Thermal Energy System Resilience: Temperature Decay in Cold/Arctic Climates—Part I

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ABSTRACT

Thermal energy systems' resilience is especially important in extreme climates such as arctic or tropical environments. While metrics and requirements for availability, reliability, and quality of power systems have been established (DOD 2020), similar metrics and requirements for thermal energy systems are not well understood. In one of the first attempts to address this deficiency, a study was conducted to better understand the level of reliability required for energy supply systems that will be capable of supporting environmental conditions required for the facility's mission, the comfort of people, and sustainment of a building in arctic environments under predominant threat scenarios.

This paper is split into two parts. The purpose of Part I is to present the methodology and results of a novel temperature decay test conducted during the winter, along with blower door tests on five representative military buildings in Alaska. In Part II, a building modeling analysis is compared and calibrated to the experimental data collection for the thermal decay test (TDT) and a reliable building model that allows prediction of the maximum time available to repair the heat supply system before the building needs to be evacuated when damage is done to equipment or facilities is described.

The results from the field tests described in Part 1 indicate that the rate of decay is dependent on the time of day (i.e., amount of sunlight) and building features, and will vary within the building relative to wind direction. This study, combined with the modeling analysis addressed in Part II, will provide guidance to building managers on evacuation and sustainment procedures for buildings in arctic climates that are affected by thermal energy supply systems, HVAC systems, fuel, or electrical disruptions.

BACKGROUND

Thermal energy systems' resilience is especially important for extreme climates, such as arctic or tropical environments. While metrics and requirements for availability, reliability, and quality of power systems have been established (DOD 2020), similar metrics and requirements for thermal energy systems are not well understood. For this paper, thermal energy systems are comprised of both the demand and supply sides (Figure 1). The demand side includes mission-related active and passive systems, including thermal demand by the process, HVAC systems maintaining required environmental conditions for the building's operations and the comfort of people, and a shelter/building that houses them. The supply side includes energy conversion, distribution, and storage system components. Requirements to maintain thermal/environmental conditions in the building (or in a part of the building) needed for housing critical mission-related processes and occupants include criteria to maintain thermal comfort and health, support process needs, and prevent mold, mildew, and other conditions that can damage building materials or furnishings. These requirements for normal (i.e., blue skies) and emergency (i.e., black skies) operations are described in detail in Zhivov et al. (2021a). Thermal comfort conditions in a mission-critical facility during normal operations differ from the cold stress threshold limits above which mission operators can conduct mission-critical tasks. This results in a difference between the total heat load during normal operations and a critical heat load during emergency operations. This affects requirements for energy availability (EA) provided by the supply system. The time to restore the system to its baseline state is another requirement for the energy supply system. EA and mean time to repair (MTTR)

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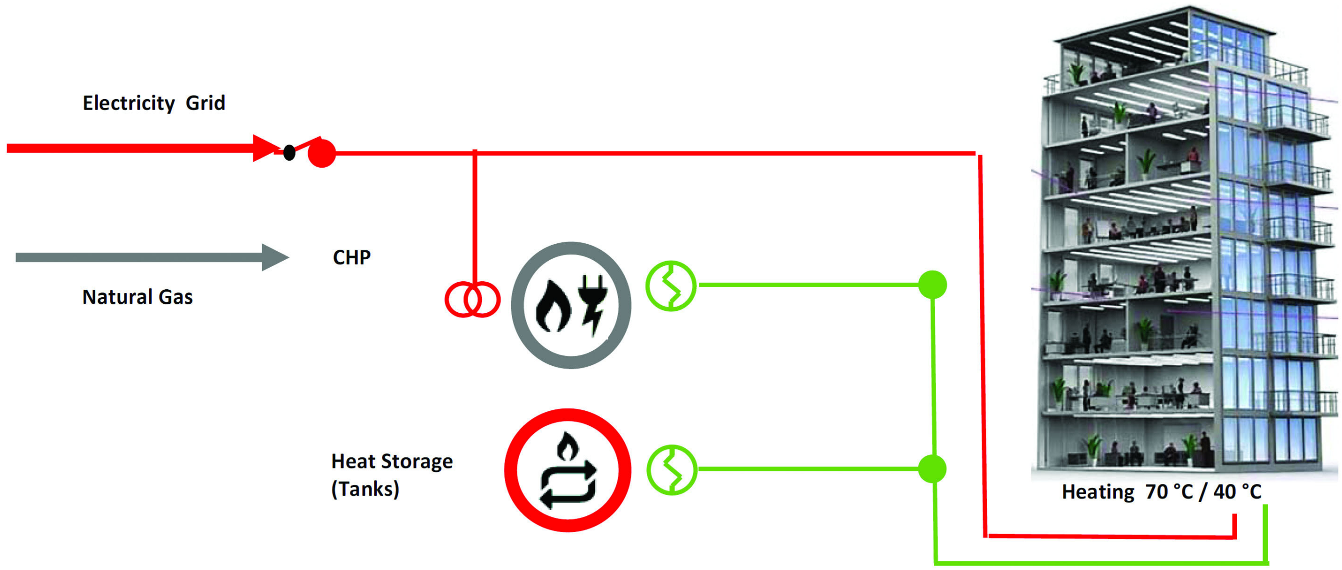


Figure 1 *Component of the notional thermal system.*

are two critical metrics of the thermal system characteristics of any assets affected by the event and may be affected by several factors including site remoteness, event severity, and environmental conditions.

Previous work on the resilience of thermal energy systems in cold/arctic climates is relatively limited. While the effects of thermal mass on building efficiency with active heating and cooling were studied by Reilly et al. (2017), the authors confirm that there is a lack of research focusing on the performance of thermal mass in cold climates. The study used experimental data from Byrne et al. (2013), which identified discrepancies between measured U-factors and those predicted by static calculation methods. The experimental data (Byrne et al. 2017) were collected at one building located on the coast of Ireland, where exterior temperatures ranged from 39°F to 61°F (4°C to 16°C). In the present study, data were collected and analyzed for five buildings with temperatures ranging from –40 °F to –9°F (–40°C to –23°C). The buildings were chosen, in part, because they were constructed with varying methods and materials. Moreover, these two previous studies were primarily focused on building efficiency; the goal of the present work is to evaluate the resilience of the thermal energy systems in cold/arctic environments, during emergency situations. Several studies using a building energy simulation (Stevens 2016, Aidan 2017) were conducted to study the effect of the building mass on energy consumption and thermal comfort in hot and cold climates that demonstrated advantages of mass buildings over light frame buildings in locations with a high diurnal variation. Other building energy simulation studies, (e.g., documented in IEA ECBS Annex 46 [2014] and Ng et al. [2014]) show the effect of building airtightness and thermal resistance on annual energy consumption in different climate conditions. However, all these studies have been conducted with a controlled indoor air temperature.

The U.S. Department of Defense (DOD) has determined that resilience is an emerging need. The concept of resilience is separate but complementary to sustainability. If a building can maintain continuity of operations in regards to occupant safety, health, and comfort over an extended period of time without significant damage to the building and its systems, it is said to be resilient. In cold and arctic climates, additional attention to the power and heating systems is crucial (ASHRAE 2015). Military installations are similar to many building types found in cities all over the country in that they comprise a condensed version of commercial, residential, and industrial building types. Military installations typically contain such common building types as offices, child development centers, multifamily/dormitory housing, laboratories, and warehouses. While the design of individual buildings may vary based on function type, a number of other factors remain relatively constant, including but not limited to accessibility, aesthetics, cost-effectiveness, operations, preservation, productive environment, safety and security, and environmental sustainability (NIBS 2020).

Climate impacts building performance, and thus affects resilience planning. Alaska encompasses four separate climate zones—Department of Energy (DOE) Zones 6–8 including Cold, Very Cold, and Subarctic and an additional Alaskan Zone 9, Arctic. Awareness of climate zones and how they affect different parts of the country is important when determining the proper use of energy codes and standards. The challenge for building design in Alaska is that there is still a need for cooling in the summer. Existing designs do not always include cooling options even though recent summer temperatures have reached up to 95°F (35°C).

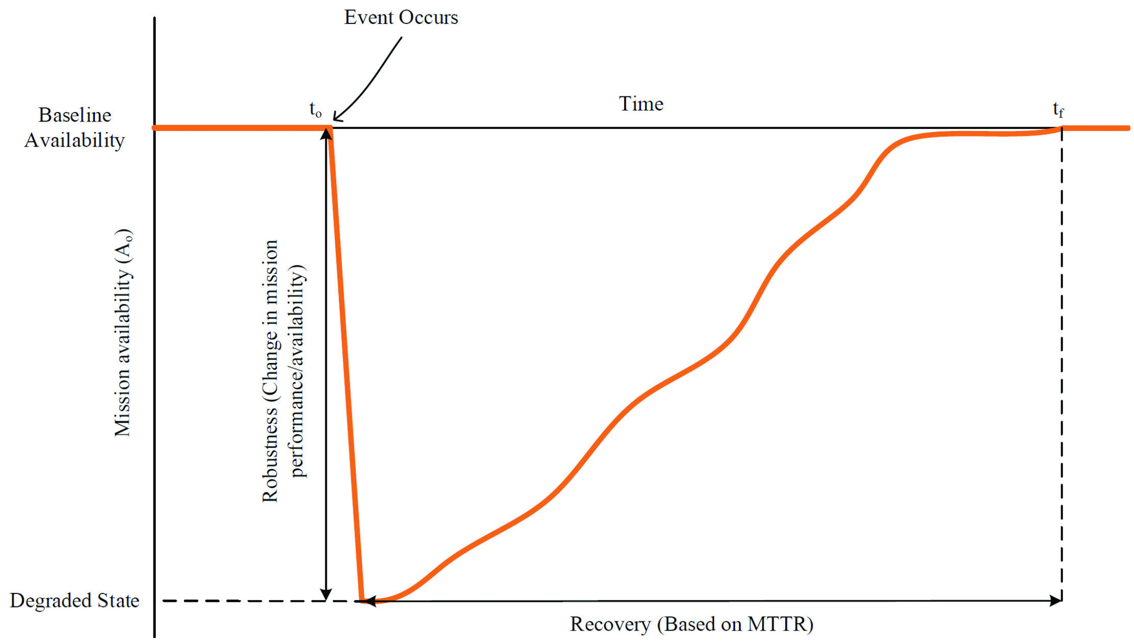


Figure 2 *System response to a disruptive event.*

Depending on the type of critical facility and the total heating load for a mission, there is also a difference between the total deviation from these requirements. Maintaining these parameters, especially in cold-climate conditions, establishes a way to address the required level of reliability for energy supply systems that will be capable of supporting thermal conditions under predominant threat scenarios.

Resilient energy systems are those that can prepare for and adapt to changing conditions, and recover rapidly from disruptions, including deliberate attacks, accidents, and naturally occurring threats (U.S. Office of the Press Secretary 2013). A quantitative approach to the resilience of a system supplying energy to the building can include (but is not limited to) the following metrics (Zhivov 2021a):

- energy system robustness
- energy system recovery time
- energy availability
- energy quality

The first three parameters are critical for the selection of the energy supply system architecture and technologies that comprise it to satisfy requirements related to energy system resilience. Energy quality is another important quantitative metric for the energy system serving critical functions and should be considered as a design parameter for internal building energy systems. Energy robustness is defined as "the ability to absorb shocks and continue operating" (NERC 2018). Energy robustness is a metric showing power availability, P in kW (kBtu/h) to satisfy critical mission loads over a period of time immediately following a disruptive event, measured as a fraction of the mission-critical requirement or a fraction of the baseline energy requirement. Using the energy robustness metric, we can quantify the overall resilience of a system in two phases: absorption of the event and recovery. Figure 2 illustrates system performance disturbance, which occurs without warning, such as with seismic events. Immediately following the event, there is a sharp drop in mission availability. The change in mission availability from the baseline to the degraded state represents the robustness of the system to that particular event. The smaller the change in mission availability, the more robust the system. The time required to restore the system to its baseline state is referred to as *recovery*.

Depending on mission needs, it may be more important to prioritize either robustness or recovery. System robustness may be beneficial for improving overall resilience at remote sites where recovery time is limited by the physical demand of getting replacement parts to the site. In other cases, it may be more important to prioritize recovery from an event as opposed to robustness.

ENERGY QUALITY

For thermal energy systems, the energy quality required by the building/mission can be described in terms of the type of thermal energy required by the process and thermal comfort systems. This may include steam; high-temperature, medium-temperature, or low-temperature hot water; chilled water; water-antifreeze mixture; electricity for heating or cooling; gas or other fossil fuels; and so on. The energy quality concept for thermal energy systems is less important than for electric systems. If an internal system is water-based or uses antifreeze, energy supply systems can be steam or hot water and use steam to hot-water heat exchange. Conversion from a steam to a hot-water energy supply system requires a change of heat exchangers, radiators, or convectors inside the building to support the heating load. If some processes, e.g., sterilization or industrial process, require steam, a local steam boiler can be installed to complement the heating system converted to hot water. In most cases, a closed-loop building heating system can be designed to accommodate any type of thermal energy provided to the building. Adding thermal storage can accommodate for a variation in energy flow.

ENERGY AVAILABILITY

Based on (TM 5-698-1 [2007]), energy availability is defined as *the percentage of time that an energy system is available to perform its required function(s)*. Energy availability is measured in a variety of ways but it is principally a function of downtime. Availability can be used to describe a component or system but it is most useful when describing the nature of a system of components working together. Because it is a fraction of time spent in the "available" state, the value can never exceed the bounds of $0 < A < 1$. Thus, availability will most often be written as a decimal, as in 0.99999, as a percentage, as in 99.999%, or equivalently spoken, "five-nines of availability." Energy availability can be calculated using one of two equations:

$$\text{EA} = \text{MTBF}/(\text{MTBF} + \text{MTTR}) \times 100\% \quad (1)$$

or

$$\text{EA} = \text{Uptime}/(\text{Uptime} + \text{Downtime}) \quad (2)$$

where

MTBF = mean time between failures

MTTR = mean time to repair

Practical data-based availability studies have their origins with electrical and mechanical data collected by the Institute of Electrical and Electronics Engineers (IEEE) and the U.S. Army Corps of Engineers (Koval et al. 2007, TM 5-698-1 [2007]). Data gathered by these organizations have made years of developed theory and analysis possible.

Following a contingency event, the facility or site should have a plan in place to adapt to the contingency and recover quickly from its effects. Due to limitations of personnel, resources, and logistics, repairs for all components cannot occur simultaneously. Some assets may also be required to be restored in sequence. The priority shall be given to restoring energy to the level of satisfying the needs of mission-critical loads. In this case, the MTTR of the system providing mission-critical load shall be smaller than the maximum allowable downtime assigned based on the configuration of the internal energy system and a storage capacity for heat and power.

BUILDING ENVELOPE CHARACTERISTICS INFLUENCING MAXIMUM ALLOWABLE DOWNTIME

Maximum time to repair thermal systems can be defined in terms of how long the process can be maintained or the building remains habitable or protected against damage from the freezing of water pipes, sewer, fire suppression system, protect sensitive content, or start growing mold during the extended loss of energy supply with extreme weather events. A thermal resilience design guide (Kesik 2019) defines the threshold for building habitability during the heating season as 60°F (16°C) and for the cooling season as 86°F (30°C). Mission operators may select different thresholds based on age, health, or level of training of inhabitants.

Building total heat consumption per the unit of time can be calculated using the following equation:

$$Q_{tot} = Q_{loss\ \mathrm{tr}} + Q_{inf} + Q_{vent} - Q_{int} \quad (3)$$

where

$Q_{loss\ tr}$ = heat flow to compensate for thermal losses due to heat transfer by conduction,

Q_{inf} = heat flow to heat outdoor air due to infiltration,

Q_{vent} = heat flow to heat ventilation air, and

Q_{int} = internal heat flow from people and internal processes.

$$Q_{loss\ \mathrm{tr}} = U\,A(T_{out} - T_{in}) \quad (4)$$

where

U = overall coefficient of heat transfer,

A = total area of fenestration, and

$(T_{out} - T_{in})$ = difference between indoor and outdoor air temperatures.

$$Q_{inf} = AL\ A\ C_p(T_{out} - T_{in}) \quad (5)$$

where

AL = air leakage rate

C_p = specific heat of air

$$Q_{vent} = L\ C_p(T_{out} - T_{in}) \quad (6)$$

where

L = outdoor air ventilation rate

Based on these simplified equations, the major factors affecting the heat flow rate, and therefore the time, when the internal temperature reaches the threshold based on building habitability or sustainment include:

- Difference between indoor and outdoor air temperatures
- Building envelope leakage rate
- Building envelope insulation properties, including insulation levels of its components and thermal bridging.
- Internal thermal load (i.e., people and appliances/equipment connected to electric power).

Also, the thermal mass of the building structures composed of concrete, masonry, or stone materials that constitute a high level of embodied energy enables the building to absorb and store heat to provide "inertia" against temperature fluctuation. The amount of heat that can be absorbed by the building mass can be calculated using the following equation:

$$Q_{storage} = M\ C_p \Delta T \tag{7}$$

where

$Q_{storage}$ =amount of energy that can be stored by the building mass

M = building mass

C_p = specific heat of the building material

ΔT = allowable change in the room air temperature

Figure 3 shows how these factors will influence building habitability and sustainment.

During emergency situations, maintaining optimal comfort conditions may not be feasible. In this case, mission-critical areas can be conditioned to different thresholds of thermal energy requirements. These requirements include the ability to perform the required work in safely and efficiently, support the processes housed in the building, and ensure the long-term sustainability of the building. In the event of thermal energy disruption, air temperatures in spaces with mission-critical operations must be maintained above 60.8°F (16°C) (Zhivov et al. 2021b).

OBJECTIVES AND SCOPE

The objectives of the studies described in this paper were to obtain real-life information on the indoor air temperature decay in buildings when they experience a problem with heat supply and evaluate how much time is available to fix the problem before the indoor air temperature reaches habitability or sustainability thresholds (Zhivov et al. 2021a), identify areas in the building that are the most vulnerable to heat disruption, and provide the information to calibrate models (see Part II of this paper [Liesen et al. 2021]) that can be used to predict temperature decay in different archetypes of mission-critical facilities (i.e., building mass, insulation characteristics) and air leakage rate. Tests were conducted in five buildings located at Fort Wainwright (FWA) and Fort Greely (FGA) in January 2020 with the outdoor air temperature ranging between –20°F and –40°F (–20°C and –40°C). As discussed in the previous section of the paper, building airtightness is a significant factor affecting the loss of heat by the building. To obtain this information for the five selected buildings, blower door tests were conducted in July 2020. Prior to these tests, the team collected the data available from drawings, specifications, retrofits, and building walkthroughs.

METHODOLOGY

To establish guidelines for the maximum time to repair thermal systems before habitability or sustainability thresholds are reached, it is important to understand the external factors that contribute to a building's thermal decay, to what extent these factors play a role, and the distribution of indoor

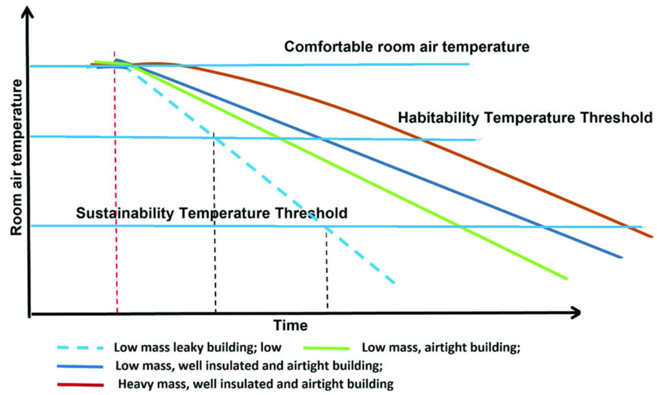


Figure 3 *Notional example of temperature decay rate for different types of building envelopes.*

air temperature throughout the building during a thermal energy disruption. To better understand these factors, a novel thermal decay test (TDT) was developed to simulate a thermal energy disruption to a military installation. This test involved instrumenting the building with temperature sensors, removing the heat sources to the building, and recording air and surface temperatures in different areas of the building over an extended period of time. To establish some level of consistency and streamline the process, a test protocol was established for this test (see Appendix A). Data collected in this test was used in conjunction with building models to predict the maximum time to repair across different building types.

Indoor temperatures were recorded using surface and ambient temperature sensors. These sensors were placed in key locations throughout the buildings. These locations were chosen to capture baseline data, critical areas (i.e., mechanical rooms, exposed waterlines, and so on), and areas that are susceptible to the effects of the wind. Additionally, sensors were placed near exterior doorways to better understand the effects of researchers opening doors while monitoring the buildings. For the surface temperatures, UX120-006M HOBO data loggers with four TMC20-HG temperature probes (with an accuracy of ±0.27°F [±0.15°C]) were used. These sensors were placed in the corners of the buildings to analyze temperature differences in windows, walls, ceilings, and floors. The surface temperature on internal and external walls was measured and analyzed with special attention paid to the difference between internal versus external walls, wall orientation, and walls below versus above grade. For the interior ambient temperatures, UX100-003 HOBO data loggers (with a temperature accuracy of ±0.38°F [±0.21°C] and a relative humidity (RH) accuracy of ±2.5%) were used and were typically suspended from the ceilings in the center of rooms. These sensors also captured relative humidity, but over the course of the test, they did not show any significant change. External temperature, wind speed, and direction were recorded using a local base meteorological (MET) station. Internal loads were estimated using typical electrical load and occupancy data.

a. Fort Wainwright Bldg. 3002, Aviation Battalion Headquarters

b. Fort Wainwright Bldg. 3013, Directorate of Public Works Plans Vault.

c. Fort Wainwright Bldg. 4070, Cold Regions Research Engineering Laboratory

d. Fort Greely Bldg. 603, Directorate of Public Works Headquarters (southwest corner)

e. Fort Greely Bldg. 603, Directorate of Public Works Headquarters (northeast corner)

f. Fort Greely Bldg. 650, Theater and Gross Motor Facility

Figure 4 *Installation buildings in the study.*

Building insulation properties were estimated using building design documents, taking samples from exterior walls, and on-site inspections. Information about the protocol and results of the air barrier tests can be found in Leffel (2021).

Selection of Buildings for Tests

Using building inventory information, including building type classification, square footage, and airtightness tests administered to 30 buildings at the two sites in 2019 by an external agency, the research team identified five buildings for the study. Each building varied by building type and had unique characteristics. These five buildings were selected primarily based on availability, the era of construction, and building design. This allowed the modeling portion of this study to analyze different building designs and different materials' capacities for retaining thermal energy. At Fort Wainwright, two offices and a laboratory were selected (Figure 4). At Fort Greely, an office and a multiuse facility were chosen.

Fort Wainwright. Bldg. A, a battalion headquarters, was constructed in 2015. This predominately military-utilized office includes administrative areas, classrooms, and special function space. It is not uncommon to find small gyms, weapons storage rooms, and dining areas located within the building. This particular building received LEED's Silver certification and consists of metal wall panels and a metal roof. When the airtightness test was conducted at the facility, it initially failed to meet the minimum U.S. Army Corps (USACE) requirements. This air leakage rate is 0.208 CFM75/ft^2[1] and has an EqLA75 of 5.7 ft^2 and was primarily located at the roof to wall barrier joint. Upon correction and sealing, a 26% reduction was achieved (Leffel 2021). The walls and roof were estimated to have an R30 and R60 (IP) insulation rating, respectively.

1. "75" denotes "@75 Pa."

Bldg. B, a small open floor designed building that includes an unconditioned storage area, was built in 1999 and consists of a wooden frame with metal siding. This building was originally constructed to serve as a small warehouse for a recycling facility. When it was repurposed and renovated in 2010, radiant floors and radiant ceiling panels were installed. During the airtightness test, the leakage rate was 0.095 CFM75/ft^2 with an EqLA75 of 0.5 ft^2. Leakage was primarily found at the interior gypsum sheathing, window and door sills, and the common wall between the main conditioned room and the unconditioned storage room. This building was found to be overheating due to the heating systems and the poorly ventilated mechanical room. The walls and the roof were estimated to have an R26 and R30 insulation rating, respectively.

Bldg. C, a laboratory facility, was constructed in the 1950s but has undergone a complete renovation in recent years. The building consists of office and meeting spaces as well as medical laboratories. The facility has two floors and a basement. The construction consists of concrete walls with an exterior surface of expanded polystyrene (EPS). An airtightness test was not administered on this building in the previous study. The walls and the roof were estimated to have an R30 and R20 insulation rating, respectively.

Fort Greely. Bldg. D, a multipurpose warehouse, has two separate zones and is divided by a concrete masonry unit (CMU) wall. The facility was constructed in 1955 but includes more recent upgrades made in 2012 such as exterior insulation and finish system (EIFS) to the exterior walls, roofing improvements, overhead door and window replacements, and upgrades made to the ventilation systems. On one side of the CMU wall, there is a woodshop with a two-story office space. On the other side is a garage bay. The airtightness test found an air leakage rate of 0.155 CFM75/ft^2 and an EqLA75 of 3.3 ft^2 and showed that there is a significant amount of leakage at the roof-to-wall joint in the garage bay, multiple windows and doors, as well as the second floor's south roof-to-wall joint. The walls and the roof were estimated to have an R15 and R28 insulation rating, respectively.

Bldg. E, a multiuse facility, contains three separate isolated zones—a theater, classrooms, and an indoor recreational area. Built in the 1950s, the construction consists of concrete with a steel roof and metal studs. The building envelope was upgraded in 2012, but when the airtightness test was administered, leakage was found at the wall-to-roof joints at the steel roof, HVAC penetrations, and doors. The airtightness test found a leakage rate of 0.146 CFM75/ft^2 and an EqLA75 of 2.8 ft^2. The walls and the roof was estimated to have an R15 and R22 insulation rating, respectively.

Constraints

The selection of these buildings was based on the era of their construction and their availability. Researchers were limited as to which buildings could be used for this test due to the risks and the invasiveness the tests require. To ensure that the buildings incurred no substantial damage, the thermal decay study was halted when the internal ambient air temperatures reached but were not less than 45°F (7°C). Allowing for a buffer point before entering the threshold of freezing temperatures was necessary to allow maintenance staff adequate time to restore heat to the buildings. This ensured continuity of operations without any permanent disruption to the thermal systems. Additionally, prior to the start of the study, it was important to identify any vulnerable areas of the building, such as mechanical rooms, exposed water pipes, and poorly insulated areas such as arctic entries. FWA and FGA's Directorate of Public Works (DPW) staff were on-call throughout the duration of the tests in case the temperature threshold was met before the anticipated time.

The buildings were monitored approximately once every two hours during the test to ensure damage was not being done to them. Since the two locations are 100 mi (161 km) from one another, it was necessary to conduct the study on separate dates; however, multiple buildings on each installation were able to be tested concurrently. Additionally, the tests were conducted when the buildings were unoccupied or with as few personnel as possible to minimize potential sources of error. This was a coordinated effort with the DPW at both locations, who were critical in gaining awareness of the importance of the study for installation personnel, and permission to contact maintenance staff in case of an emergency, as well as other risk management measures that were not initially considered by the research team. Additionally, it was important to engage with the DPW as they are key stakeholders for this study.

TEST RESULTS

The TDTs at Fort Wainwright, Alaska (FWA) and Fort Greely, Alaska (FGA) were conducted over the course of several months from January through February. Data were logged using timestamps in Alaska Standard Time (AKST), Table 1 lists the results of the TDTs at Fort Wainwright, Alaska, and Fort Greely, Alaska.

The temperatures at FWA ranged from –20°F to –40°F (–29°C to –40°C) with virtually no wind (0 mph). The temperatures at FGA stood at –9°F (–23°C), but there was significant wind speeds up to 62 mph (100 kph). The tests on Bldgs. D and E at FGA started at approximately 3:00 p.m. on January 17, 2020, and ended at approximately 8:30 a.m. on January 18, 2020. Bldg. C at FWA was tested on January 9, 2020, starting at 8:30 a.m. and ending at 4:30 p.m. The outdoor temperatures were –40 °F (–40 °C) and rose to –37°F (–38°C) throughout the course of the test. Bldg. A at FWA was tested on January 17, 2020, from 8:00 a.m. to 4:00 p.m. with temperatures reaching –20°F (–29°C). Bldg. B at FWA was tested from 8:00 a.m. on February 26, 2020, to 1:00 p.m. on February 27, 2020, during which temperatures ranged from –20°F to –40°F (–29°C to –40°C).

Table 1. Thermal Decay Test Timeline and Environmental Conditions.

Building	Date Tested	Test Duration	Outdoor Temperature	Wind Speed and Direction
C	Jan. 09, 2020	8 hours	–40 °F (–40°C)	0 mph
A	Jan. 17, 2020	8 hours	–20°F (–29°C)	0 mph
E	Jan. 18, 2020	17 hours	–9°F (–23°C)	62 mph (100 kph), gusts east
D	Jan. 18, 2020	17 hours	–9°F (–23°C)	62 mph (100 kph), gusts east
B	Feb. 26, 2020	29 hours	–20°F (–29°C)	0 mph

FWA Bldg. A—BNHQ

Bldg. A showed no significant change in internal building temperature over the course of the test. The only rooms that showed any sign of thermal decay were rooms that did not have a second story above them. There are several reasons why this might be the case. For one, this building was only studied for eight hours as opposed to the longer test studies at 17 and 29 hours, respectively. However, other buildings showed a significant temperature decay after eight hours. This can be attributed to its higher insulation values in the walls and the roof, as well as its large thermal mass. This test was conducted throughout the day so the building would have experienced heat gains from solar radiation. Additionally, it should be highlighted that this building achieved LEED® Silver certification. In comparison, the other buildings that were tested as a part of this study had no LEED® certification and were not held to the same energy efficiency standards. This designation contributes to the reduction in energy demands, and it addresses envelope requirements, such as overheating, ventilation, thermal conductivity, exposed surfaces, temperature differential, airtightness, and façade orientation. Façade orientation is an important consideration for construction in cold climates, as the direction of the openings and the window area proportion must be oriented in a manner that considers solar radiation and control.

FWA Bldg. B—Storage Warehouse

The test at Bldg. B started at approximately 8:00 a.m. on February 26, 2020. The test ran throughout the course of the day while the building was occupied by several DPW employees. Figure 5a shows the ambient temperatures from several rooms distributed throughout the building. The test showed a relatively uniform temperature decay throughout the building, with a slight exception to the south restroom, which stayed a few degrees cooler than the other rooms throughout the test. This is likely due to the north restroom door being propped open, allowing heat to flow freely from the plans room to the restroom leading these rooms to follow a similar pattern.

The building continued to increase in temperature several hours into the test until about 10:00 a.m. on February 26, 2020, for the south restroom and 4:00 p.m. on February 26, 2020, for the north restroom and the plans room. There are several

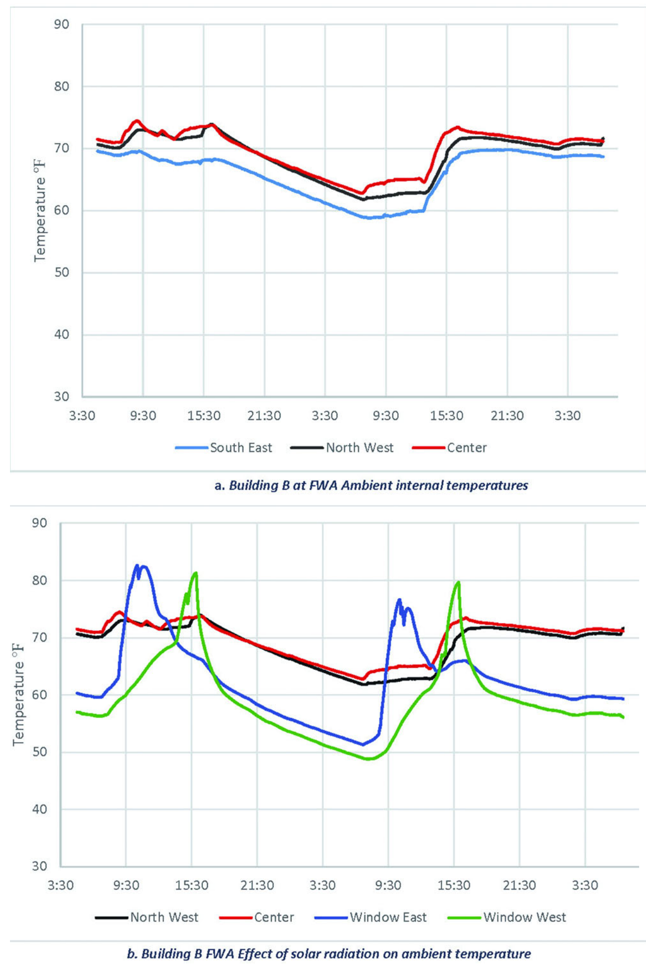


Figure 5 *Test results from Bldg. B, (a) ambient internal temperatures and (b) effect of solar radiation on ambient temperature.*

explanations for this. One is that this building has a glycol heating system that continued to pump glycol throughout the building during the test. The residual heat stored in the glycol provided some amount of heat to the building until that heat eventually came to an equilibrium with the rest of the building. The second reason is heating from solar radiation. The plans room had several windows that allowed sunlight to enter at sunrise from the east (8:00 a.m.) and was connected to a

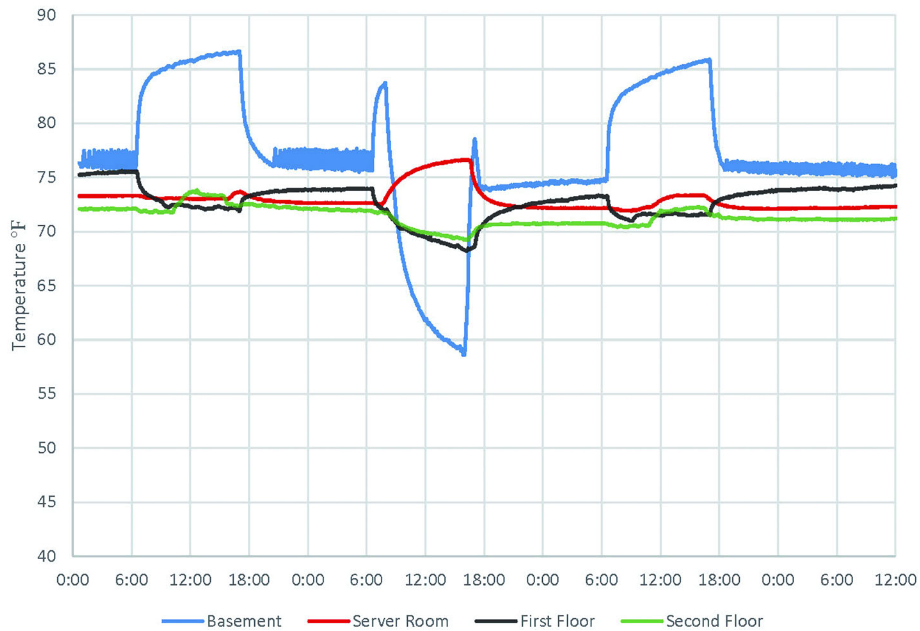


Figure 6 *Ambient temperatures throughout Bldg. C.*

conference room, via an open door, with windows allowing sunlight to enter during the sunset from the west (6:00 p.m.).

The surface temperatures on the eastern and western windows spiked throughout the day as they were exposed to direct sunlight as shown in Figure 5b. This increase in surface temperature corresponds to increases in ambient temperature. This even occurred throughout the test when the primary heat source had been removed. The heat gained from solar radiation and the residual heat in the glycol heating system provided this building with extended operation time with most rooms not exceeding the habitable threshold.

FWA Bldg. C—Laboratory

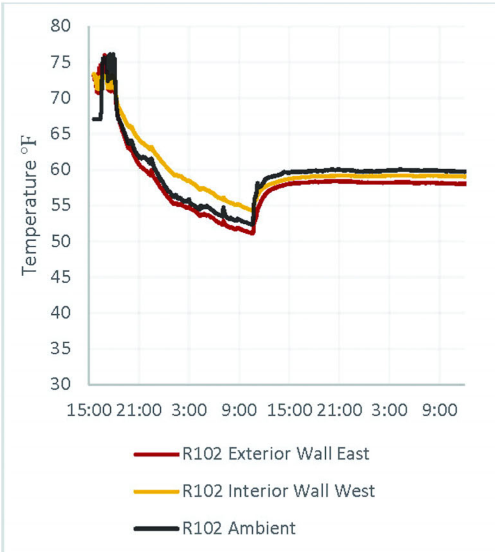
Bldg. C was a trilevel building with a semibasement that was partially above and below grade. For the most part, the temperature decayed relatively uniformly and as expected, with the thermal decay rate becoming faster moving from the second floor through to the basement. This was different from other building basements that were tested in that the additional insulation and thermal mass from the surrounding soil did not seem to inhibit the rate of decay, as was found in other buildings. This is due to the large fenestration area throughout the building and especially in the basement. Additionally, there was a large open stairway column that ran from the second floor to the basement allowing more cold air to infiltrate and sink to the bottom of the building.

Figure 6 shows the ambient temperatures from rooms located at different heights throughout the building. Bldg. C had a server room on the second floor that continued to operate throughout the test. While temperatures in other rooms were dropping, this room actually increased in temperature throughout the course of the test. It was not clear to what extent this affected the other second-floor rooms. In emergency scenarios, internal loads such as information technology (IT) equipment, could be used to extend operation time for mission-critical staff, but this would be limited to the room in which the equipment is being housed.

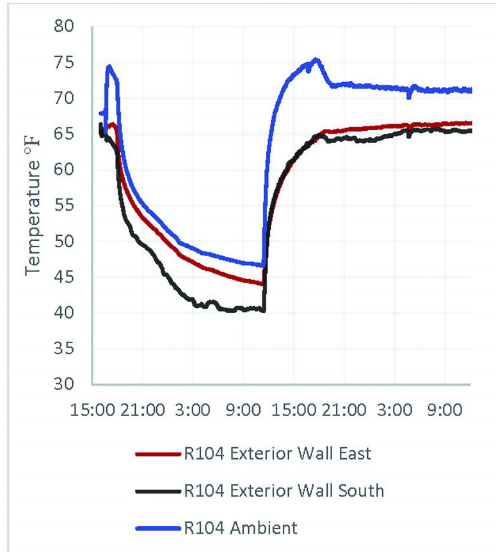
FGA Bldg. D – DPW Building

The tests at FGA started at approximately 3:00 p.m. on January 17, 2020, and ran until 8:30 a.m. on January 18, 2020. Bldg. D did not decay uniformly as the buildings at FWA did. Room 104 approached the critical temperature for the thermal decay test. Rooms 104 (the garage bay) and 103 (the woodshop) were connected by an open hallway and had air flowing freely between the two rooms. Despite Room 103's pretest temperatures being approximately 10°F (5.6°C) lower than Rooms 102 (office) and 104, its rate of decay was slower. Rooms 102 and 103 were on opposing corners of the building and air was not able to flow freely between the rooms. Rooms 102's rate of thermal decay was faster than that of Room 103 despite both having similar insulation properties and Room 103 having a larger fenestration area.

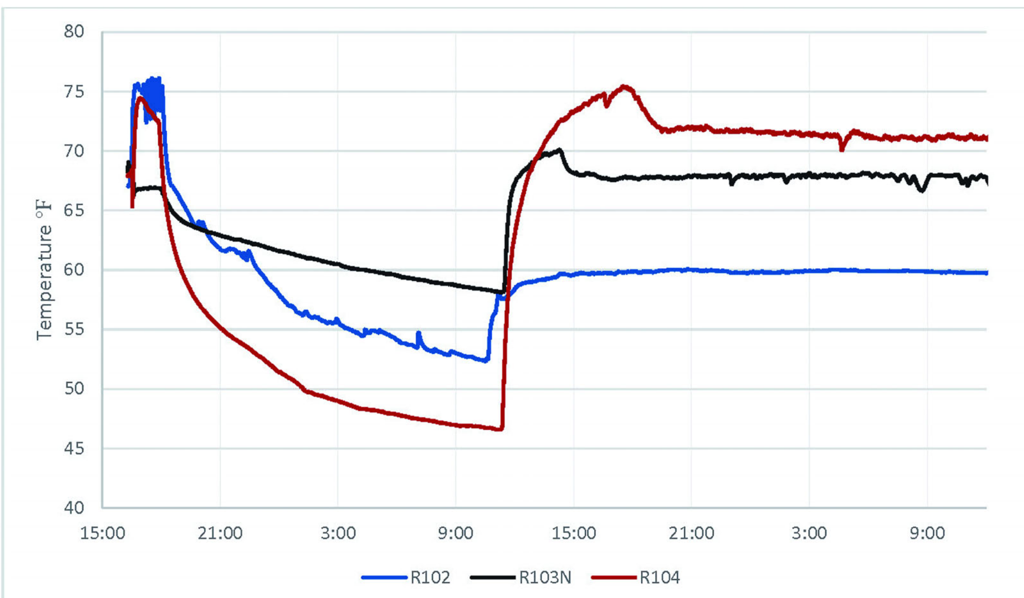
Figure 7c compares the ambient temperatures for three different rooms in Bldg. D. Room 102 decayed significantly faster than Room 103. This is due to Room 102 being directly in the path of 60+ mph (97+ kph) easterly winds experienced at FGA during the night of the test, as Room 102 was located on the southeast corner of the building. This caused positive pressure on the side of the building where Room 102 was located and negative pressure on the side where Room 103 was located. This set up a pressure gradient throughout the building, causing warm air to exit the building on the west side and cold air to enter the building on the east side. This accelerated



a. *Fort Greely, Building D, Room 102 Ambient and Surface temperatures*



b. *Fort Greely, Building D, Room 104 Ambient and Surface temperatures*



c. *Fort Greely, Building D, Rooms 102 (exposed to wind), 103 North (protected from wind), and 104 (exposed to wind)*

Figure 7 *Test results from FGA Bldg. D: (a) Room 102's ambient and surface temperatures, (b) Room 104's ambient and surface temperatures, and (c) Rooms 102 (exposed to wind), 103 North (protected from wind), and 104 (exposed ot wind).*

air infiltration in Rooms 102 and 104. In addition to the wind effect, Room 104 appeared to have less insulation than other rooms as this section of the building was built using different materials (metal sheeting) than the rest of the building.

Building materials with a larger thermal mass will release stored energy during a thermal energy disruption, inhibiting the rate of thermal decay. The data in Figures 7a and 7b may be used to compare two rooms with different building materials and different insulation values. Figure 7a shows the ambient temperature (solid line) follows just above the exterior wall (CMU/EIFS) surface temperature (dashed line) closely but remains colder than the interior wall surface temperature (dotted line).

Figure 7b shows that with building materials with less thermal mass and insulation values (i.e., metal sheeting) the ambient temperature deviates significantly from the surface temperatures. This causes the ambient temperature to lag the surface temperature, as the metal sheeting is less resistant to changes in temperature. This ultimately leads to a faster rate of thermal decay and a shorter maximum time to repair.

FGA Bldg. E—MWR Building

Bldg. E is separated into three sections isolated from one another. From east to west the main rooms in each of these sections are Sections 125, 100, and 108. Underneath Section 100 is a fully below-grade basement, which is composed of two rooms (Room 001 and 002). Room 001 is the mechanical room and entrance for the steam pipes. The two rooms were separated by a wall with an open doorway. Room 002 is located near the staircase to the basement, which allowed for cold air to sink to the basement. Both rooms did not reach the critical threshold, despite being in the basement. Because there is no direct access to the outdoor temperatures, this allows the thermal mass of the CMUs and soil to insulate the basement.

Over the course of the 17-hour test, Section 100 had the longest projected operation time. One reason for this is that it is shielded on both east and west sides by Sections 125 and 108, respectively. Another reason is the thermal energy rising from the basement. The thermally saturated foundation and surrounding soil acted as a thermal battery, dissipating heat over the course of the test. Sections 108 and 125 are on opposing corners of the three-part building, with Section 100 being located in the center. Section 125 had the most dramatic thermal decay curve and was located on the east side, directly in the path of the wind. Section 125 also had the largest fenestration area, with large windows on the north and south side. The wind was a significant contributor to the thermal decay rates in FGA. The effects of wind can be seen in Figure 8c, which shows the difference in surface temperatures between the southeast and northwest corners of Bldg. E. At the start of the test, the southeast corner was approximately 5°F (2.8°C) warmer than the northwest.

DISCUSSION

The data obtained during this study allowed the documentation of temperature decay in different areas of tested buildings and wall surfaces to provide information for building model calibration.

This study confirmed that building airtightness, thermal mass, insulation properties, and internal loads affect the maximum time to repair thermal energy systems during a thermal energy disruption. Additionally, it was found that, depending on the environmental conditions, the rate of thermal decay is not uniform throughout the building. It was found that wind and solar positions can accelerate or impede the rate of thermal decay within a building, depending on building orientation and fenestration location. If possible, for fenestrations not exposed to direct sunlight, it is recommended to place an insulated barrier over windows and along door thresholds. Certain rooms were seen to have design issues, air leakage rates that may vary throughout the building, and certain rooms that are more vulnerable to a thermal energy disruption. This needs to be considered for predicting the maximum time to repair thermal energy systems, as it is necessary to factor in a tolerance for this estimate.

The wind was found to accentuate the rate of thermal decay in specific areas of buildings sustaining high-speed winds. The wind creates positive pressure on the upstream side of the building and negative pressure on the downstream side, setting up a pressure gradient throughout the building. This causes warm air to escape the downstream side of the building, allowing for cold air to infiltrate the building on the upstream side. This is an important factor to consider for new construction and the placement of mission-critical staff and equipment, as rooms downstream of the wind have an extended operation time compared to rooms upstream of the wind.

Internal loads were shown to extend operation time but are dependent on the scale of the load and limited to the room the load is being housed in. The temperature in a room housing a server rack increased in temperature over the course of the test, despite the other rooms losing thermal energy. According to Zhivov et al. (2021a), many mission-critical facilities or dedicated spaces within these facilities house computer systems. This would add an additional layer of thermal resilience to these dedicated spaces within these facilities.

Insulation ratings appear to significantly increase operation time during a thermal energy disruption. Buildings with higher insulation ratings performed better in colder temperatures. After eight hours of testing in –40°F (–40°C), Bldg. A in FWA showed little to no sign of thermal decay. In contrast, after eight hours of testing, buildings with lower insulation ratings at FGA showed a significant amount of thermal decay. This was even found within Bldg. D, which had a garage bay. It was built with a lower insulation rating, which showed a faster rate of decay than other parts of the building. Buildings with a larger thermal mass were found to operate for longer periods of time. Additional information can be found in Part II of this paper (Liesen et al. 2021).

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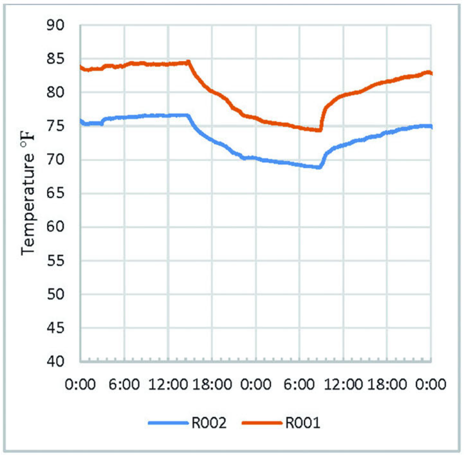
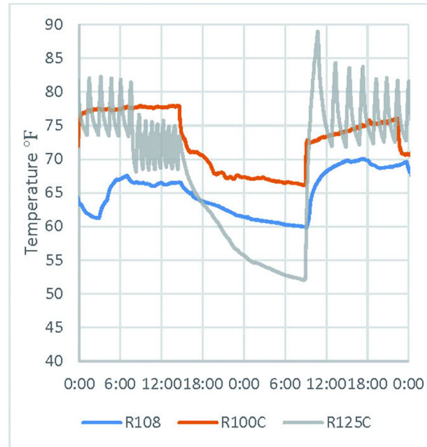
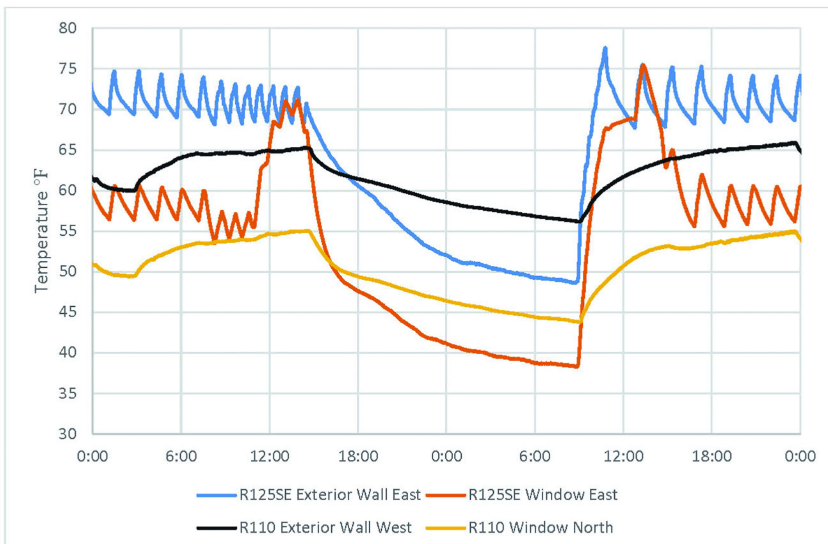


a. Fort Greely, Building E, Basement Ambient temperatures



b. Fort Greely, Building E, room centers ambient temperatures



c. Fort Greely, Building E, rooms 125 and 110 surface temperatures

Figure 8 *Test results from FGA Bldg. E: (a) Basement ambient temperatures, (b) room centers ambient temperatures, and (c) Rooms 125 and 100 surface temperatures.*

"Shawn" Baker, Mr. Todd Hayden, and Mr. Clay Trabel, and Fort Wainwright DPW Staff: Mr. Bill Chedister.

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APPENDIX A: BUILDING TEMPERATURE DEGRADATION TESTING PROTOCOL

PURPOSE

The purpose of this protocol is to define a repeatable method of testing the thermal degradation of structures in cold climates, specifically, on Fort Wainwright, AK, and Fort Greely, AK. This protocol will also define the method used to measure outdoor variables, meter location recommendations, and data management practices best suited for this project.

TEMPERATURE

Internal building temperature data is needed to identify critical building areas where temperature needs to be controlled to prevent damage to the building components and its systems and to calibrate computer models against real data.

RELATIVE HUMIDITY

Internal building relative humidity data is needed to supplement temperature data in identifying critical building areas where temperature needs to be controlled to prevent damage to the building components and its systems and to calibrate computer models against real data.

WEATHER STATION

The data gathered by weather stations will be used for reference temperature, humidity, wind speed and wind direction to identify boundary conditions across the building envelope and to establish temperature and humidity gradients to be used for test results generalization.

STEP-BY-STEP PROTOCOL

Step 1: Measurements and Equipment

The following measurements will be made:

- Date /time
- Interior temperature
- Interior relative humidity
- Exterior temperature
- Exterior wind speed
- Exterior wind direction.

All measurements will be taken at a minimum interval of one min. Shorter intervals are acceptable if required. This will give loggers sufficient memory and battery life to sustain the testing duration. This will also give enough data to create simulations to predict trends.

Step 1a: 4-CH T Loggers

These tests will use wall-mounted HOBO data loggers made by Onset to measure and store the data. These loggers are small (about 2 in. × 4 in. [51 mm × 102 mm]) battery-powered, four-channel loggers with onboard storage. They can be programmed to log at a variety of time intervals and can store 1.9 million measurements (329 days of T data per channel at one-minute intervals). For this study, we will use the UX120-006M HOBO loggers with four TMC20-HD temperature probes (Accuracy: ±0.27°F [±0.15 °C] for temperature measurements in critical areas). The "Push Button" box in the "Stop Logging" section of the "Launch Logger" window when launching the logger to prevent the accidental termination of data logging.

Step 1b: T&RH Loggers

The T&RH loggers are also wall-mounted HOBO data loggers made by Onset. They are very similar in size and operation but have the added capability of measuring Relative Humidity. They can be programmed to log at a variety of time intervals and can store 84,650 measurements (52 days of T&RH data at one-minute intervals). For this study, we will use the UX100-003 HOBO loggers (Accuracy—Temperature: ±0.38°F [±0.21 °C; RH: ±2.5%) for T&RH measurements of specified rooms. The "Push Button" box in the "Stop Logging" section of the "Launch Logger" window when launching the logger to prevent the accidental termination of data logging.

Step 1c: Weather Stations

These tests require local weather information to compare with interior sensor data. This will be provided by the on-site weather stations at Fort Wainwright and Fort Greely.

The Fort Wainwright weather station is located next to Bldg. 4070 (CRREL Building) and it consists of a Campbell Scientific CR1000 Datalogger, a Gill Instruments WindSonic anemometer (Accuracy – Dir/Vel: ±2 deg.@ 12m/s), a Campbell Scientific CS215 air temperature and relative humidity probe (Accuracy – Temp ±0.72 °F [±0.4°C]; RH: ±2%) and a Vaisala PTB101B barometric pressure sensor (Accuracy – Press: ±1hPa @ –4.0°F to +104.0°F [–20°C to 40°C]). The anemometer and air temperature/relative humidity sensors are located three meters above ground.

Step 2: Placement Guidelines

The success of this test will depend on the careful and consistent placement of the sensors in each structure. Inconsistencies in placement or poorly placed sensors (such as in direct sunlight) will greatly reduce the usefulness of the data and may lead to skewed results. Critical spaces will be instrumented with a higher number of sensors (see Figure 9).

Step 2a: 4-CH Placement

The 4-channel Temp loggers should be installed in areas defined as critical locations (critical corners, doorways, etands on). The four TMC20-HD temperature probes will be distributed as follows:

- To the right of the logger.
- To the left of the logger.
- Above the logger (mounted on the ceiling if possible).
- Below the logger (mounted on the floor if possible).

The temperature probes can either provide surface or air temperature data, depending on which is required for specific locations.

Step 2b: T&RH Placement

The T&RH loggers should be installed in conjuncture with the 4-channel Temp loggers. Locations that are deemed critical will have at least one T&RH logger installed to measure ambient air temperature and relative humidity. These areas include, but are not limited to the center of external walls, slabs above unheated space and below unheated attics, in the middle of representative rooms on the first, last, and middle floors.

Step2c: Logger Settings

The following settings must be initiated via the Onset software:

- A logger name description should be put in the Onset software and printed on the logger (or a label placed on the logger).
- Logger name description should include logger serial number, logger type, specific Fort, building number, room number/name, cardinal direction of wall-mounted on.
- Naming convention should be: S/N.LoggerType.Location.BldgNo.RoomNo.
- Example name description for UX100 deployed in Room 206, Bldg. 4070 on Fort Wainwright: 20718840.100.W.4070.206.
- Probes should be individually labeled for the UX100 logger to give an adequate description of the deployment location.
- Check to make sure the battery level is at 100%.
- Sensor on/off state: Do not measure the logger battery voltage during the field test.
- A logging interval. Recommended 30 s for this test.
- Note the logger timestamp matches your computer's timestamp, make sure the computer's timestamp is consistent with the time zone.
- Stop logging: "When memory fills."

There may be instances where it is impossible to follow the above guidelines. In these cases, the installer should use best judgment.

Step 3: Building Requirements

The buildings that are selected for temperature decay testing should follow the below guidelines whenever possible to ensure uniform data collection. It is recommended that all exterior doors remain closed for the duration of the testing.

Step 3a: Personnel Equipment

To maximize the accuracy of interior sensors, it is recommended that personnel turn of all computers, lights, and other plug-in electronics to eliminate residual heat sources. All lights, plug-in equipment, and the number of people inside the building during the test should be documented.

Step 3b: Building Conditioning

DPW personnel supporting this test will turn off heating equipment at a designated time after all the loggers have been installed. This time must be recorded. Once the internal temperature of the building has reached approximately 40°F (4°C), the heating equipment should be turned back on. It must be verified visually that the temperature of the building is increasing before personnel leave the building.

Step 4: Documentation

A detailed record of the loggers and the buildings is essential to assure correct interpretation of the data collected. It is recommended to populate a spreadsheet with all pertinent information.

Step 4a: Logger Information

The following information should be recorded for each logger:

- Logger name (S/N).
- Location (Fort Wainwright/Fort Greely)
- Building number
- Floor
- Room
- Detailed location (i.e., on the north wall, 5 ft (2 m) above the floor)
- Any extra notes that may be useful.

Step 5: Log Time Duration and Removal

The loggers should be left in place for at least 24 hours before the building conditioning equipment is turned off and at least 24 hours after building temperature has returned to normal to make sure building loads and environmental conditions have stabilized after buildings have been in use by tenants and returned to normal conditions.

Step 6: Data Collection and Aggregation

The information obtained during testing will be downloaded into Microsoft® Excel® documents by team members to analyze.

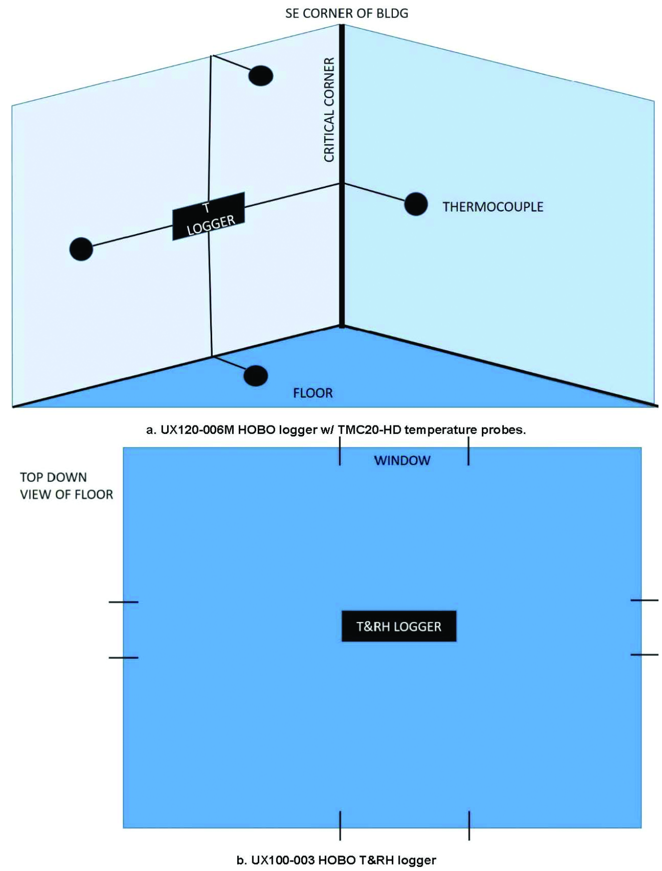

Figure 9 *Proposed layouts for the logger positions.*

LOOKING AHEAD

The main goal of the thermal degradation testing is to identify critical building areas where temperature needs to be controlled to prevent damage to the building components and its systems and to calibrate the computer model against real data.

The data recorded in this test may also be of interest to other researchers to answer research questions. Therefore, when the final analysis report is published, the raw dataset will be as accessible as possible.

METER LOCATION DIAGRAMS

Figure 9 shows diagrams of the proposed layouts for the logger positions.