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Summer Indoor Thermal Conditions and Heat Adaptation in Chicago Residences

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Executive Summary

As the climate warms, there is growing momentum towards characterizing heat exposure and vulnerability to extreme heat. Much research relies on outdoor temperature to understand heat exposure, yet indoor temperature is often a more accurate metric of heat exposure since the majority of Americans spend most of their time indoors. Specifically, thermal conditions within the home are less studied but some models of home temperature indicate dangerously high temperatures during extreme heat events (i.e., heat waves). Studies have shown that acute and chronic exposure to indoor heat can be harmful for health, resulting in effects like heatstroke and disturbed sleep quality. Perceptions on the risks of indoor heat are also not yet well understood but are important to study since those who are most at risk may not accurately perceive their risk and take appropriate actions during heat waves.

This study measured temperature and relative humidity in ten Chicago homes without central air conditioning during the summer of 2023. The homes included in the study represent five common housing types in Chicago, and the lack of central air conditioning in these homes is also a common characteristic of Chicago's residential building stock. Surveying the study participants yielded key insights on heat adaptive behaviors (e.g. closing blinds, opening windows) and participants' opinions on central cooling systems and perceptions of extreme heat.

Results were consistent with other studies, showing that indoor temperatures can reach dangerous levels and can even exceed outdoor temperature at times. While the sample size is too small to determine conclusive findings, it provides initial evidence of the thermal conditions of various home types in Chicago during the summer. Heat index findings show extreme conditions in many of the homes, with a maximum heat index of 120.1°F and a maximum heat index differential of 32°F within one home (between the basement and second floor). The study also showed that all participants used various behaviors and strategies to cope with extreme heat in their homes. Additionally, survey results showed that half of participants believed the temperature in their home reached unsafe temperatures at times during the summer, yet the results showed all homes hit "extreme caution" or "danger" levels during the worst heat wave.

The findings presented in this report specify the occurrence and severity of high indoor temperatures in archetypal Chicago homes and underscore the importance of policies and programs to protect people from extreme heat and prevent future heat-related health issues. We conclude with four main recommendations: access to safe conditions, additional risk assessment, improved risk communication and education, and additional research. These recommendations offer solutions toward reduced heat vulnerability and increased resilience among Chicago communities.

Introduction

Extreme heat is the leading cause of weather-related death in the United States, and exposure to extreme temperatures is a growing public health concern as temperature and humidity increase globally (National Weather Service, 2022). Heat waves in Chicago are projected to become more frequent, intense, and prolonged (Hayhoe et al., 2010). Chicago's heat wave season is expected to expand by one to two months, and heat wave duration is expected to increase by two to eight times depending on future greenhouse gas emissions levels (Hayhoe et al., 2010). The previous record occurred during Chicago's 1995 heat wave that resulted in over 700 deaths (National Weather Service, 2023; Semenza et al., 1996). Research indicates that mortality rates from extreme heat in Chicago will double over the next few decades (Petkova et al., 2014). Additionally, people living in historically colder climates like Chicago face greater health risks from extreme heat than populations in warmer climates, indicating a need for investment in increased awareness, preparedness, and adaptation efforts in cold climate locations as climate patterns shift (Howe et al., 2019; Kenny et al., 2018; Basu, 2009).

The use of mechanical cooling like central air conditioning (AC) protects people against heat-related morbidity and mortality, but access to AC varies across geography and demographics (Romitti et al., 2022). Nationally, 76% of single-family buildings have a central cooling system, but in Chicago only 30% of single-family buildings and 9% of 2-4 unit buildings have a central cooling system (Elevate & NREL, 2022a). Previous research on disparities in AC prevalence across four cities, including Chicago, found that central AC among Black households was less than half that among White households (O'Neill, Zanobetti, and Schwartz, 2005). Examining the interior temperatures of homes that do not have a central cooling system provides insight into the conditions of many households across Chicago and exposes opportunities for heat mitigation strategies and investment. This research focused on the five most common housing types in Chicago, representing over 333,000 homes citywide, allowing for a better understanding of how these building types perform during extreme heat events.

Illinois Institute of Technology and Elevate collected indoor temperature and humidity data in ten homes without central AC in Chicago for approximately four weeks during July 2023 and August 2023. Data was also collected about participants' experiences with extreme heat and their coping strategies. Our research questions were: (1) What are the interior temperature ranges within commonly occupied spaces in typical Chicago 1-4 unit homes? (2) What are the temperature differentials in masonry and frame constructed homes? (3) How do the temperatures compare to NREL and others' thermal resilience models? (4) Are temperature differential ranges smaller in homes that have been weatherized? (5) What adaptive capacity strategies and passive cooling strategies do households use to cope with extreme heat?

This project was funded by the Buffett Institute for Global Affairs at Northwestern University through the Defusing Disasters Working Group. Northwestern's Defusing Disasters Working Group aims to reduce the harmful impacts of extreme weather, and their current portfolio of work includes the development of a public health-based, community-driven Heat Vulnerability Index (HVI) with the Chicago Department of Public Health (CDPH). The HVI is a commitment under the 2022 Climate Action plan and is currently under development. The HVI will also be informed by data and community feedback gathered through the 2023

Chicago Heat Watch campaign.[1] Heat Watch is a community-guided urban heat island mapping campaign sponsored by the National Oceanic and Atmospheric Administration (NOAA), CAPA (Climate, Adaptation, Planning, Analytics) Strategies, CDPH, Chicago's Department of Environment (DOE), and Defusing Disasters. Together with resident scientists, the research partners used car-mounted sensors to assess outdoor temperature differentials across neighborhoods on 7/28/2023 (Heat Watch Activation Day), a date that coincided with the data collection period of this study. The building-level analysis of heat vulnerability in this study will be used with the community- and individual-level work led by Defusing Disasters. Together, this research seeks to understand different dimensions of vulnerability to inform the development of municipal and regional policies and programs for community climate resilience.

Background

Impacts of Heat Exposure

Habitable indoor conditions in the home are essential to human health as most people in the U.S. spend around 69% of their time at home (Klepeis et al., 2001). Much research on the health effects of extreme heat uses ambient temperatures to estimate human heat exposure and heat stress, though indoor temperatures provide a more accurate representation of heat exposure for most of the population. There is a limited body of research on thresholds for hazardous indoor thermal conditions, in part because the precise temperature at which heat could negatively impact health varies based on a multitude of factors like an individual's physiology, environment, clothing, and capacity to respond (Holmes et al., 2016; Kenny et al., 2018; WHO, 2018a). The Occupational Safety and Health Administration (OSHA) does not currently have a national standard for indoor temperatures but recommends office temperatures to be in the range of 68-76°F (20-24°C) with humidity in the range of 20%-60% (OSHA, 1995). The World Health Organization (WHO) guidelines state that an indoor temperature range of 64-75°F (18-24°C) is considered to have minimal health risk among healthy individuals and no heat-related health impact can be expected below 75.2°F (24°C) (WHO, 2018a). Guidelines for residential buildings in the United Kingdom state that diminished sleep quality and comfort occur when bedroom temperatures surpass 75.2°F (24°C) and established an overheating threshold of 78.8°F (26°C) for bedrooms (CIBSE, 2006).

The optimal indoor temperature range is also specific to a region since people are acclimatized to different temperatures in different climate regions (WHO, 2018a). The City of Chicago requires certain residential buildings to install air conditioning equipment in indoor common gathering areas when Chicago's heat index exceeds 80°F (City of Chicago, 2023). In 2023, the State of Illinois lowered the temperature at which electric and gas utilities can disconnect service to a residence where gas or electricity is used for space cooling; previously, shutoffs were prohibited when local temperatures were 95°F or greater, shutoffs are now prohibited when the temperature is 90°F or greater (Illinois Public Act 103-0019, 2023).

[1] Chicago Heat Watch Report:
https://www.chicago.gov/content/dam/city/depts/cdph/environment/heat_watch/Summary-Report-Heat-Watch-Chicago_CAPA-12.15.2023.pdf

The physiological stress of heat on the body can result in fatal outcomes, particularly for vulnerable groups. Acute and chronic heat exposure can inhibit the body's ability to regulate its core temperature and can result in heatstroke, hyperthermia, reduced cognition, elevated cholesterol levels, respiratory problems, reduced sleep quality, and can exacerbate existing medical conditions like cardiovascular disease (WHO, 2018b; Hajat et al., 2010; Basu, 2009). High indoor temperatures have been associated with increased risk of symptoms like fatigue, thirst, dry mouth, less frequent urination, trouble sleeping, increased heart rate, and reduced cognitive function (Teyton et al., 2022; Cedeño Laurent et al., 2018; Williams et al., 2019). Elevated levels of humidity also hinder the body's thermoregulation since the body cools itself through evaporative cooling of sweat, and excess water in the air slows down that process (Hajat et al., 2010). The Environmental Protection Agency states that relative humidity for a home should ideally be between 30%-50% and should remain under 60% while the National Weather Service (NWS) classifies dew point temperature of 65°F or greater as very uncomfortable.

Heat-related mortality and morbidity are strongly influenced by regional climate and human adaptation. There is particular risk to individuals who live in colder climates like Chicago compared to warm climate locations, and the temperature threshold for heat-related mortality is lower in cooler climates (Kenny et al., 2018; Hajat & Kosatky, 2009; WHO, 2018a; Curriero et al., 2002). Epidemiological studies show that populations in colder climate states face greater health risks from heat in comparison to warmer state populations that are more acclimatized and prepared for warm weather (Howe et al., 2019; Anderson & Bell, 2009; Kenny et al., 2018). Populations with limited experience and acclimatization to extreme heat, along with less infrastructure to respond to such events, are increasingly at risk for negative health issues as climate change increases the severity and duration of extreme heat events beyond what the population has experienced in the past. That risk is coupled with the Midwest having relatively low concern and risk perception around extreme heat, making for a potentially dangerous scenario in which the population does not adequately perceive the danger of extreme heat and is unable to sufficiently respond during extreme heat events (Saposhnik et al., 2022).

Factors Affecting Indoor Thermal Conditions

Indoor temperature and humidity can be influenced by outdoor temperature, building characteristics, surrounding environment (e.g., tree canopy, air quality, building density, proximity to large body of water, waste heat sources), and resident behavior (e.g., use of AC, ventilation, etc.) and occupancy. This section focuses on the impacts of outdoor temperature, building characteristics, and occupant behavior.

OUTDOOR TEMPERATURE

Increased outdoor temperatures correlate with increased mortality, but there are limitations to relying on outdoor temperature to understand the relationship between heat and health. Temperature varies across a city because of variables like urban design and vegetation, and heat exposure varies among households (Basu, 2009; Williams et al., 2019; White-Newsome et al., 2012; Smargiassi et al., 2008; Teyton et al., 2022). There is evidence supporting that indoor temperature varies significantly across different homes, even when outdoor temperatures are similar (Wright et al., 2005; White-Newsome et al., 2012). Smargiassi et al. (2008) measured indoor temperatures in homes without AC during the summer and determined that outdoor temperature explained only 22% of the indoor temperature variance. Previous studies have found that indoor temperatures of residential buildings can exceed outdoor temperatures. Residential indoor air temperature monitoring in Detroit showed that the average maximum indoor temperature was 34.85°C, which was 13.8°C higher than average maximum outdoor temperature (White-Newsome et al., 2012).

Research also suggests that outdoor temperatures often decrease at nighttime during heat waves while indoor temperatures remain high (Williams et al., 2019; Kenny et al., 2018; Wright et al., 2005). A temperature monitoring study by Quinn et al. (2017) found that, across homes with various types of AC, average nighttime bedroom temperatures were higher than outdoor temperatures. These results also showed that nighttime bedroom temperatures exceeded the UK's bedroom overheating threshold of 26°C in homes without central AC, and homes with central AC surpassed the 24°C sleep impairment threshold on the warmest nights of the summer.

BUILDING CHARACTERISTICS

Research has shown substantial variation in indoor temperatures across residential building types, and susceptibility to overheating varies based on the building's characteristics (Oikonomou et al., 2012; White-Newsome et al., 2012; Larsen et al., 2022). A study of indoor temperature in different housing types in Detroit, MI, found higher indoor temperatures in single-family homes compared to high-rise and two flat buildings (White-Newsome et al., 2012). A model of indoor temperatures in homes across 3 cities (Atlanta, GA; Detroit, MI; Phoenix, AZ) during a heat wave showed that single-story, single-family homes had the lowest insulation values and the highest rate of indoor temperature increase while apartments experienced lower temperatures (Stone et al., 2021). Larsen et al. found that larger homes were cooler than smaller homes, and multifamily homes had significantly lower indoor temperatures than single-family homes across Atlanta, Detroit, and Phoenix. (2022). These findings could be explained by multifamily and high-rise buildings having fewer exterior surfaces that are exposed to solar radiation, greater heat capacity because of increased interior air volume, and higher insulation levels.

Many of the residential buildings in cold climates like Chicago's were designed to retain heat in cold weather which can result in these buildings also retaining heat during extreme heat events (Williams et al., 2019). Research suggests that masonry homes are slower to warm up but retain heat over longer periods and are slower to release heat at night (Wright et al., 2005). Larsen et al. (2022) found that masonry exteriors exacerbated the influence of high outdoor temperature on indoor temperature, suggesting that masonry exterior is a predictor for higher indoor temperatures. However, White-Newsome et al. (2012) found that homes with wood or vinyl exteriors were more susceptible to internal heat gains and sensitive to outdoor temperature than masonry homes. The authors found that masonry homes were more resilient to heat, due to being constructed with more insulation, while frame homes had less insulation and higher indoor temperatures. Oikonomou et al. (2012) found higher indoor temperatures among London homes with very low insulation and homes with very high insulation that lacked methods of reducing solar heat gains. The age of the building also influences indoor temperature, with older buildings experiencing higher indoor temperatures than newer buildings (Nahlik et al., 2017; White-Newsome et al., 2012; Larsen et al., 2022). This finding could be attributed to less insulation and the use of single-pane windows in older buildings.

Additionally, those living on the top floor of a building are also shown to be at increased risk for high indoor temperatures (Semenza et al., 1996; Oikonomou et al., 2012). Results from a study of indoor temperature in New York City indicate that, regardless of AC presence, apartments on the top floor of a building were significantly hotter than other apartments (Quinn et al., 2017).

RESIDENT BEHAVIOR

Research indicates that heat-mitigating behaviors can effectively reduce temperatures during extreme heat events (Georgescu, Broadbent, & Krayenhoff, 2023). A study of indoor thermal conditions modeled during a heat wave showed that using shading and natural ventilation (e.g. window opening) can lower indoor temperatures by up to 25°F and reduce the number of hours of dangerous temperatures in the home (Rempel et al., 2022). Additionally, individual behaviors like opening windows and using AC have been shown to have the strongest influence on indoor heat index (Tsoulou et al., 2020).

Using AC, using electric fans, and opening windows are among the most used adaptive behaviors (White-Newsome et al., 2011; Quinn et al., 2017; Tsoulou et al., 2020). Research suggests there may be a geographic or demographic component to the relative utilization of each of these behaviors. For example, elderly people in Detroit opened windows and used fans more often than AC while residents in New York City used AC and closed window shades more often than they used fans (White-Newsome et al., 2011; Quinn et al., 2017). Studies of residential indoor temperature have found that buildings without central AC are significantly warmer than buildings with central AC (Larsen et al., 2022; Williams et al., 2019). Buildings without central AC but with access to window AC units or portable AC units were warmer than buildings with central AC (Quinn et al., 2017; Williams et al., 2019). There is also evidence that the presence of AC alone cannot predict safe indoor temperatures since factors like limiting AC use to avoid excessive costs, lack of electricity, and non-functioning AC equipment can all contribute to heat-related illness and death (Rempel et al., 2022).

Some of the less frequently reported cooling strategies include taking a cool shower, changing clothes, going to the basement or the porch, and leaving home for a cooler place (White-Newsome et al., 2011; Quinn et al., 2017; Milando et al., 2022; Lane et al., 2023). Madrigano et al. (2018) found that most people stay home during hot weather, with only 12% of people leaving home to go to a public place with AC. This finding is consistent with other research showing that leaving the house is one of the least utilized adaptive behaviors, and findings suggest that the decision to leave home during hot weather may be unrelated to high indoor temperatures (White-Newsome et al., 2011; Quinn et al., 2017; Tsoulou et al., 2020).

Methods

To address the existing knowledge gaps identified in the literature, this study developed five main research questions:

- <u>*Question 1:*</u> What are the interior temperature ranges within commonly occupied spaces in typical Chicago 1-4 unit homes without central AC, such as the first floor vs. the second floor?
- <u>*Question 2:*</u> What are the temperature differentials in masonry and frame constructed homes?

- *Question 3:* How do the temperatures compare to NREL and others' thermal resilience models?
- *Question 4:* Are temperature differential ranges smaller in homes that have been weatherized, (i.e., have air sealing and insulation)?
- *Question 5:* What are the adaptive capacity strategies (e.g., taking frequent showers, using fans, vacating the home, etc.) and the passive cooling strategies employed (e.g., opening windows when exterior temperatures drop below indoor, closing drapes on windows when they experience direct sun, etc.)?

This section introduces the methods used to address these questions in the results section.

Study Recruitment and Duration

Findings presented in this study rely on two primary data sources: (1) data collected from 40 sensors in ten homes that measured indoor temperature and relative humidity at high temporal and spatial resolution; and (2) survey data collected from ten residents focusing on risk perception, heat adaptation, and AC usage. The study was conducted during July and August 2023. Participants were recruited by Elevate via a convenience approach using outreach to personal contacts. Eligibility for participation included the following criteria: own and reside in a 1-4 unit home in Chicago that is one of the five prevalent home types (Elevate & NREL, 2022a), reside in a home without central air conditioning or heat pumps, and reside in a home in which no members of the household were vulnerable to heat stress. Participants were also required to have Wi-Fi in their home since some of the sensors needed Wi-Fi connection to operate. The study was approved by the Institutional Review Board of the Illinois Institute of Technology.

Building Information and Survey

A visit was conducted to each home to install temperature and relative humidity monitors and to collect data on the location and number of window air conditioning units, most and least-often occupied rooms, the warmest and coolest rooms, and the number of floors. Building age, type (single-family or 2-4 unit), and exterior construction were collected from the Cook County Property Assessor database[2].

Participants were also asked to complete a survey with questions about extreme heat concerns, risk perception, strategies, and behaviors to mitigate heat exposure, and reasons for not having central cooling. The full survey can be found in Appendix A: Survey Questions.

Indoor Temperature and Humidity Measurement

This study used two sets of instruments to collect indoor data: (1) custom wet bulb globe temperature (WBGT) loggers that enable long-term measurement of indoor globe temperature, temperature, and relative humidity (Figure 1-a) and (2) Wi-Fi loggers that enable short-term real-time data collection (Figure 1-b).

[2] Cook County Property Assessor: https://www.cookcountyassessor.com/

(a) (b)

Figure 1. The two sets of instruments that were used: (a) the WBGT logger and (b) the Wi-Fi logger

The custom WBGT logger included a black body sphere with a TMC20-HD Onset temperature sensor (Onset-a, 2023) inside of the black sphere to measure the globe temperature (Ali et al., 2020). The globe temperature sensor was connected to an MX-1104 Onset logger channel (Onset-b, 2023) that recorded temperature, relative humidity, and light levels. All the parameters were recorded at a one-minute time interval, and the data were stored on the MX 1104 logger. The Wi-Fi loggers measured temperature and relative humidity at a 15-minute interval, the highest resolution of time interval available for the instrument (TempStick-a, 2023). The data were sent via 2.4 GHz Wi-Fi to an online dashboard for real-time visualization and data download (TempStick-b, 2023). Table 1 summarizes the sensor information and their specifications.

Table 1. Information about the time interval of data collection and sensor specifications

Name	Time interval	Parameter	Range	Accuracy	Resolution
WBGT logger	1-minute	Globe temperature	-40°F to 212°F	±0.27	0.003° at 77°F
		Air temperature	-4°F to 158°F	±0.36°F from 32° to 122°F	0.004°F at 77°F)
		Relative humidity	0% to 100% at -4°F to 158°F	±2.5% from 10% to 90% (typical) to a maximum of ±3.5%	0.01%
		Light level	0 to 167,731 lux (15,582 lum/ft^2)	±10% typical for direct sunlight	-
Wi-Fi logger	15-minute	Air temperature	-40°F to 125°F	±0.27	-
		Relative humidity	0-100%	±2%	-

For each home, four loggers were installed, including two WBGT loggers and two Wi-Fi loggers. For homes with two stories, one WBGT logger and one Wi-Fi logger were installed on each floor. For homes with one floor, all four loggers were installed on the same floor and, when possible, some of them were co-located to evaluate consistency between the two logger types. For homes with an occupied basement, one sensor was placed in the basement. To ensure the Wi-Fi sensors could successfully transmit data, they were located near the Wi-Fi router.

Indoor Temperature and Humidity Analysis

To assess potential impacts of summer extreme heat, several metrics were analyzed: (1) indoor atmospheric properties such as air temperature (i.e., dry bulb temperature), relative humidity, dew point temperature, and wet bulb temperature, (2) standard effective temperature (SET), (3) wet bulb globe temperature, and (4) heat index.

Standard Effective Temperature (SET) is a method of evaluating temperature conditions and the impact on the body, accounting for air speed, operative temperature, and occupant metabolic rate and clothing worn. ASHRAE 55-2020 defines SET as "the temperature of an imaginary environment at 50% relative humidity, < 0.1 m/s [20 fpms] average air speed, and mean radiant temperature equal to average air temperature, in which total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level." SET accounts for a more detailed representation of human physiology accounting for skin temperature and skin wetness.

Wet Bulb Globe Temperature (WBGT) is a measure of radiant (20%), convective (10%), and adiabatic cooling (70%) heat transfer processes (or sometimes for indoors the convective and radiant are merged together). This metric is a function of wet bulb temperature (T_W), globe temperature (T_G), and ambient (dry bulb) temperature (T_D). For this study, the black body spheres measured the globe temperature values, and next to them, there was a built-in sensor to measure the room temperature, which is the dry bulb temperature. Figure 2 shows ranges of WBGT values and their associated recommendations.

WBGT	Non-acclimatized, unfit or high risk individuals	Acclimatized, fit, low-risk individuals
65.1-72.0	Increase the rest:work ratio. Monitor fluid intake	Normal activity
72.1-78.0	Increase the rest:work ratio. Decrease total duration of activity	Monitor fluid intake
78.1-82.0	Decrease intensity and total duration of activity	Monitor fluid intake
82.1-86.0	Increase the rest:work ratio to 1:1. Limit intense exercise. Watch at-risk individuals carefully	Plan intense for prolonged activity with discretion. Watch at-risk individuals carefully
86.1-90.0	Cancel or stop practice and competition	Limit intense exercise and total exposure to heat and humidity. Watch for early signs/symptoms of heat stress
>90.0	Cancel exercise	Cancel exercise. Heat stress exists for all athletes
American College of Sports Medicine (ACSM) guidelines for training or non-continuous activities.		

Figure 2. The ranges of WBGT values

For this study, an air temperature (i.e., dry bulb temperature) of 80°F is used as a threshold for high temperature since this is a temperature at which indoor conditions are considered potentially unsafe (WHO, 2018b). This study also reports on heat index, which accounts for temperature and humidity, and a heat index of over 103°F is used to indicate danger. The NWS classifies a heat index threshold of 103°F as dangerous since prolonged exposure is likely to result in heat cramps or heat stroke. As indicated by the NWS, an alert is generated when the heat index is expected to exceed 105-110°F for at least two consecutive days (NWS, 2023). Additionally, Chicago's Cooling Ordinance requires certain residential buildings to install air conditioning in common gathering areas when the outdoor heat index exceeds 80°F (City of Chicago, 2023). Figure 3 shows the recommended ranges of caution, extreme caution, danger, and extreme danger for the heat index metric.

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure and/or Strenuous Activity
Caution | Extreme Caution | Danger | Extreme Danger

Figure 3. The ranges of heat index and likelihood of heat disorders; source: National Weather Service

The results in this report focus on temperature and heat index since these two metrics are commonly used by different stakeholders for communications and are easier to understand. Results of other metrics are presented in the Appendices.

Results

Building Characteristics

The five housing types included in the study were single-family frame construction 1-2 stories built pre-1942, single-family masonry construction 1-2 stories built pre-1942, 2-4 unit frame construction built pre-1942, 2-4 unit masonry construction built pre-1942, and single-family masonry construction built 1943-1978. Table 2 shows detailed building characteristics for each home. These five housing types were selected due to their prevalence in Chicago, as these home types make up over 75% of the total residential building stock (Elevate & NREL, 2022a). Additionally, these home types are common in Chicago's low-income neighborhoods, environmental justice communities, and communities that have historically experienced disinvestment. Table 3 includes photos representing the housing types of each of the ten homes in the study.

Table 2. Building characteristics and data collection periods for each home

Home #	Start date	End Date	Duration (days)	Exterior	Type	Year Built	No. of Occupied Floors	Community Area
1	8/2	8/28	26	Frame	Single-Family	1894	2	Logan Square
2	7/25	8/28	34	Frame	Single-Family	1899	2	Logan Square
3	7/27	9/8	43	Masonry	Single-Family	1964	1	Calumet Heights
4	7/25	8/28	34	Masonry	Single-Family	1931	3	Hermosa
5	7/25	8/28	34	Masonry	Single-Family	1899	2	Logan Square
6	7/31	10/3	64	Frame	2-4 Unit	1899	2	Logan Square

Table 2. Building characteristics and data collection periods for each home (continued)

Home #	Start date	End Date	Duration (days)	Exterior	Type	Year Built	No. of Occupied Floors	Community Area
7	8/2	9/8	37	Masonry	2-4 Unit	1879	2	West Town
8	8/3	8/29	26	Masonry	2-4 Unit	1917	1	Albany Park
9	7/25	8/28	34	Masonry	2-4 Unit	1928	2	Logan Square
10	7/25	8/29	35	Masonry	2-4 Unit	1924	2	Edgewater

*Table 3. Photos of the ten homes in the study**

Home 1	Home 2	Home 3	Home 4	Home 5
				
Home 6	**Home 7**	**Home 8**	**Home 9**	**Home 10**
				

**Not all photos show the actual home in the study, but all represent the housing type of the actual home*

While most of the sensors were installed in unconditioned spaces, there were some spaces that utilized a simple cooling system in the form of window air conditioners (AC) or portable air conditioners (PAC). Sensors were placed in the following semi-conditioned spaces: two spaces in Home #2 with a window AC, one space in Home #3 with a window AC and one space with a PAC[3], one space in Home #4 with a window AC, two spaces in Home #5 with a window AC and one space with a PAC[4], one space in Home #6 with a window AC[5], two spaces with a window AC in Home #8[6], and one space with a window AC in Home #10.

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[3] All spaces in Home #3 are categorized as unconditioned since the AC was not in use during the majority of the study period.
[4] The remaining unconditioned space in Home #5 is also categorized as semi-conditioned since PAC significantly impacted the nearby unconditioned space due to its proximity.
[5] All spaces in Home #6 are categorized as unconditioned since the AC was not in use during the majority of the study period.
[6] All spaces in Home #8 are categorized as semi-conditioned since the window ACs significantly impacted the two unconditioned spaces due to their proximity.

The AC was not used all the time in these spaces, but they are still categorized as semi-conditioned spaces. Overall, five other spaces are categorized as semi-conditioned due to their proximity to spaces with window AC or PAC: two spaces in Home #5, two spaces in Home #8, and one space in Home #10[7]. All other spaces with sensors are categorized as unconditioned. Refer to Appendix D: Floor Plans for more detail on the location of each air conditioning unit per home.

Temperature and Heat Index Distributions

Table 4 and Table 5 provide the distribution of the heat index and temperature values for all spaces for four different time intervals: (1) monitoring period from 7/25/2023 to 8/31/2023 excluding the extreme heat days of 7/8/2023, 8/23/2023, and 8/24/2023; (2) the extreme day of 7/28/2023 (Heat Watch Activation Day); (3) the extreme day of 8/23/2023; and (4) the extreme day of 8/24/2023.[8]

On each floor, two types of sensors were used, WBGT loggers and Wi-Fi loggers. Two different approaches were followed in assessing the data. The initial approach was to combine data from each sensor on each floor by taking an average of the values, and then comparing the values between floors. However, the averaging approach was not pursued for two reasons: (1) the averaging process could change the peak value observed for the hottest (or coldest) reading which could lead to different differential values and, (2) because the WBGT loggers and Wi-Fi loggers differed in granularity of time series, the average approach could not be taken without finding a way to match time stamps between the sensors. This was accomplished by resampling data from the Wi-Fi loggers, meaning it was assumed all readings between the 15 minutes were the same.

The second approach, used in developing Table 4 and Table 5, was to report the data from each space and not consider resampling the data. Minimum, maximum, and average values were reported alongside total time above danger threshold for each sensor based on the actual readings. For the heat index, the value of 103°F is used as the danger threshold and the number of hours in danger are shown in the tables. For temperature, the number of hours over 80°F are reported. The maximum differential between the floors were obtained by calculating maximum differentials between each two sensors and selecting the largest value among them. Differentials between floors were calculated to better understand the risk of extreme heat within the homes, to address one of the research questions, and determine which areas of the home are safer. The differential between floors is based on the unconditioned spaces unless the home does not have any unconditioned spaces, or the home does not have unconditioned spaces between the floors. It is also worth noting that even though maximum differentials are a good indicator of the risk of extreme heat within the homes, it does not necessarily mean that the homes did not experience a differential close to the maximum differential at other times. Therefore, assessing differentials through the course of temperature monitoring is also important.

[7] The first floor spaces in Home #10 are categorized as semi-conditioned since the window AC significantly impacted the neighboring unconditioned space due to their proximity.

[8] During the monitoring period, temperatures were generally moderate and similar to historic averages. However, Chicago Office of Emergency Management issued a heat advisory for 7/28/2023 and an excessive heat warning for 8/23/2023 and 8/24/2023.

Table 4 shows heat index values for monitored spaces in each home. All ten homes met or exceeded the NWS Heat Index thresholds of caution (heat index of 80°F or higher) and extreme caution (heat index of 90°F or higher) on 8/24/2023. On that same day, eight homes met or exceeded the danger threshold of (103°F or higher) for 2 to 23 hours. Three homes (both floors) were in the danger category for over 12 hours on 8/24/2023. Table 4 shows a maximum heat index of 120.1°F in Home #2 for two consecutive days, on 8/23/2023 and 8/24/2023.

The maximum heat index differential of 32.0°F was observed in Home #4 and occurred between the basement and the second floor. The maximum heat index differential between the first and second floor was 31.4°F in Home #2. The large differential in Home #4 occurred between the basement and second floor, indicating that the presence of a basement can result in large heat index differentials, and below ground spaces can have moderate temperature values closer to outdoor temperatures or lower compared to the above ground spaces. This finding is not only valid for extreme heat days but also for other days of the study as the highest temperature differential occurred on a day with moderate weather. Most of the homes in the study had unfinished basements, which is common in Chicago, and are often used as retreat areas during tornado warnings. The heat index differential was highest in a single-family masonry home and, generally, frame homes showed less fluctuation in heat index differential while masonry homes showed higher fluctuations. The average heat index differentials for each home type were: 2-4 unit frame: 8.6°F, single-family frame: 18.2°F, 2-4 unit masonry: 14.0°F, single-family masonry: 23.1°F.

Some semi-conditioned spaces also experienced time above the danger threshold, such as the second-floor spaces of Home #5 which exceeded the danger threshold for over seven hours on 8/24/2023. In contrast, Home #8, which has all semi-conditioned spaces, never reached the dangerous heat index threshold since the window AC units were continuously operated during the heat wave days. This finding shows the importance of cooling units to decrease the potential threat of heat waves. Home #10 has semi-conditioned spaces on the first floor and unconditioned spaces on the second floor but none of these spaces, including unconditioned ones, experienced a dangerous heat index. As shown in Figure 4, this home is located in a neighborhood with lower outdoor temperatures during the summer.

For Home #4, the sensors were in one unconditioned space and one semi-conditioned space on the first floor. The sensor on the second floor was in an unconditioned space. In Home #4, only the second floor unconditioned space experienced time above the danger threshold, and the first floor unconditioned space never exceeded the danger threshold. The results show less temperature fluctuations of both first floor spaces compared to the second floor space, and this could be due to the first floor unconditioned space's proximity to a semi-conditioned space which lowers the diurnal temperature and heat index.

Home #2 also has semi-conditioned spaces on both floors. Both semi-conditioned spaces on the first and the second floors experienced about nine hours above the heat index danger threshold. This is likely because the AC units in both semi-conditioned spaces did not operate continuously due to noise and also personal preferences.

To further assess the indoor thermal conditions, Table 5 shows temperature values for all monitored spaces as well as each home's largest temperature differential between floors (Max T Differential) and hours over 80°F. The results show a maximum temperature of 100.4°F in Home #2, a maximum temperature differential of 18.8°F in Home #4 between the basement and the second floor, and a temperature differential of 16°F in Home #2 between the first floor and second floor. On 8/24/2023, eight of the ten homes experienced temperatures greater than 90°F, even with the use of air conditioning in Homes #2, 5, 8 and 10. Similar to the results shown in Table 4, the largest differential occurred in the home with the basement (Home #4) and the temperature differential was greatest among single-family masonry homes. Comparisons between Table 4 and Table 5 illustrate that some variation exists when humidity is accounted for, as there are some differences in which types of homes experience the highest values and lowest values. Further exploration between temperature and heat index across housing types are available in the subsequent figures.

Table 4. Distribution of the heat index values for monitored spaces

Heat Index for Monitored Spaces																					
		Monitoring period (excluding 7/28, 8/23, 8/24)					7/28/2023					8/23/2023					8/24/2023				
Home #	Sensor	Min	Max	Avg	Max HI Differential*	HI>103 (Danger)	Min	Max	Avg.	Max HI Differential*	HI>103 (Danger)	Min	Max	Avg.	Max HI Differential*	HI>103 (Danger)	Min	Max	Avg.	Max HI Differential*	HI>103 (Danger)
1	1W	70.9	100.3	79.4	13.2°F 8/25 02:41	00:00	-	-	-	-	-	78.4	94.6	82.9	13.3°F 09:47	00:00	88.9	101.6	96.5	15.6°F 06:00	00:00
	1WB	67.8	95.5	77.2		00:00	-	-	-		-	84.4	95.1	82.1		00:00	94.8	105.3	98.9		05:30
	2W	68.4	90.1	77.3		00:00	-	-	-		-	84.6	94.9	88.1		00:00	94.7	104.2	98.5		05:15
	2WB	70.2	90.3	78.8		00:00	-	-	-		-	75.1	88.4	79.5		00:00	85.9	98.6	90.2		00:00
2	1W	70.4	93.4	79.0	24.8°F 8/20 15:59	00:00	87.1	92.7	89.5	13.6°F 16:59	00:00	77.7	96.8	85.3	31.4°F 14:14	00:00	76.1	98.3	91.3	15.5°F 15:29	20:00
	1WB	69.4	95.3	78.3		00:00	85.8	92.8	89.2		00:00	85.0	104.6	90.7		03:00	95.1	107.2	101.4		09:00
	2W	63.7	102.5	78.9		00:00	80.3	105.1	92.3		3:30	81.2	120.1	100.4		14:00	93.9	120.1	105.8		12:00
	2WB	68.0	95.8	78.3		00:00	77.6	100.4	88.7		00:00	76.7	107.6	91.2		04:30	66.5	102.5	81.3		09:30
3	1W	73.9	94.1	80.2	-	00:00	87.9	93.8	90.4	-	00:00	-	-	-	-	-	-	-	-	-	-
	1W	74.1	95.8	80.7		00:00	87.0	93.2	89.1		00:00	85.9	92.6	88.8		00:00	91.9	96.1	92.9		00:00
	1WB	73.9	98.0	81.0		00:00	88.8	95.1	91.7		00:00	86.5	94.6	90.1		00:00	92.2	99.1	94.7		00:00
	1WB	73.0	98.1	81.5		00:00	83.4	92.8	88.2		00:00	85.9	101.4	93.1		00:00	94.0	104.2	98.4		02:00
4	0WB	69.2	85.6	74.8	23.7°F 8/20 15:41	00:00	77.4	78.6	78.0	18.8°F 15:41	00:00	77.3	82.2	79.1	18.0°F 17:41	00:00	81.5	85.8	83.2	32.0°F 14:26	00:00
	1WB	71.6	89.8	78.1		00:00	76.7	88.3	82.3		00:00	83.3	88.5	84.7		00:00	86.3	93.4	89.5		00:00
	1W	71.3	89.2	78.0		00:00	78.6	83.3	81.1		00:00	80.0	84.5	81.6		00:00	82.9	88.8	85.2		00:00
	2W	66.5	99.7	79.7		00:00	76.8	96.9	84.7		00:00	76.2	89.3	82.3		00:00	83.6	116.1	110.9		11:00
5	1W	71.0	88.5	78.3		00:00	77.0	88.4	82.6		00:00	78.2	86.5	82.3		00:00	81.8	86.8	84.5		00:00
	1WB	67.0	88.4	76.7		00:00	86.9	87.2	81.8		00:00	77.3	87.3	81.1		00:00	81.6	86.5	84.2		00:00
	2W	69.0	98.2	78.9		00:00	80.5	86.0	82.6		00:00	77.7	97.0	85.0		00:00	84.5	110.7	95.1		07:30
	2WB	69.8	96.8	79.4		00:00	80.2	87.5	82.7		00:00	76.2	96.6	84.4		00:00	86.6	93.2	89.1		07:30

**Max differential between unconditioned spaces between floors*

Key: semi-conditioned spaces
Sensors: W = Wi-Fi loggers, WB = WBGT loggers

Table 4. Distribution of the heat index values for monitored spaces (continued)

Heat Index for Monitored Spaces																					
		Monitoring period (excluding 7/28, 8/23, 8/24)					7/28/2023					8/23/2023					8/24/2023				
Home #	Sensor	Min	Max	Avg	Max HI Differential*	HI>103 (Danger)	Min	Max	Avg	Max HI Differential*	HI>103 (Danger)	Min	Max	Avg	Max HI Differential*	HI>103 (Danger)	Min	Max	Avg	Max HI Differential*	HI>103 (Danger)
6	1W	68.6	99.3	78.0	6.4°F 8/3 21:03	00:00	-	-	-	-	-	82.5	113.7	98.7	7.6°F 13:28	12:00	94.6	114.7	103.7	11.7°F 03:03	11:00
	1WB	69.6	98.6	79.2		00:00	-	-	-		-	86.2	109.3	97.7		10:00	96.9	107.8	102.7		12:00
	2W	72.1	90.9	78.8		00:00	-	-	-		-	86.9	110.4	98.5		11:00	100.3	110.2	105.6		17:30
	2WB	69.4	98.1	79.2		00:00	-	-	-		-	86.6	112.8	100.2		13:00	97.5	111.1	105.4		17:00
7	1W	70.6	93.1	77.6	10.1°F 8/20 10:22	00:00	-	-	-	-	-	83.9	107.3	95.4	11.0°F 11:52	07:30	93.6	110.6	103.6	8.1°F 10:52 T1H2O	12:00
	2W	69.3	92.1	79.3		00:00	-	-	-		-	86.8	109.8	98.8		12:00	89.6	112.7	105.1		15:00
	2WB	71.7	98.7	80.8		00:00	-	-	-		-	88.9	112.2	100.1		11:00	98.4	117.1	109.0		23:00
	2WB	67.5	91.7	78.6		00:00	-	-	-		-	86.4	113.1	100.9		14:00	87.6	114.7	106.7		18:00
8	1W	72.7	83.1	76.8	-	00:00	-	-	-	-	-	80.8	84.9	82.0	-	00:00	82.6	86.6	84.6	-	00:00
	1W	72.6	86.7	77.0		00:00	-	-	-		-	77.4	81.4	78.4		00:00	76.5	83.4	78.8		00:00
	1WB	72.7	83.1	76.8		00:00	-	-	-		-	80.4	85.9	81.9		00:00	82.5	86.6	84.6		00:00
	1WB	70.6	88.3	78.3		00:00	-	-	-		-	83.3	90.2	85.5		00:00	83.1	91.4	87.4		00:00
9	1W	67.7	91.5	77.3	13.7°F 7/27 23:59 or 8/3 22:01	00:00	78.8	91.4	86.5	16.8°F 03:17	00:00	82.5	95.7	88.4	18.6°F 23:46	00:00	88.5	105.4	98.6	20.0°F 05:46 or 20.7°F 20:31	02:00
	1WB	67.6	92.9	75.1		00:00	80.7	91.2	86.4		00:00	83.2	95.3	88.1		00:00	89.7	102.4	97.6		00:00
	2W	70.1	91.5	78.0		00:00	83.1	91.4	87.7		00:00	83.8	100.9	91.1		00:00	92.1	104.2	99.8		06:00
	2WB	66.4	87.4	75.4		00:00	70.7	88.3	79.8		00:00	74.0	92.3	80.6		00:00	75.5	97.6	84.3		00:00
10	1W	71.3	87.6	77.7	-	00:00	75.5	83.7	80.0	-	00:00	76.2	85.1	81.4	-	00:00	80.6	87.3	84.3	-	00:00
	1WB	71.2	87.6	77.7		00:00	73.6	83.5	83.6		00:00	76.5	85.5	81.1		00:00	80.0	87.3	83.9		00:00
	2W	72.9	87.9	79.6		00:00	74.3	88.4	82.1		00:00	87.6	102.4	93.2		00:00	77.5	101.7	89.9		00:00
	2WB	72.4	87.3	78.6		00:00	80.7	83.1	82.1		00:00	83.6	102.3	91.4		00:00	93.1	103.0	97.9		00:01

** Max differential between unconditioned spaces between floors*

Key: semi-conditioned spaces

Sensors: W = Wi-Fi loggers, WB = WBGT loggers

Table 5. Distribution of the temperature values for monitored spaces

Temperature for Monitored Spaces																					
		Monitoring period (excluding 7/28, 8/23, 8/24)					7/28/2023					8/23/2023					8/24/2023				
Home #	Sensor	Min	Max	Avg	Max T Differential*	Hours >80°F	Min	Max	Avg	Max T Differential*	Hours >80°F	Min	Max	Avg	Max T Differential*	Hours >80°F	Min	Max	Avg	Max T Differential*	Hours >80°F
1	1W	70.7	89.4	78.3	7.0°F 8/21 03:26	158:00	-	-	-	-	-	78.3	86.7	81.3	6.2°F 09:47	13:00	85.1	90.1	88.1	5.3°F 06:11	24:00
	1WB	68.2	88.0	76.4		91:00	-	-	-		-	80.5	85.6	82.3		24:00	85.6	89.7	87.5		24:00
	2W	68.8	88.1	76.6		91:00	-	-	-		-	80.7	85.9	82.5		24:00	86.0	90.2	87.6		24:00
	2WB	70.6	87.1	77.9		164:30	-	-	-		-	75.4	84.8	78.8		07:00	83.1	90.4	85.7		24:00
2	1W	70.7	86.6	78.0	16.0°F 8/20 15:59	136:00	83.3	85.9	84.7	8.7°F 16:14	24:00	77.3	86.1	81.3	15.8°F 16:44	19:00	76.1	87.6	84.3	9.7°F 15:29	20:00
	1WB	69.9	87.9	77.3		157:30	81.9	85.4	84.0		24:00	80.73	88.7	83.4		24:00	86.1	92.2	89.0		24:00
	2W	64.4	92.8	78.1		256:00	78.2	93.6	86.5		21:00	78.5	99.7	88.8		18:00	84.7	100.4	92.2		24:00
	2WB	68.7	89.0	78.0		177:00	78.1	89.3	83.2		23:00	76.7	91.6	84.0		21:30	67.3	89.7	78.5		09:30
3	1W	73.7	88.4	79.2	-	193:00	84.2	86.5	85.4	-	24:00	-	-	-	-	-	-	-	-	-	-
	1W	74.4	88.0	79.4		280:00	83.9	86.1	84.7		24:00	82.3	85.7	83.6		24:00	85.3	88.1	86.4		24:00
	1WB	73.7	89.1	79.4		286:00	84.2	86.4	85.4		24:00	82.6	87.1	84.4		24:00	86.1	89.4	87.4		24:00
	1WB	73.3	89.7	80.1		358:00	80.8	92.8	91.7		24:00	82.1	90.6	85.9		24:00	86.3	92.9	89.1		24:00
4	0WB	69.4	84.6	74.5	15.9°F 8/20 15:41	05:15	76.8	77.8	77.3	11.0°F 14:41	00:00	76.5	79.3	77.6	10.9°F 18:11	00:00	78.9	81.1	79.8	18.8°F 16:11	06:00
	1WB	72.1	84.7	77.4		110:00	79.6	81.8	80.7		21:30	80.2	82.7	81.1		24:00	82.4	85.7	83.8		24:00
	1W	71.8	87.9	77.3		72:15	78.2	80.5	79.4		04:30	78.1	81.7	79.5		07:00	80.8	84.4	82.1		24:00
	2W	66.7	91.3	78.8		276:00	76.7	88.3	82.4		17:00	76.2	89.3	82.3		13:00	80.9	99.2	90.1		24:00
5	1W	71.6	85.0	77.4	-	118:15	77.0	83.3	80.3		12:00	77.8	82.0	79.7	-	11:15	80.3	82.3	81.6	-	24:00
	1WB	67.5	83.5	76.1		66:30	77.1	82.9	79.9		09:00	77.1	82.6	79.3		10:00	80.4	83.5	81.7		24:00
	2W	69.5	89.2	78.2		233:00	80.2	84.3	81.6		24:00	77.8	88.3	82.1		14:00	81.8	92.4	86.9		24:00
	2WB	70.3	89.3	78.5		260:00	80.2	87.5	82.7		23:45	76.2	87.1	81.5		13:30	86.6	93.2	89.1		24:00

**Max differential between unconditioned spaces between floors*

Key: semi-conditioned spaces
Sensors: W = Wi-Fi loggers, WB = WBGT loggers

Table 5: Distribution of the temperature values for monitored spaces (continued)

Temperature for Monitored Spaces																					
		Monitoring period (excluding 7/28, 8/23, 8/24)					7/28/2023					8/23/2023					8/24/2023				
Home #	Sensor	Min	Max	Avg	Max T Differential*	Hours >80°F	Min	Max	Avg	Max T Differential*	Hours >80°F	Min	Max	Avg	Max T Differential*	Hours >80°F	Min	Max	Avg	Max T Differential*	Hours >80°F
6	1W	68.9	90.6	77.3	5.0°F 8/8 22:48	153:00	-	-	-	-	-	79.2	98.8	88.1	3.7°F 13:43	18:30	85.0	97.8	90.7	4.24°F 16:48	24:00
	1WB	70.0	89.8	78.2		180:00	-	-	-		-	81.6	92.8	87.22		24:00	86.7	92.3	89.9		24:00
	2W	72.1	90.9	78.8		207:00	-	-	-		-	82.6	94.0	88.0		24:00	89.6	93.9	91.6		24:00
	2WB	69.8	89.7	78.2		185:00	-	-	-		-	81.6	95.5	88.4		24:00	88.5	94.3	91.2		24:00
7	1W	70.7	87.1	76.8	6.7°F 8/20 10:22	100:00	-	-	-	-	-	80.0	91.2	85.5	6.2°F 14:37	24:00	86.3	94.9	90.1	5.1°F 10:52	24:00
	2W	69.9	87.0	78.3		154:00	-	-	-		-	81.7	94.1	87.7		24:00	84.8	96.5	91.2		24:00
	2WB	72.3	91.3	79.6		257:00	-	-	-		-	83.3	94.4	88.8		24:00	90.2	98.5	93.7		24:00
	2WB	68.3	86.5	77.7		157:00	-	-	-		-	81.5	96.1	89.0		24:00	83.6	97.4	92.4		24:00
8	1W	73.5	85.2	77.4	-	50:30	-	-	-	-	-	78.6	81.3	79.5	-	05:30	81.1	82.8	81.7	-	24:00
	1W	73.4	85.6	76.5		02:30	-	-	-		-	76.6	78.9	77.4		00:00	76.4	80.2	77.8		00:15
	1WB	72.7	83.1	76.8		37:00	-	-	-		-	78.3	81.7	79.4		05:30	80.5	82.8	81.6		24:00
	1WB	71.3	84.0	77.4		100:00	-	-	-		-	80.6	85.0	82.2		24:00	81.9	85.8	84.0		24:00
9	1W	68.1	87.9	76.5	11.4°F 7/31 18:16	119:00	77.8	84.5	82.0	10.6°F 03:17 or 03:01	18:30	79.1	85.4	82.0	8.7°F 23:46	18:00	83.3	89.3	86.7	9.9°F 05:46 or 10.0°F 5:31	24:00
	1WB	67.2	84.4	75.7		67:00	78.3	84.4	81.9		20:00	79.5	85.2	91.9		18:00	84.4	88.1	86.4		24:00
	2W	70.5	85.55	77.1		136:00	80.1	84.9	83.0		24:00	79.9	87.7	83.5		21:00	85.8	90.3	88.0		24:00
	2WB	67.6	82.8	75.1		36:00	71.6	83.2	78.1		10:00	73.5	84.0	78.0		08:00	75.4	86.2	80.6		15:00
10	1W	71.7	83.2	76.9	-	64:00	76.0	80.8	78.7	-	07:30	76.2	81.5	79.2	-	05:30	79.6	83.4	81.5	-	18:00
	1WB	71.5	82.7	76.6		44:00	74.1	80.5	77.9		07:30	76:00	81.5	79.0		05:30	78.7	83.0	80.9		17:00
	2W	73.4	83.1	78.6		220:00	74.4	83.6	79.7		13:30	82.4	88.3	84.8		24:00	77.3	89.4	83.9		18:00
	2WB	72.4	87.3	78.1		186:00	80.7	83.1	82.6		24:00	80.3	88.0	83.7		24:00	85.5	90.0	87.7		24:00

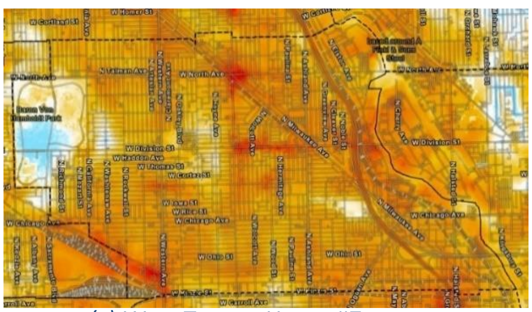
** Max differential between unconditioned spaces between floors*

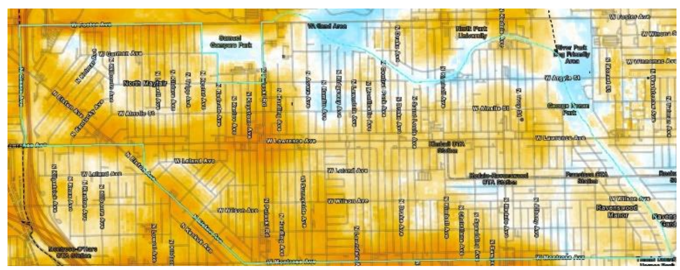
Key: (grey) semi-conditioned spaces
Sensors: W = Wi-Fi loggers, WB = WBGT loggers

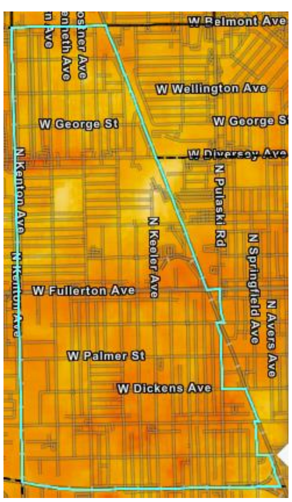
Six of the homes had sensors in place on 7/28/2023, the Heat Watch activation day in Chicago. Results of the Heat Watch Campaign provide insight into the outdoor temperatures for each of the community areas in this study. Figure 4 shows heat maps from 7/28/2023, for each of the Community Areas and the homes located in those areas. The maximum temperature differential between neighborhoods was 22°F, which occurred between Archer Heights (99.1°F) and Rogers Park (77.1°F). More details and information about Heat Watch are available in the [Chicago Heat Watch Report] and [Chicago Heat Watch Maps].

(a) Logan Square – Home #1,2,5,6,9

(b) Calumet Heights – Home #3


(c) West Town – Home #7


(d) Albany Park – Home #8



(e) Hermosa – Home #4

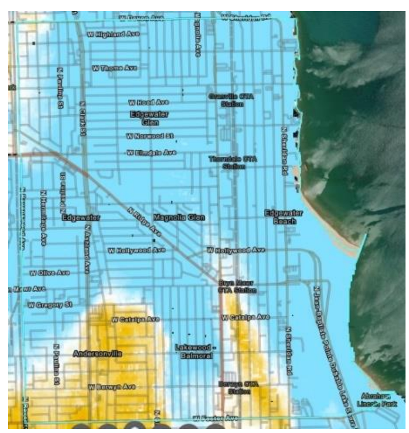

(f) Edgewater – Home #10

Figure 4. Average modeled outdoor temperature heat maps, 7/28/2023: (a) Logan Square, (b) Calumet Heights, (c) West Town, (d) Albany Park, (e) Hermosa, (f) Edgewater; source: Chicago Heat Watch

To have a better understanding of how temperature varies between the single-family versus 2-4 unit homes, and between different floors and their enclosure, Figure 5-Figure 7 compare the box plots of indoor and outdoor dry bulb temperature, dew point temperature, and relative humidity for semi-conditioned and unconditioned spaces, respectively. When looking at the entire home (unconditioned and semi-conditioned spaces) throughout the study period, masonry homes show a lower range of variation compared to frame homes. This is noticeable, especially for the first floor of single-family homes. In addition, the second floors experience a higher range of temperature variations when compared with the first floors. Less variation in temperature and relative humidity is expected for semi-conditioned spaces compared to unconditioned spaces, but the box plots do not reflect this, likely because some of the semi-conditioned spaces were not occupied during the heat wave days. Time-series plots may provide a better understanding of variation of different variables inside different home types, especially during the heat wave days. Analyses in this regard are provided in the rest of this report.

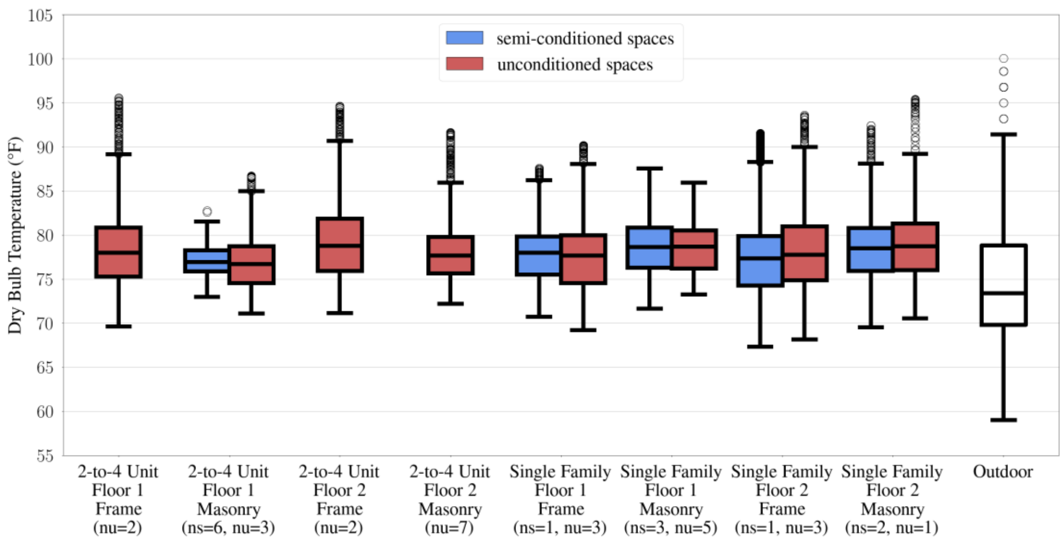


Figure 5. Variation of indoor and outdoor dry bulb temperature for different building types and floors (ns: number of semi-conditioned spaces, nu: number of unconditioned spaces)

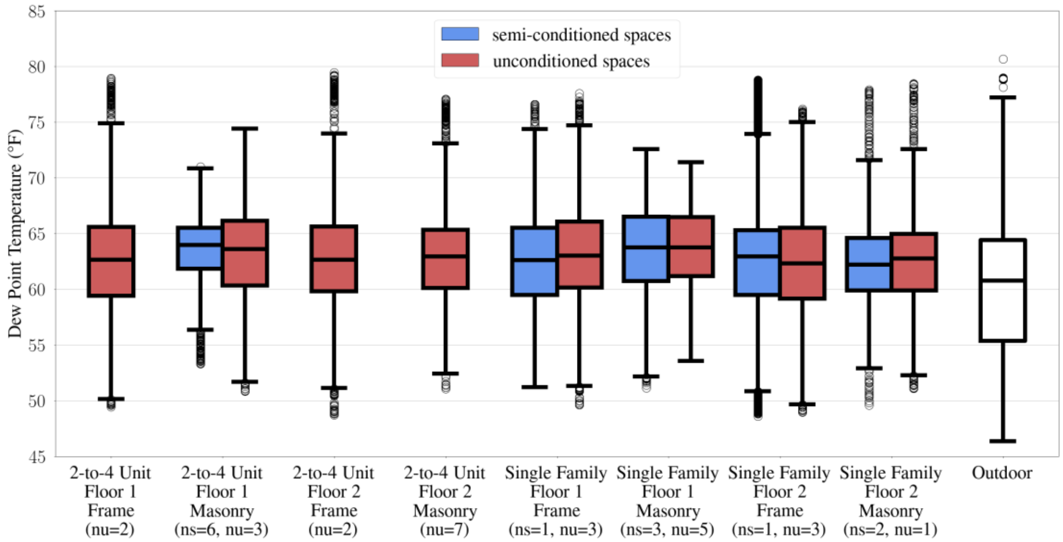


Figure 6. Variation of indoor and outdoor dew point temperature for different building types and floors (ns: number of semi-conditioned spaces, nu: number of unconditioned spaces)

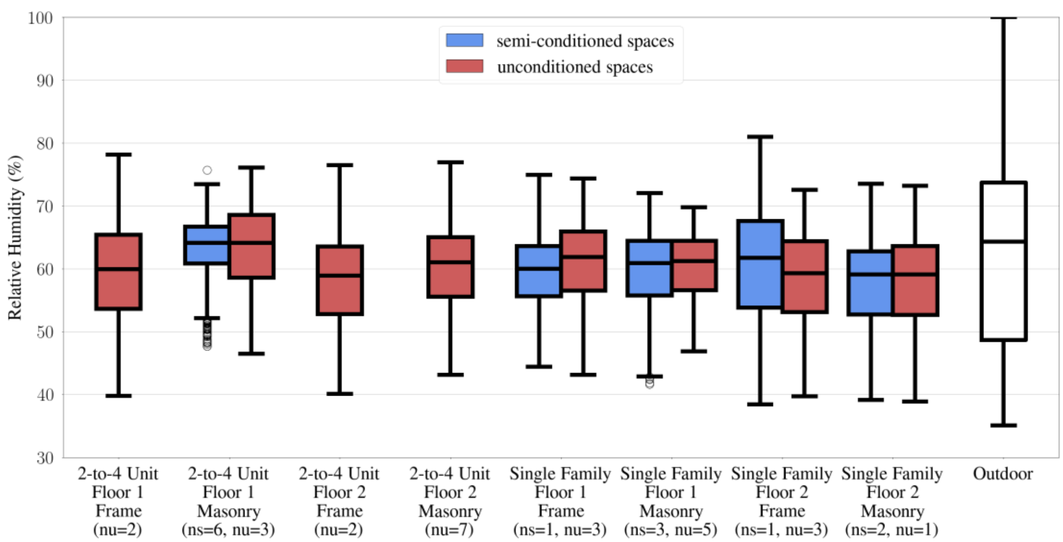
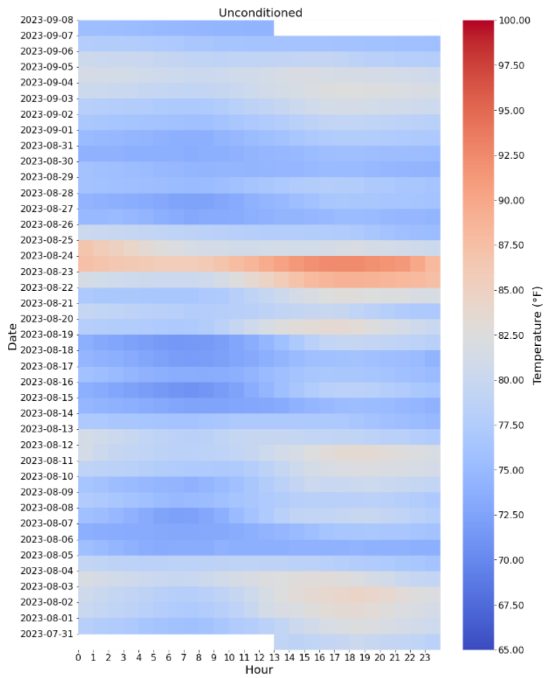
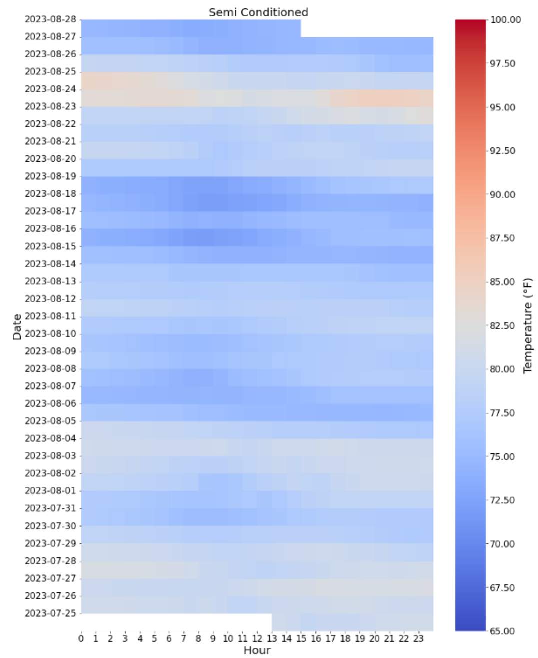


Figure 7. Variation of indoor and outdoor relative humidity for different building types and floors (ns: number of semi-conditioned spaces, nu: number of unconditioned spaces)

This section assesses several distributions of temperature in indoor spaces. First, the average of all spaces that are semi-conditioned and unconditioned are compared. The aim is to highlight the overall temperature patterns for these homes as Figure 8-a and Figure 8-b show the heat map for unconditioned and semi-conditioned space, respectively. Several observations are: (1) the heat waves of 7/28/2023, 8/23/2023, and 8/24/2023 can be seen in both heat maps; (2) the semi-conditioned spaces experienced less temperature increase compared to unconditioned spaces; (3) the heatwave in August had a more severe effect on the indoor temperature compared to the July heatwave; and (4) the temperature increase usually happened after noon until midnight, which might be related to not only the heatwave, but also the heat retention from the building material.



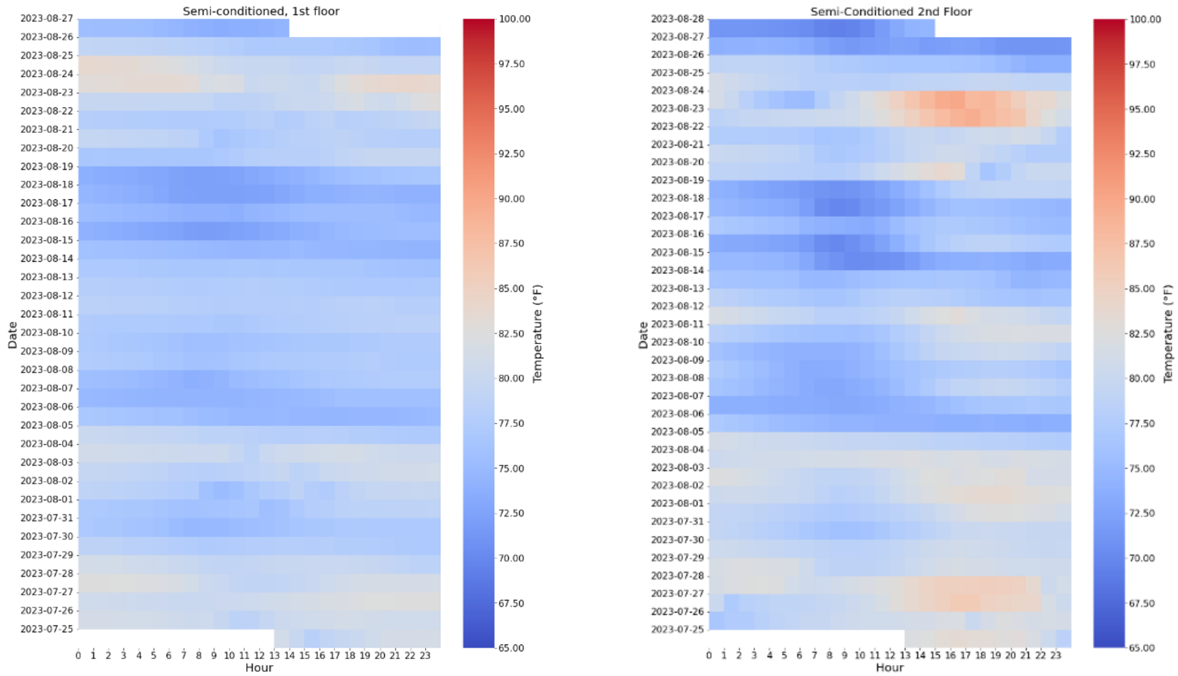
(a)



(b)

Figure 8. Heat map for indoor temperature readings: (a) unconditioned spaces and (b) semi-conditioned spaces

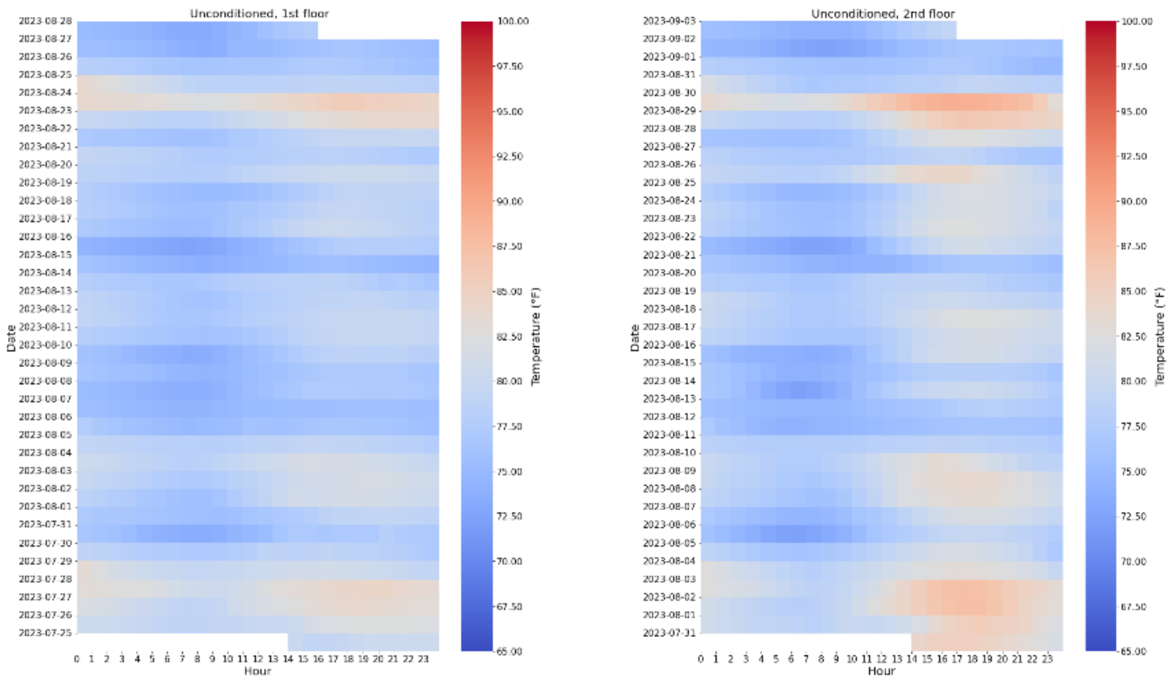
Figure 9 shows the temperature patterns for semi-conditioned spaces between the first and second floors of the buildings. The overall observations as expected are: (1) the second floor generally has temperatures closer to the outdoor temperature; and (2) the effect of heatwave is evident on the second floor but is not severe on the first floor.



(a) *(b)*

Figure 9. Heatmap of semi-conditioned spaces for indoor temperature: (a) Floor 1 and (b) Floor 2

Figure 10 illustrates the indoor temperature patterns for unconditioned spaces between the first and the second floors. The results show that, like the previous figure, the second floors were affected by outdoor temperature and their temperatures were closer to the outdoor temperatures. In addition, the August heat wave can be seen in both heatmaps, and the heatwave impact was more severe for the first floor compared to the first floor from Figure 9, which is likely related to the lack of AC in the unconditioned spaces.

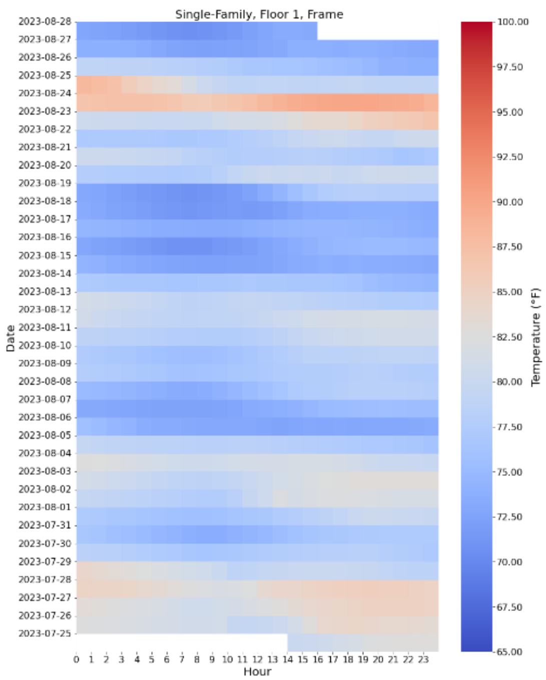


(a) (b)

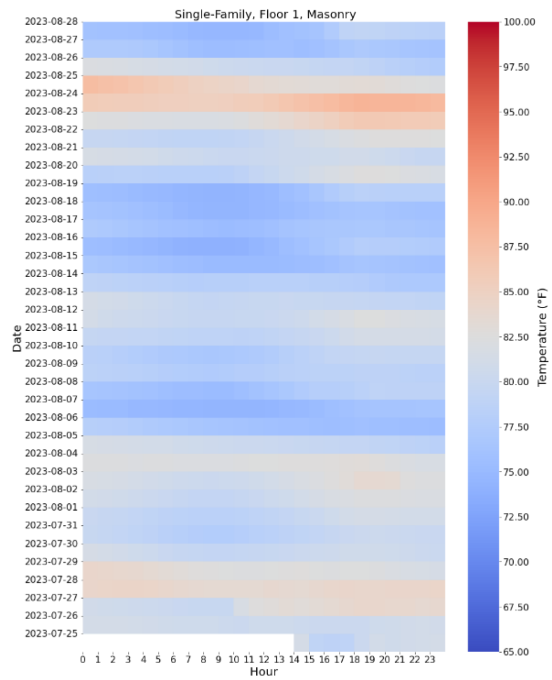
Figure 10. Heatmap of unconditioned spaces for indoor temperature: (a) Floor 1 and (b) Floor 2

The comparison between the semi-conditioned and the unconditioned spaces on the first floors shows that: (1) the AC kept temperatures lower in semi-conditioned spaces; (2) the temperature for semi-conditioned spaces was lower and more uniform than unconditioned spaces; and (3) during the heat waves, the AC helped to maintain a tolerable indoor temperature. Similarly for second floors, the comparisons between the semi-conditioned and unconditioned spaces show that: (1) the effect of outdoor temperature is apparent for the second floor since they absorb more solar radiation; and (2) although both semi-conditioned and unconditioned spaces have more heat gains, AC units could decrease the indoor temperatures. For instance, during the August heatwave, the temperature reached around 88°F in semi-conditioned spaces, but the temperature in unconditioned spaces exceeded 90°F.

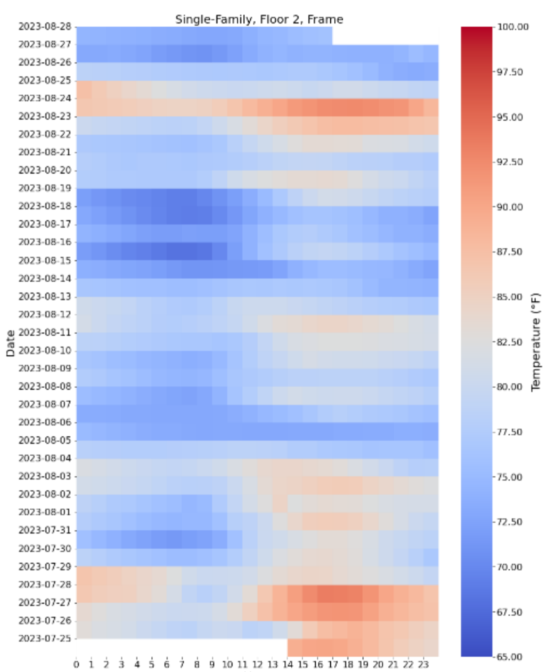
To have a better understanding of how the temperature varies between different home types, the semi-conditioned and unconditioned spaces are assessed here. Figure 11 shows the temperature patterns for the unconditioned spaces for masonry versus frame for different floors of single-family homes. Comparing Figure 11-a with Figure 11-b, and Figure 11-c with Figure 11-d, the temperature distribution is more uniform in masonry homes during the study period. This may be because the rate of heat gain and release for masonry homes is lower than frame homes. Although the temperature distribution is slightly more uniform in Figure 11-d than Figure 11-c, the effect of heat gain from the outdoor temperatures is still dominant in Figure 11-d. In general, second floor spaces are more prone to have the same temperature pattern as the outdoor temperatures. By looking at only frame homes, the temperature is generally lower from midnight to noon on the next day.



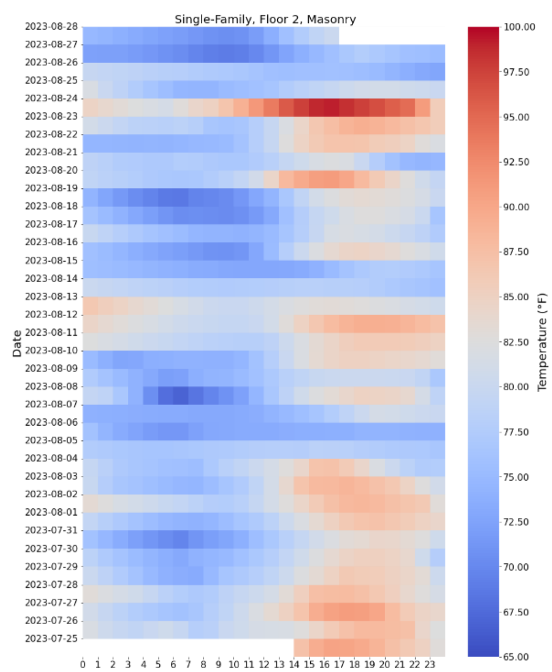
(a)



(b)



(c)



(d)

Figure 11. Heatmap of unconditioned single-family house: (a) Floor 1 - Frame, (b) Floor 1 - Masonry, (c) Floor 2 - Frame, and (d) Floor 2 – Masonry

The time-series plots shown in Figure 12-Figure 15 show the patterns of indoor and outdoor temperatures during the study period. In these figures, the green line represents the 80°F threshold.

Figure 12 shows the temperature patterns for the duration of the study for semi-conditioned spaces in single family homes for different floors and home types. For these homes, the temperature exceeds 80°F frequently and this is noticeable especially for the August heat wave. In addition, the second floors experience higher temperatures. Relatively more severe diurnal fluctuations in temperature can be observed in unconditioned spaces.

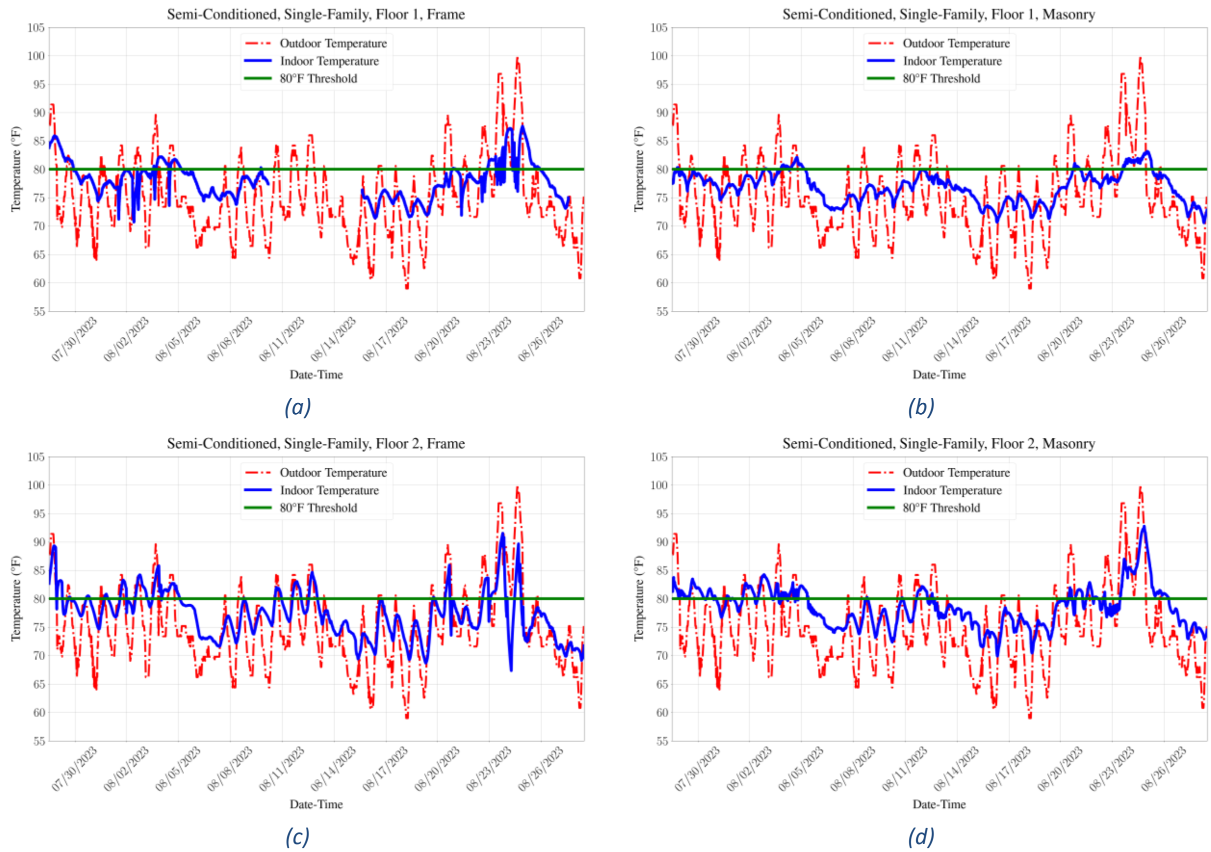


Figure 12. Indoor dry bulb vs outdoor dry bulb temperature for semi-conditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Figure 13 shows the temperature patterns for the duration of the study for unconditioned spaces for single-family homes for different floors and home types. Figure 13 shows similar patterns to Figure 12 with a few additional notes. All floors experience high temperatures and during the extreme heat of August, all homes and spaces had a temperature over 80°F. The diurnal outdoor temperature variations had more impact on frame homes than the masonry homes.

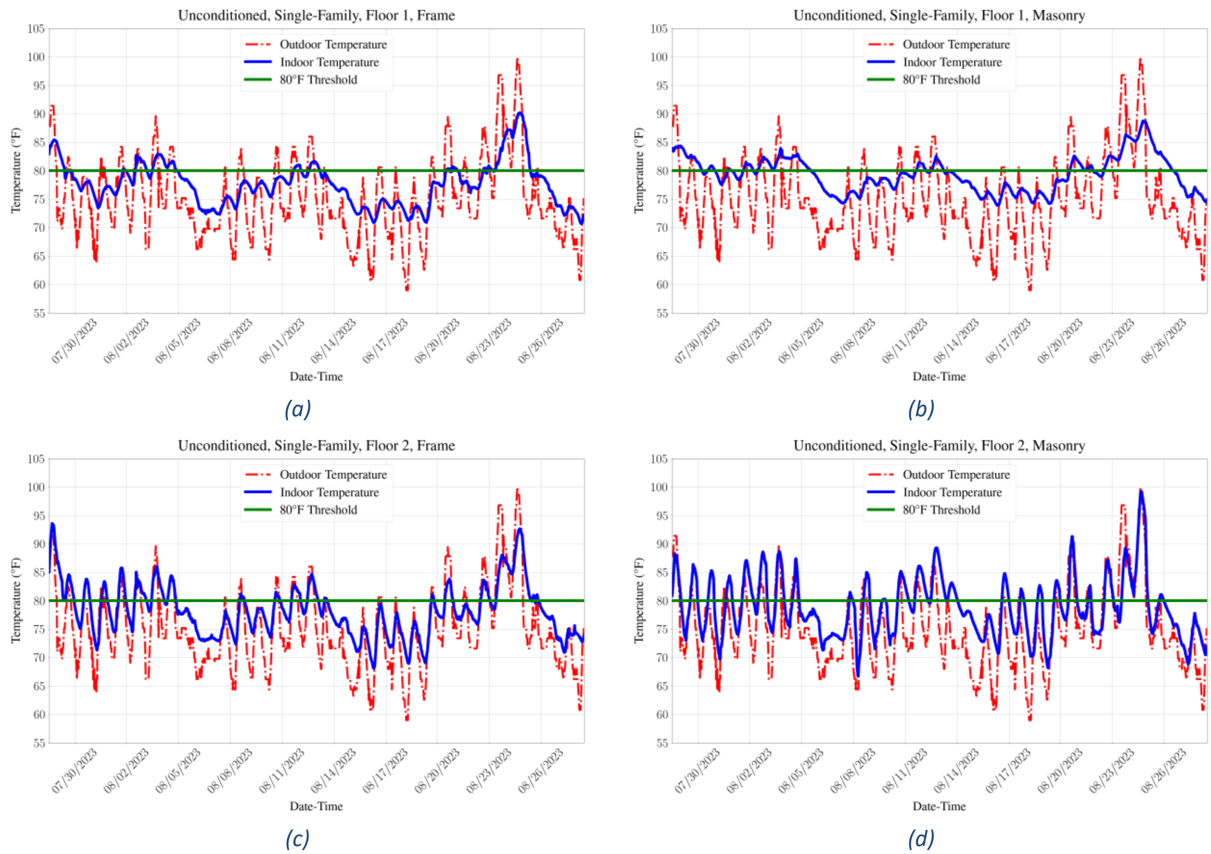


Figure 13. Indoor dry bulb vs outdoor dry bulb temperature for unconditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Figure 14 illustrates the indoor air temperature for semi-conditioned 2-4 unit homes for floor 1 only since not all the homes have semi-conditioned spaces. Since theses spaces are semi-conditioned, the indoor temperature rarely exceeds 80°F except for a few hours during the 8/24/2023 heat wave.

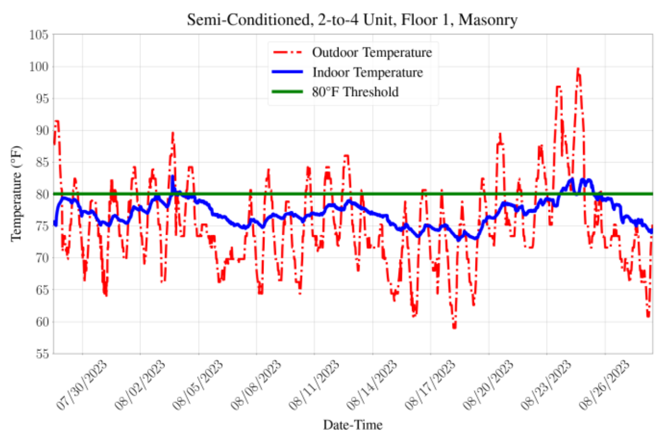
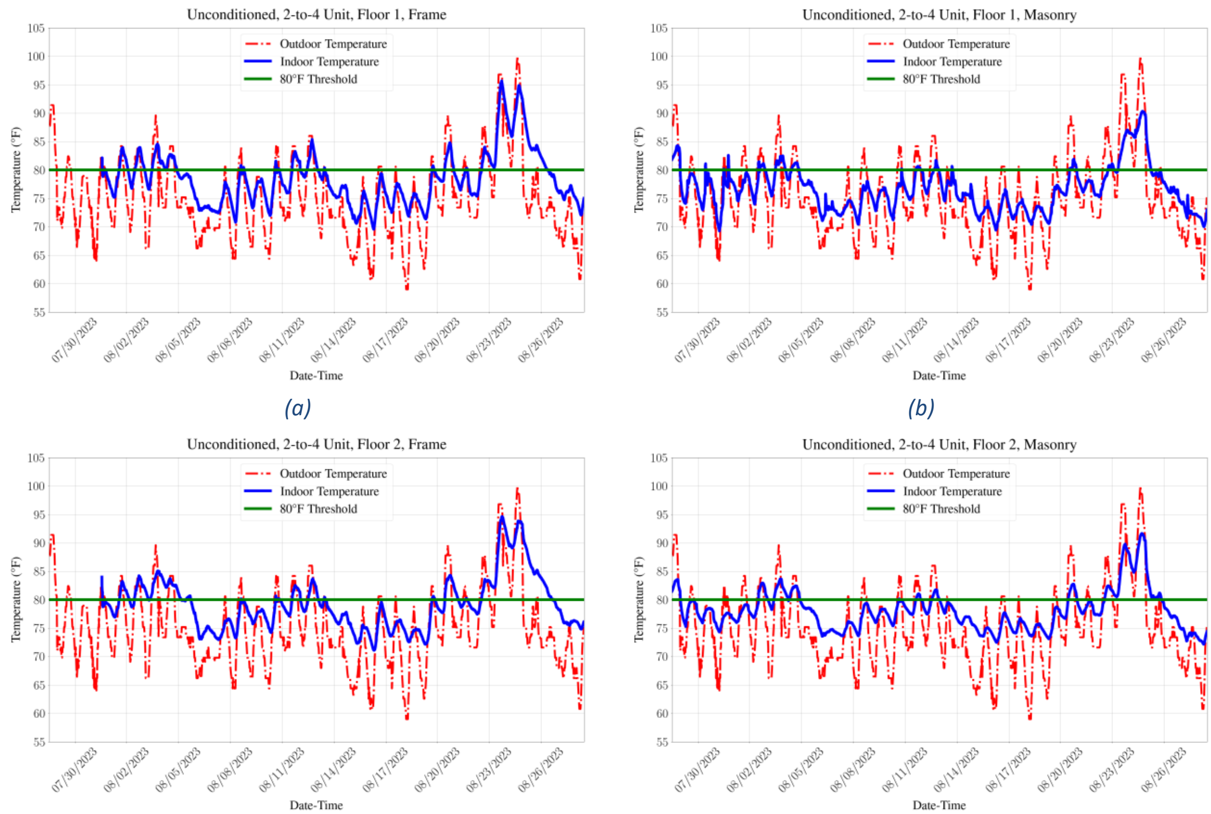


Figure 14. Indoor dry bulb vs outdoor dry bulb temperature for semi-conditioned 2-4 unit homes: Floor 1 – Masonry (not all the homes have semi-conditioned rooms)

Figure 15 illustrates the indoor air temperature for unconditioned 2-4 unit homes for different floors and home types. Comparing Figure 15 with Figure 13 reveals that unconditioned 2-to-4-unit spaces experienced higher temperatures for a longer amount of time compared to unconditioned single-family spaces.

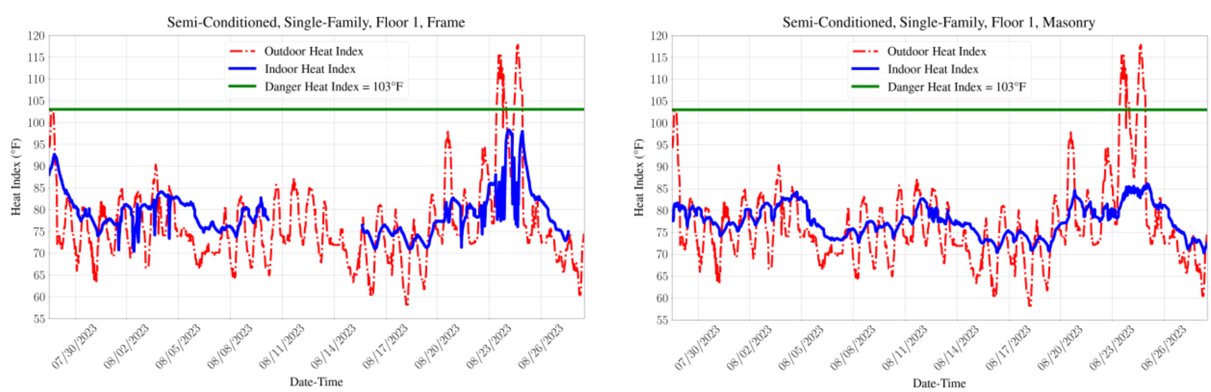


(a) (b)

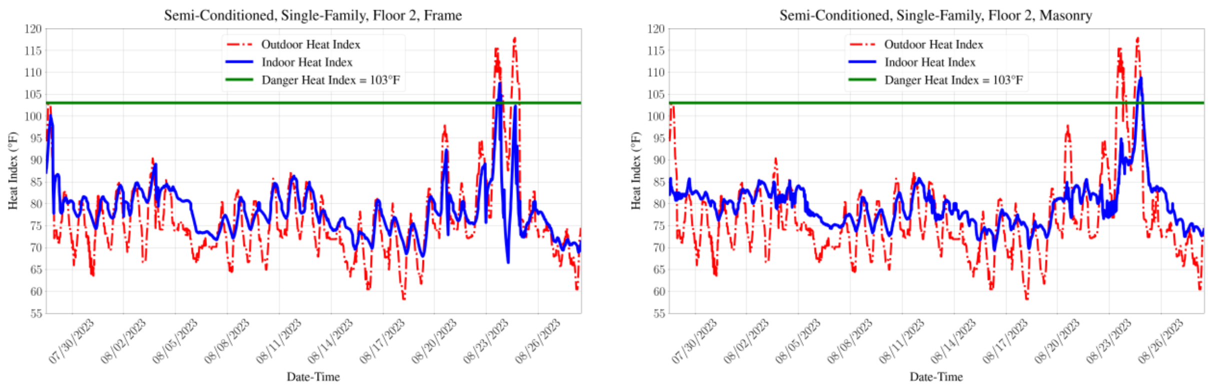
(c) (d)

Figure 15. Indoor dry bulb vs outdoor dry bulb temperature for unconditioned 2-4 unit homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Figure 16-Figure 19 show the indoor and outdoor heat index patterns during the study period. The 103°F reference line represents the danger threshold. Notably, these figures illustrate that second floor spaces experienced higher heat indexes compared to first floor spaces.

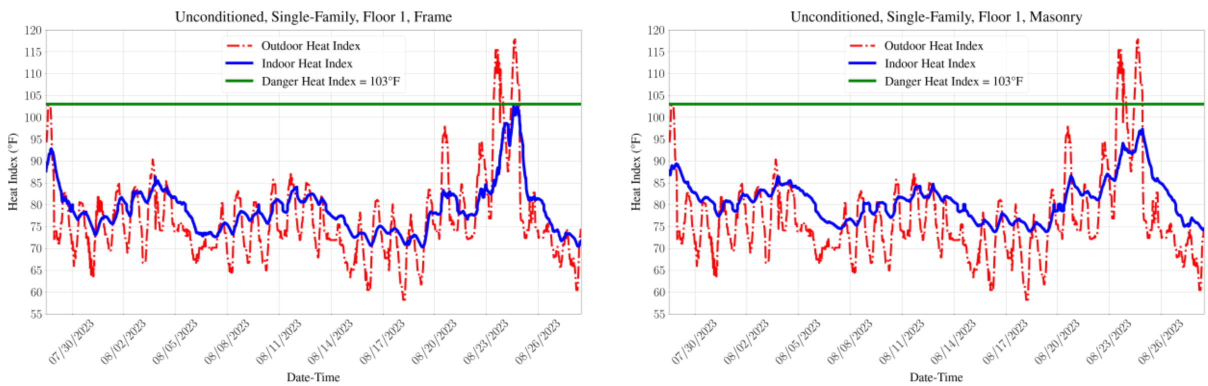


(a) (b)

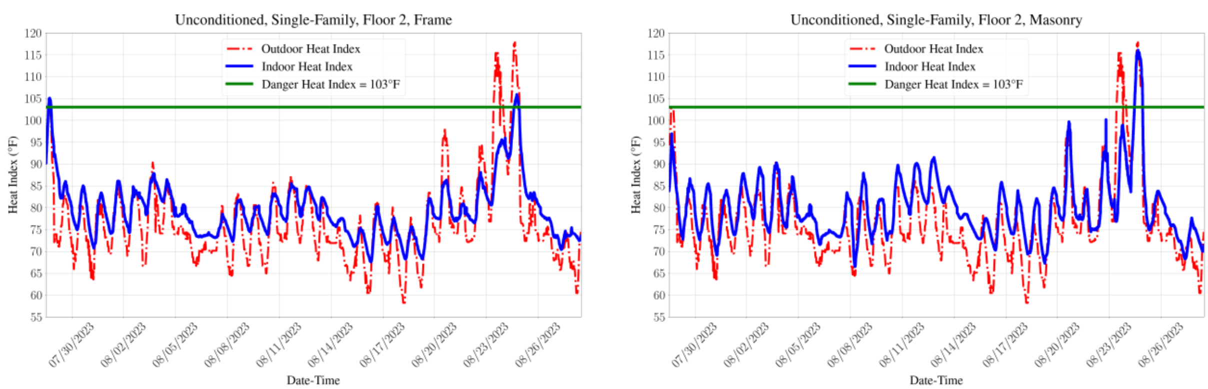


(c) *(d)*

Figure 16. Indoor heat index vs outdoor heat index for semi-conditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry



(a) *(b)*



(c) *(d)*

Figure 17. Indoor heat index vs outdoor heat index for unconditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

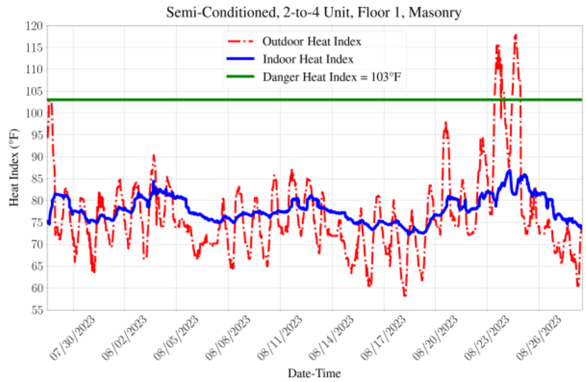
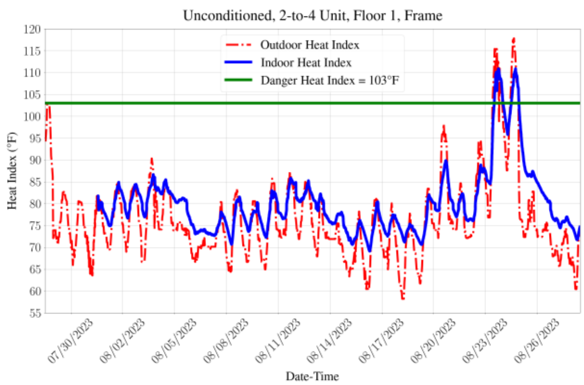
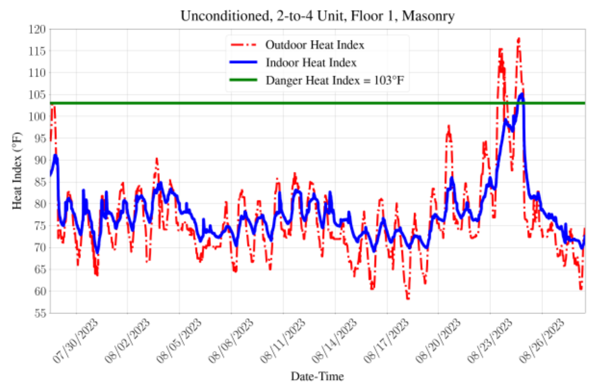


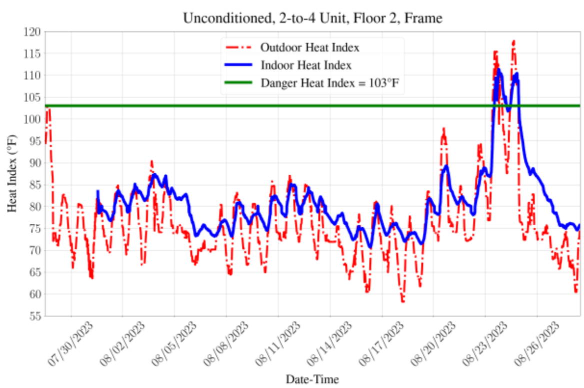
Figure 18. Indoor heat index vs outdoor heat index for semi-conditioned 2-4 unit homes: Floor 1 – Masonry (not all the homes have semi-conditioned rooms)



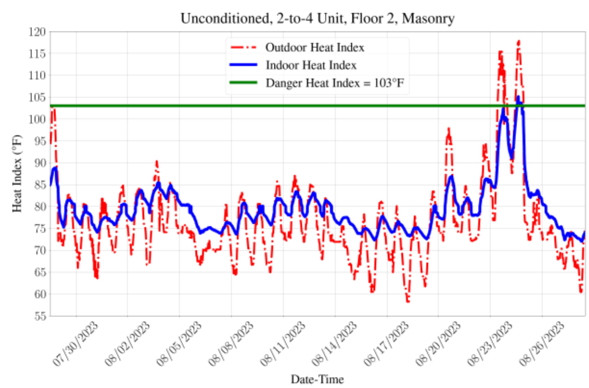
(a)



(b)



(c)



(d)

Figure 19. Indoor heat index vs outdoor heat index for unconditioned 2-4 unit homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Additional information and analysis are in the following appendices:

- Appendix B: Temperature Time Constant
- Appendix C-1: Regression Analysis (Heat Index vs WBGT)
- Appendix C-2: Regression Analysis (Globe Temperature vs Indoor Temperature)
- Appendix C-3: Regression Analysis (Indoor Temperature vs Outdoor Temperature)
- Appendix C-4: Summary of Regression Analysis

Survey: Heat Adaptation Strategies, Risk Perception, and Concerns

The response rate for the survey was 100%, with all participants in the study completing the survey. The results are described below in three sections: adaptive behaviors and cooling strategies, risk perception and safety, and opinions on central cooling.

ADAPTIVE BEHAVIORS AND COOLING STRATEGIES

To assess adaptive behaviors and strategies, participants were given a selection of 17 behaviors and asked to select which ones they use on the hottest days of summer (Table 6). All ten participants reported using three of these strategies: using fans to cool down, using curtains/blinds/shades, and wearing lighter clothing. Sixteen of the 17 strategies were used by at least 50% of respondents. The least utilized coping strategy was leaving the home, with only three people (30%) choosing this option. Among those who leave the home when it is too warm, most go to an air-conditioned business (e.g., grocery store) rather than an air-conditioned public place like a community center or library (one person) or a park or area with tree shading (one person). Though leaving the home was the least-used strategy, 60% of respondents reported going to an outdoor space of the home (e.g., porch or yard) when the indoors is too hot. Other less-utilized coping strategies were reducing sources of electronic and electrical heat in the home (50%), using a cool cloth to cool off while inside (50%), and eating light or iced foods to cool off (50%).

Some participants wrote about additional strategies they use that were not included in our list. These responses included strategies like using a portable dehumidifier since reducing humidity helps improve comfort. Another participant added detail to the reducing electrical heat strategy by noting, “We plugged devices in outside (toaster, rice cooker, etc.) and I also have a convention/microwave oven that I used to do some baking since it gives off some heat but not a lot.” Another person noted, “Our main cooling strategy is keeping good airflow in the house. Most every room has a ceiling fan, we leave the windows open, without screens and can create a chimney effect with different combinations of open upstairs windows, depending on wind direction.”

Table 6: Heat adaptation strategies used by participants

Strategies used on the hottest days of summer	Percent
Wear lighter clothes	100%
Turn a fan(s) on	100%
Use curtains, blinds, or window shutters	100%
Turn an air conditioner unit(s) on	90%
Drink beverages to cool off	80%
Close doors of warmer spaces	80%
Move to cooler areas of the home	70%
Use thinner bedding	70%
Open windows or doors	70%
Try to create airflow in spaces with window opening, AC(s), fans(s), and closing doors	70%
Check weather reports and base behaviors on this information	60%
Move to an outdoor space of the home	60%
Take a shower or bath	60%
Eat fresh, light, or iced foods to cool off	50%
Use a cool, wet cloth to cool off while inside	50%
Reduce sources of electrical and electronic heat in the home	50%
Leave the house	30%

The participants who reported using fans or AC units were asked to estimate how many hours and during which parts of day they use fans or AC units on the hottest days of summer. Of the nine people who had AC units in their homes, the average number of hours of AC use was 16.7 hours, with a range of 8-24 hours of usage per day. The AC usage was highest at night (10:00pm-8:00am) and lowest in the morning (8:00am-12:00pm). All ten participants used fans, and the average usage per day was 19.2 hours, ranging from 10-24 hours a day. Like AC use, fans were most used at night and least during the morning and early afternoon.

In addition to these behavioral strategies, passive cooling strategies were used to reduce heat in the home. The most reported passive cooling strategies were insulation (70%) and tree canopy (70%) while reflective cooling (e.g., cool roof coating) was the least reported (30%).

RISK PERCEPTION AND SAFETY

When asked if their homes reached unsafe temperatures during the summer, five people (50%) reported that they believe their home reaches unsafe temperatures. When asked where in the home reaches unsafe temperatures, most reported the second floor or attic as considerably hotter than other areas in the home. Three respondents wrote about hazardous temperatures at night and sleep disruption, with one saying, “Our second floor is unbearable when the outside temps hit 100 degrees. We have a window unit that cools the sleeping areas, but it's not enough.” And another reporting, “My daughter sleeps on the top floor in the finished attic. It can get really hot up there. We do have AC but it has to run all the time just to keep it bearable. Sometimes she sleeps in the basement [to keep cool].” Additionally, there was some uncertainty about what temperature qualifies as unsafe, with three people answering “unsure” if their home reaches unsafe temperatures and two people stating that they don’t know what temperature threshold qualifies as unsafe.

The survey results show that all ten participants were at least somewhat concerned about facing heat waves this summer, with 10% being "extremely concerned", 80% "moderately concerned", and 10% "somewhat concerned." In addition to general concern about heat waves, most participants (70%) expressed extreme concern about the wellbeing of their friends, family, and community during extreme heat events (Figure 20). One individual shared, "I am mostly concerned about others who are sensitive to heat. I never had AC growing up so am used to using fans, opening windows at night etc. And we do have one room with an AC we can retreat to." Other concerns included changes in sleep quality and duration due to increased temperatures and financial concerns from higher electric bills due to increased energy use for cooling. Despite the concerns about extreme heat, the majority (90%) of participants reported that they did not believe this summer was warmer than previous years.

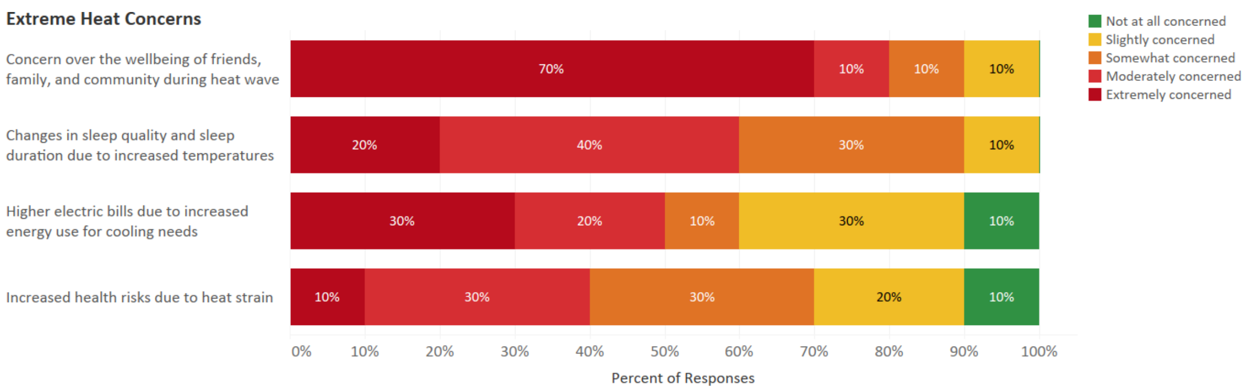


Figure 20. Homeowner ranking of extreme heat concerns

OPINIONS ON CENTRAL COOLING SYSTEMS

Participants were asked about the reasons for not having a central cooling system in their home. Three people (30%) selected "I am environmentally conscious and do not think all homes should have a central cooling system in Chicago", while another 30% reported, "I never lived in a home with a central AC system growing up, and I do not feel the need for it now." Five people (50%) indicated that they plan to install a heat pump that they would use for cooling in the summer. Several people added written responses that addressed their financial concerns for installing central cooling. One person stated, "[Getting central cooling] would be an invasive, expensive project and there typically are not that many brutal days. Having a window AC in a room or two is sufficient." Another added, "I do have environmental concerns about getting central air, but I don't see any good alternative so I would probably get some kind of AC if it was affordable."

Discussion

A summary of the five research questions is presented in this discussion, along with interpretation of the findings.

(1) What are the interior temperature ranges within commonly occupied spaces in typical Chicago 1-4 unit homes?

Among the unconditioned spaces, the average heat index on a heat wave day (8/24/2023) ranged from 83.2°F to 110.9°F while average heat index on non-extreme days ranged from 74.8°F to 81.5°F. The lower limits of these ranges occurred in the basement of Home #4. If this space is excluded, the lower limits are slightly higher. The minimum heat index on 8/24/2023 ranged from 75.5°F to 100.3°F, indicating a lack of relief from high heat on that day as the minimum heat index for many of the homes was in the mid-80s and 90s. The maximum heat index shows extreme conditions in many of the homes, with 120.1°F being the highest heat index recorded in the study. The maximum indoor heat index of 120°F occurred on 8/24/2023, when the maximum outdoor heat index that was recorded on that date was also 120°F. Additionally, all ten homes reached the extreme caution (90°F) or danger (103°F) threshold for heat index on 8/24/2023. Eight homes exceeded 103°F (danger) for 2-23 hours on 8/24/2023, and two of those homes were in the danger category for over 20 hours on that day.

Notably, the upper floors experienced a higher heat index than lower floors. This finding is consistent with other studies showing that upper floors are more likely to have higher temperatures (Oikonomou et al., 2012; Quinn et al., 2017). The heat index differentials were higher than expected, with the highest being a 32.0°F difference between the basement and the second floor of Home #4 on 8/24/2023. The largest heat index between a first and second floor was 31.4°F, which occurred in Home #2 on 8/23/2023. Overall, heat index differentials on heat wave days were large, with multiple homes having differentials greater than 15°F, suggesting high variability within the home itself. This finding also suggests the importance of occupants remaining on lower floors on heat wave days, when possible.

Though the summer weather conditions during 2023 were moderate on most days, the monitoring period excluding the heat wave days (i.e., 7/28/2023, 8/23/2023, 8/24/2023) showed that most unconditioned spaces experienced temperatures over 80°F throughout the study. Among the unconditioned spaces, the average temperature on 8/24/2023 ranged from 79.8°F to 93.7°F. The maximum temperature was 100.4°F (Home #2) and the maximum temperature differential was 18.8°F between the basement and the second floor of Home #4. The number of hours above 80°F in the unconditioned spaces ranged from 2% of the time (11 hours) to 39% of the time (406 hours). Additionally, the heat wave days were associated with higher indoor temperatures in the homes. On 8/24/2023, every home exceeded the 80°F threshold and almost all unconditioned spaces were over 80°F for 24 hours. This temperature has been associated with reduced sleep quality, duration, and shortened REM cycles, which have important implications for health, especially when the time exceeding the threshold is long-lasting (Minor et al., 2022; Xiong et al., 2020). Additionally, the WHO set a maximum acceptable indoor temperature of 77°F for Boston, MA, a comparable climate to Chicago (WHO, 2018a). The risk to human health increases significantly above the maximum acceptable temperature. This study shows evidence of homes regularly exceeding 80°F throughout the study period, on moderate summer days and heat wave days.

(2) What are the temperature differentials in masonry and frame constructed homes?

The maximum temperature differential for a masonry home was 18.8°F (Home #4) and the maximum temperature differential for a frame home was 16.0°F (Home #2). Masonry homes showed greater temperature and heat index differentials between floors. Among the unconditioned spaces, the single-family, single-story masonry home (Home #3) experienced the most amount of time over 80°F–358 hours on non-heat wave days which is nearly 15 days. The basement of the masonry single-family home (Home #4) experienced the least amount of time over 80°F. As noted, there is substantial variation within different spaces in the home, especially among the masonry homes.

Over the course of the study, the results show that masonry homes experienced a lower range of temperature variation compared to frame homes, especially for the first floor spaces. Frame homes were able to cool down more during the nighttime while the masonry homes were unable to cool down as quickly and appeared to retain heat for longer than the frame homes. Generally, the temperature and heat index in masonry homes were more uniform while the frame homes showed more impact from diurnal outdoor temperature variations. This aligns with White-Newsome et al. (2012) study of indoor temperature in Detroit homes that found homes with frame construction were more sensitive to outdoor temperature than masonry homes.

(3) How do the temperatures observed in this study compare to NREL and others' thermal resilience models?

Elevate and NREL (2022a) partnered on the Advanced Building Construction Initiative project funded by the U.S. Department of Energy to model energy upgrades in the residential 1-4 unit building stock for the City of Chicago. Using ResStock tools, project researchers modeled the stock's thermal resilience, the ability of a building to retain its heating and cooling in an outage, with air sealing and insulation upgrades. Generally, the models predicted that homes retained heating and cooling longer with air sealing and insulation than homes without (McCreery et al., 2022).

NREL and Elevate found that thermal resilience varied by housing stock and by season (Elevate & NREL, 2022b). The winter data showed that for all building types, the indoor dry bulb temperature decreased more slowly in the weatherized homes than in the baseline case. Furthermore, weatherized homes were found to be below the winter threshold temperature for fewer hours than their corresponding baseline homes. Frame homes were found to have a greater reduction in variability of temperature after weatherization than masonry homes; this is because the exterior walls of frame homes can be insulated.

Wet bulb temperature was used as the metric for determining occupant habitability in homes during the summer. For all building types and scenarios, wet bulb temperatures did not have a significant variability, and all remained below the threshold temperature for the time period analyzed. Weatherization slightly reduced the variability in indoor dry bulb temperature over time for all home types for winter and summer. However, weatherization did not result in a significant reduction in indoor wet bulb temperature variability which indicates that weatherization does not have as much of an impact on thermal resiliency during the summer as it does during the winter.

It is also worth noting that for both winter and summer, masonry homes were found to be warmer than the frame homes for both the baseline and weatherized cases with an exception of single-family detached homes in winter where frame weatherized is more thermally resilient than the weatherized masonry home. This is because masonry is more thermally conductive and has higher thermal capacitance than typical siding and acts as a thermal mass, storing heat during the day as the sun shines and letting it warm the house during the night when the sun goes down. This is an advantage for the thermal resilience for masonry homes during the winter but a slight disadvantage for these homes in the summer.

NREL's ResStock, as a building analysis tool, was not designed as a thermal resilience modeling tool. ResStock's primary function is to model "the diversity of the housing stock and the distributional impacts of building technologies in different communities," which was the primary objective of the Chicago Retrofit analysis. The ResStock tool models the building as a whole but does not have the technical capability to assign and model temperatures on each of the floors in the home, such as the basement, floor 1, 2, attic etc. Instead, temperature is modeled as consistent across the entire building. This is a limitation of ResStock, and points to the research need for better tools, but also underscores broadly the need to better understand risk. Specifically, as extreme heat becomes a chronic issue and not an acute issue - how, when, where, and who are at risk, in their homes? And at what heat, humidity and duration thresholds?

NREL completed an additional thermal resilience analysis in 2023 for Elevate using the same Chicago housing and upgrade measures data used in the DOE funded project. In this analysis NREL ran ResStock using weather data from the deadly 1995 Chicago heatwave (White, 2023). The purpose was to model the existing residential building stock with building upgrades, such as air-source heat pumps, envelope improvements, and full electrification, to understand the thermal resilience impacts in future heat waves.

NREL's thermal resilience analysis used the metric SET degree hours. SET stands for Standard Effective Temperature (described above), and the degree hours is an integrated measure of both SET temperature above/below a threshold and duration. NREL cited guidance from USGBC that indoor SET temperature above 86°F or below 54°F presents dangerous exposure to occupants. The goal was to understand how the retrofits may reduce dangerous temperatures and duration of dangerous temperatures in heat waves. The models predicted that the electrification packages with air source heat pumps would reduce dangerous exposure (in SET degree hours) by 16% in pre-1942 masonry homes and by 34% in pre-1942 wood frame homes. Yet, it's important to note that temperatures in both baseline and retrofit case exceeded the USGBC's recommended threshold. The mid-century wood frame home type (1942-78) was the one type that came closest to staying below the 86°F threshold. This housing type is more prevalent in surrounding Cook County suburbs than within the City of Chicago.

(4) Are temperature differential ranges smaller in homes that have been weatherized with air sealing and wall insulation?

Homeowners from all three frame homes in the study indicated that their homes had wall and attic insulation. The sample included no frame homes without insulation, so a larger sample of frame residences without insulation would be needed for comparison to masonry homes. Fully weatherized frame homes are not prevalent in Chicago and are not representative of the population. The 100% weatherized homes are likely due to the convenience sample of Elevate friends and family. Therefore, it is not possible to make an assessment of whether and/or how the temperature or heat index differentials differ in homes with and without air sealing and wall insulation.

(5) What adaptive capacity strategies and passive cooling strategies do households use to cope with heat?

Sixteen of the 17 strategies were used by at least 50% of respondents. The most utilized heat adaptation strategies in this sample were: using electric fans, using window shades and curtains, and wearing lighter clothing. This is consistent with findings from Portland, OR where public housing residents without AC employed many strategies to keep cool like keeping blinds closed all day and turning lights off (CAPA Strategies, 2023). Participants in this study reported opening windows and doors at a slightly lower rate than some other studies. For example, Tsoulou et al. (2020) study of temperature monitoring in public housing in New Jersey found that participants opened windows more often than they adjusted their clothing during heat waves. This difference in behavior could be explained by a trend of persistent overnight heat which lowers the effectiveness of window opening at nighttime, particularly because the survey asked about strategies used on the hottest days of summer and nighttime radiative cooling is often reduced on extremely hot days.

The least-reported heat adaptation strategy was leaving the home, indicating that participants may utilize their home as the main place of refuge during extreme heat events and remain inside despite elevated temperatures. This finding aligns with studies from other areas of the U.S. showing that leaving the homes is one of the least utilized strategies in a heat wave. Madrigano et al. (2018) found that most people stay home during hot weather, with only 12% of people leaving home to go to a public place with AC while Lane et al. (2023) found that most people prefer to stay home during extreme heat events, with the main reason being that the home was comfortable. This finding aligns with that of Lane et al. (2023) that also showed participants were slightly more likely to go to a business rather than a public place (e.g., library, community center) during hot weather.

Social vulnerability, the susceptibility to negative impacts from natural hazards, is a key factor to consider in the discussion of adaptive capacity to extreme heat. The CDC's Social Vulnerability Index (SVI) uses data from the U.S. Census to map census tracts that are expected to have a higher level of vulnerability and require additional support during a disaster (CDC, 2020). An SVI score of 0 represents the lowest level of vulnerability while a score of 1 represents the highest level of vulnerability. Five of the homes in this study are in tracts with medium-high or high vulnerability, while the remaining five are in areas with low or low-medium vulnerability. The overall SVI for each of the ten homes in this study are shown in Table 7.

Table 7. Social Vulnerability Index for census tracts of each home; source: CDC

Home #1	Overall SVI: 0.7498 (medium-high vulnerability)
Home #2	Overall SVI: 0.586 (medium-high vulnerability)
Home #3	Overall SVI: 0.3758 (low-medium vulnerability)
Home #4	Overall SVI: 0.7643 (high vulnerability)
Home #5	Overall SVI: 0.4777 (low-medium vulnerability)
Home #6	Overall SVI: 0.396 (low-medium vulnerability)
Home #7	Overall SVI: 0.0372 (low vulnerability)
Home #8	Overall SVI: 0.8019 (high vulnerability)
Home #9	Overall SVI: 0.7498 (medium to high vulnerability)
Home #10	Overall SVI: 0.4502 (low to medium vulnerability)

Conclusions & Recommendations

The findings of this study quantify the occurrence and severity of high indoor temperatures in archetypal Chicago homes and underscore the importance of policies and programs to protect people from high temperatures and prevent future heat-related morbidity and mortality. The results presented here highlight a need for preventative measures and solutions that address the indirect and direct consequences of extreme heat. We conclude with four themes of recommendations to lessen heat vulnerability and increase resilience: access to safe conditions, additional risk assessment, improved risk communication and education, and additional research.

Recommendation 1: Access to safe conditions

- *Increase access to affordable cooling in homes.* Access to safe conditions is critical to reducing the hazards of extreme heat exposure. As noted previously, our results and others' show that people tend to stay home despite warm indoor conditions. Future efforts should focus on improving thermal comfort within homes so that residents can stay home in safe, comfortable, and affordable conditions during extreme weather. One method of improving thermal resilience is to combine weatherization with heat pumps. Research shows that heat pumps are more effective and efficient at providing comfortable indoor conditions on extreme heat days, in comparison to standard air conditioners (Tan & Fathollahzadeh, 2021). All building electrification programs that serve the City of Chicago should prioritize homes without central cooling as part of their recruitment, assessment, and deployment strategy.
- *Reinstate Illinois' LIHEAP cooling assistance program and provide cooling as part of LIHEAP and utility program offerings.* Subsidized support from utilities and cooling assistance via LIHEAP would help address affordability concerns with using mechanical cooling during the summer and help reduce exposure to excess indoor heat. New York State and Portland, Oregon offer air-conditioning distribution programs that could be a model for an air-conditioning distribution. The program should be designed to offer a stipend to offset energy bill increases.
- *Increase access to public cooling areas, especially after 7:00pm during an extreme heat event.* This is particularly important for communities where environmental factors cause greater heat retention and lower cooling capacity during evenings. The Mayor's Office can work with OEMC, DFSS, community service centers, Chicago Parks and Libraries to extend the hours of Chicago Parks water features, increasing the number of sites that can remain open for 24 hours for cooling centers, and potentially invest in other water infrastructure (i.e. mobile fountains).
- *Review temperature threshold for alerts to begin promotion and activation of cooling programs and services.* It is important that residents are aware of cooling services, programs, and how to access them well before an emergency event. Additionally, considering high indoor air temperature is a direct stressor on health and wellbeing, the City should consider activating policies and programs that support individuals (i.e. mobile cooling buses) sooner than standard emergency protocols and in neighborhood with the highest ambient air temperatures and highest concentrations of at-risk residents.
- *Create neighborhood-designed and executed resiliency plans that prioritize community-owned assets and local businesses that complement city-sponsored services*. Deployment of citywide

services and programs do not account for socioeconomic and structural differences between neighborhoods that influence a community's climate resilience. As an initial step, the City and sister agencies can support highly customizable adaptation strategies that allow community-leadership and autonomy. These plans and augmented infrastructure networks enable communities to appropriately care for themselves until Emergency Services arrive thus alleviating some pressures on Emergency Services. These plans also serve as the base of a community-led resiliency and capacity building strategy.

- *Co-design and administer cooling kits with community and corporate partners.* Preparedness and response efforts among social service organizations and emergency management departments could help mitigate harmful impacts of extreme heat by providing resources to help with cooling such as cooling kits, window shades, and other tools to help lower indoor temperatures and keep individuals safe during heat events. Cooling kits enable an individual to respond to the conditions when most appropriate for themselves. This reusable kit can include base materials provided by corporate sponsors (i.e. water bottle, towel, visor), information about municipal resources, and can be customized by distributing partners to meet unique community needs.

Recommendation 2: Need for additional risk assessment

- *Implement community conversations about adaptive capacity to assess community risks and hyper-local mitigation strategies*. A community risk assessment that accounts for heat vulnerability at the community, individual, and building-level would help in identifying people that are at increased risk during extreme heat events. The 1995 Chicago heat wave revealed that the risk of heat related mortality was increased for those who had underlying medical problems, were confined to beds, or living alone (Semenza et al., 1996). Further assessment could also highlight community assets and identify specific strategies to mitigate risk. Additionally, it could utilize data from the Chicago Heat Watch campaign, the Heat Vulnerability Index, and the findings of this report to better understand community needs and risk. Though our study is limited by its sample size, the results indicate that more information is needed to better understand community adaptive capacity, effective interventions, adaptive behaviors and cooling strategies, risk perception and safety, and access to and use of (or not) cooling, and community needs, assets, and solutions. Community residents have the hyper-local knowledge and experience with the climate, landscape, and strategies for achieving cooler indoor temperatures. The outcomes of such a risk assessment should be used to prioritize investment into efforts that reduce heat exposure and increase resilience for those who are at greatest risk.

Recommendation 3: Improved education and communication

Our third theme of recommendations are for improved education and communication (including emergency notifications) regarding heat-related risks. Some participants in our sample didn't know if they were at risk for unsafe temperatures, though they acknowledged uncomfortable temperatures in their homes and many expressed extreme concern for others during heat waves. Participants expressed limited knowledge on dangerous temperature thresholds, so we recommend improved communications about risk, specifically for public communication for heat events. Communications could aim to be more specific with messaging and danger warnings, and education on the most effective strategies for cooling the body and the home would make it easier to recognize danger and take appropriate caution and steps to reduce exposure.

- *Utilize networks of hyper-local partners to create and disseminate health and safety information about extreme weather events.* Communities engage with government communication channels in various ways and there may be gaps in the government's ability to reach more vulnerable communities. By equipping trusted community voices with current and relevant information about municipal programs and services, it allows them to extend the reach of traditional communication channels to reach those who can benefit greatly. For example, a community-led wellness check that is activated at an agreed upon threshold temperature could help residents that may be at a higher risk for hospitalization or death at lower temperatures than the thresholds NWS uses. The co-creation and amplification process are ways to build greater trust between civic parties, prioritize culturally relevant messaging, and initiate a deeper relationship for more robust conversations about climate resiliency at the neighborhood level.
- *Explore opt-in push alerts from two-way communicating thermostats via utility smart meters when indoor air temperatures exceed certain thresholds.* IFTT technology and two-way communicating thermostats with ComEd's smart meter rollout could enable residents, especially those who live alone, to identify trusted family or friends to receive an automated phone call when temperatures in their homes exceed certain thresholds.

Recommendation 4: Additional Research Needed

- This study relies on data collected from ten homes, and a larger and more diverse sample size would enable more robust conclusions. Monitoring temperature and heat index in additional home types like multi-family buildings and manufactured housing could help further identify housing types most vulnerable to heat. Further research into the impact of weatherization (insulation and air sealing, etc.) and other envelope measures is needed to better understand the impact of adding mechanical vs envelope upgrades for cooling. Also, further research could help better understand how indoor heat metrics compare to local outdoor heat metrics to improve our ability to map indoor heat risk assessment. Additional data collection of heat index and survey data would allow for more accurate assessment of the most vulnerable home types, individual's responses to and perceptions of extreme heat events, and help shape overall extreme heat risk assessment for Chicago.

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Appendix A: Survey Questions

Heat Concerns

1. When it comes to facing hotter temperatures in the summer, please rate your level of concern around the following*: [Matrix of options: Not at all concerned; Slightly concerned; Somewhat concerned; Moderately concerned; Extremely concerned]*
    a. Higher electric bills due to increased energy use for cooling needs.
    b. Increased health risks due to heat strain.
    c. Changes in sleep quality and sleep duration due to increased temperatures.
    d. Concern over the wellbeing of family, friends, and community during heat waves

2. Are there any additional concerns about hotter summer temperatures that you would like to share? (If not, leave blank and continue to next question.)

3. Do you believe that your home reaches unsafe temperatures at times during the summer?
    a. Yes
    b. No
    c. Unsure

4. [If Yes/Unsure is selected] Can you expand on where in your home you feel might reach unsafe temperatures, and why?

5. How concerned do you feel about facing potential heat waves this summer? A heat wave is a period of unusually hot weather in which temperatures exceed the historical averages for a given area.
    a. Not at all concerned
    b. Slightly concerned
    c. Somewhat concerned
    d. Moderately concerned
    e. Extremely concerned

6. Do you feel that this summer was warmer than previous years and you had to use more cooling strategies than before (i.e. opening windows more, using more fans and AC)?
    a. Yes
    b. No

Adaptive Capacity - Behavioral

7. Which of the following strategies do you typically use **on the hottest days of the summer**? (Select all that apply.)

a. I check weather reports and base behavior on this information.
b. I open windows or doors.
c. I turn a fan(s) on.
d. I turn an air conditioner unit(s) on.
e. I use curtain, blinds, or window shutters to protect against heat.
f. I reduce sources of electrical and electronic heat in the home.
g. I move to cooler areas of the home, such as a basement.
h. I close doors of spaces that are usually warmer than other spaces.
i. I try to create air flow in certain spaces with a combination of window opening, AC(s), fan(s), and closing the doors to warmer spaces.
j. I move to an outdoor space of the home, such as the porch or yard.
k. I leave the house.
l. I take a shower or bath.
m. I wear lighter clothes.
n. I use a cool wet cloth to cool off while inside.
o. I use thinner bedding.
p. I drink beverages to cool off.
q. I eat fresh, light, or iced foods to cool off.

8. [If LEAVE THE HOUSE was selected] Where do you usually go? Do you… [check all that apply.]
    a. Go to someone else's air-conditioned home.
    b. Go to an air-conditioned community center, library, or other public place.
    c. Go to an air-conditioned business.
    d. Go to a park or area with tree shade
    e. Other, specify ____

9. [If AC was selected in No.5] **On the hottest days of this summer**, can you estimate about how many hours your AC unit(s) was turned on? If you have multiple units, select the one most often used in order to respond. [Min 0, Max 4 for each)
    a. Number of hours in the morning (8 am- 12 pm)
    b. Number of hours in the afternoon (12 pm – 4 pm)
    c. Number of hours in the evening (4 pm – 10 pm)
    d. Number of hours at night (10 pm – 8 am)

10. [If Fans was selected in No.5] **On the hottest days of this summer**, can you estimate about how many hours your fan(s) was turned on?? If you have multiple fans, select the one most often used in order to respond. [Min 0, Max 4 for each)
    a. Number of hours in the morning (8 am- 12 pm)
    b. Number of hours in the afternoon (12 pm – 4 pm)
    c. Number of hours in the evening (4 pm – 10 pm)
    d. Number of hours at night (10 pm – 8 am)

11. Which of the following strategies also assist in cooling your home? (Check all that apply.)
    a. Shading (i.e., overhangs, awnings, and/or exterior shading devices)
    b. Insulation
    c. Reflective cooling (i.e., cool roof coating)
    d. Tree canopy (i.e., trees around the home that help shade it)

12. Do you have a specific reason(s) for not installing a central cooling system? (Select all that apply.)
    a. I am environmentally conscious and do not think all homes should have a central cooling system in Chicago.
    b. I never lived in a home with a central AC system growing up, and I do not feel the need for it now.
    c. I plan to install a heat pump at some point and would use it during the summertime for central cooling.
    d. I plan to install a central cooling system at some point.
    e. Other (comment box)

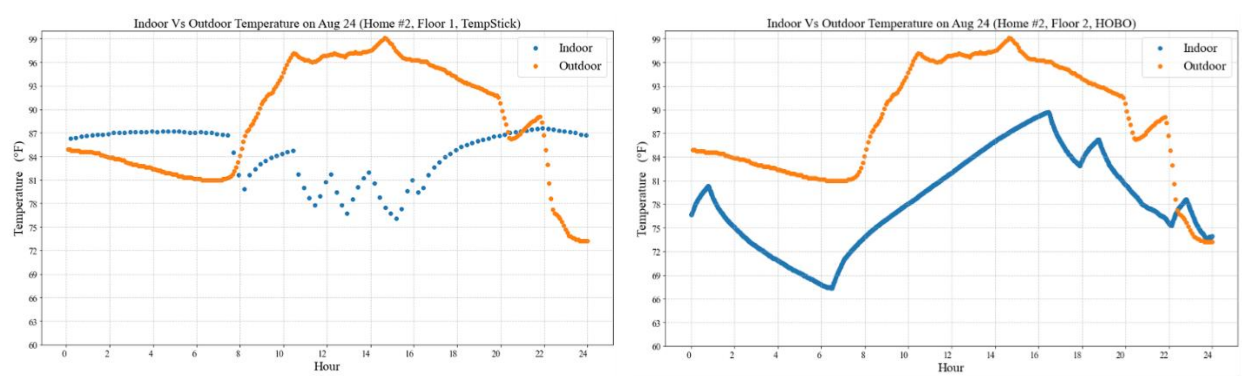
13. Is there anything else you would like to share with us about heat waves, cooling strategies, etc.?

Appendix B: Temperature Time Constant

One important aspect of developing a thermal resiliency strategy is to provide temporary mitigation measures in order to utilize them during extreme heat conditions. One temporary solution could be to consider a small room with a window air conditioner (AC) which can serve as a mitigation measure to cool down the space quickly. We investigated the time that is needed to cool down a space significantly to reach 77-78°F which is important for the vulnerable population. Among the extreme days this summer (i.e., July 28, August 23, August 24). For this temperature time constant, August 24 is used due to the higher values of outdoor temperature. As the previous results showed the single-family frame houses experience higher indoor temperature fluctuations, this type of home is considered here. Home #2 is a single-family frame house.

As Figure 21-a shows this was the second day of the August heatwave with severe temperatures rising. The outdoor temperature is significantly higher than Aug. 23, and the outdoor was experiencing higher temperature especially between 10 am to 4 pm. Table 8 also summarizes the findings for different times that the AC was on. Based on Figure 21-a and Table 8, a few observations for the first floor are: (1) the window AC was able to decrease the indoor temperature to approximately 76°F throughout the day when it was in operation; (2) from 7:30 am the time constant decreased constantly from 70 minutes to 45 minutes. By looking at the data between 12 pm to 6 pm, the time constant could be considered 75 min. This suggests around 75 minutes is needed to cool down the space on the first floor for this frame home; and (3) because of higher outdoor temperature, the indoor temperature increased in a shorter period and the AC was more engaged in cooling down the temperature.

For the second floor, as Figure 21-b shows, the effect of the AC system can be observed by looking at indoor temperature between 4:27 pm until midnight. The AC system was turned on at 4:27 pm for the first time. It took 84 minutes to cool down the temperature from 89.7°F to 82.9°F. The second sign of AC being turned on is at 6:45 pm, and it took 202 minutes to cool down the temperature. Since the temperature decrease in the second decline can be partially related to the outdoor temperature trend, 84 min is considered as time constant.



(a) *(b)*

Figure 21. Indoor vs outdoor temperature on Aug 24, 2023 for Home #2: (a) Floor 1 and (b) Floor 2

Table 8. HVAC function cycles on Aug 24 (Home #2, Floor 1)

Decline	Time	Temperature (°F)	Incline	Time	Temperature (°F)
D1	7:26 - 8:11	86.7 - 79.8	I1	8:11 - 10:26	79.8 - 84.7
	Δt = 70 min	ΔT = -6.9		Δt = 140 min	ΔT = 4.9
D2	10:26 - 11:26	84.7 - 77.8	I2	11:26 - 12:11	77.8 - 81.7
	Δt = 60 min	ΔT = -6.9		Δt = 40 min	ΔT = 3.9
D3	12:11 - 12:56	81.7 - 76.7	I3	12:56 - 13:56	76.7 - 82
	Δt = 45 min	ΔT = -5		Δt = 60 min	ΔT = 5.3
D4	13:56 - 15:11	82 - 76.1	I4	15:11 - 15:56	76.1 - 81
	Δt = 75 min	ΔT = -5.9		Δt = 40 min	ΔT = 4.9
D5	15:56 - 16:11	81 - 79.4	I5	16:11 - 23:56	79.4 - 86.7
	Δt = 15 min	ΔT = -1.6		Δt = 465 min	ΔT = 7.3

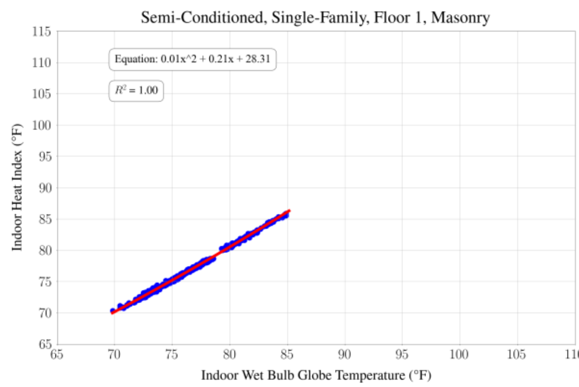
Table 9. HVAC function cycles on Aug 24 (Home #2, Floor 1)

Decline	Time	Temperature (F)	Incline	Time	Temperature (F)
D1	16:27 - 17:54	89.7 - 82.9	I1	17:54 - 18:45	82.9 - 86.2
	Δt = 84 min	ΔT = -7.9		Δt = 69 min	ΔT = 3.33
D2	18:45 - 22:07	86.2 - 75.3	I2	22:07 - 22:48	75.3 - 78.6
	Δt = 202 min	ΔT = -10.91		Δt = 41 min	ΔT = -3.3
D3	22:48 - 23:56	78.6 - 73.7			
	Δt = 68 min	ΔT = 4.92			

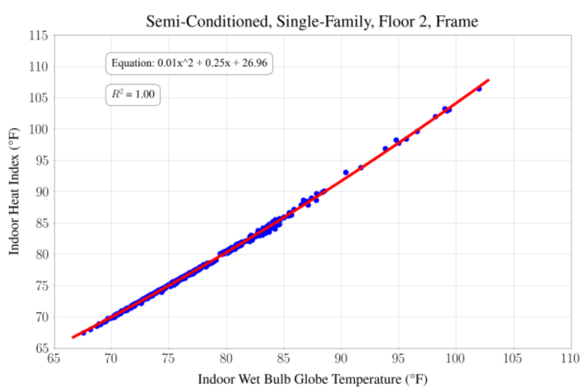
Overall, the results indicate that as a mitigation measure, the first floor of frame homes is an ideal candidate for this strategy, and it could take up to 75 minutes to cool down the space.

Appendix C-1: Regression Analysis (Heat Index vs WBGT)

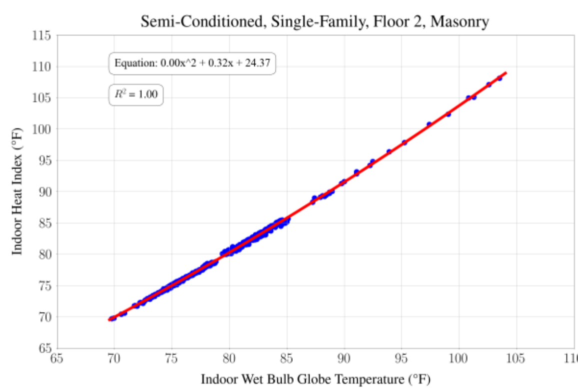
This appendix shows the correlation between the heat index and WBGT temperature values. Given the nature of the equations and also the lack of significant correlation between the globe temperature and the air temperature, heat index values follow the WBGT values. Figure 22 to Figure 25 show the indoor heat index with respect to the indoor wet bulb globe temperature for semi-conditioned and unconditioned spaces with different construction types. Since most of the spaces are unconditioned, there are only semi-conditioned spaces for floor 1 of masonry homes, floor 2 of frame homes, and floor 2 of masonry homes.



(a)

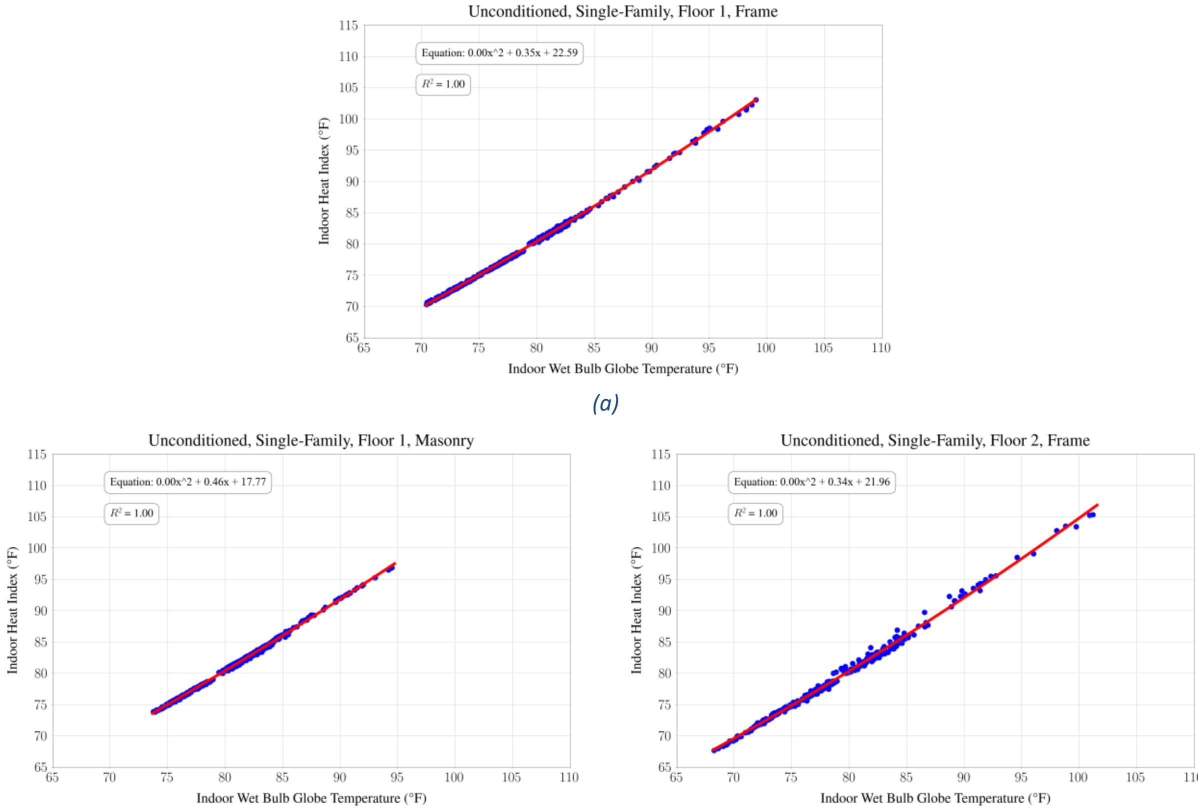


(b)



(c)

Figure 22. Heat index versus web-bulb globe temperature for semi-conditioned single-family homes: (a) Floor 1 – Masonry, (b) Floor 2 – Frame, and (c) Floor 2 – Masonry (not all the homes have semi-conditioned rooms)



(b) (c)

Figure 23. Heat index versus web-bulb globe temperature for unconditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, and (c) Floor 2 – Frame

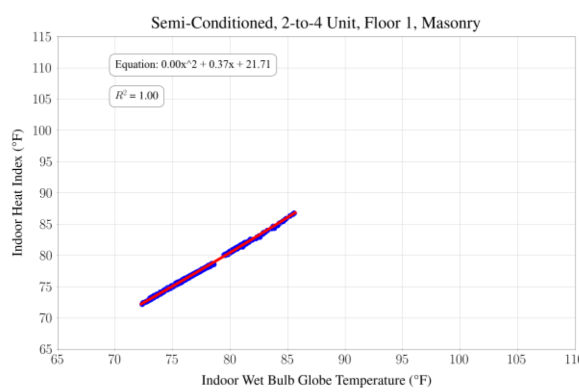


Figure 24. Heat index versus web-bulb globe temperature for semi-conditioned 2-to-4 unit homes: Floor 1 – Masonry (not all the homes have semi-conditioned rooms)

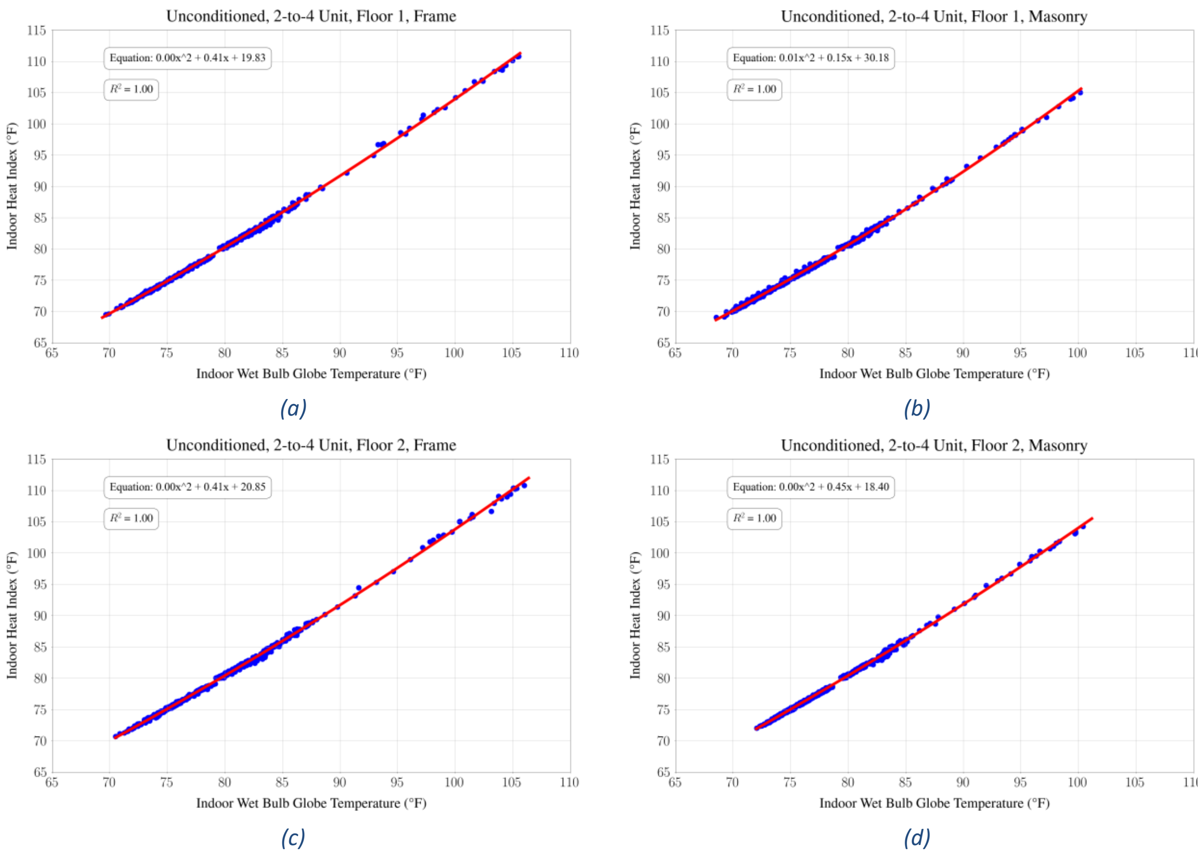
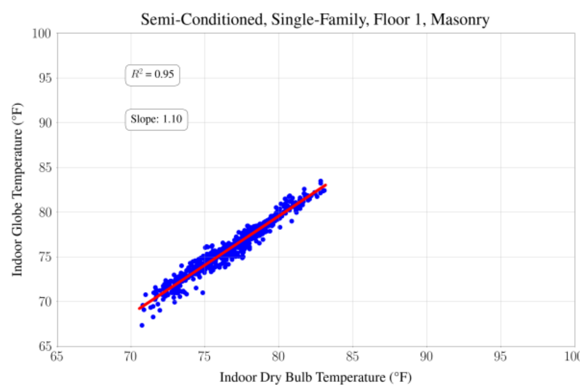


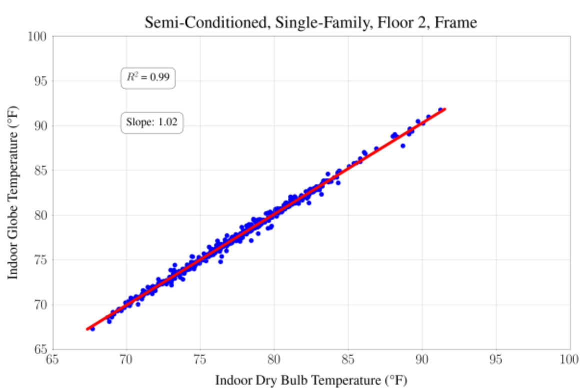
Figure 25. Heat index versus web-bulb globe temperature for unconditioned 2-4 unit homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Appendix C-2: Regression Analysis (Globe Temperature vs Indoor Temperature)

Figure 26 to Figure 29 show the indoor globe temperature versus the indoor air temperature for single-family and 2-4 unit homes.



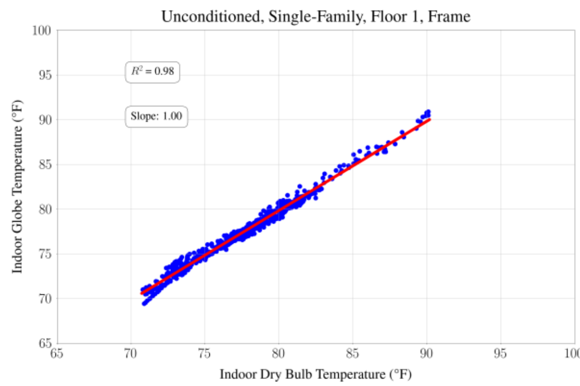
(a)



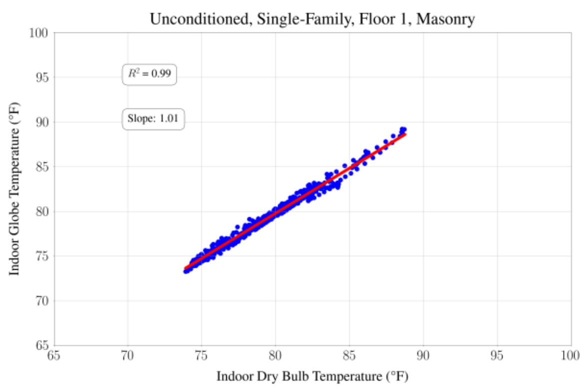
(b)

(c)

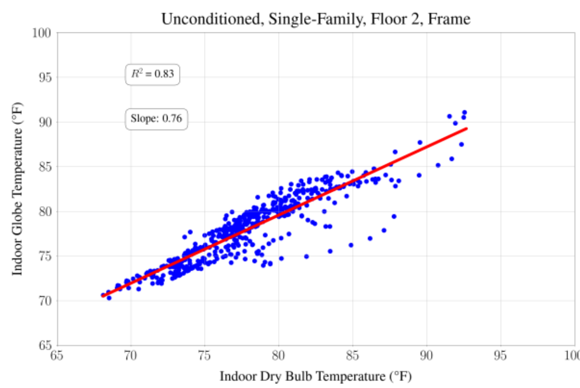
Figure 26. Globe temperature vs. dry bulb temperature for semi-conditioned single-family homes: (a) Floor 1 – Masonry, (b) Floor 2 – Frame, and (c) Floor 2 – Masonry (not all the homes have semi-conditioned rooms)



(a)



(b)



(c)

Figure 27. Globe temperature vs. dry bulb temperature for unconditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, and (c) Floor 2 – Frame

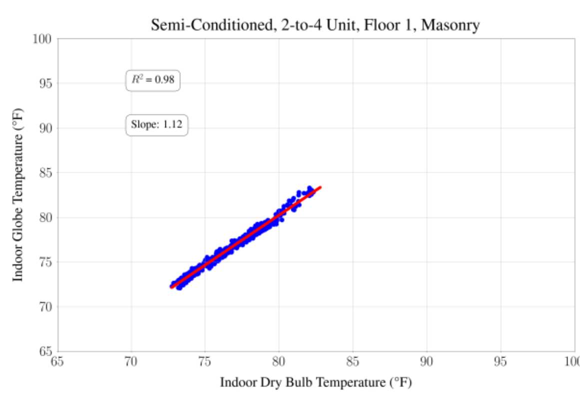
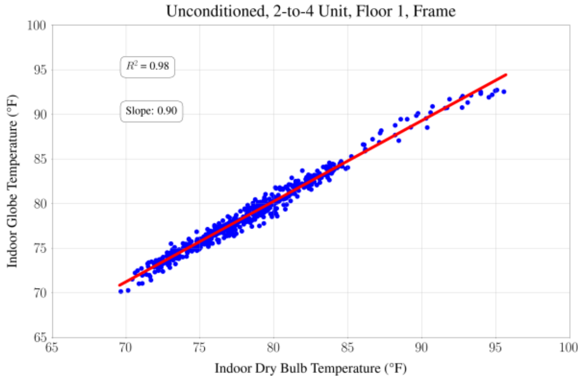
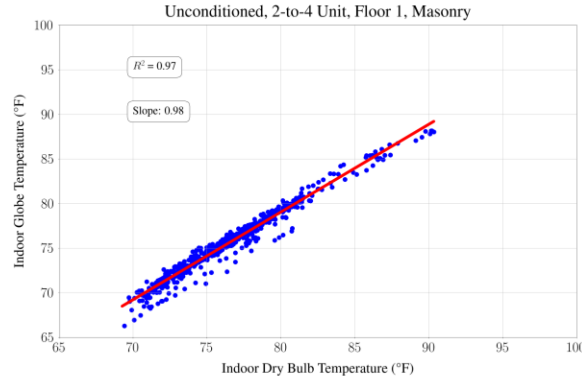


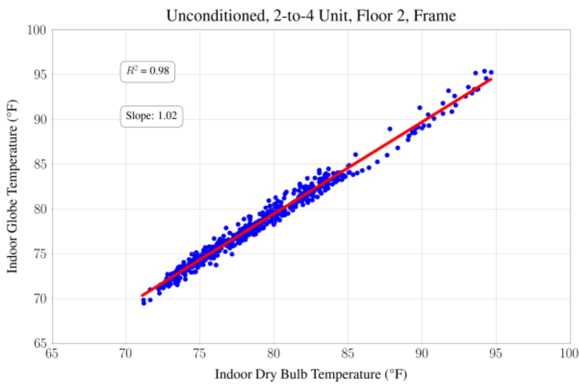
Figure 28. Globe temperature vs. dry bulb temperature for semi-conditioned 2-to-4 unit homes: Floor 1 – Masonry (not all the homes have unconditioned rooms)



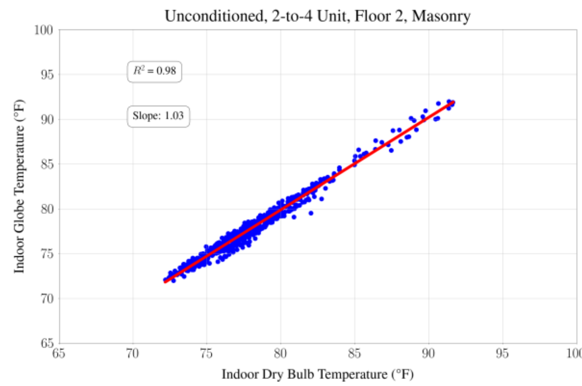
(a)



(b)



(c)



(d)

Figure 29. Globe temperature vs. dry bulb temperature for unconditioned 2-4 unit homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Appendix C-3: Regression Analysis (Indoor temperature vs outdoor temperature)

Figure 30 and Figure 33 show the indoor air temperature with respect to the outdoor air temperature. As it can be observed, there are more significant correlations between indoor and outdoor dry bulb temperature in semi-conditioned homes than unconditioned spaces.

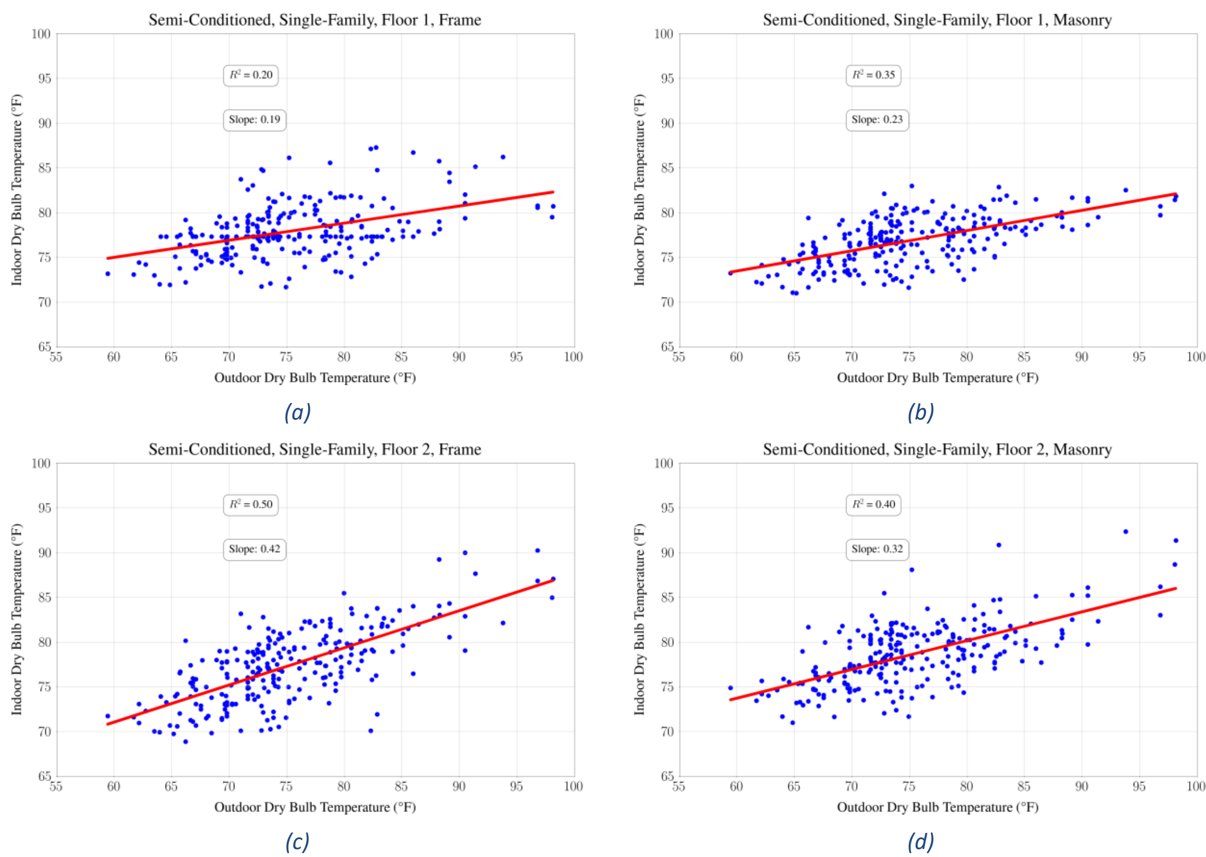


Figure 30. Indoor dry bulb vs outdoor dry bulb temperature for semi-conditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, (b) Floor 2 – Masonry

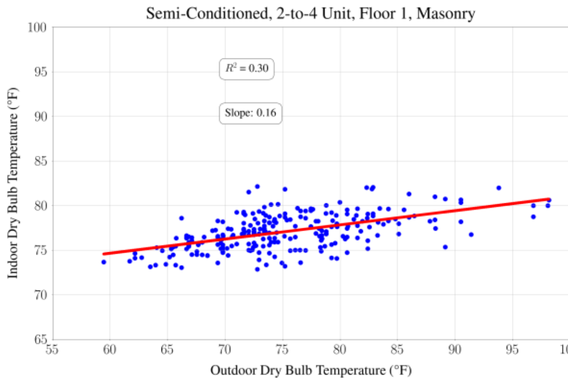
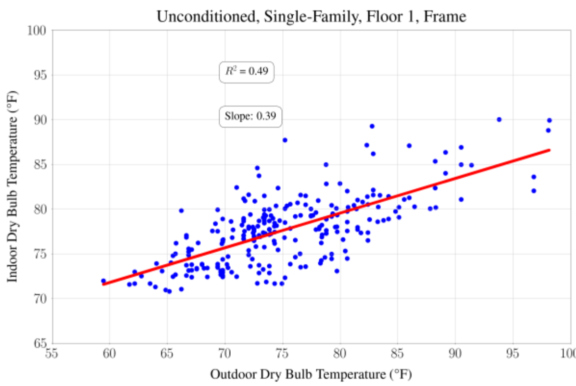
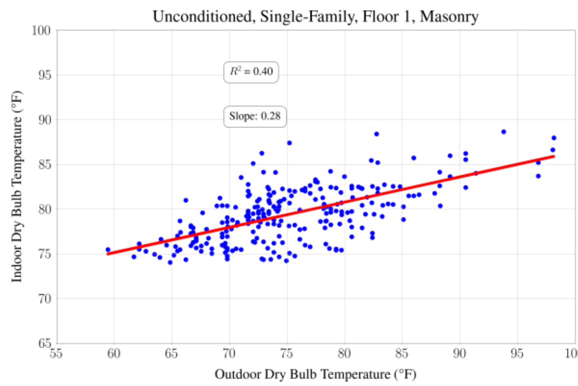


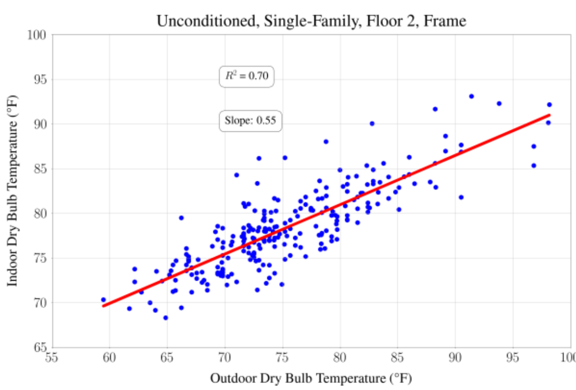
Figure 31. Indoor dry bulb vs outdoor dry bulb temperature for semi-conditioned 2-4 unit homes: Floor 1 – Masonry (not all the homes have semi-conditioned rooms)



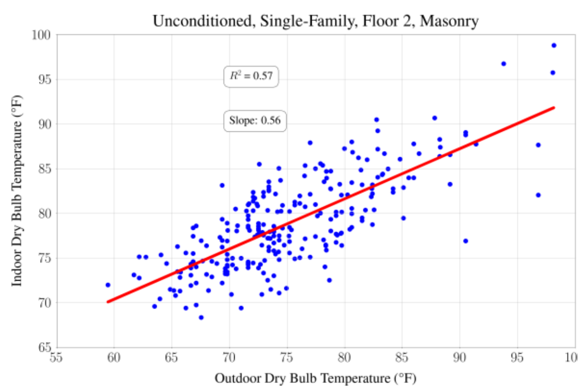
(a)



(b)



(c)



(d)

Figure 32. Indoor dry bulb vs outdoor dry bulb temperature for unconditioned single-family homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

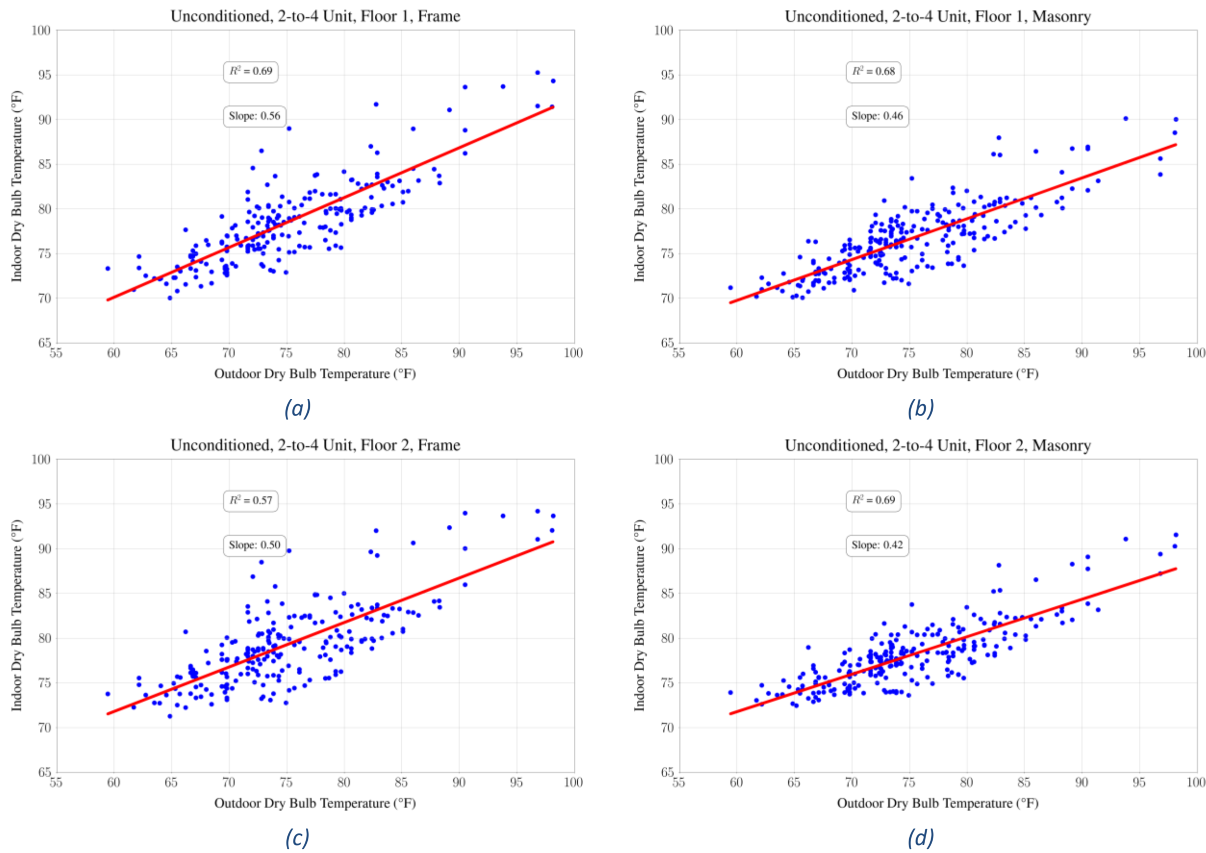


Figure 33. Indoor dry bulb vs outdoor dry bulb temperature for unconditioned 2-4 unit homes: (a) Floor 1 – Frame, (b) Floor 1 – Masonry, (c) Floor 2 – Frame, and (d) Floor 2 – Masonry

Appendix C-4: Summary of Regression Analysis

Table 10 and Table 11 summarize the regression analysis presented in the previous appendices for semi-conditioned and unconditioned spaces.

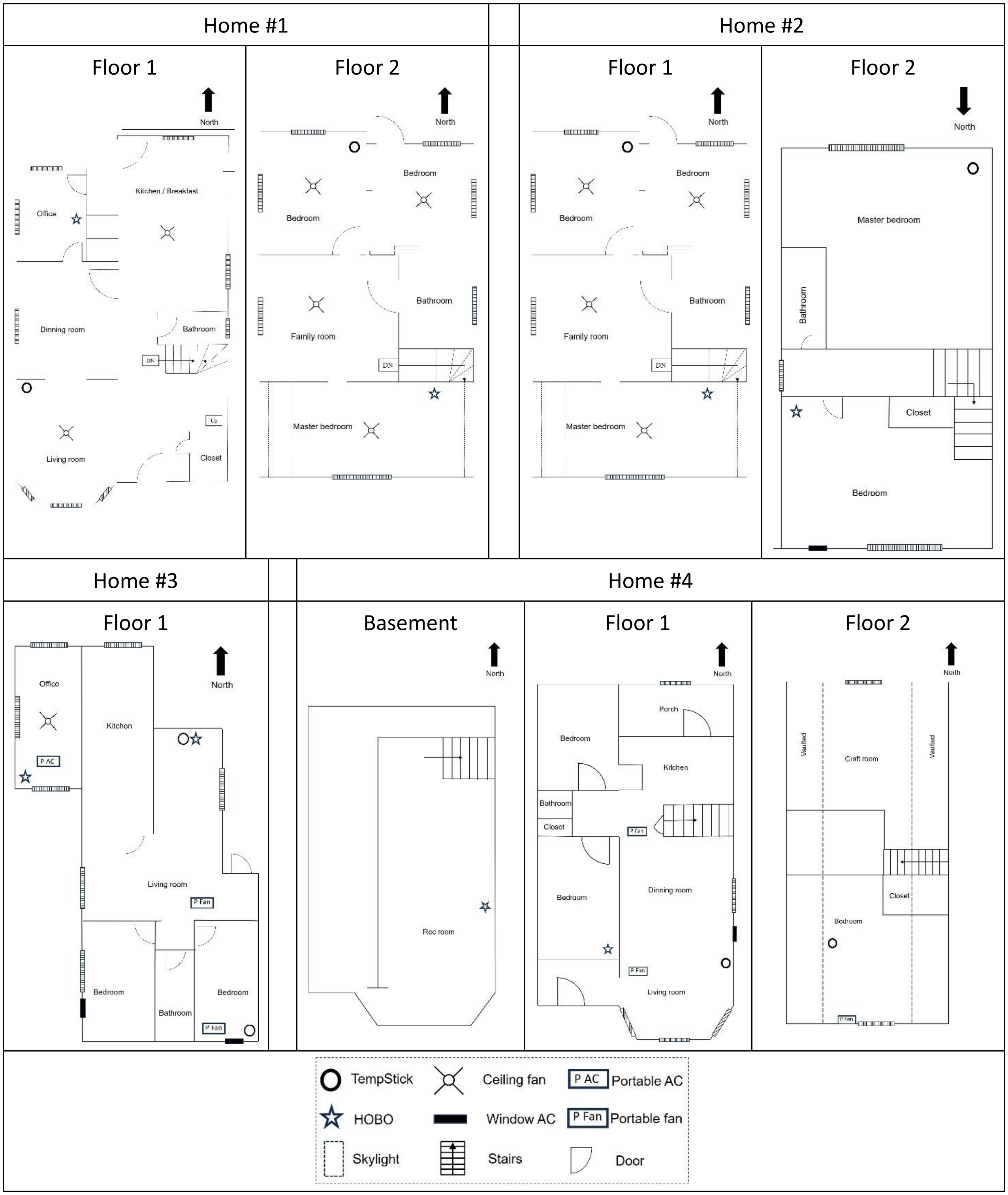
Table 10. The summary of regression analysis for semi-conditioned homes

Building Type	Floor	Indoor Temperature Vs. Outdoor Temperature		Indoor Globe Temperature Vs. Indoor Dry Bulb Temperature		Indoor Heat Index Vs. Indoor Wet Bulb Globe Temperature	
		R^2	Slope	R^2	Slope	R^2	Slope
2 to 4 Units - Masonry	1	0.30	0.16	0.98	1.12	1.00	-
Single-family - Frame	1	0.20	0.19	-	-	-	-
Single-family - Masonry	1	0.35	0.23	0.95	1.10	1.00	-
Single-family - Frame	2	0.50	0.42	0.99	1.02	1.00	-
Single-family - Masonry	2	0.40	0.32	0.98	1.02	1.00	-

Table 11. The summary of regression analysis for unconditioned homes

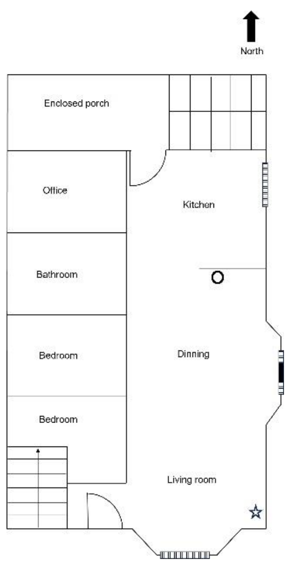
Building Type	Floor	Indoor Temperature Vs. Outdoor Temperature		Indoor Globe Temperature Vs. Indoor Dry Bulb Temperature		Indoor Heat Index Vs. Indoor Wet Bulb Globe Temperature	
		R^2	Slope	R^2	Slope	R^2	Slope
2 to 4 Units - Frame	1	0.69	0.56	0.98	0.90	1.00	-
2 to 4 Units - Masonry	1	0.68	0.46	0.97	0.98	1.00	-
2 to 4 Units - Frame	2	0.58	0.50	0.98	1.02	1.00	-
2 to 4 Units - Masonry	2	0.69	0.42	0.98	1.03	1.00	-
Single-family - Frame	1	0.49	0.39	0.98	1.00	1.00	-
Single-family - Masonry	1	0.40	0.28	0.99	1.01	1.00	-
Single-family - Frame	2	0.70	0.55	0.83	0.76	1.00	-
Single-family - Masonry	2	0.57	0.56	-	-	-	-

Appendix D: Floor Plans

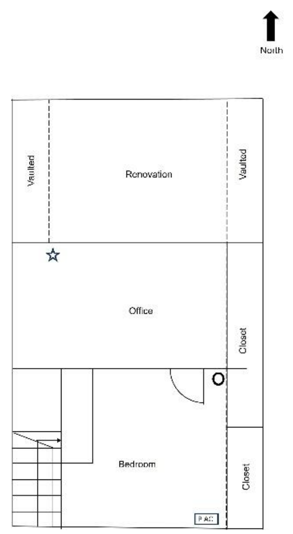


Home #5

Floor 1

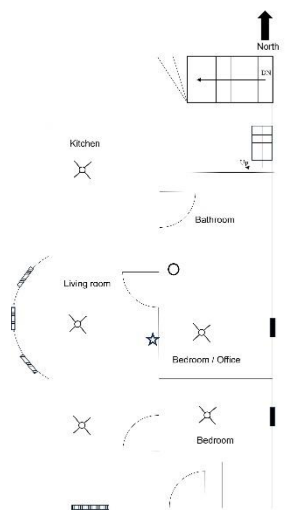


Floor 2



Home #6

Floor 1



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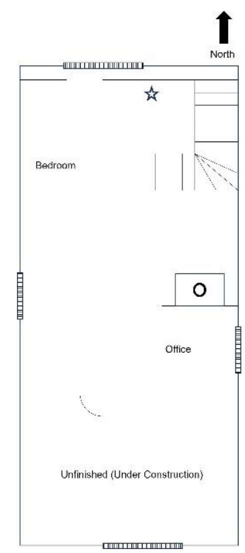
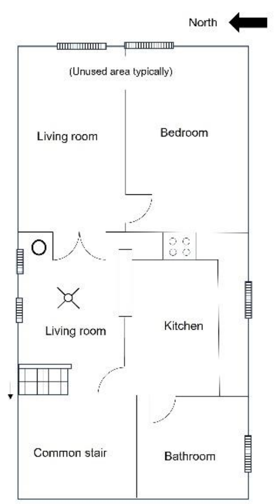
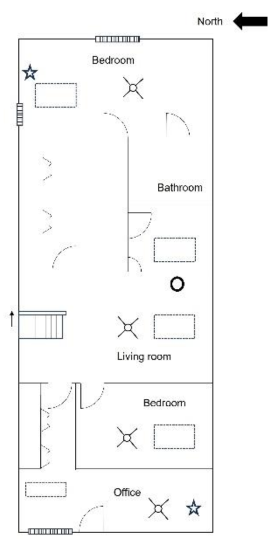


Home #7

Floor 1

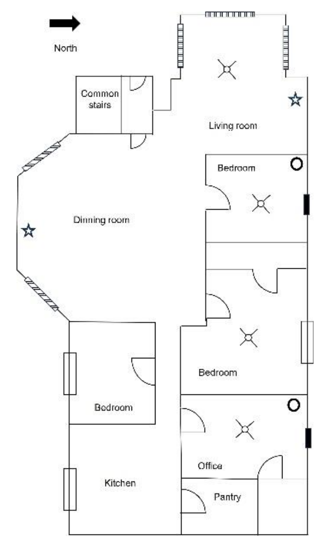


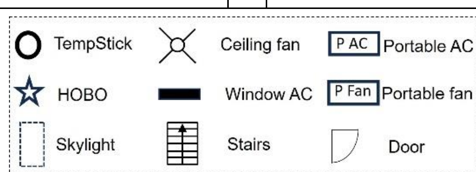
Floor 2



Home #8

Floor 1





Home #9		Home #10	
Floor 1	Floor 2	Floor 1	Floor 2