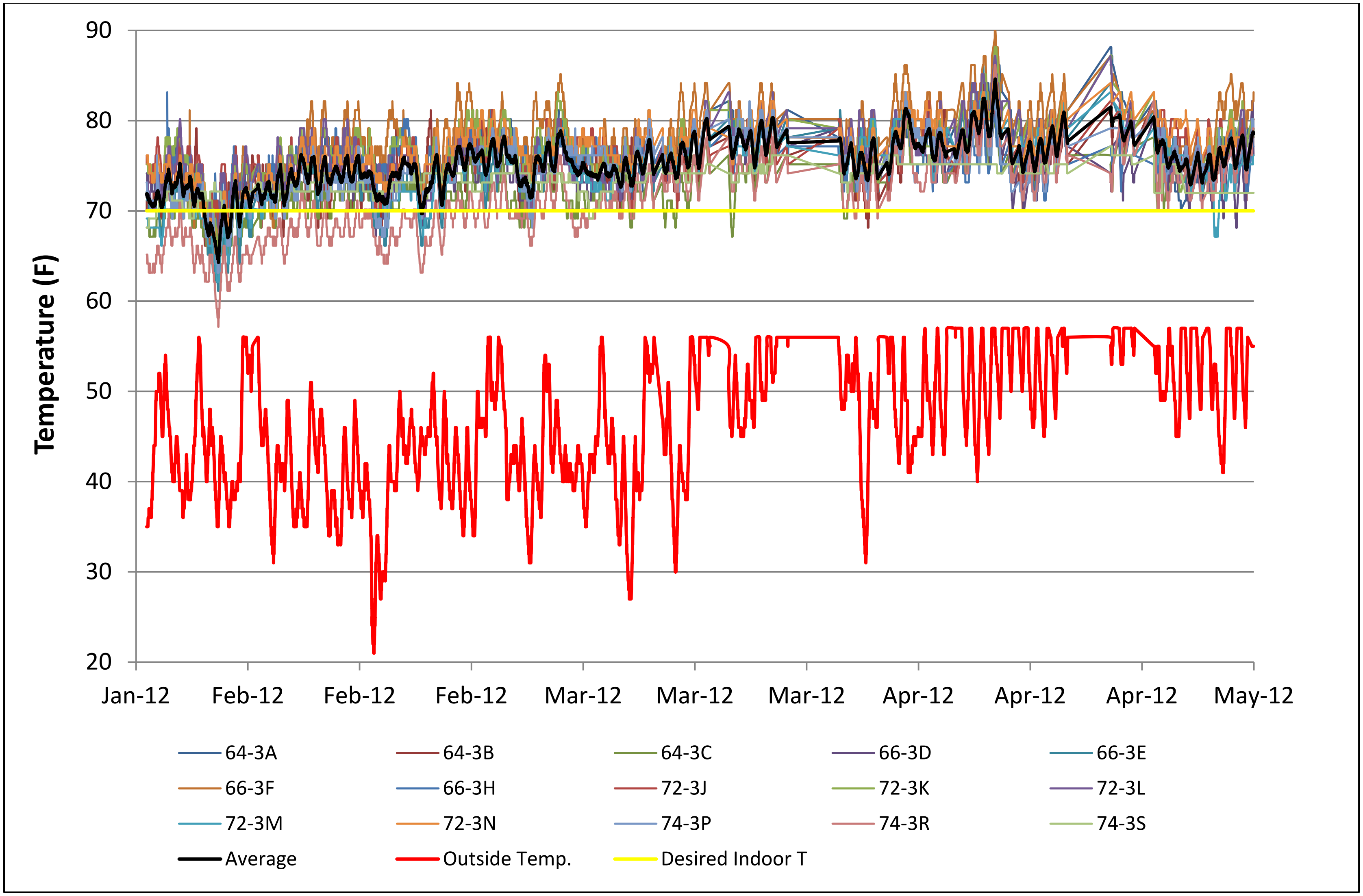


Figure 11. Building 2 temperatures

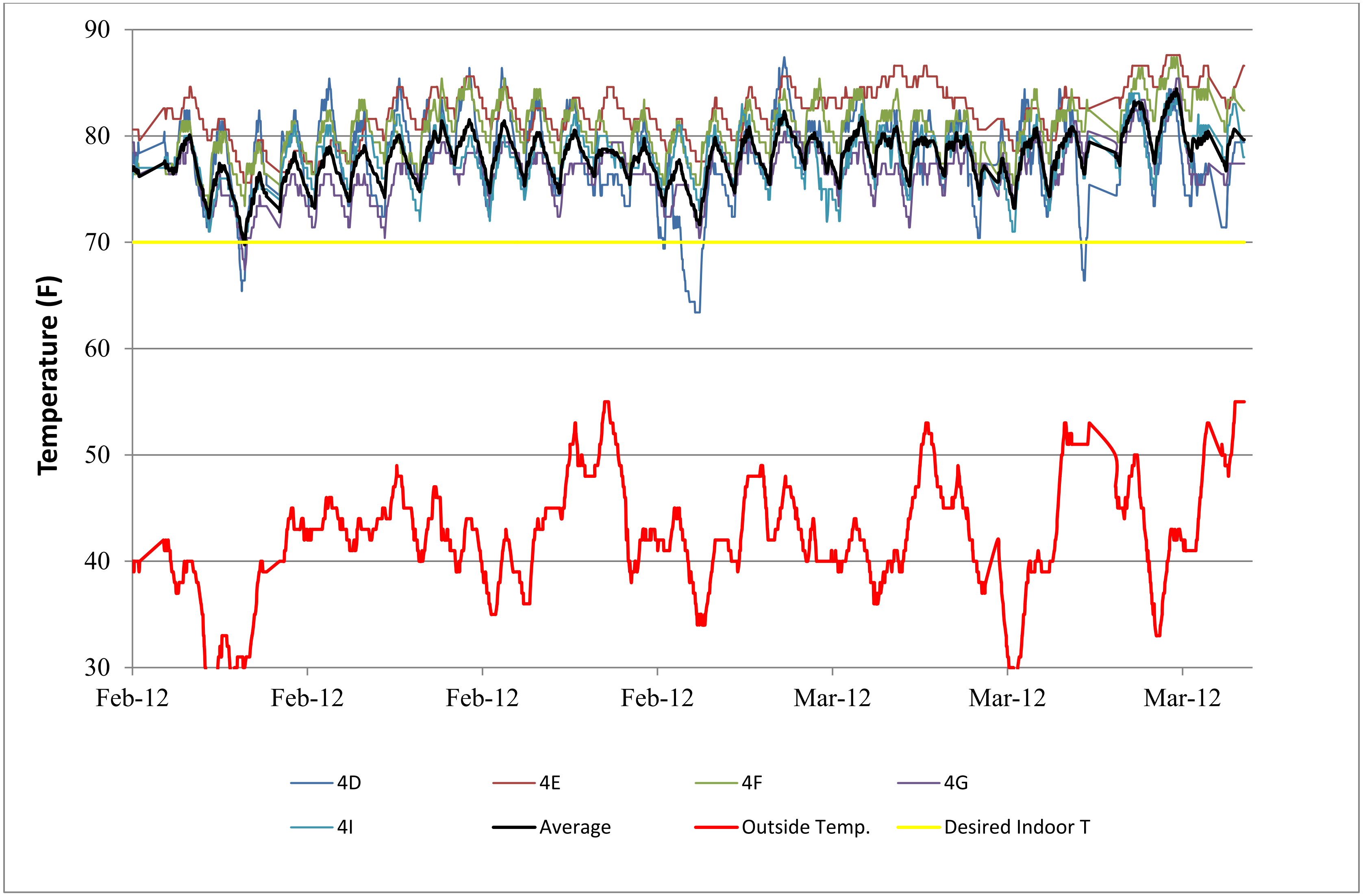


Figure 12. Building 3 temperatures

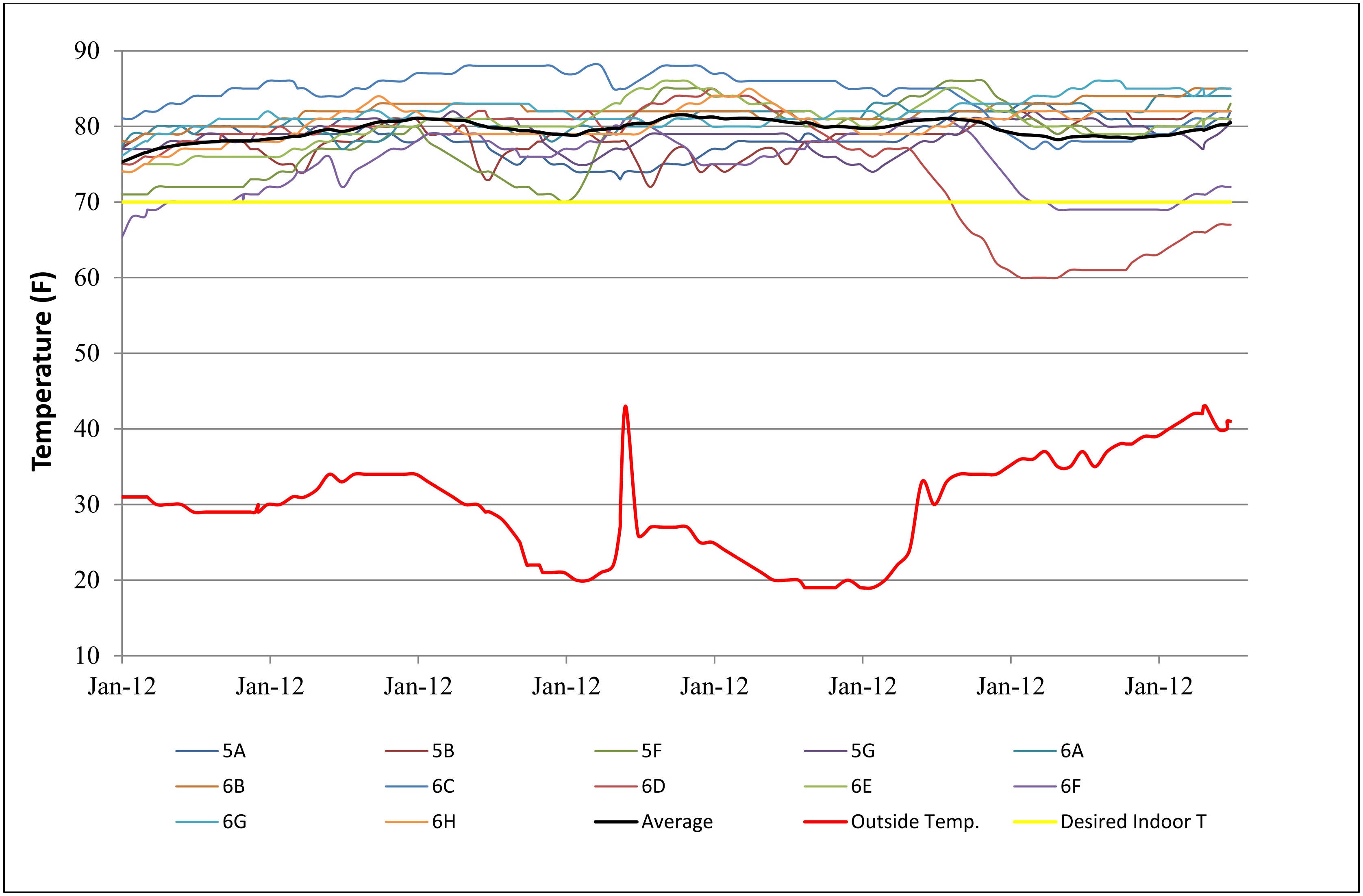


Figure 13. Building 4 temperatures

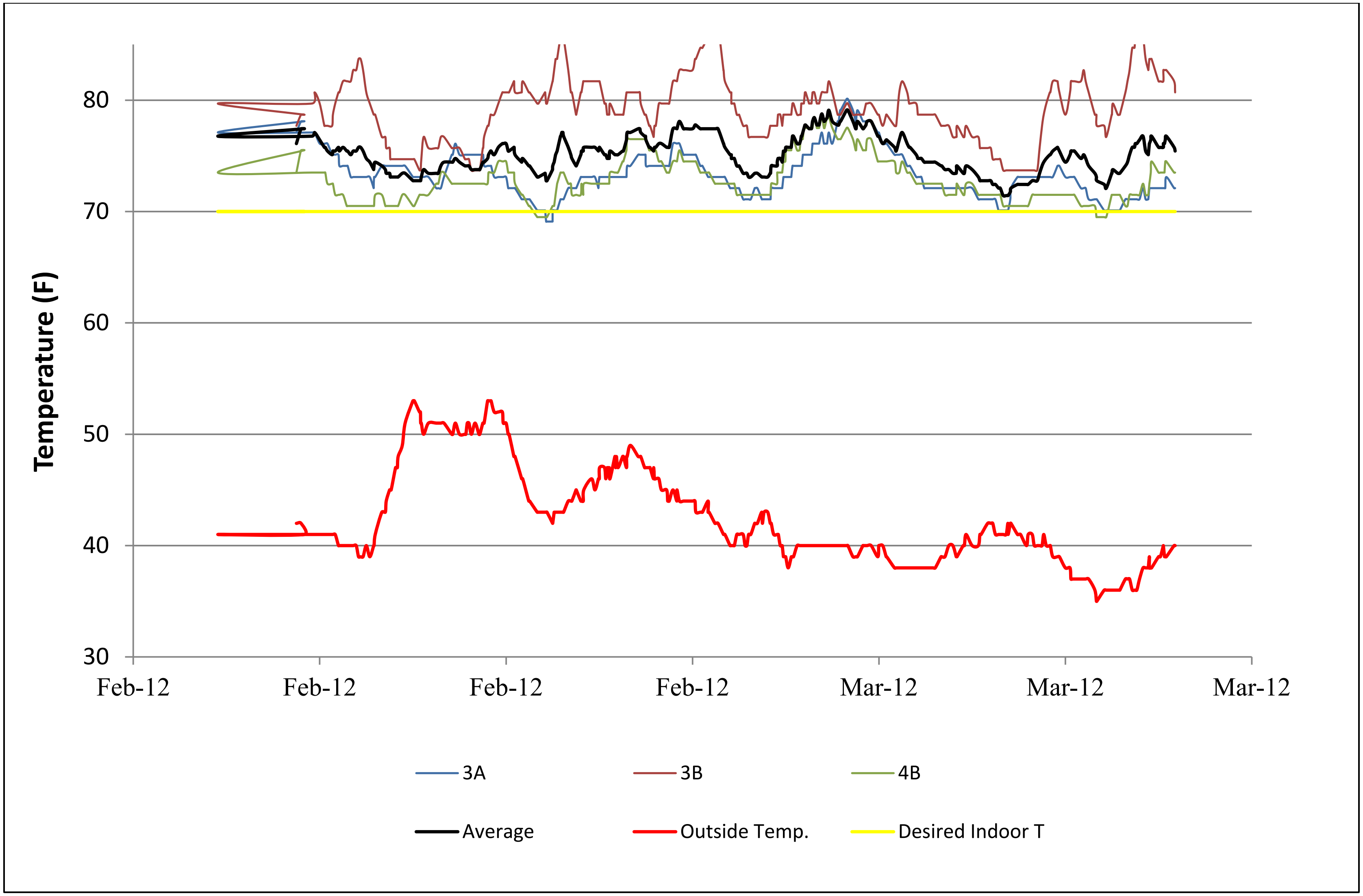


Figure 14. Building 5 temperatures

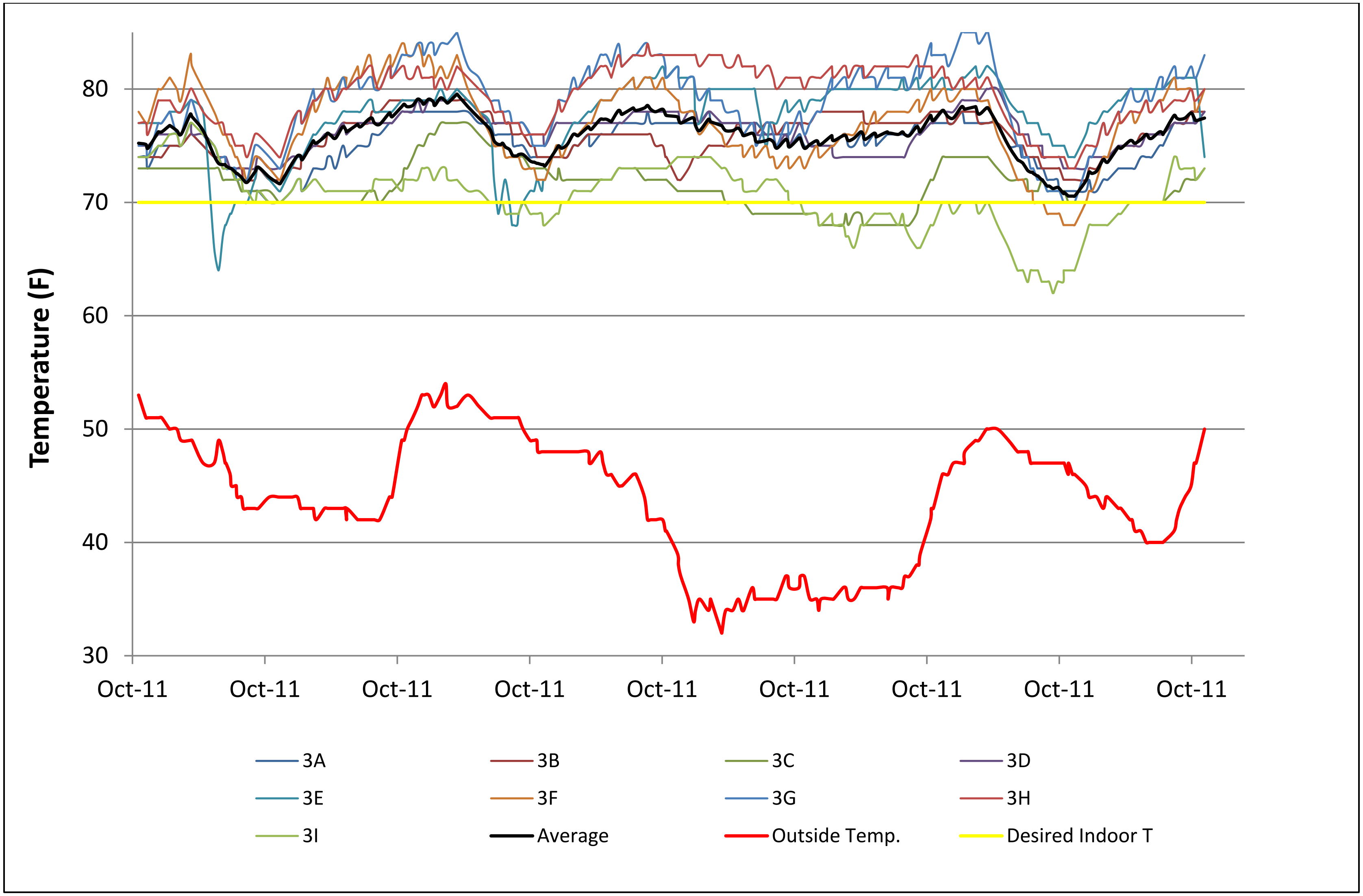


Figure 15. Building 6 temperatures

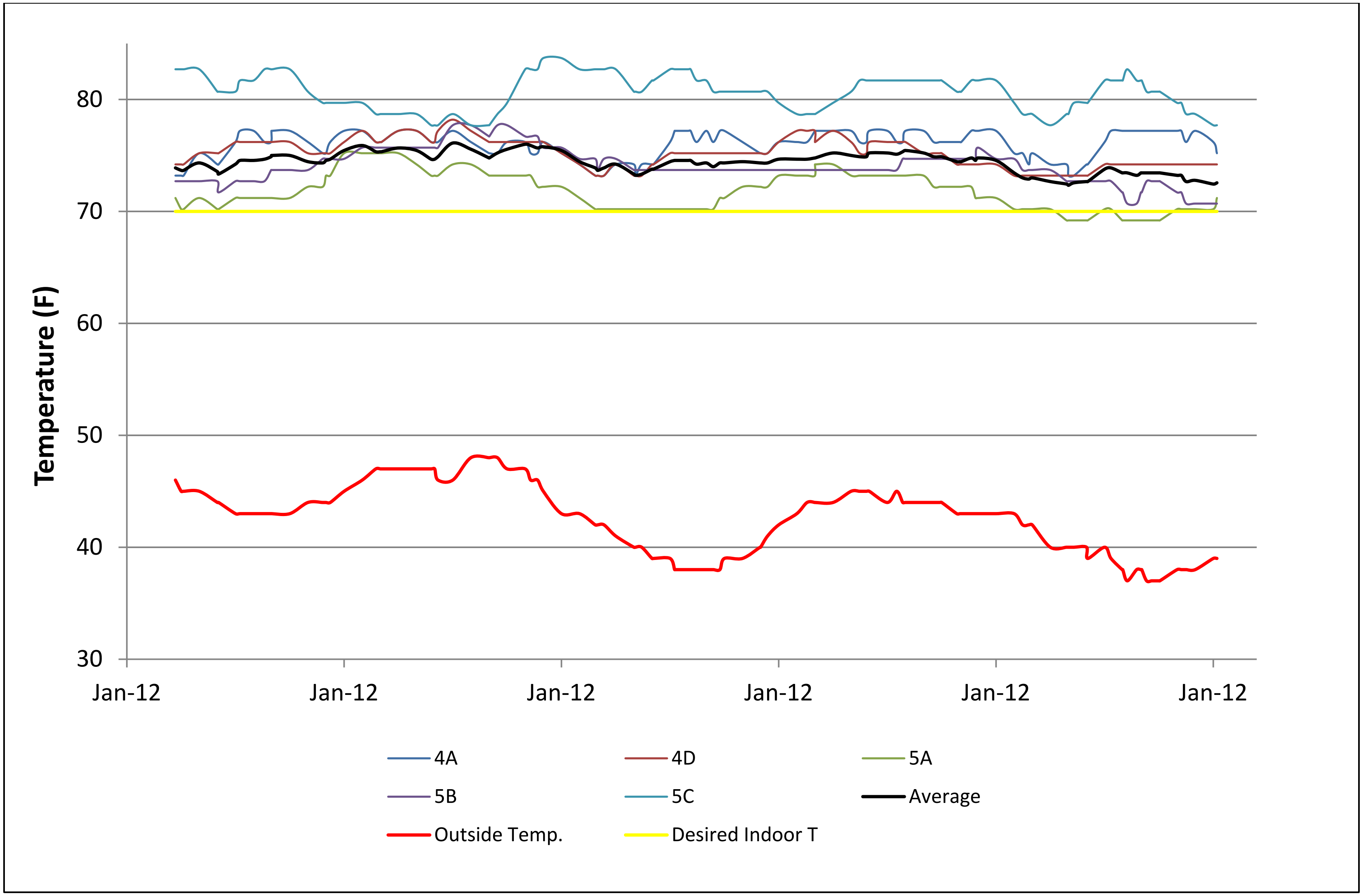


Figure 16. Building 7 temperatures

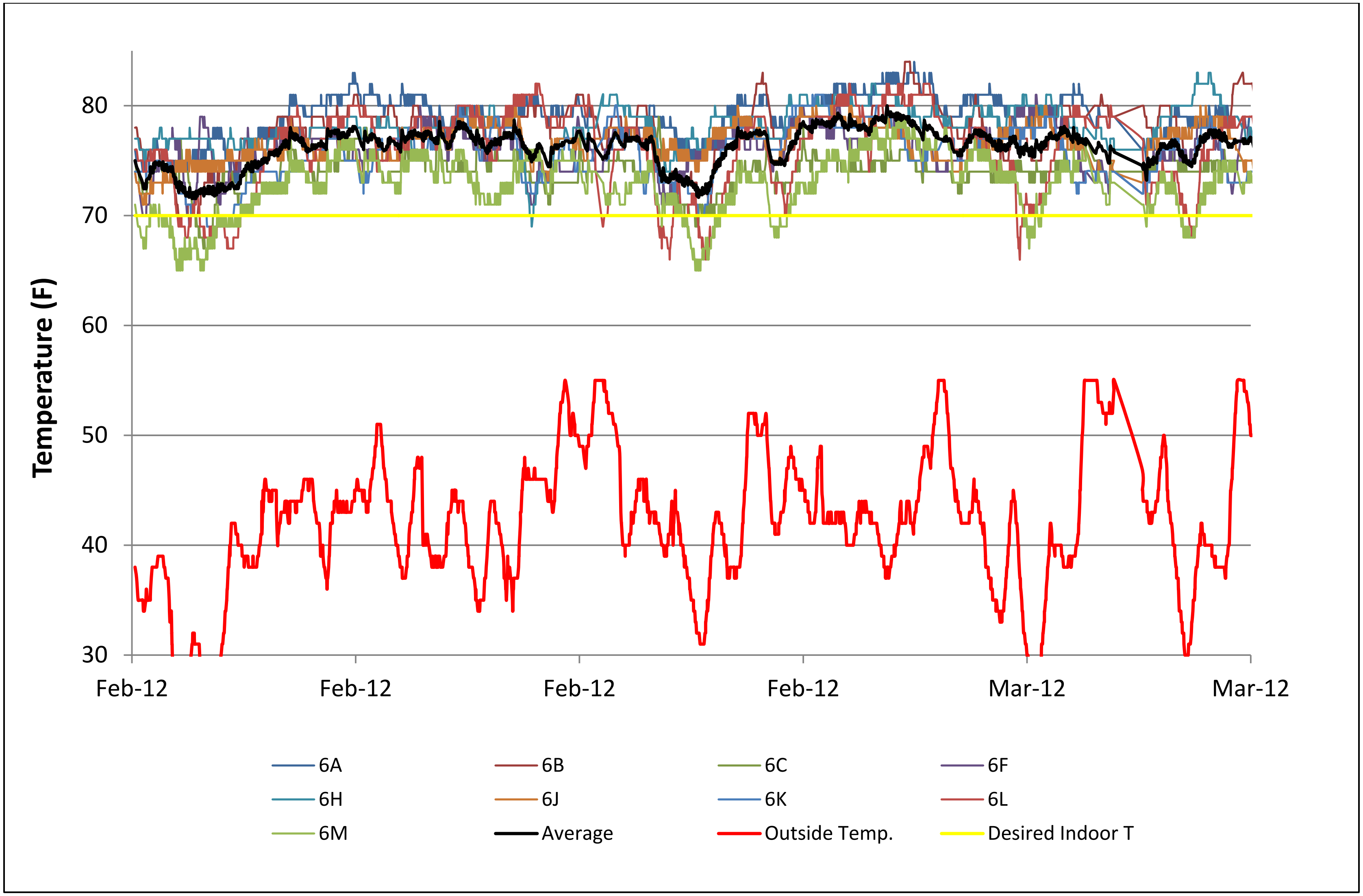


Figure 17. Building 8 temperatures

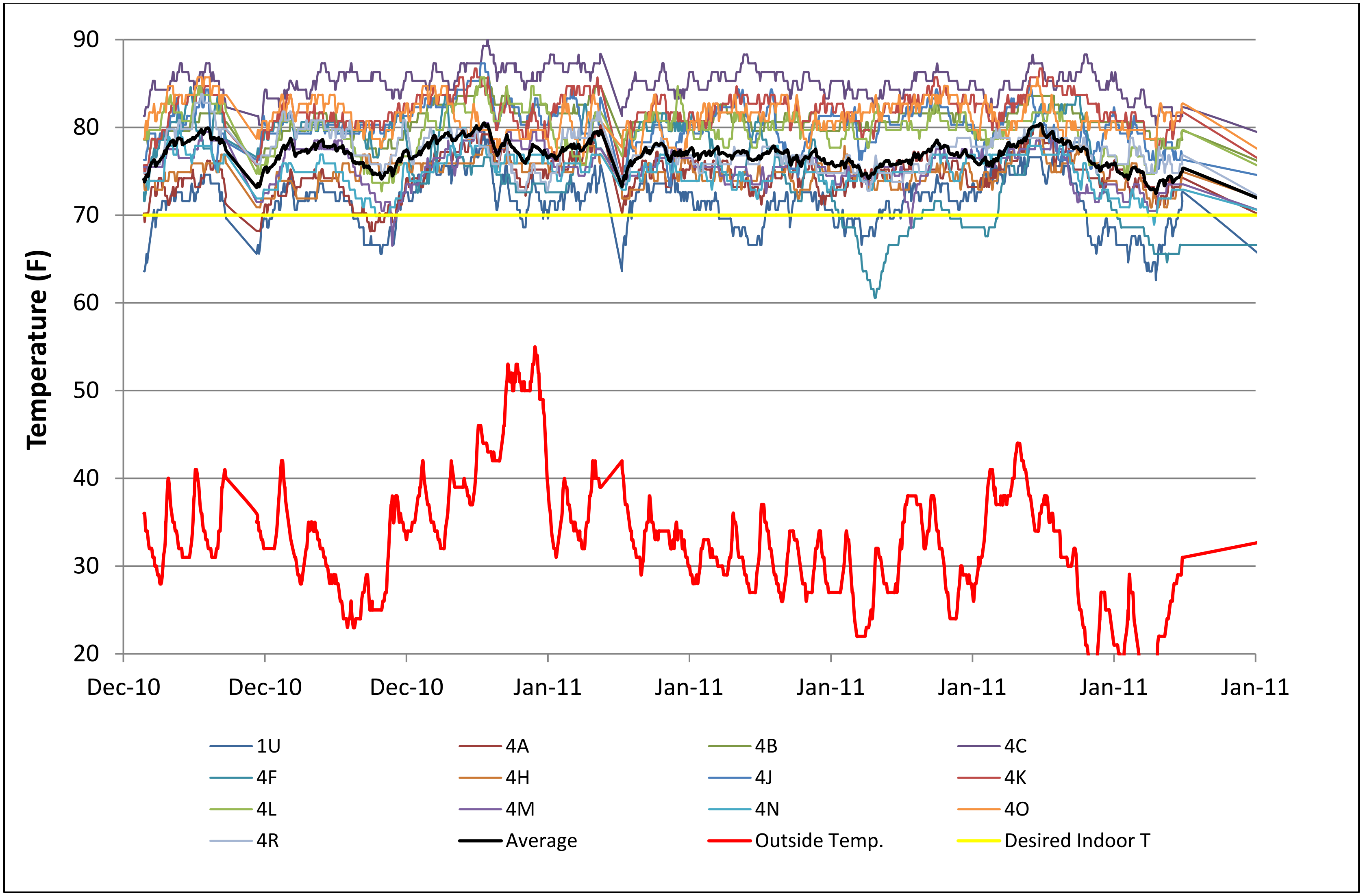


Figure 18. Building 9 temperatures

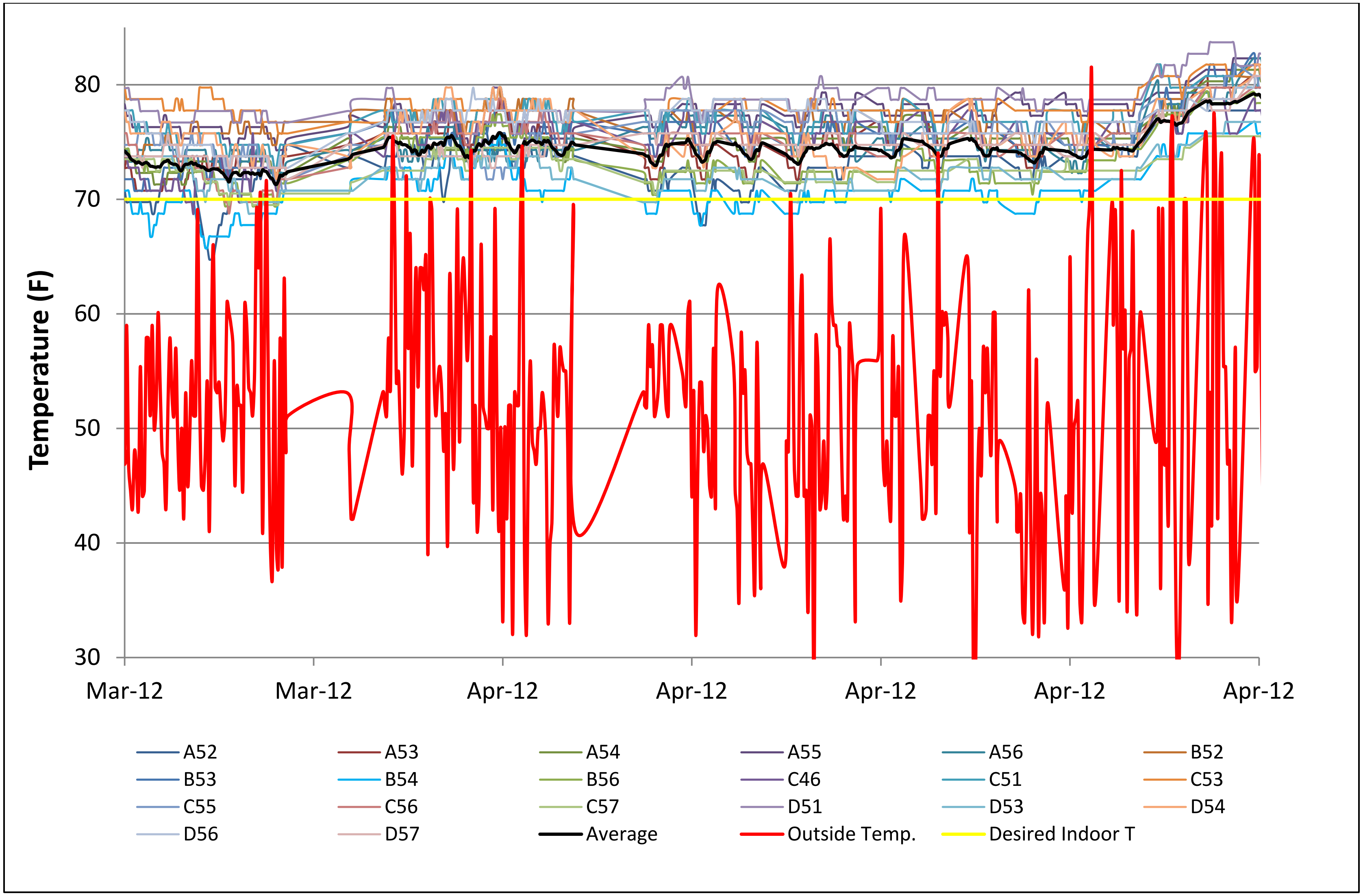


Figure 19. Building 10 temperatures

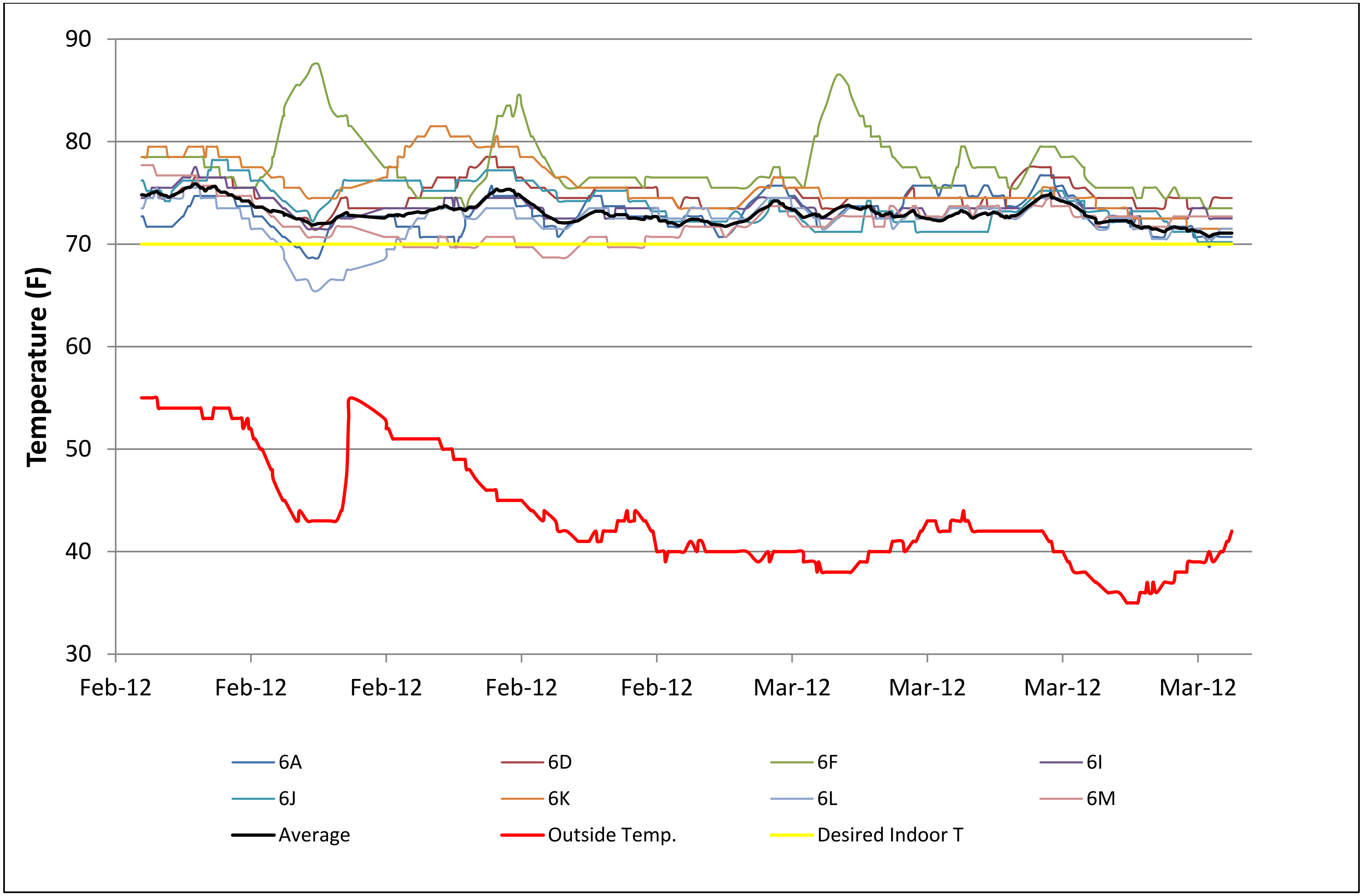


Figure 20. Building 11 temperatures

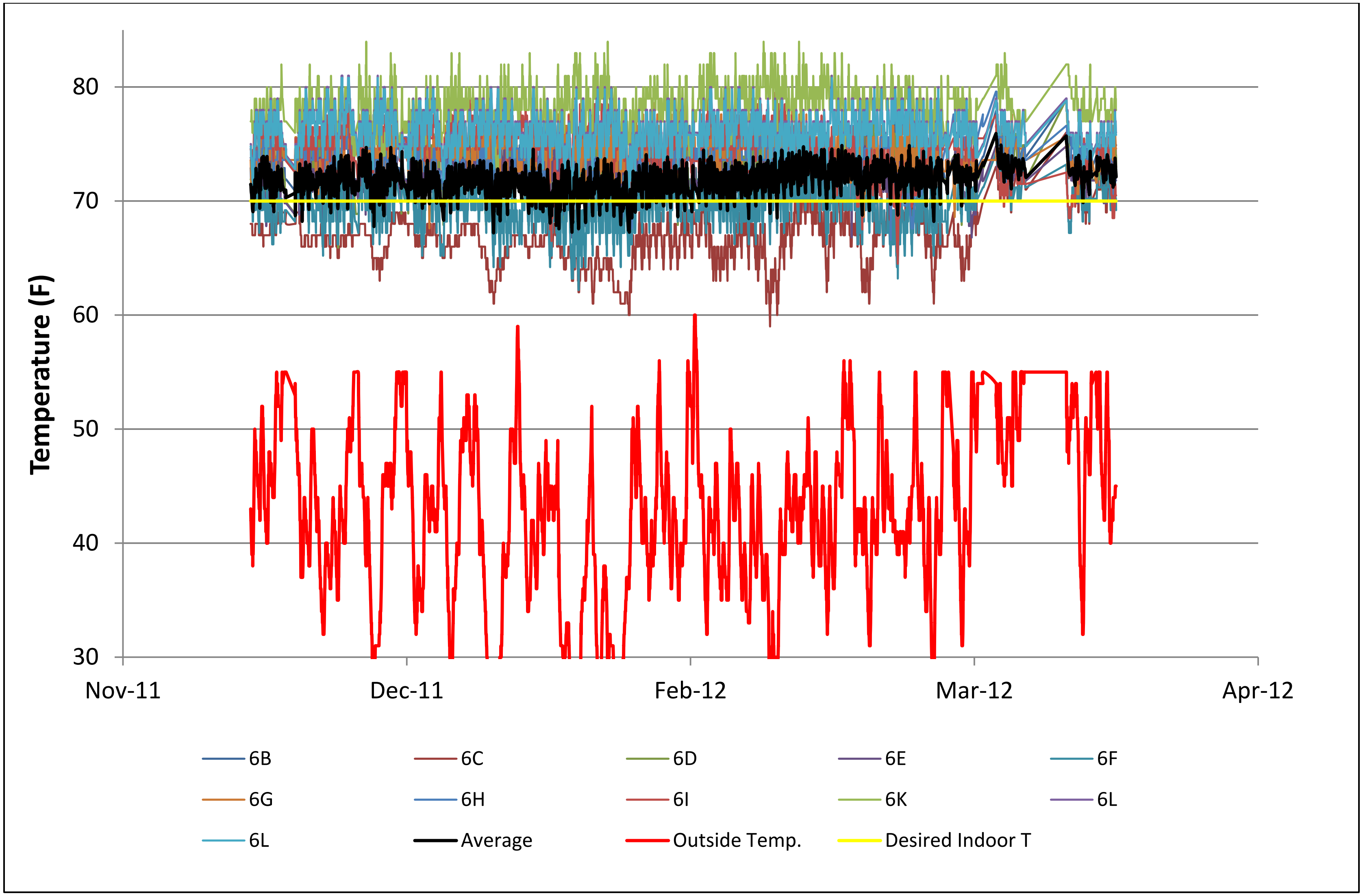


Figure 21. Building 12 temperatures

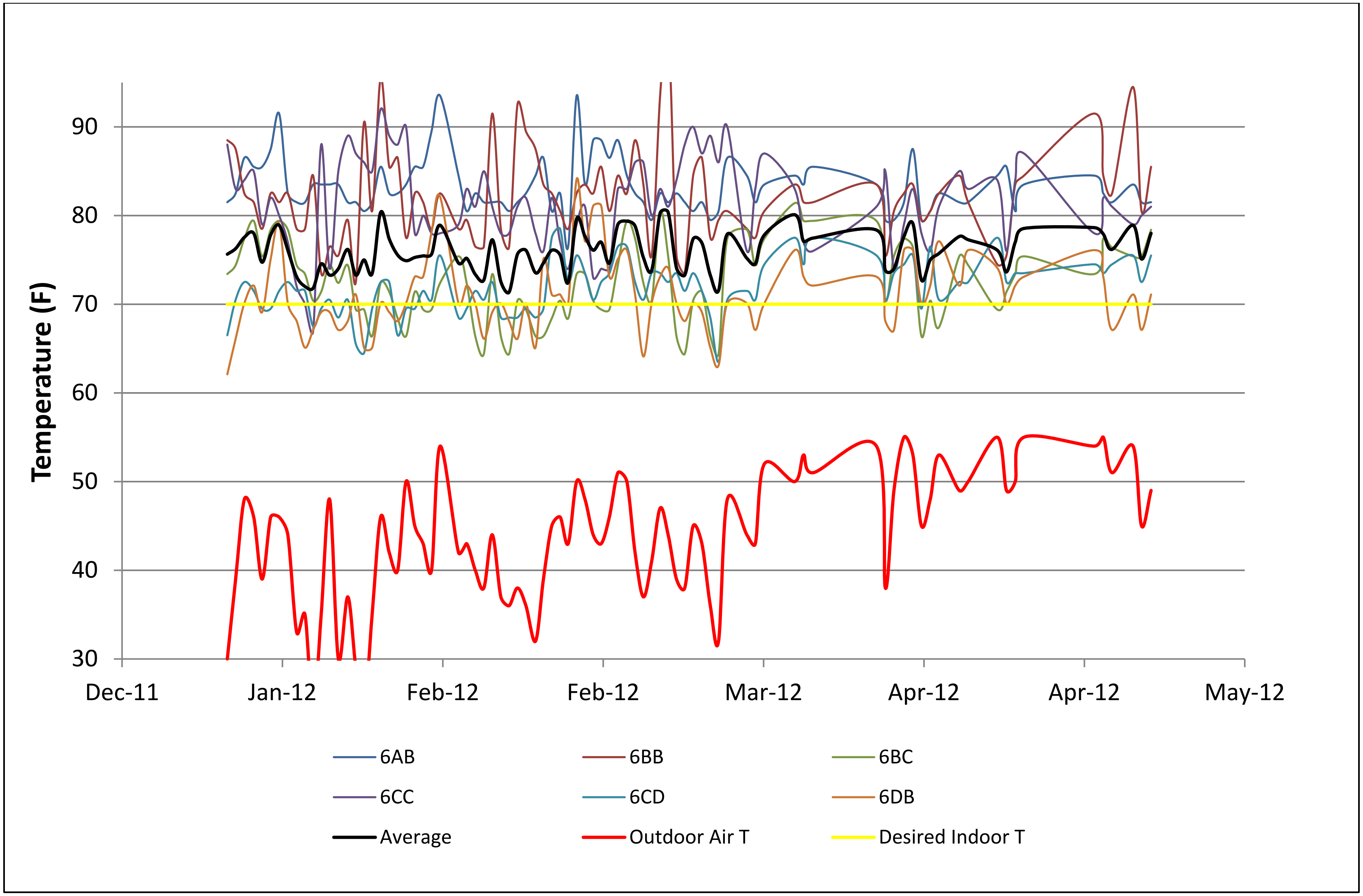
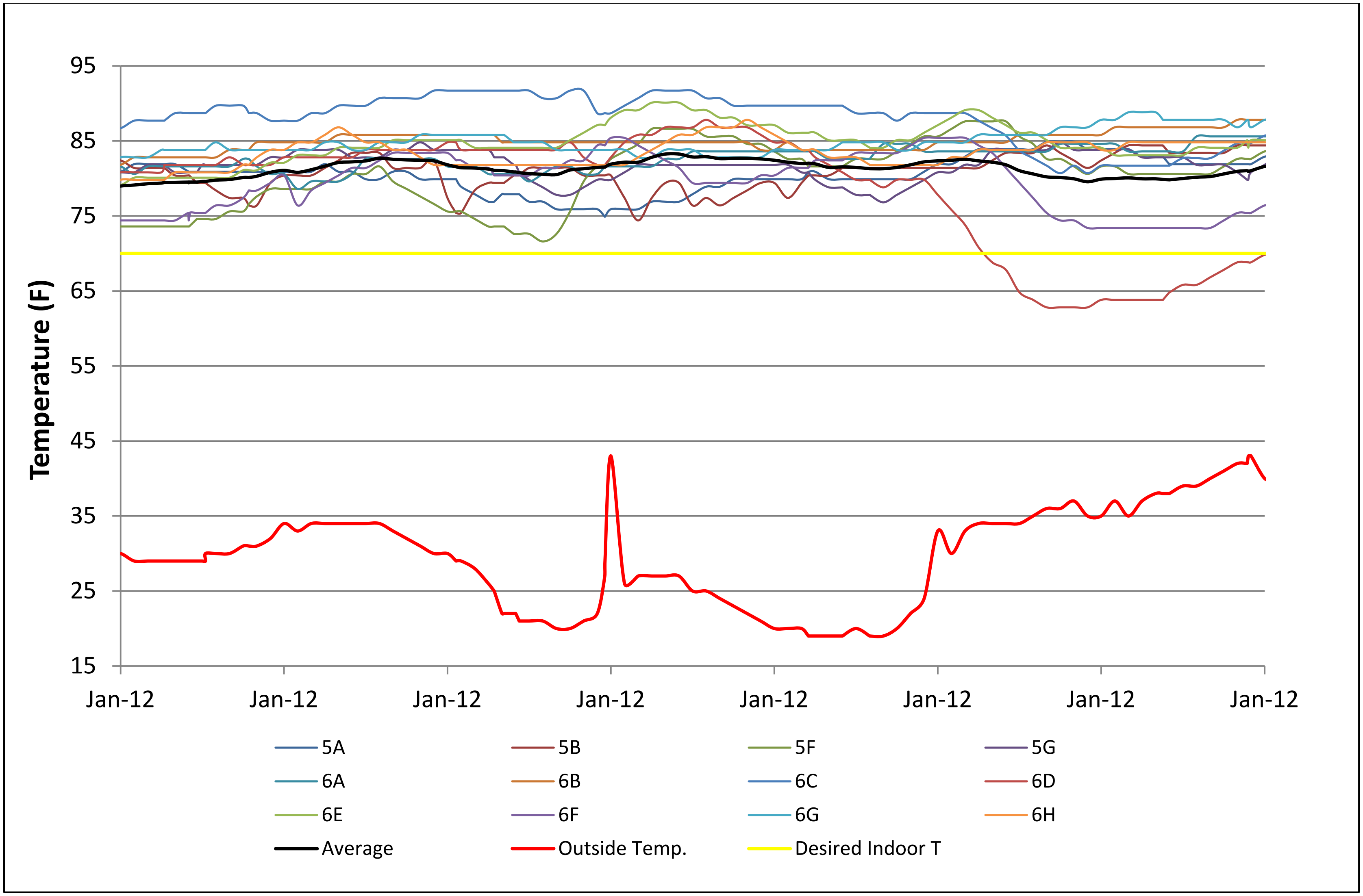


Figure 22. Building 13 temperatures



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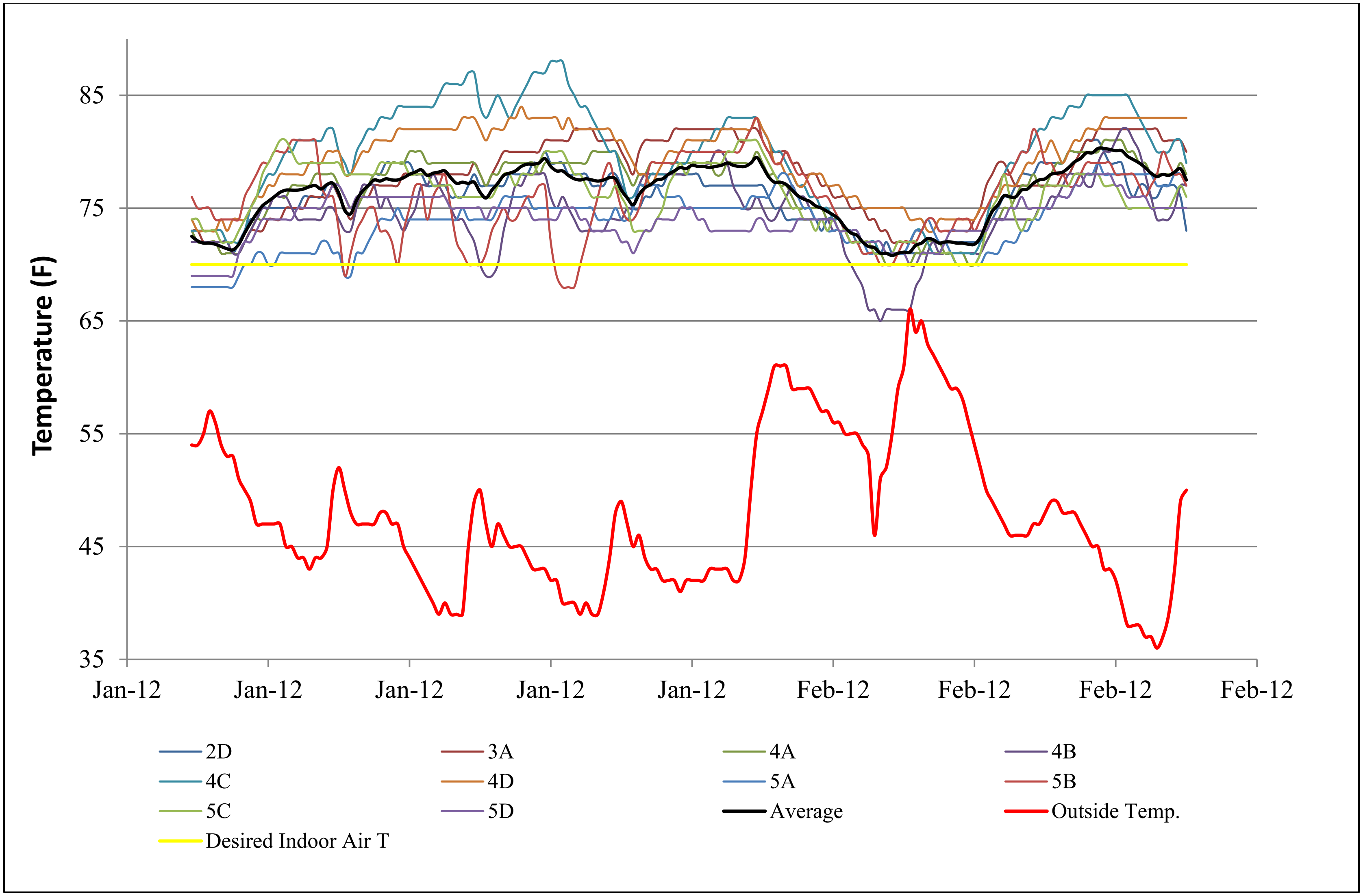

Figure 24. Building 15 temperatures

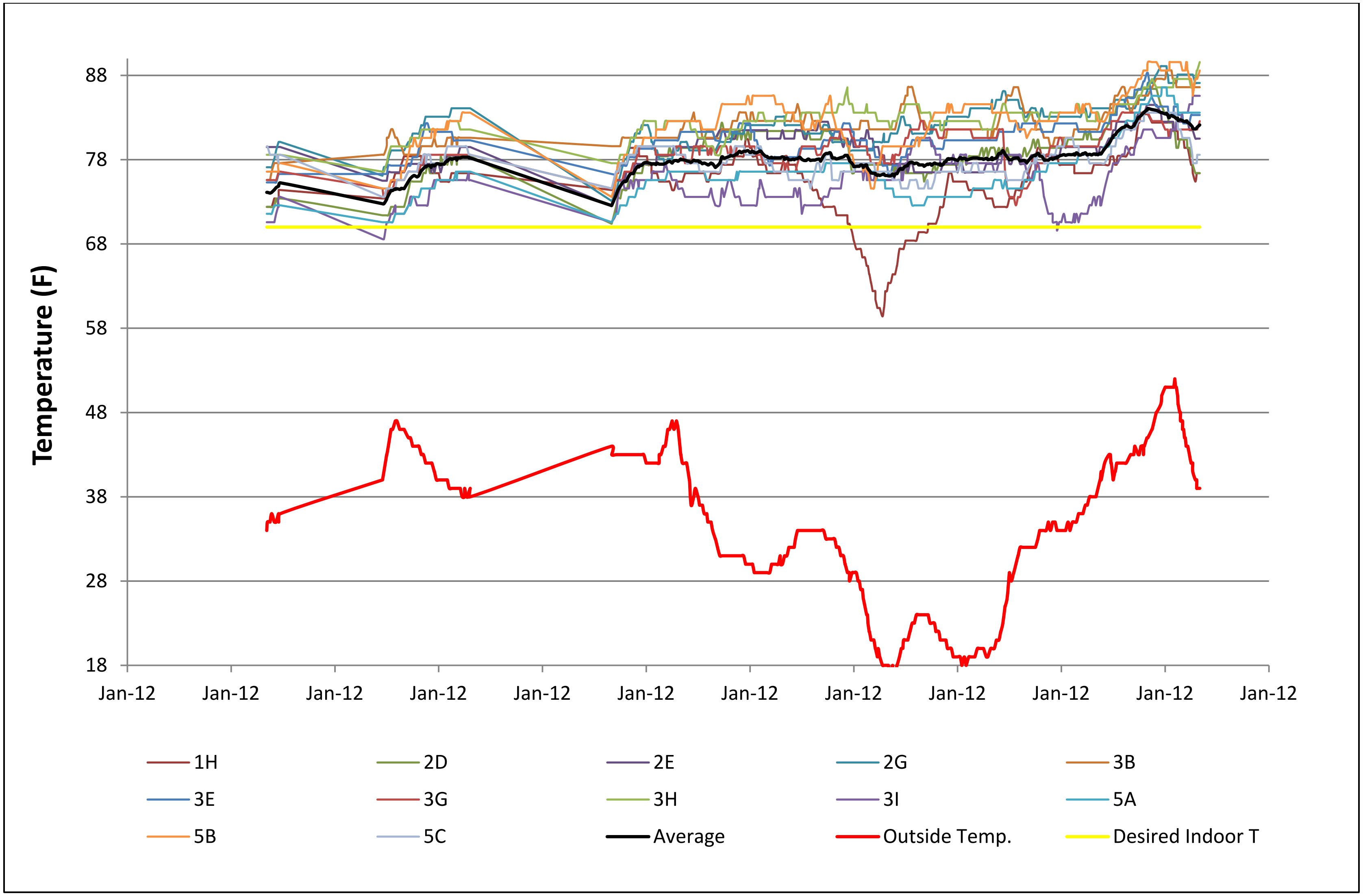

Figure 25. Building 16 temperatures

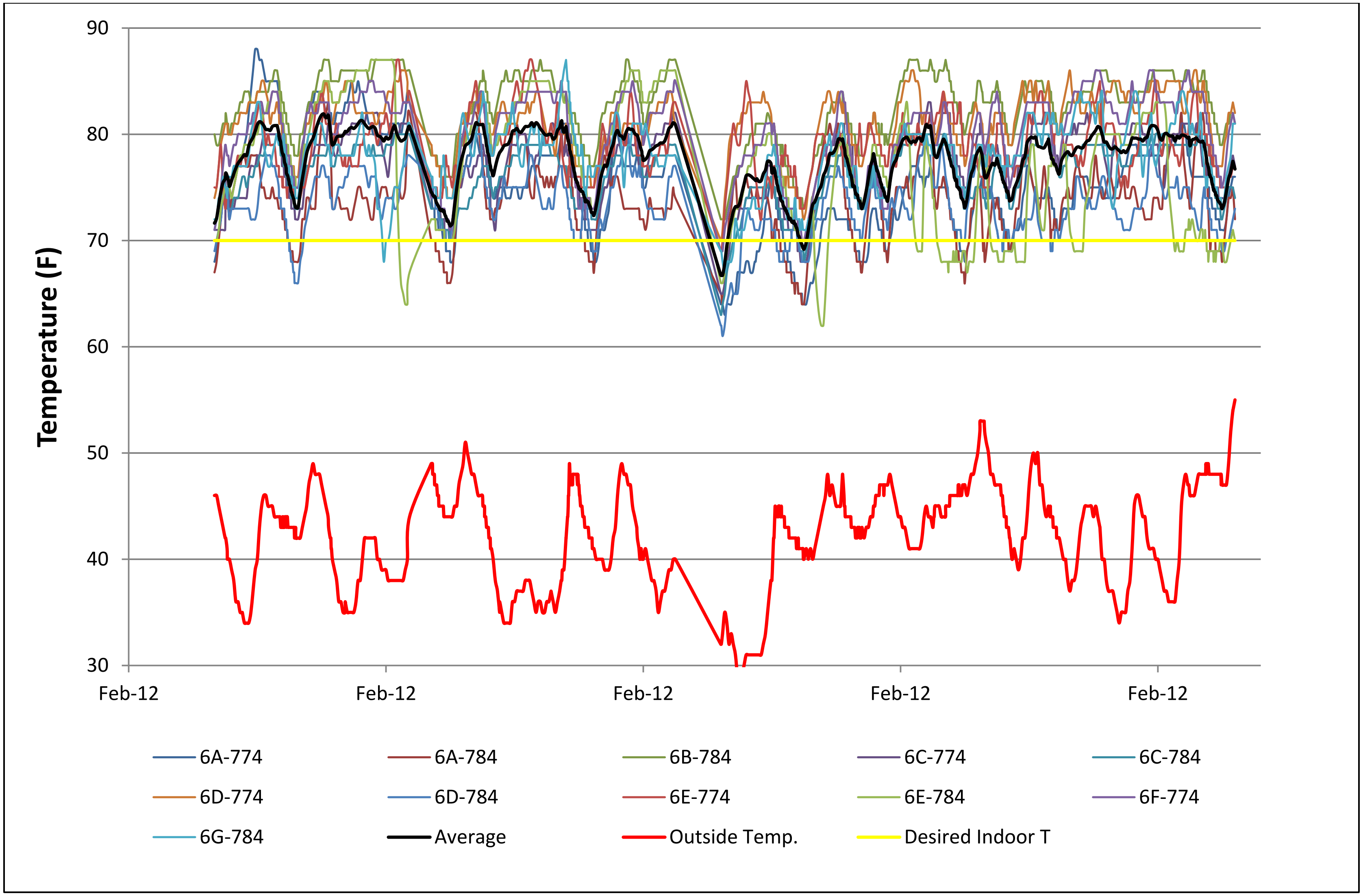

Figure 26. Building 17 temperatures

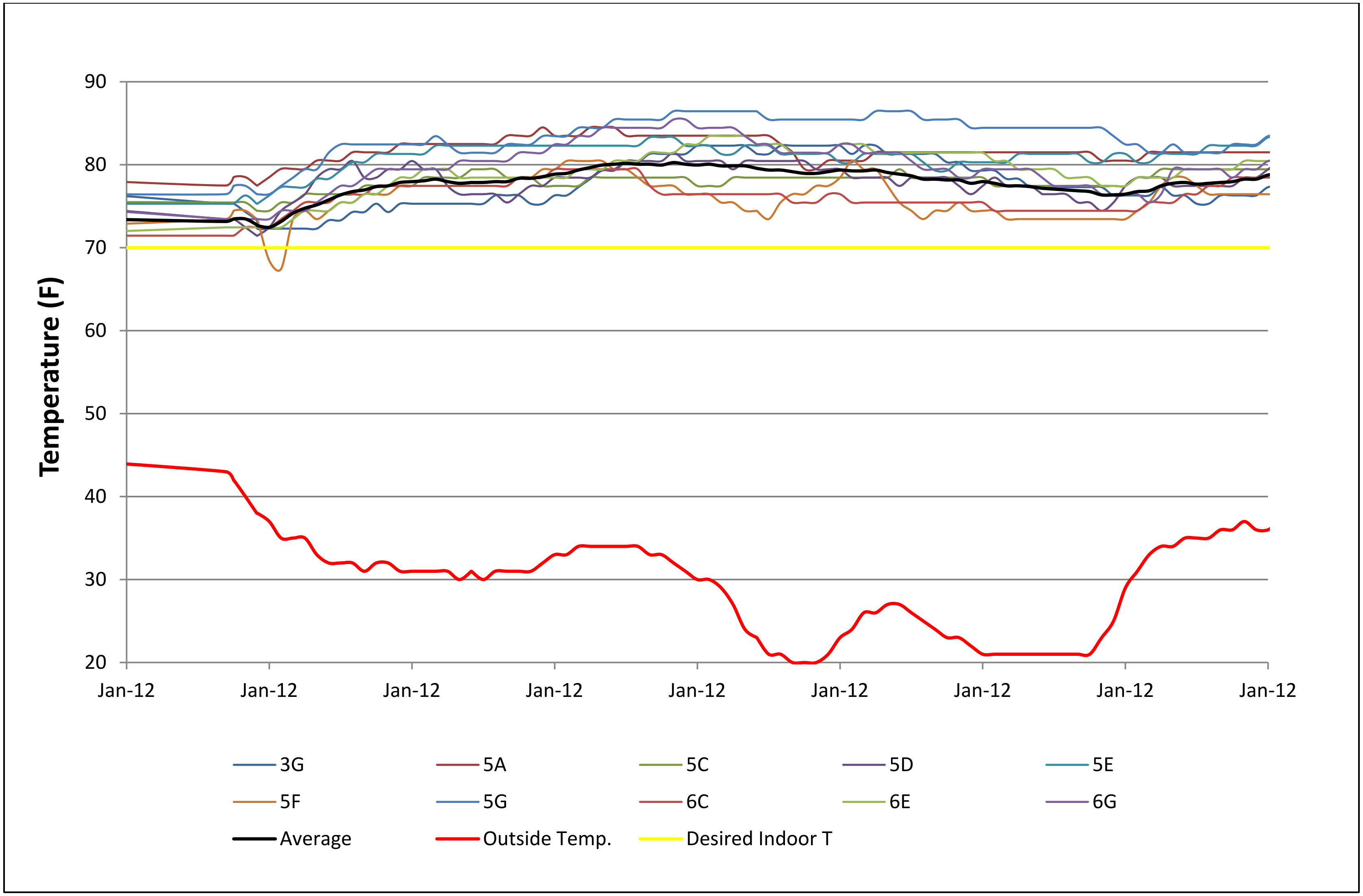

Figure 27. Building 18 temperatures

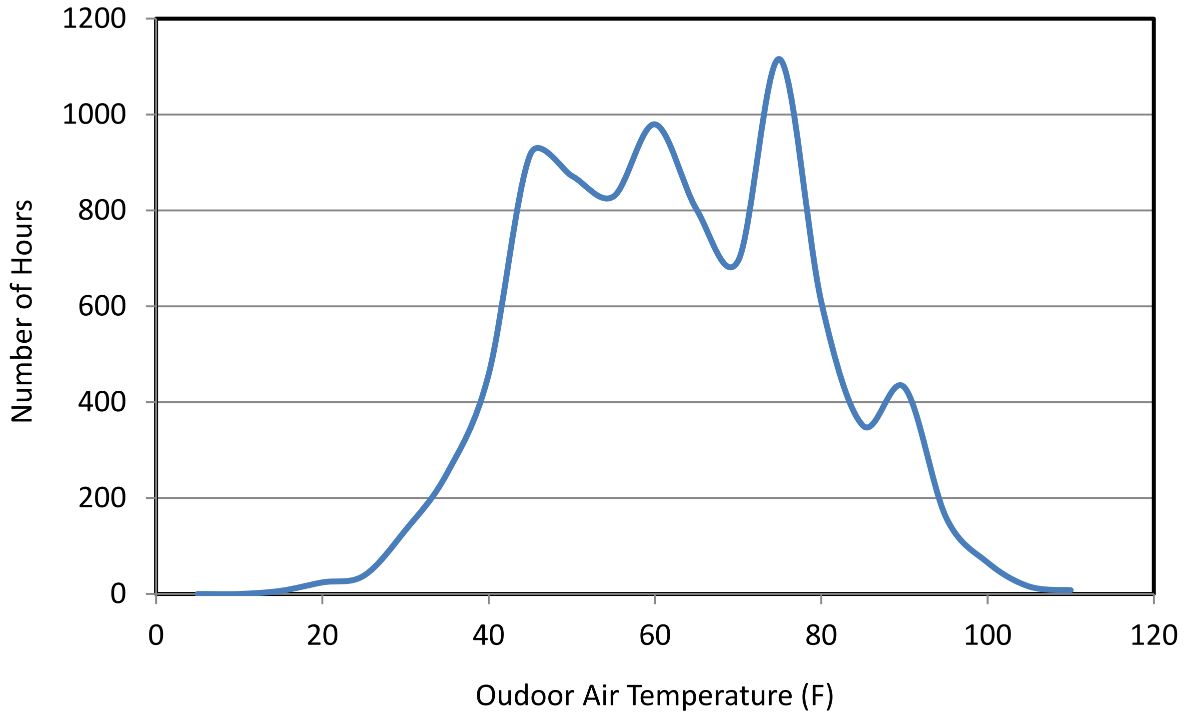

Figure 28. Outdoor air temperature in New York City from June 2011 to May 2012

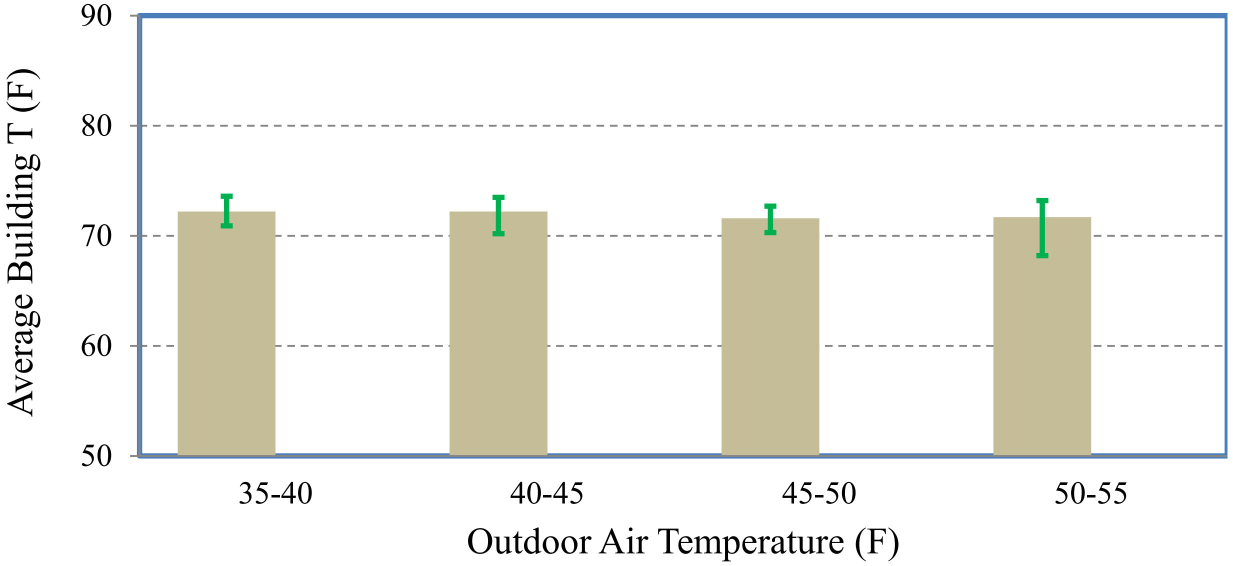

Figure 29. Indoor air temperature dependence on outdoor air temperature in building 1

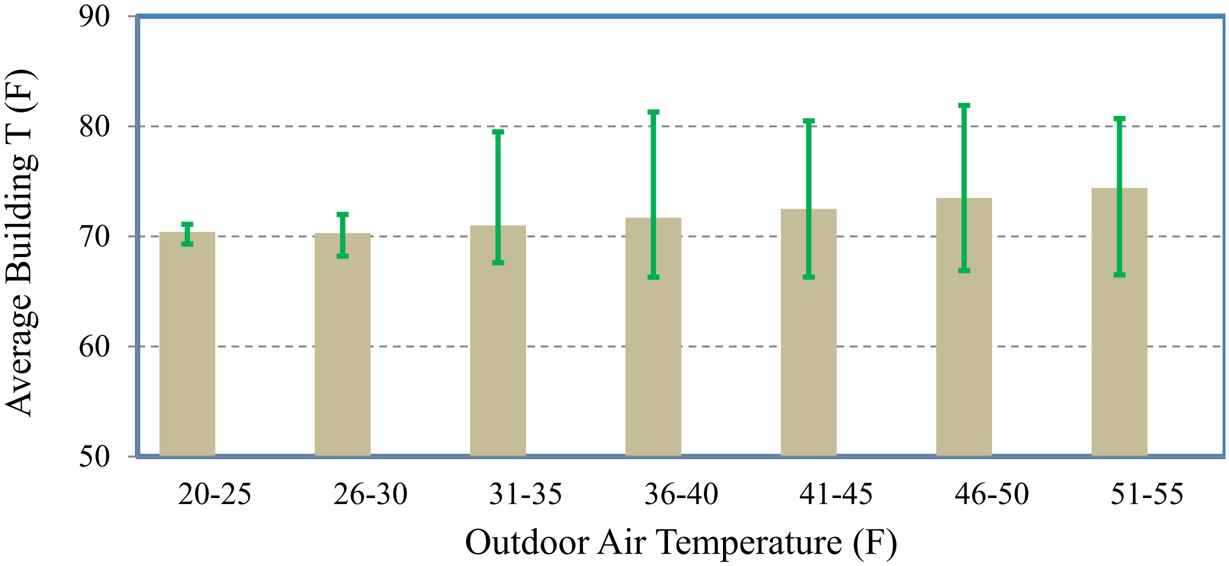

Figure 30. Indoor air temperature dependence on outdoor air temperature in building 2

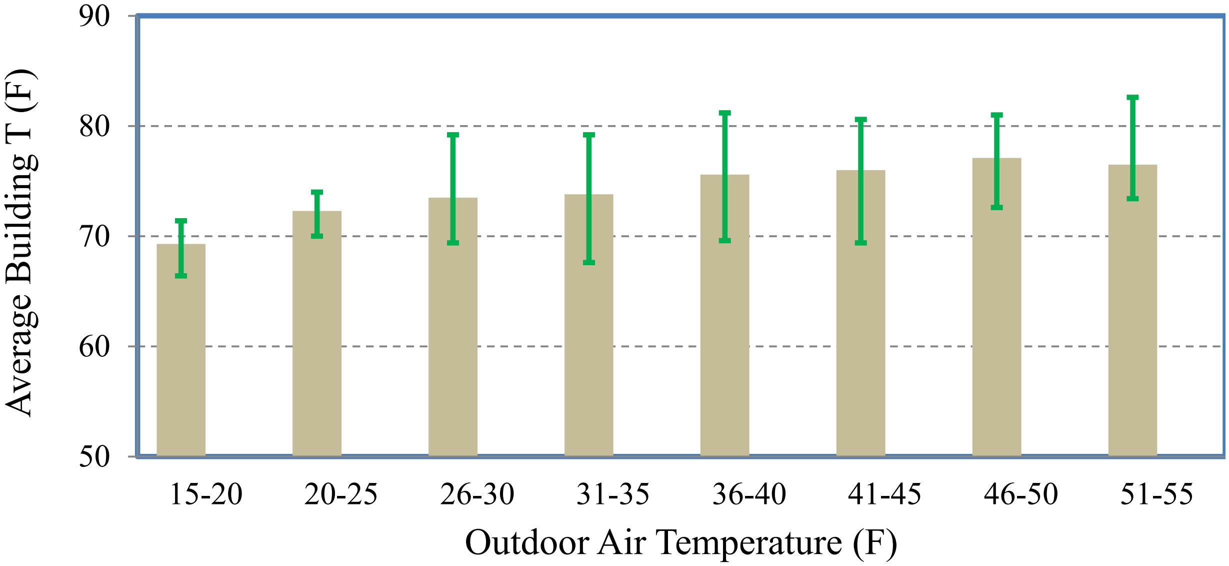

Figure 31. Indoor air temperature dependence on outdoor air temperature in building 3

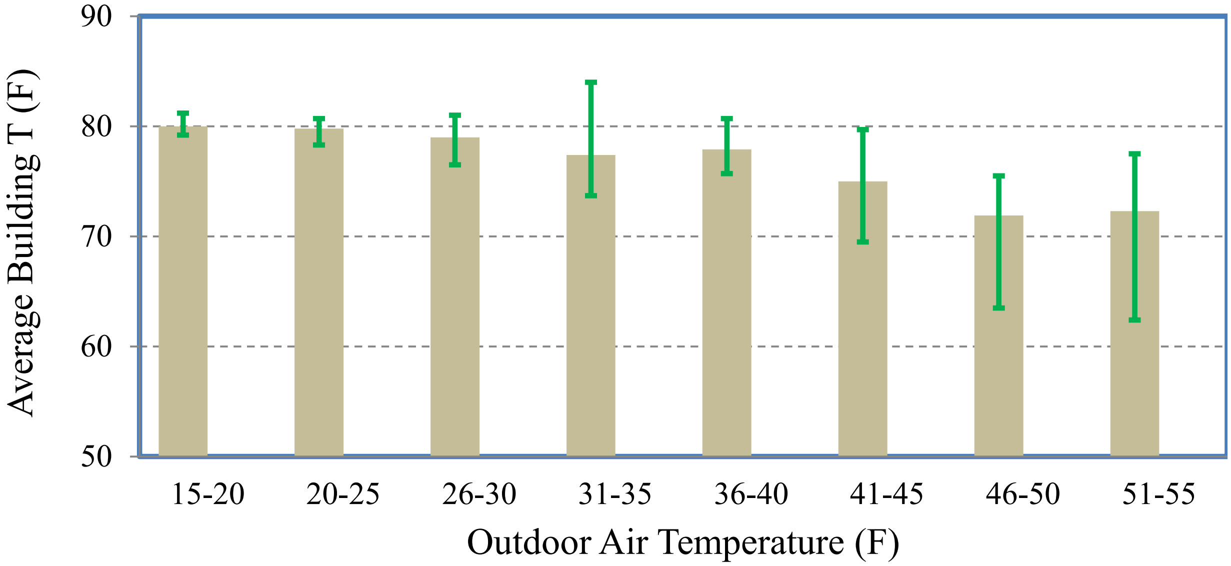

Figure 32. Indoor air temperature dependence on outdoor air temperature in building 4

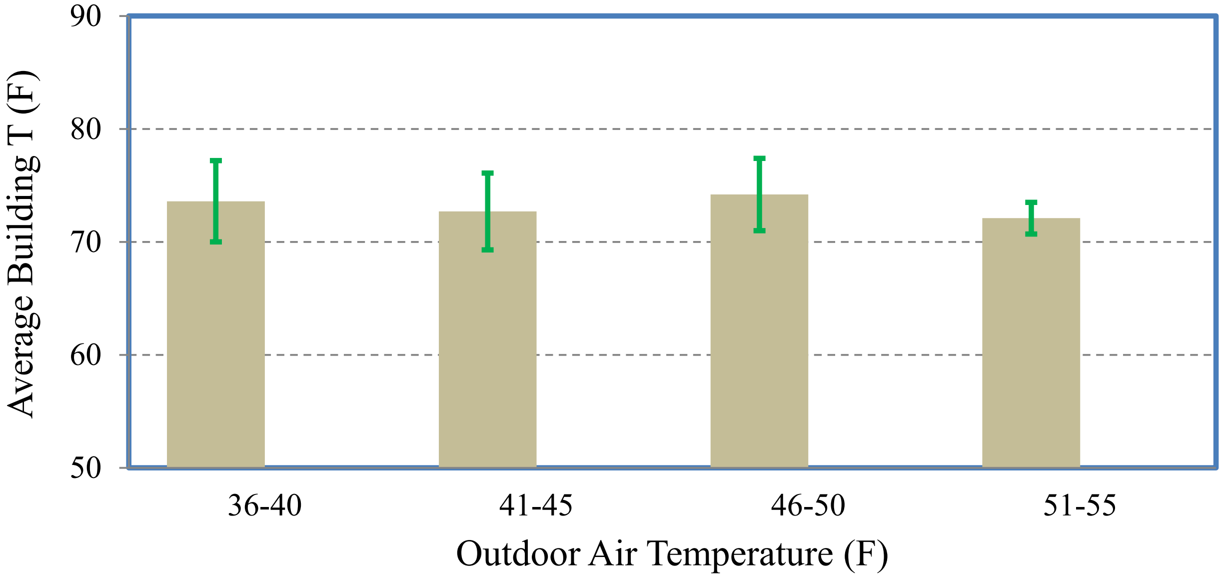

Figure 33. Indoor air temperature dependence on outdoor air temperature in building 5

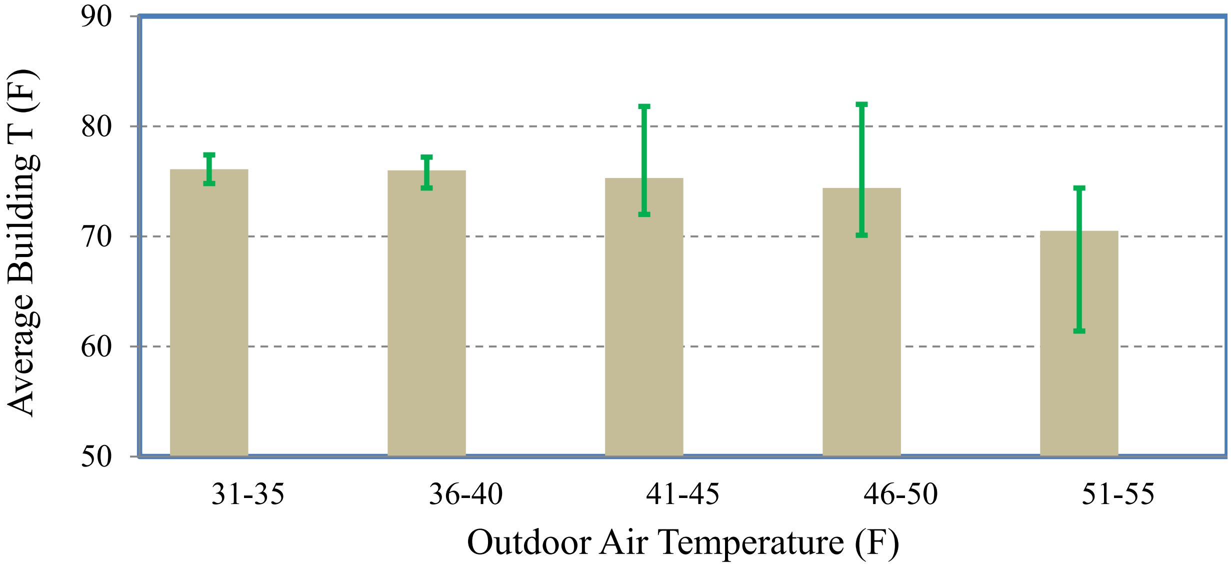

Figure 34. Indoor air temperature dependence on outdoor air temperature in building 6

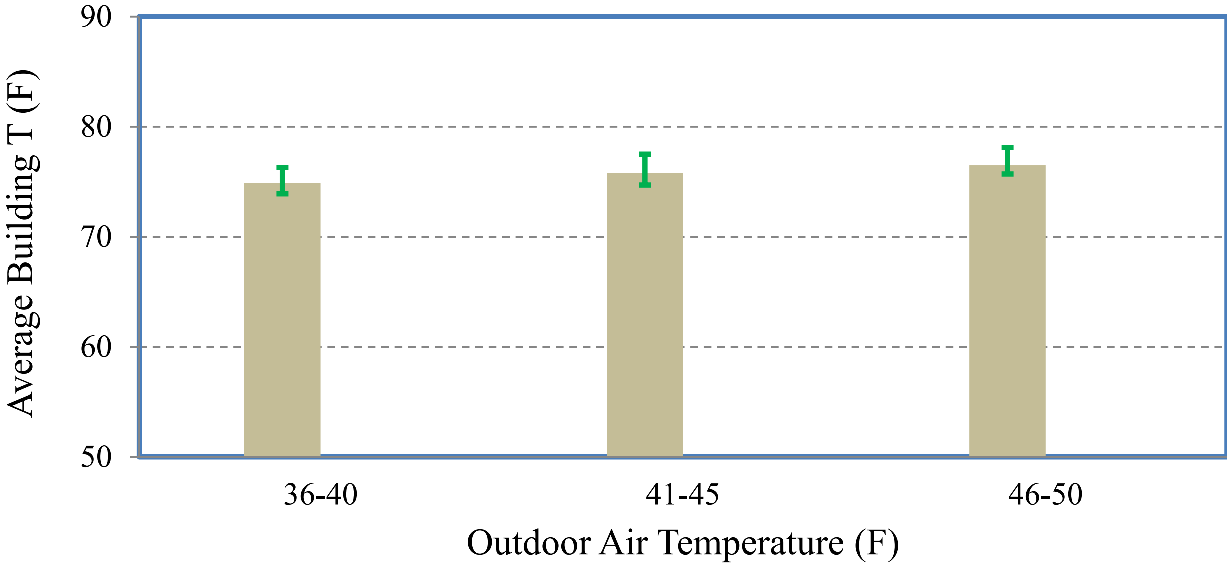

Figure 35. Indoor air temperature dependence on outdoor air temperature in building 7

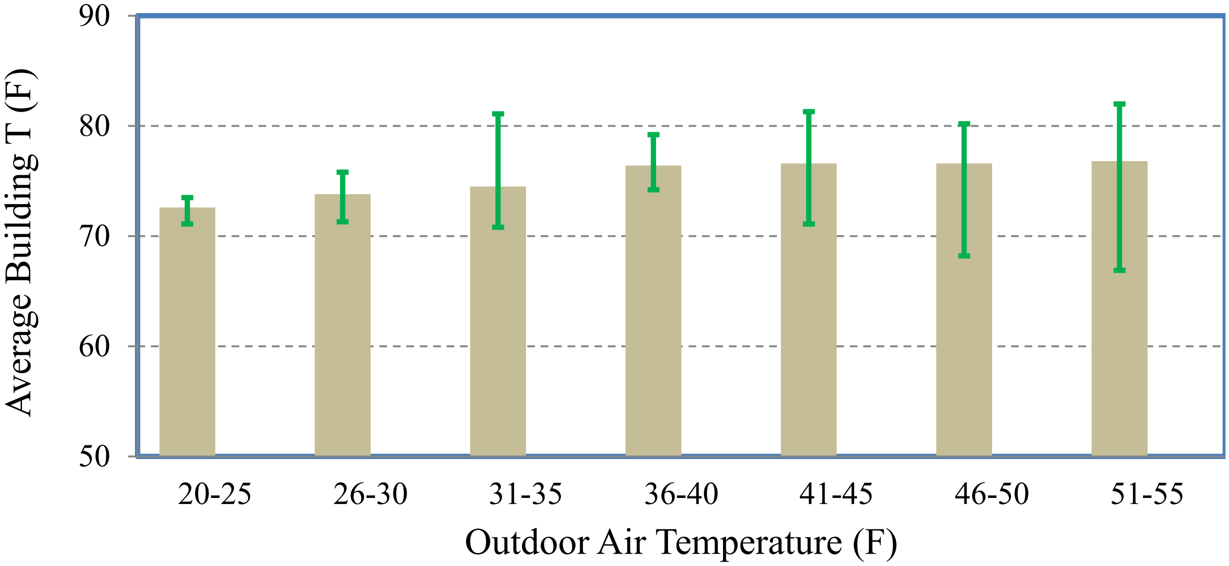

Figure 36. Indoor air temperature dependence on outdoor air temperature in building 8

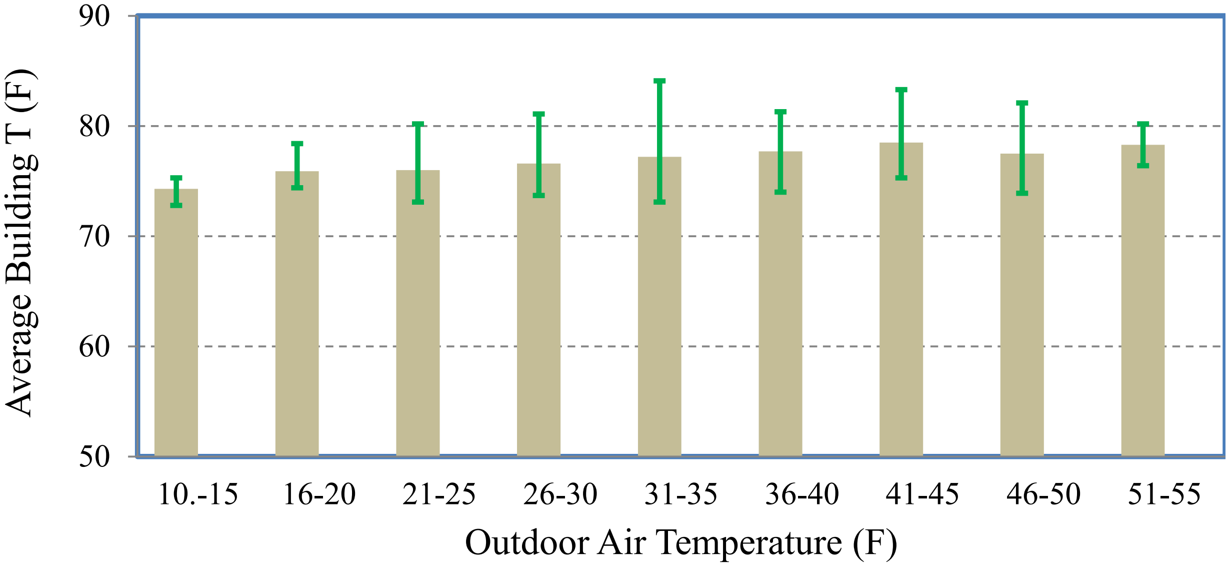

Figure 37. Indoor air temperature dependence on outdoor air temperature in building 9

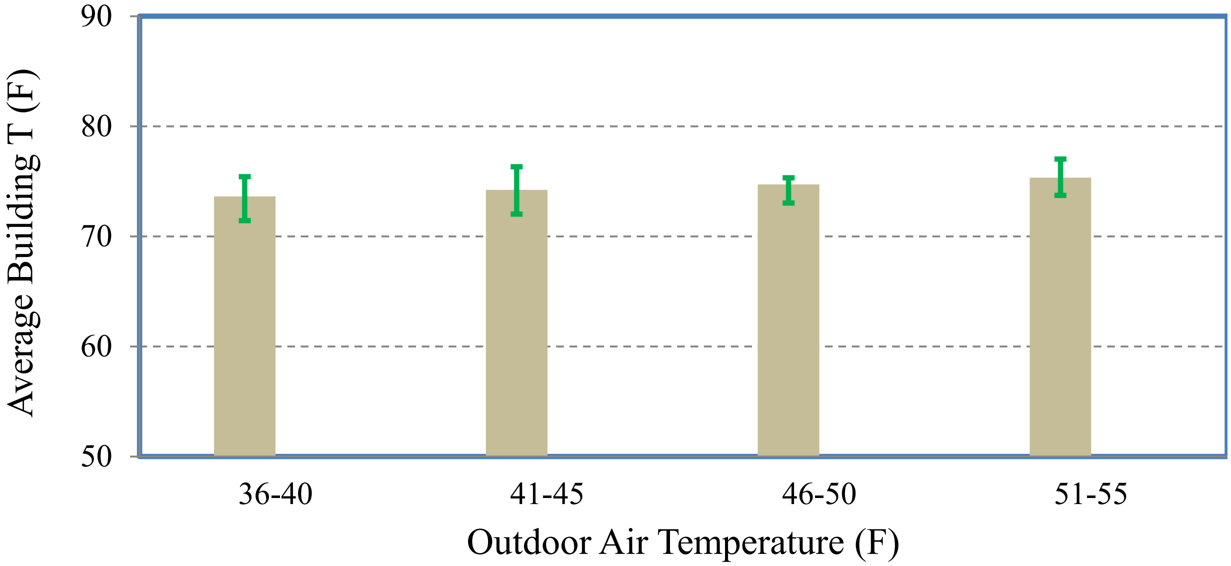

Figure 38. Indoor air temperature dependence on outdoor air temperature in building 11

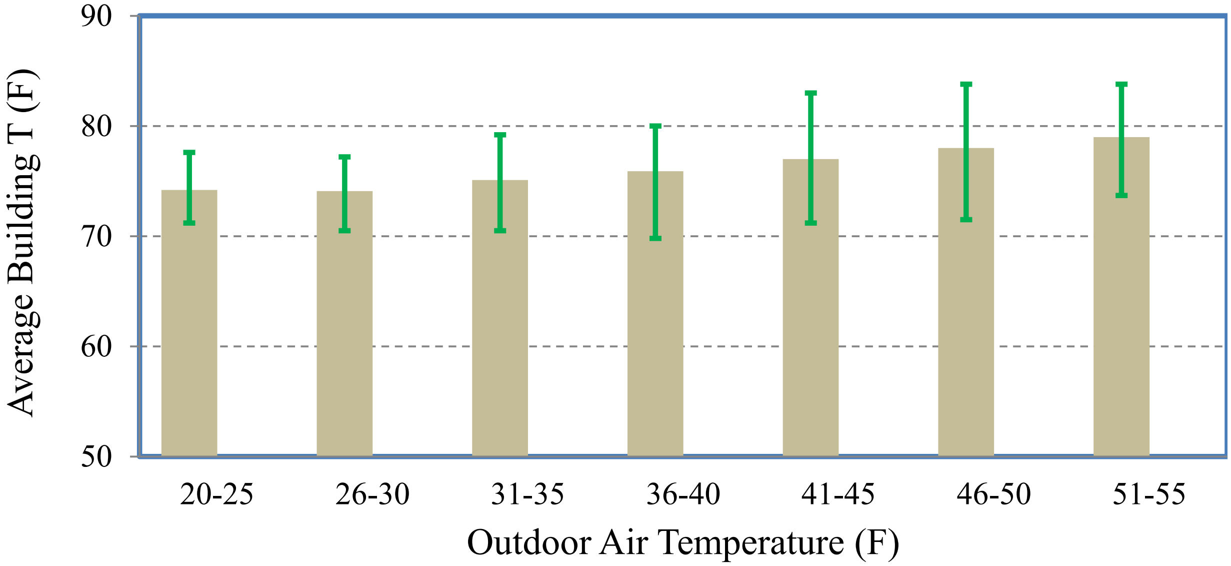

Figure 39. Indoor air temperature dependence on outdoor air temperature in building 13

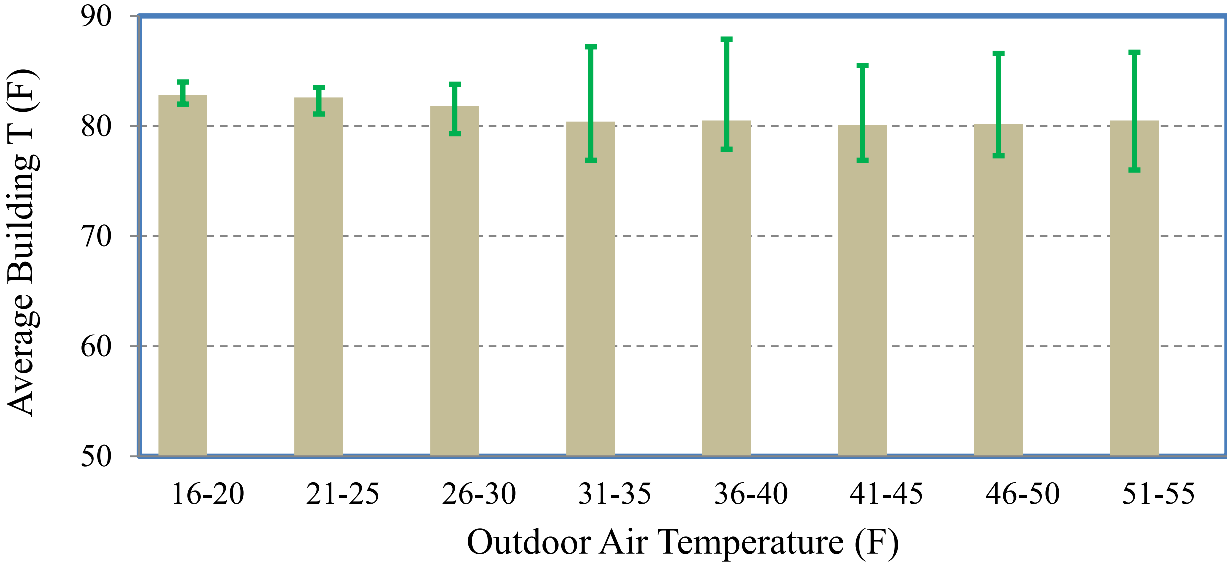

Figure 40. Indoor air temperature dependence on outdoor air temperature in building 14

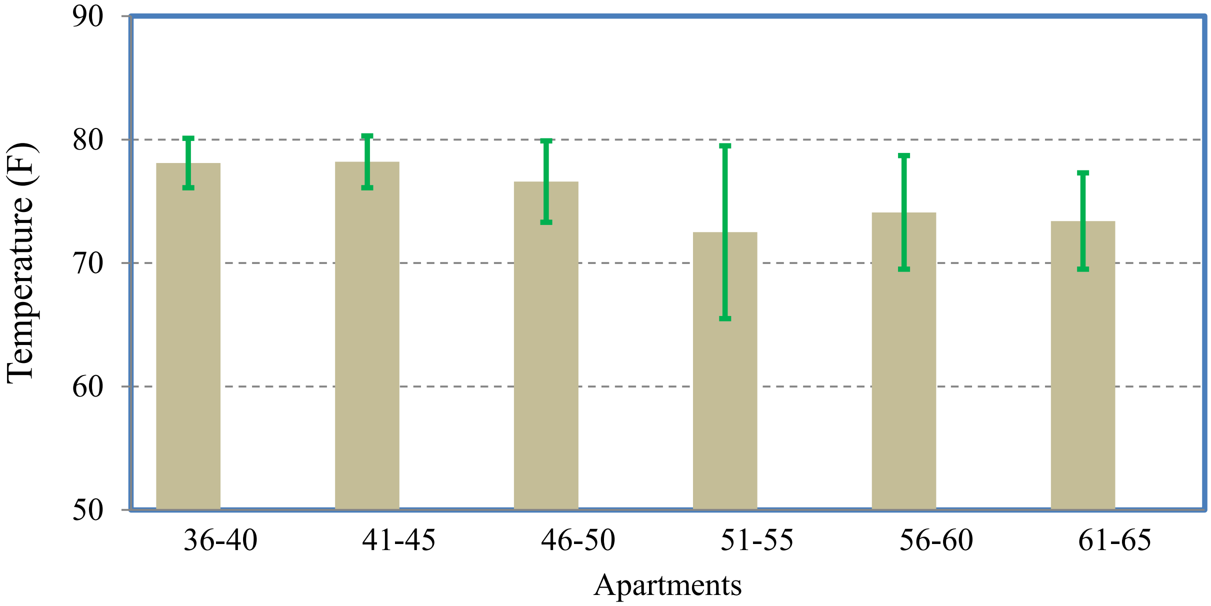

Figure 41. Indoor air temperature dependence on outdoor air temperature in building 15

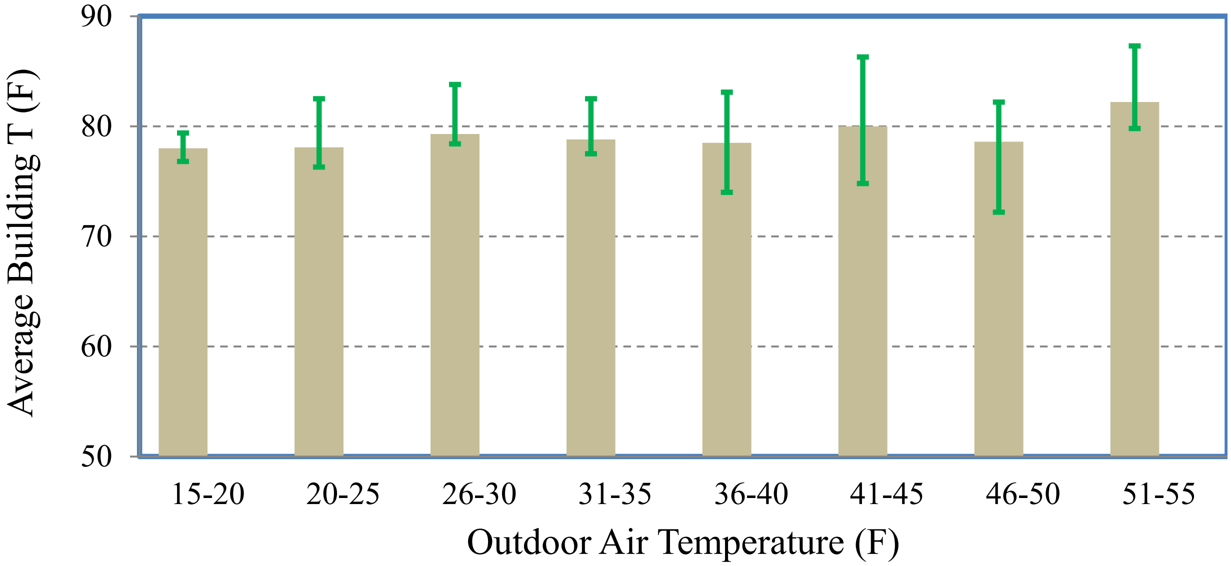

Figure 42. Indoor air temperature dependence on outdoor air temperature in building 16

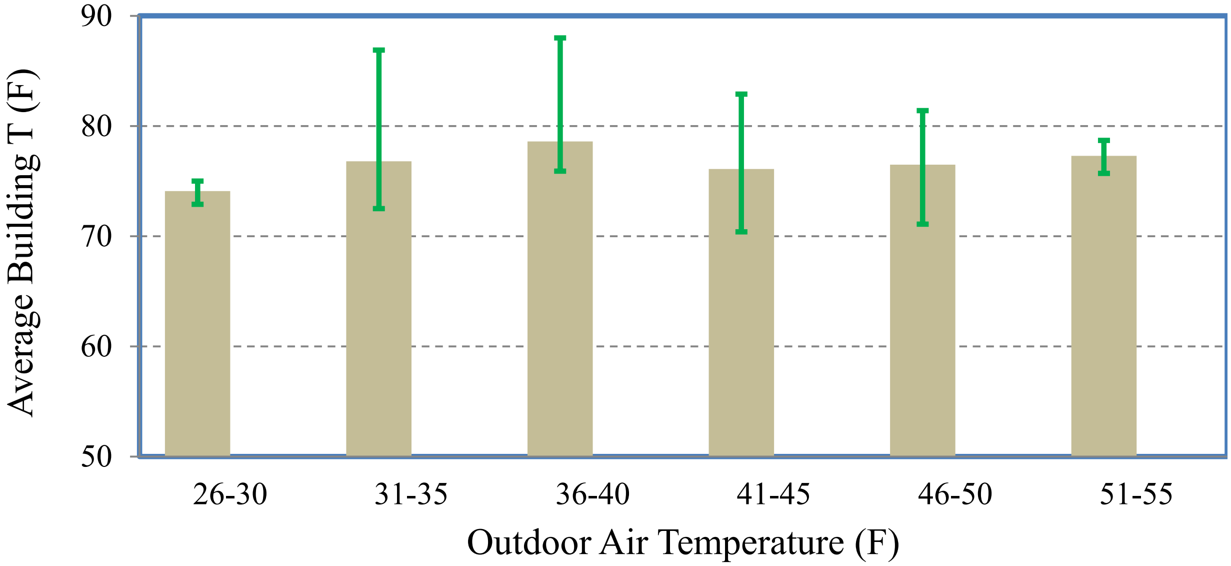

Figure 43. Indoor air temperature dependence on outdoor air temperature in building 17

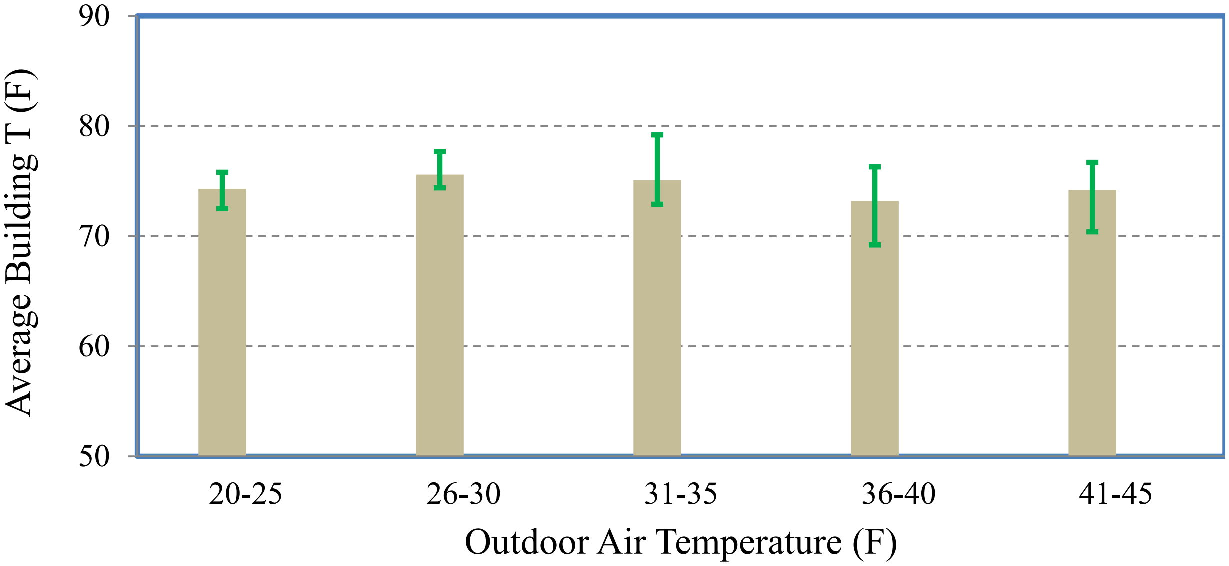

Figure 44. Indoor air temperature dependence on outdoor air temperature in building 18

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