Thermal Energy System Resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates—Part II: Modeling

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ABSTRACT

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. 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 unique temperature decay test conducted during the winter, along with blower door tests on five representative military buildings in Alaska. In Part II, the modeling analysis is compared and calibrated to the experimental data collection for the thermal decay test (TDT). A reliable building model allows us to predict 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 critical to the building operations, or when damage is done to the building itself. This will provide guidance to building managers on evacuation and sustainment procedures for buildings in arctic climates that are affected by fuel or electrical disruptions.

BACKGROUND

For this paper, the thermal energy system is comprised of both demand and supply sides. The demand side from the building includes mission-related active and passive systems including thermal demand by the process, HVAC systems maintaining required environmental conditions for the process and the comfort of people, and a shelter/building that houses them. The requirements to maintain thermal or environmental conditions in the building or maintain its critical mission-related processes to support housing and building occupants include criteria for thermal comfort and health, process needs, and criteria preventing mold and mildew and other damage to the 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. (2021). During normal operations, thermal comfort conditions in the mission-critical facility differ from the cold stress threshold limit 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 to energy availability (EA) provided by the supply system. The time to restore the system to its baseline state is another requirement to the energy supply system. EA and mean time to repair (MTTR) 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 condition. Part I of this paper (Oberg et al. 2021) presents more background information.

OBJECTIVES

The objectives of the studies described below are to produce a reliable building model that can be used to predict and identify the maximum allowable time available to fix the problem with energy supply to a mission-critical facility for different facility archetypes (i.e., building mass and insulation

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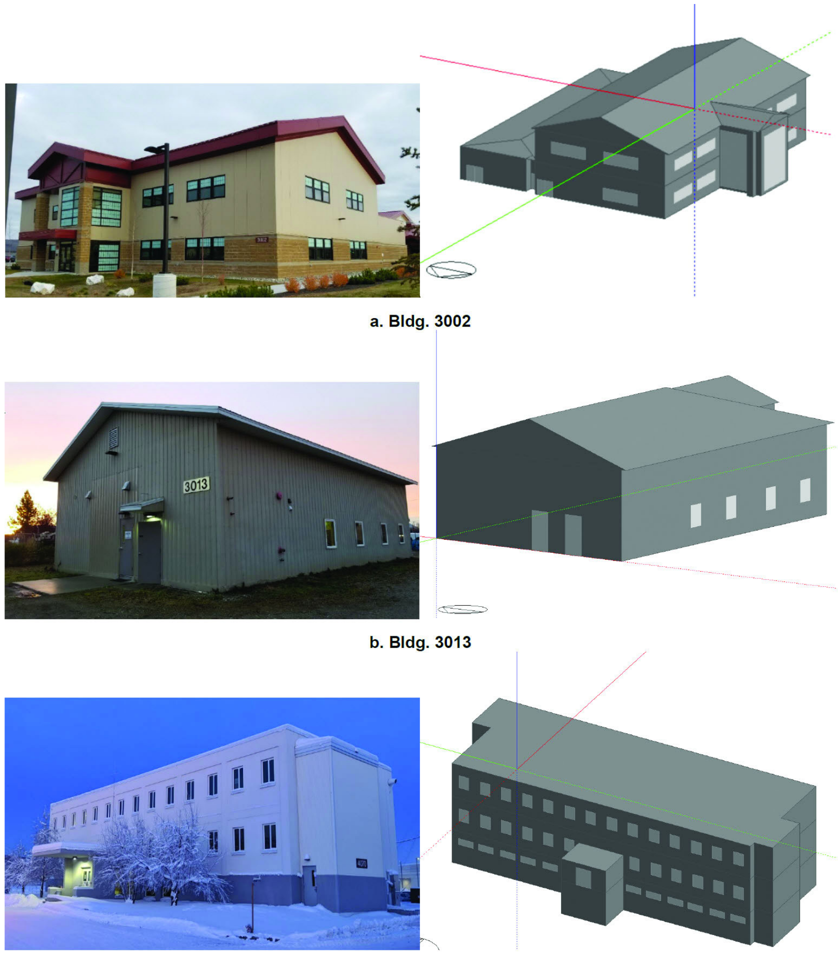


Figure 1 *Photo and model representations of (a) Bldg. 3002, (b) Bldg. 3013, and (c) Bldg. 4070 at Fort Wainwright, AK.*

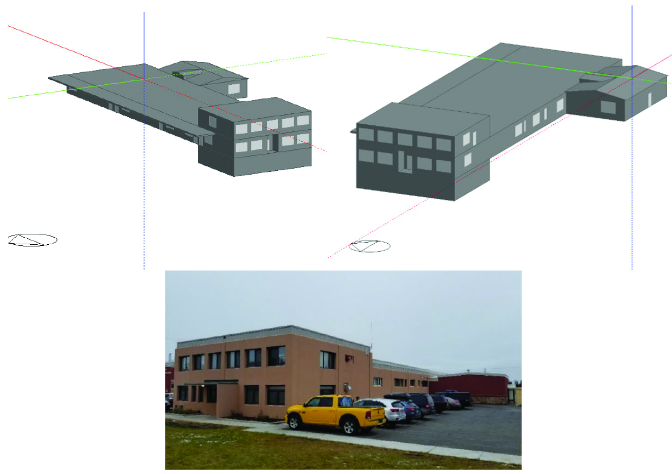
characteristics) and air leakage rate. To show the building model reliability, the five buildings described and tested in Part I of this paper are developed using all the data available from drawings, specifications, retrofits, and building walk-throughs for the model inputs. These models were simulated and then the failure mechanism was specified and matched to the test procedure in Part I and replicated in the equipment schedules with the building model. The model failure temperatures are compared to the TDT results from Part I to determine how reliable the results are for a conservative prediction of the maximum time available to repair for other buildings. In most cases, the TDT was terminated long before the buildings reached the 40°F (4.4°C) threshold, but in the models, a failure period of approximately five days from 8:00 a.m. on Friday was sustained and heating was restored at 12:00 a.m. Wednesday morning. The slope and final temperature can be determined from the simulated model. Then the amount of time was observed when the building reached the heating set point. For comparison, the last part of the paper explores some properties of the building capacitance, insulation levels, and airtightness. EnergyPlus, Version 8.9, a whole-building hourly energy model with DesignBuilder as the interface, was used to produce all the simulated model data in this paper, which was compared to the TDT results.

BUILDINGS MODELED

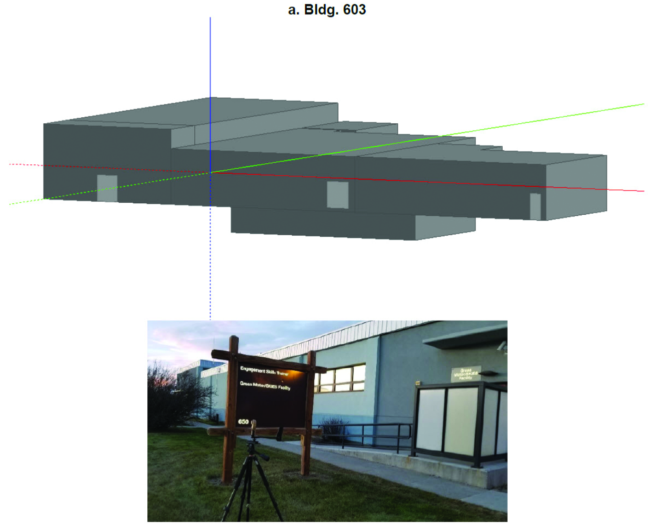
Fort Wainwright

Bldg. 3002. Bldg. 3002 (Figure 1a), which resides in south post at Fort Wainwright, AK, was constructed in 2016. The building consists of administrative space, areas for special functions, and classrooms. The 20,136 ft^2 (1872.6 m^2) building is constructed with a thermal envelope consisting of insulated metal wall panels of a minimum R-30 and a metal roof assembly at a minimum R-60. The building achieved the Leadership in Energy and Environmental Design (LEED®) Silver certification. The structure consists of two stories on the west side and a single story on the east side. The building's orientation has the entrance facing west.

Bldg. 3013. Bldg. 3013 (Figure 1b) resides in south post at Fort Wainwright, AK. The building primarily houses office and meeting spaces but also has an unconditioned storage area.



a. Bldg. 603



b. Bldg. 650

Figure 2 *Photos and model representations of (a) Bldg. 603 and (b) 650 at Fort Greely, AK.*

Bldg. 3013 was constructed in 1999. The facility has a wooden frame and metal siding. The building has an eave height of 16 ft (4.9 m), while the internal ceiling drop is 9 ft (2.7 m) from the floor. The facility has a total of six windows. Two of these windows are on the eastern wall of the facility, while the remaining four are on the westernmost wall. All windows are of the same construction, with widths of 36 in. (91 cm) and heights of 48 in. (1.22 cm). The windows are double-paned with aluminum frames and low-emissivity coatings. The walls have a total R-value of approximately 26 while the roof is estimated as having a total R-value of approximately 30, as these were not known. The building also has low-intensity slab heating in the floors with mechanical ventilation for fresh air.

Bldg. 4070. Bldg. 4070 (Figure 1c) is located at Fort Wainwright, AK. The building houses office and meeting spaces, medical examination facilities, and medical laboratories. Bldg. 4070 was constructed in the 1950s and recently had a major renovation. The facility has two floors plus a basement. The above-grade walls consisted of an 8 in. (20 cm) layer of concrete with a standard 16-in. (41-cm) furring that allowed for 2 in. (5 cm) of fiberglass insulation and ½ in. (1 cm) of gypsum board. During a later update to the facility, 4 in. (10 cm) of expanded polystyrene (EPS) was added to the outermost surface of the building. According to calculations performed using DesignBuilder software, this construction gives the facility walls an R-value of approximately 29.7.

The basement walls had a similar construction. However, the initial concrete layer was 1 in. (3 cm) thicker than that of the above-grade walls. A portion of the basement walls remained above grade to allow for the installation of windows. There were 21 windows of this type, 12 on the western face of the building and nine on the eastern face. These windows were approximately 6 ft (1.8 m) long and 2.5 ft (0.8 m) tall. The windows for the second and first floor of the building differed from those for the basement. Most of these windows are located on the east and west faces of the building, with the north and south faces containing only one window each. Windows of this type were approximately 4 ft (1.2 m) wide and 5 ft (1.5 m) tall with triple glazing. In total, 42 of these windows were present on the first and second floors.

Fort Greely

Bldg. 603. Bldg. 603 (Figure 2a) resides in south post at Fort Greely, AK. The building was once used as a multipurpose warehouse and also contained workshops but is now outfitted with office space, some workshops, and an unconditioned basement. Constructed in 1955, Bldg. 603 is a Department of Public Works building. The two-story building uses concrete masonry units (CMU) in the interior wall construction with an exterior insulation and finish system (EIFS) exterior building construction. There are a variety of windows of various sizes, with entry and overhead garage doors. The roof on the preexisting structure is flat, and the building addition has a gabled roof.

Bldg. 650. Bldg. 650 (Figure 2b) is located at Fort Greely, AK. The building houses a variety of recreational facilities, including a theater and a woodshop. Bldg. 650 was constructed in the 1950s and was later expanded. The building also had updates to the building envelope. There are very few windows in Bldg. 650. Per the window submittal document, these windows possess triple glazing and an aluminum frame. The walls consist of 8-in. (20.3-cm) concrete block with 2 in. (5 cm) of batt insulation and ½ in. (1.3 cm) of gypsum board.

BUILDING AIR LEAKAGE

The air infiltration rate was determined using Alaska Thermal Imaging[1] and results were determined for each building. The infiltration study performed on the facility provided an air leakage rate in units of CFM75/ft^2, which must be converted for use in the DesignBuilder software.[2] The software only accepts values in air changes per hour (ach) as the input for modeling infiltration.

1. Alaska Thermal Imaging, Inc, Palmer, Alaska. http://alaskathermalimaging.com/Home_Page.html.

The following shows the conversion process for Bldg. 3013. The study provided an initial air leakage rate of 0.095 CFM75/ft^2. To convert CFM75/ft^2 to ach, the provided value first had to be converted to cubic feet per minute (CFM) at standard pressure. This was done by first multiplying the initial value by the six-sided square footage of the facility and them converting CFM75 to CFM at standard pressure. These operations were performed as follows:

$$\frac{0.095\ \text{CFM75}}{\text{ft}^2} \times 8488.8\ \text{ft}^2 = 806.4\ \text{CFM75}$$

$$\text{CFM} = \text{CFM75} \times \left(\frac{5}{75}\right)^{0.65} = 0.172 \times \text{CFM75}$$

$$\text{CFM} = 0.172 \times \text{CFM75}$$

$$\text{CFM} = 0.172 \times 806.4\ \text{CFM75} = 138.7\ \text{CFM75}$$

These conversions provided a value of 138.7 CFM at standard pressure. From here, CFM would be converted into ach using the relation:

$$\text{ach} = 60 \times \frac{\text{CFM}}{V_{tot}} \tag{1}$$

where V_{tot} is the total volume of conditioned room in ft^3. Carrying forward with the calculation

$$\text{ach} = 60 \times \frac{138.7\ \text{CFM}}{38400\ \text{ft}^3} = 0.217\ \text{ach}$$

The final value of 0.217 ach was used for the simulation of Bldg. 3013. Table 1summarizes the rest of the results.

2. CFM75 is air leakage rate in cubic feet per minute at 75 Pa, i.e., the static pressure between the building's interior and the buildings ambient, and CFM is air leakage rate in cubic feet per minute at standard pressure, and EqLA75 is equivalent leakage area at 75 Pa.

Table 1. Simulation Results

FTG & FTW ABT-2019	Year of Const.	Bldg. Const. Type	6-Sided Area, ft^2(m^2)	CFM75/ ft^2 (m^3/h·m^2)	EqLA75 (ft^2/m^2)	ACH
FTW 3002	2016	IMP	39,822 / 3,703.5	0.208 / 3.744)	5.7 / 0.53	0.342
FTW 3013	1999	Wood Framed	8,488.8 / 789.5	0.095 / 1.710	0.5 / 0.047	0.217
FTW 4070	1950s	CMU Upgraded	N/A	N/A	N/A	N/A
FTG 603	1955	CMU/Concrete/EIFS	32005.6 / 2,976.5209	0.155 / 2.790	3.3 / 0.307	0.399
FTG 650	1955	CMU/Concrete/EIFS	28,501.6 / 2,650.6489	0.146 / 2.628	2.8 / 0.260	0.261

TDT PROCESS AND OBJECTIVE

During the thermal decay test (TDT), the primary heat source to a building is removed and researchers monitor how long and how fast the building's temperature decays. The goal of the test is to document the building's behavior and collect the needed baseline data to calibrate and validate models for thermal energy decay. A secondary purpose of these tests was to establish a TDT protocol to ensure test consistency and streamline the process for the tests at Fort Wainwright and Fort Greely (Oberg et al. 2021).

HEATING FAILURE SIMULATIONS METHODOLOGY AND TDT RESULTS COMPARISONS

Air temperature is essential for the evaluation of thermal comfort and energy consumption. The interior temperatures mostly depend on the construction, airtightness, factors in efficiency, insulation, internal loads, and occupancy.

The failure test conducted in Part I of this paper was compared to the building model data. It is important to determine a reliable model for buildings so the model can then be applied to other buildings at other locations to determine the maximum time to repair to ensure the safety of building's components, materials, and equipment.

Thermal degradation test protocol and processes were developed and applied in the 2019-2020 winter season to buildings at Fort Wainwright Alaska (W) and Fort Greely Alaska (G):

- W.4070.T1: Bldg. 4070, December 12th, 2019: 8-hour trial run at 10°F (–12.2°C).
  Trial run for testing the protocol and data collection tools.
- W.4070.T2: Bldg. 4070, January 9th, 2020: 8-hour test at –40°F (–40.0°C).
- W.3013.T1: Bldg. 3013, January 14th, 2020: 8-hour test at –20°F (–28.9°C).
- W.3002.T1: Bldg. 3002, January 17th, 2020: 8-hour test at –20°F (–28.9°C).
- G.650.T1: Bldg. 650, January 18th and 19th, 2020: 19-hour test at –40°F (–40.0°C).
- G.603.T1: Bldg. 603, January 18th and 19th, 2020: 19-hour test at –40°F (–40.0°C).
- W.3013.T2: Bldg. 3013, February 26th and 27th, 2020: 25-hour test at –20°F (–28.9°C).

The following sections compare the failure tests done at each building.

FORT WAINWRIGHT

Bldg. 3002

Bldg. 3002's heat failure test was conducted on January 17th, 2020, for an eight-hour test at –20°F (–28.9°C). The buildings mechanical room in located on the north side of the first floor. The failure began at 8:00 a.m. and ended approximately at 4:00 p.m.

First Floor. The sensor was placed on the floor, mid-height, ceilings, and windows in general office areas, classrooms, hallways, and entry areas. The sensor data shows constant air temperature during the experiment, whereas the back classroom showed a slight decline in air temperature despite having a heated floor. This second floor does not extend over the classroom area on the first floor.

Second Floor. The sensors on the second floor of Bldg. 3002 had the same placement; they were located in the general-purpose areas (open office space), office, and entry areas. The second floor does not have dedicated classrooms and is mostly individual offices. The experiment was over the same amount of time on the same day at the first floor. Figure 3 shows multiple sensors that displayed inconsistent air temperatures (Sensor 7446 located on mid-room on a desk and Sensor 10694 located on mid-room, mid-height); this could be due to changing temperature on surface areas or to sensor's proximity to a vent where mechanical ventilation was still causing air movement.

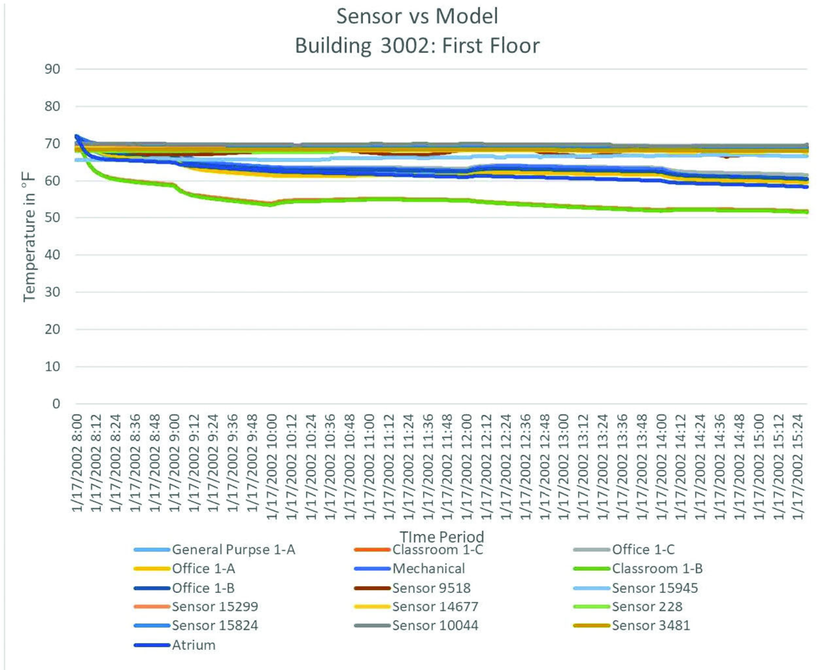
The model and sensor temperatures did reflect a decrease in the air temperature, but the model showed that the temperature reached the mid-50s °F (mid-teens °C). The air temperature for the model data could indicate infiltration and heat loss through the spaces pitched roof system.

The sensors and the model data show a good comparison and the models project a slightly lower building temperature, which is a conservative prediction.

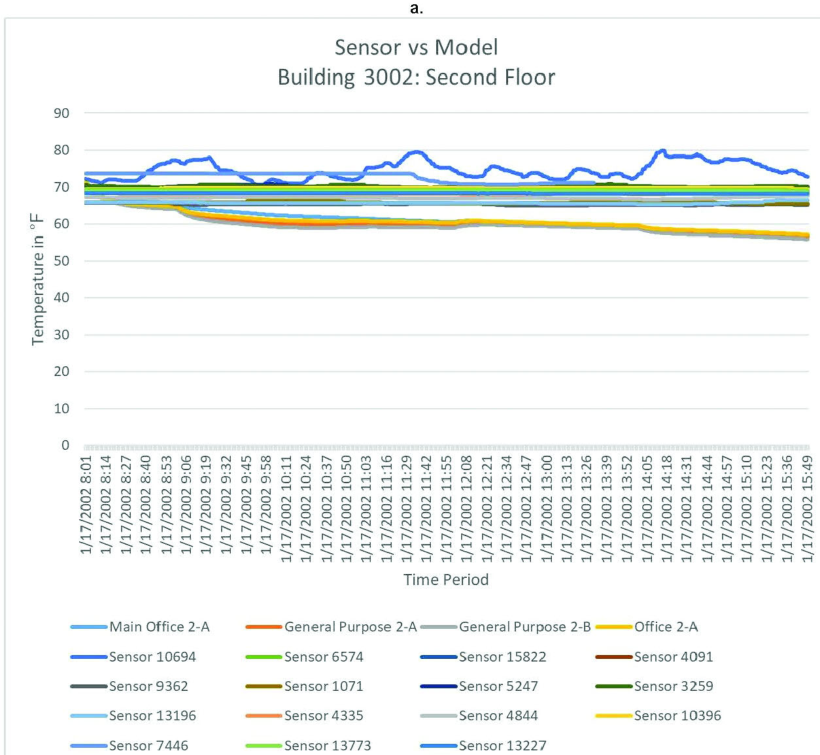
Bldg. 3013

Bldg. 3013 is a single-story building with a floor area of 2640 ft^2 (245.5 m^2). The building has two arctic entries on the north and south side. The mechanical room has a separate entrance on the north side without an arctic entrance. The test began on Wednesday, February 26th, at 8:00 a.m. AKST and ended on Thursday, February 27th, at 1:10 p.m. AKST. An overnight test was scheduled for the evening of Wednesday, February 26th, through Thursday, February 27th. The steam was disabled to Bldg. 3013 at 8:00 a.m. The HVAC air handlers were disabled at the same time. The glycol pumps were left enabled to allow comparison to the W.3013.T1 test scenario. The 25-hour test ended Thursday, February 27th, at 1:00 p.m., when steam was restored and HVAC reenabled.

What can be seen with the heating failure at 8:00 a.m. is that, for the first eight hours of the day with the otherwise normal operations of the building and the light structure with a radiant floor, there is a slow temperature decay. Then, when the business day ends and the outdoor temperatures drop, the building starts decaying and approaches 40°F (4.4°C) and crosses below at approximately 12:00 p.m. the next day. The data shown in Figure 4 may be used to compare the sensor in the main office area at midheight temperature and the EnergyPlus building model over the same time period.



a.



b.

Figure 3 *Bldg. 3002's (a) first floor and (b) second floor sensor and model comparison.*

The data in Figure 4 shows good agreement with the model and the sensor data. From 8:00 a.m. to 5:00 p.m., the temperatures are very similar. During the evening, there seems to be a heat input to the building that is not in the model. But once the temperature decay starts, the slopes are very similar. Overall, you do not want your model to underpredict the temperature decay; it is better to have the model predict that the building is getting colder sooner than the actual data. This way the prediction of when intervention is necessary happens before building damage occurs and will be a conservative estimate and more reliable to use.

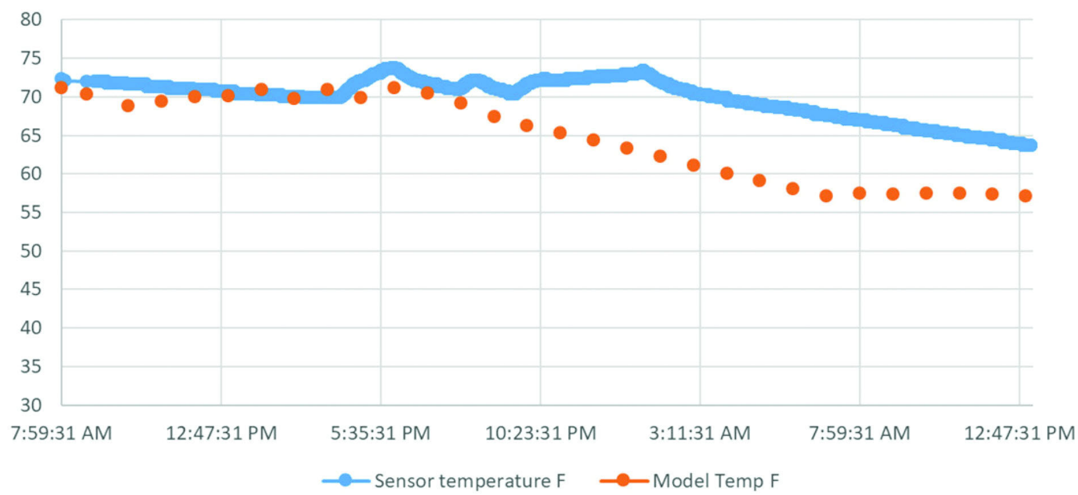


Figure 4 *Bldg. 3013's heating failure results shown for 18 hours, where the sensor data is the solid line and the model data is the dotted line.*

Bldg. 4070

The scenario simulated a heating failure on a Friday morning that was restored the following Wednesday. During the weekend failure period, the simulated building sank to a temperature of 38°F (3.3°C) before rising slightly during its occupied periods on Monday and Tuesday. A minimum temperature of 33°F (0.6°C) was reached early Wednesday morning at 2:00 a.m.

Two TDTs for Bldg. 4070 were performed. The first of these tests took place in December 2019. Outdoor temperatures averaged 10°F (–12.2°C). This test was largely used to establish testing protocols. The second TDT occurred in January 2020. During this test, outdoor air temperatures averaged –40°F (–40.0°C). The test occurred for approximately eight hours between 8:00 a.m. and 4:00 p.m. This test will be used to compare the results of the model built for Bldg. 4070 and run at –40°F (–40.0°C).

First Floor. The TDT required the placement of sensors throughout the building. For comparison, it was optimal to place sensors near the center of the wall. Sensor 6761 was one such sensor. Records show that this sensor was placed ~5 ft (~2 m) from the floor atop of a metal shelf and was against an interior wall. It was determined that a second sensor placed on the first floor of Bldg. 4070 would also be useful for analysis; Sensor 8138 was located near an interior wall ~4 ft (~1.2 m) above the floor atop a wooden shelf.

Both sensors reach a temperature minimum of 67.1°F (19.5°C) while the building model for the first floor reached a minimum or 67.7°F (19.8°C) in eight hours. It is noteworthy that, unlike the sensors, the model temperature begins to trend back upward. However, the increase accounted for only 1°F (0.56°C) of change across the trend. Sensor 8138 experiences a plateau that is not seen in the other sensor, and it can also be observed the most temperature decay seems to occur in the latter four hours. This also indicates a level of capacitance. For most of the data set, the model remains below the actual building in temperature. This indicates it may be reliable in estimating temperature, but the trend back upward is a load that was not present in the actual building.

Second Floor. As with the first floor, two sensors were chosen for the second floor of Bldg. 4070 to compare with the model data. Sensor 9663 was placed near an exterior wall and was approximately 4 ft (1.2 m) from the ground atop of a shelf. Sensor 9480 was placed near an interior wall. Like the previous sensor, it was approximately 4 ft (1.2 m) off the ground and was on top of a shelf.

The curves for each of the sensors as well as the model seem to follow the same general shape. What is most notable is the gap between each curve, or the starting point. In general, the sensor location in the actual facility had a warmer starting temperature than the model, with the model showing the set point at the thermostat. While the model began the decay at 72°F (22.2°C), Sensor 9480 began at 77°F (25.0°C) and Sensor 9663 at 81°F (27.2°C). Although there is a temperature gap between the model and the sensor data because the model never exceeds the actual temperature, it may still be useful in predicting resilience. The model shape shows the behavior of the building temperature decay is captured, while a real building will not be isotherm for all sensor locations. The temperature trend of the model would allow appropriate action to be taken as a prediction.

Basement. Once again, two sensors were selected to compare to the model data. Sensors 4728 and 10872 were each placed near interior walls atop shelves. Both sensors were approximately 4 ft (1.2 m) above the floor.

As with the second floor, the sensors show that this area is not isothermal, as expected. The model data seems to follow Sensor 10872 closely, with temperatures from the model being

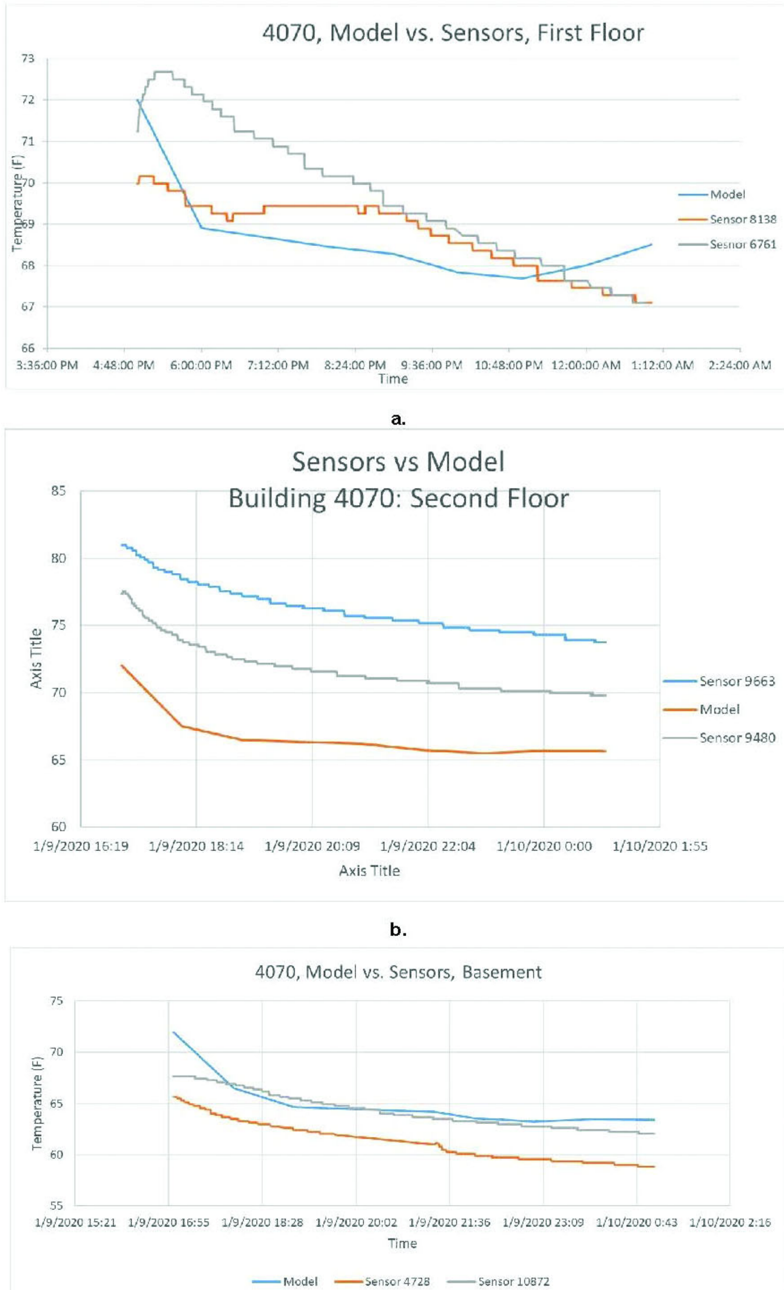


Figure 5 *Bldg. 4070's (a) first floor, (b) second floor, and (c) basement heating failure results.*

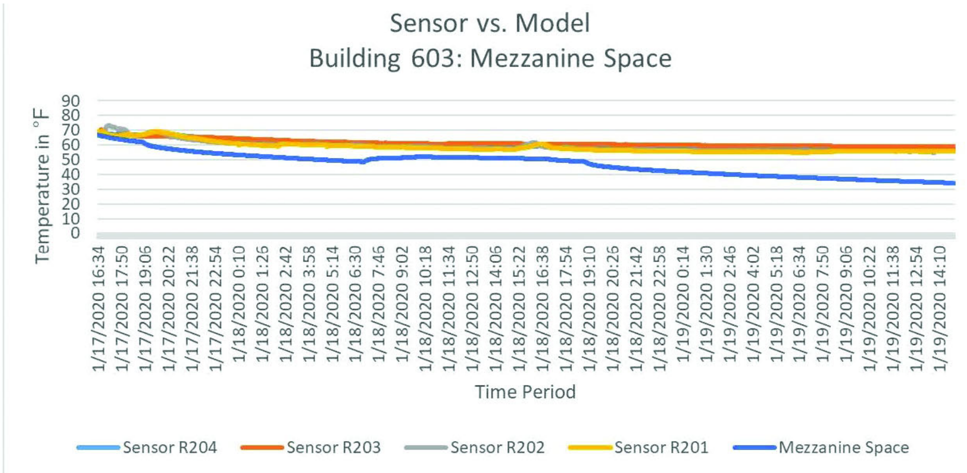
slightly above those of the sensor. The model starts at a temperature of 72°F (22.2°C), while the sensors begin nearer to 66°F (18.9°C) at those sensor locations. The temperatures plotted on this zoomed-in scale show that the model follows the trend of the collected data well.

FORT GREELY

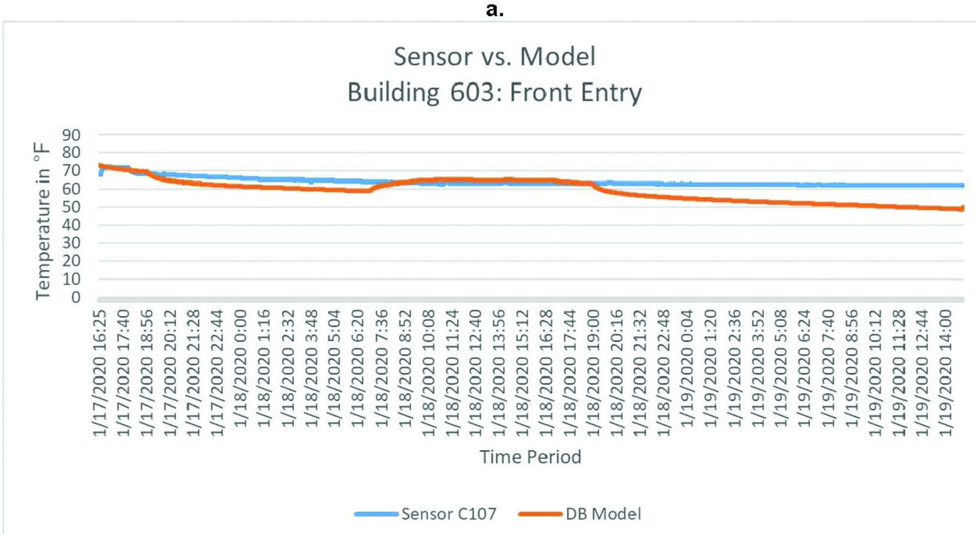
Bldg. 603

It was assumed that on Friday, January 11, employees would arrive on site for a typical business day, using lighting and other office equipment. Without the heating system, the air temperature reaches freezing condition in the twenty-third hour with operative air temperatures hovering at 38°F (3.3°C). On Monday, January 14, occupants endured an 18°F (10°C) difference from the outdoor air ranging from 6°F to 10°F (–14.4°C to 12.2°C) and an operative temperature between 23°F and 29°F (–5.0°C and –1.7°C).

Without the heating system, the air temperature did not reach above 40°F (4.4°C) until 8:00 a.m.; these conditions lasted until 7:00 p.m. The air temperature reached a freezing condition in 26 hours. This means that the restoration would



a.



b.

Figure 6 *Air temperature details for Bldg. 603's (a) mezzanine and (b) front entry.*

need to happen within the first eight hours of the building heat failure, to restore the building to temperatures above 40°F (4.4°C) within five hours.

Figure 6 shows the comparison of Sensor 104 and the DesignBuilder simulation model in conditions that occurred after 19 hours of the heat failure experiment with ambient temperatures of –40°F (–40.0 °C). The initial temperature for the sensor data shows a temperature increase at the beginning of the experiment. The model data started with the interior temperature set point of 72°F (22.2°C) at 4:00 p.m. The sensor data compared to the model data indicates that the additional space of Bldg. 603 would react to the decay in the same fashion. The building decay would affect the space temperatures but not in the critical range for damage to the building. The time of recovery happens quickly for both cases.

The mezzanine space located on the second floor on the northwest side of the building showed a gradual decline in the air temperature in the space during the –40°F (–40.0 °C) outdoor air temperature, but the model indicates a greater decrease in air temperature over the time period. Air infiltration, the exterior wall, or the wind speed could be the reason for the difference between the model and the sensor data.

The front entry of Bldg. 603 faces west. The sensor and model data show declines in the air temperature once the heat failure experiment commences. The air temperatures are similar for both sensor and model, but the model indicates a rapid decline in air temperature, reaching the upper 40s degrees Fahrenheit (4.4+°C) temperatures. The model would suggest that heat restoration would have to be implemented within the first eight hours on January 19th.

Bldg. 650

The model in Figure 7 shows an almost immediate, sharp drop in building air temperature. Within the first two hours of

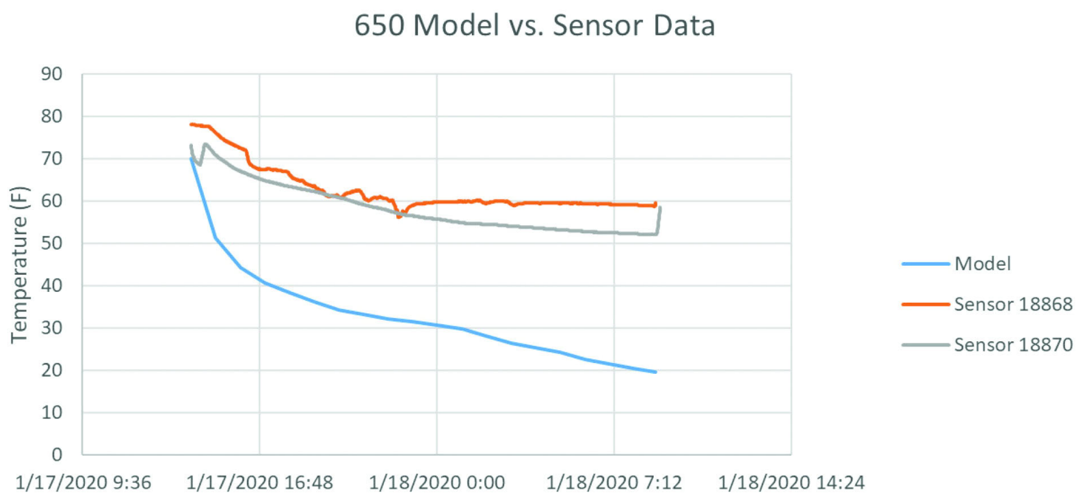


Figure 7 *Model data versus sensor data for Bldg. 650.*

failure, the temperature falls to 30°F (–1.1°C). This would indicate that the building would be almost immediately inhabitable and damage to equipment would occur quickly as well.

A 19-hour thermal decay test was conducted for Bldg. 650 on January 18th and 19th, 2020. Two sensors were selected for comparison of the model data. The sensor data was compared to the average data for the entire facility. The test was conducted with outdoor temperatures near –40°F (–40.0 °C).

While the model starts off at a similar temperature as the recorded data, it drops off much more quickly than either of the sensors. When investigating individual blocks within the building model, several areas experience a sharp temperature drop off. The only area of the building not to experience the sharp drop seen was the basement block. This block likely had extra capacitance from the ground connection, which prevented the sharp drop. The drop may indicate a need for modifications to the simulated building construction.

Overall, the building model results compared well to the sensor data collected from the TDT. Given that the models have reliable agreement with sensor data even with all the differences between models and real structures. It is concluded that the models will be a reliable, will make conservative predictions of the real building performance, and can then be used to extend to other building types and scenarios.

PARAMETRIC ANALYSIS

Once you are confident that the models are reliable and can be used to determine the required response time before damage occurs, investigate longer-term failure performance, estimate the time for the building to return to the set point after a failure, and so on. Also, environmental conditions can be adjusted from a TMY3 weather file to a steady-state temperature to determine the response times (i.e., a constant –20°F, –40°F [–28.9°C, –40.0°C]), and so on, and generate a table for a building category type. Also, construction options or standards by building category can be investigated for envelope specifications, i.e., wall and roof insulation levels, type of windows, airtightness, and so on. This section will use a prototypical building model and make some envelope comparisons. Each of the graphs has a 60°F and 40°F (15.6°C and 4.4°C) lines on them. During an emergency, maintaining optimal comfort conditions may not be feasible. In this case, mission-critical areas can be conditioned to different thresholds of thermal requirements. These requirements include the ability to perform the required work safely and efficiently, support the processes housed in the building, and that temperature will be at 60°F (15.6°C). The 40°F (4.4°C) limit is to ensure the long-term sustainability of the building or the point if the temperature goes below damage to the structure can begin. Additional information can be found on thermal energy requirements in Zhivov et.al. (2021). The 60°F (15. 6°C) limit is the habitability threshold and the 40°F (4.4°C) limit is the sustainability threshold. Both limits are conservative; the sustainability threshold is above the temperature where damage can occur in the facility.

Four scenarios are being investigated using the prototypical Bldg. 4070 but with construction, window, and air leakage changes. Table 2 lists the building parameters that vary along with the high mass or CMU and slab floor structures. Then the building structure is changed to framing elements with only small amounts of building mass compared to a CMU, poured slab building. The time to exceed the habitability threshold was selected from Floor 1 and 2’s room temperature sensors. These are the areas where personnel will attempt to continue the mission of the facility until it becomes too cold to work effectively. Even though spaces in the basement reached and exceeded the habitability threshold first, this will not harm the equipment or the facility in those locations since the personnel will not be working on this level. But for the sustainability threshold, the basement spaces were the areas used to set the times. This was determined by how the facility was being

Table 2. Varied Building Parameters and MTTR for –40°F (–40°C) Outdoor Temperature

Building Parameters	High Mass Building CMU walls and poured concrete floors and roof deck			Frame Building Frame wall, roof, and floors		
	Typical 1980	**Low Efficiency**	**High Efficiency**	**Typical 1980**	**Low Efficiency**	**High Efficiency**
Walls (R-Value IP)	20.5	40	50	20.5	40	50
Roof (R-Value IP)	31.5	45	60	31.5	45	60
Air Leakage (ach)	0.4	0.25	0.15	0.4	0.25	0.15
Window (R-Value/U-Factor)	Double Pane; R = 1.78/U =0.56	Double Pane; R =3.34/U =0.3	Triple Pane; R = 5.25/ U=0.19	Double Pane; R = 1.78/U =0.56	Double Pane; R = 3.34/U = 0.3	Triple Pane; R = 5.25/U = 0.19
MTTR Habitability, 60°F (15.6°C)	2 hours	9 hours	18 hours	1 hour	3 hours	6 hours
MTTR Sustainability, 40°F (4.4°C)	32 hours	67 hours	94 hours	14 hours	24 hours	34 hours

operated, and the mission is accomplished on Floor 1 and 2 while piping and other critical equipment would be affected when the sustainability threshold is exceeded. Given this process, the MTTR tables were developed.

Figure 8a shows a mass building with lower efficiency envelope parameters and a normal TMY3 file and files with constant low temperatures, i.e., –20°F, –40°F (–28.9°C, –40.0°C). For comparison, the first floor radiant temperature with TMY3 weather is plotted to see the impact and time delay of the radiant temperature compared to the air temperature. In the graph below with the mass building, it lags the air both on the decay, especially during the recovery back to the set point. To keep the figure from being too cluttered, only one radiant temperature is plotted but the general behavior for the other two cases would be similar.

The outdoor air temperature is plotted for the TMY3 Fairbanks, AK, weather data for reference. The graph shows how the air temperature quickly drops below the radiant temperature that lags the air temperature as the capacitance of the building is being discharged. Then, after the five days when heating is restored, the air temperature recovers in hours while the building capacitance takes days to return to its prefailure norm. Also plotted on each graph is a 60°F and 40°F (15.6°C and 4.4°C) line; note that only the TMY3 weather data did not pass through the 40°F (4.4°C) threshold and the constant low temperatures did, but not until several days had passed.

Figure 8b reflects mass building with high efficiency envelope parameters and is shown with a normal TMY3 file and several files with constant low temperatures, i.e., –20°F, –40°F (–28.9°C, –40.0°C). This is also compared with the first floor radiant temperature with TMY3 weather to see the impact and time delay of the radiant temperature compared to the air temperature. In the graph below with the mass building, it lags the air both on the decay, especially during the recovery back to the set point.

After five days when heating is restored, the air temperature for all three cases does not pass the 40°F (4.4°C) threshold. This building with a high mass and high efficiency building envelope could sustain a five-day heat outage, even with extreme constant –40°F (–40.0°C) outdoor temperatures.

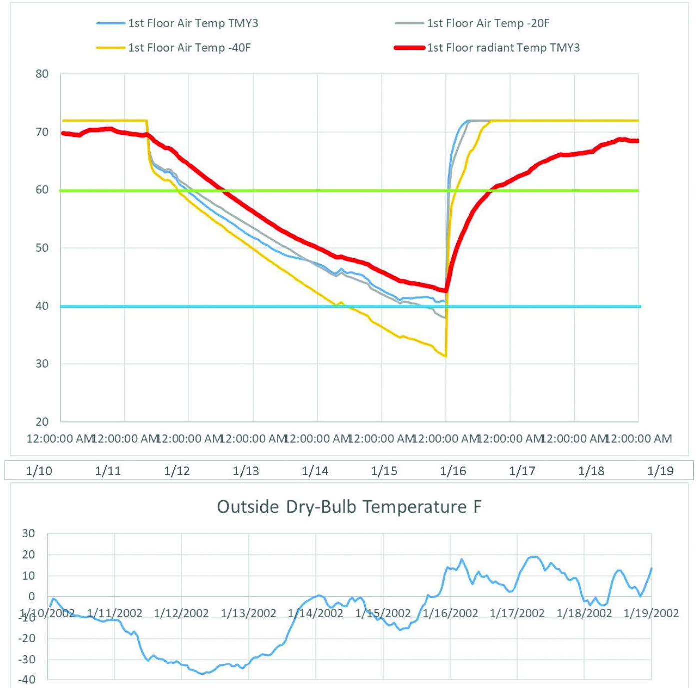
Figure 9a pertains to a frame building with lower efficiency envelope parameters and is shown with a normal TMY3 file and several files with constant low temperatures, i.e., –20°F, –40°F (–28.9°C, –40.0°C). It Is also useful to compare the first floor radiant temperature with TMY3 weather to see the impact and time delay of the radiant temperature compared to the air temperature. In the graph below with the mass building, it lags the air both on the decay, especially during the recovery back to the set point.

This low capacitance frame structure would reach the 40°F (4.4°C) threshold after about a day in all cases. This building would need to have the heat restored in the first day to prevent damage.

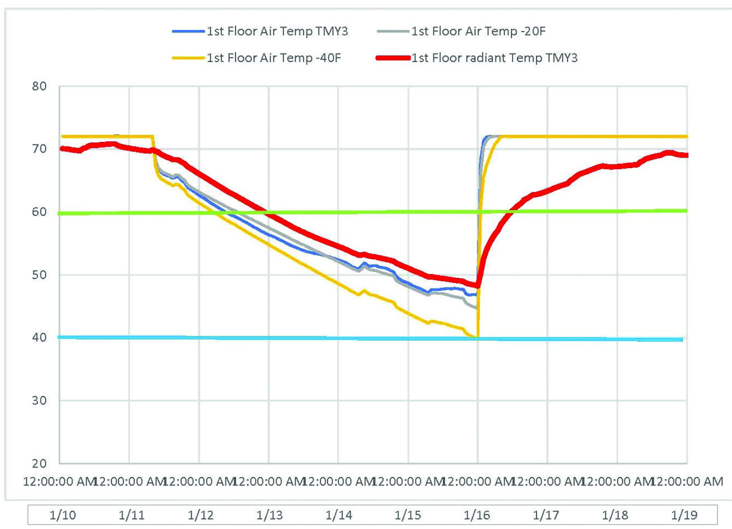
Figure 9b is a frame building with high efficiency envelope parameters and is shown with a normal TMY3 file and several files with constant low temperatures, i.e., –20°F, –40°F (–28.9°C, –40.0°C). It is also useful to compare the first floor radiant temperature with TMY3 weather to see the impact and time delay of the radiant temperature compared to the air temperature. In the graph below with the mass building, it lags the air both on the decay, especially during the recovery back to the set point.

This low capacitance frame structure would reach the 40°F (4.4°C) threshold after about a day and a half in all cases. The higher efficiency envelope parameters allow for approximately a half day of additional time for response before damage starts to occur.

Figure 10 shows a cross-comparison of the mass building with constant –40°F (–40.0 °C) weather showing the air temperature from the high efficiency, lower efficiency, and



a.



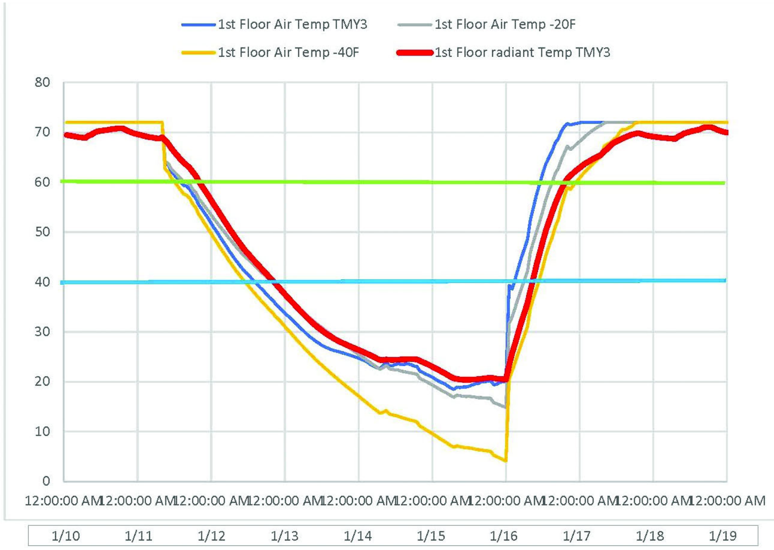
b.

Figure 8 *First floor (a) low efficiency and (b) high efficiency mass building heating failure results with TMY3, –20°F (–28.9°C) and –40°F (–40 °C) weather from January 10th to 19th.*

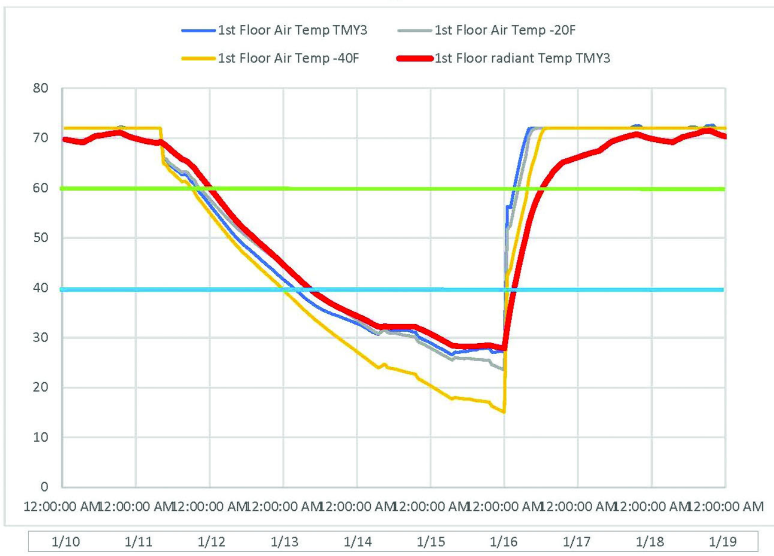
typical 1980 envelope constructions. (Note: this case represents a lower efficiency than the current standards when these buildings were built or retrofitted). This figure shows that, at the end of the fifth day of failure, the efficient building envelope parameters of the mass structure maintain a temperature about 8°F (4.5°C) higher and keeps the building above the threshold for about an extra one-and-a-half days.

Figure 11a shows a cross-comparison of the frame building with –40°F (–40.0°C) weather, showing the air temperature from the high efficiency, lower efficiency, and typical 1980 envelope parameters. The frame efficient building envelope parameters maintain temperatures for an extra half of a day before the 40°F (4.4°C) threshold is crossed as compared to the lower efficiency parameters. In a five-day heating failure, both buildings would experience freeze damage. The typical 1980 parameters are included for reference to show how older building parameters would compare.

Figure 11b shows a comparison between the frame building low efficiency and the mass building with high-efficiency building envelope parameters using –40°F (–40.0°C) weather.



a.



b.

Figure 9 *First floor (a) low efficiency and (b) high efficiency frame building heating failure results with TMY3, –20°F and –40°F (–28.9°C and –40.0°C) weather.*

This shows the best performer and the worst performer directly to see how efficient and capacitive buildings perform in extreme weather conditions. The figure shows that the difference between one day and approximately five days of heating failure can affect the survivability of an emergency heating failure in an extreme arctic environment for each type of building. This information indicates that it would be appropriate to house critical missions in efficient and capacitive buildings.

Figure 12 shows the graphed results of a simulation run with a constant –40°F (–40.0°C) outdoor temperature for the mass building with lower-efficiency envelope parameters. Under normal operating conditions, the radiant temperature gives an indication of the surface temperatures in the zone, or the windows, walls, ceiling, and floor. Prefailure for the mass building the radiant and air temperatures are very similar to the radiant temperature a couple of degrees below the air temperature. This difference is larger with the –40°F (–40°C) outdoor dry-bulb temperature (ODB) compared to an outdoor temperature of 0°F (–17.8°C). Therefore, the building capacitance would be considered charged.

During the failure, the air temperature crosses and falls lower than the radiant temperature as the air temperature leads the lagging radiant temperature. With a constant theoretical –40°F (–40.0 °C) outdoor air temperature, there is a smooth temperature decay slope for both the air and the radiant temperatures. The air temperature reaches a minimum temperature of 31.3°F (–0.4 °C) after five days. The

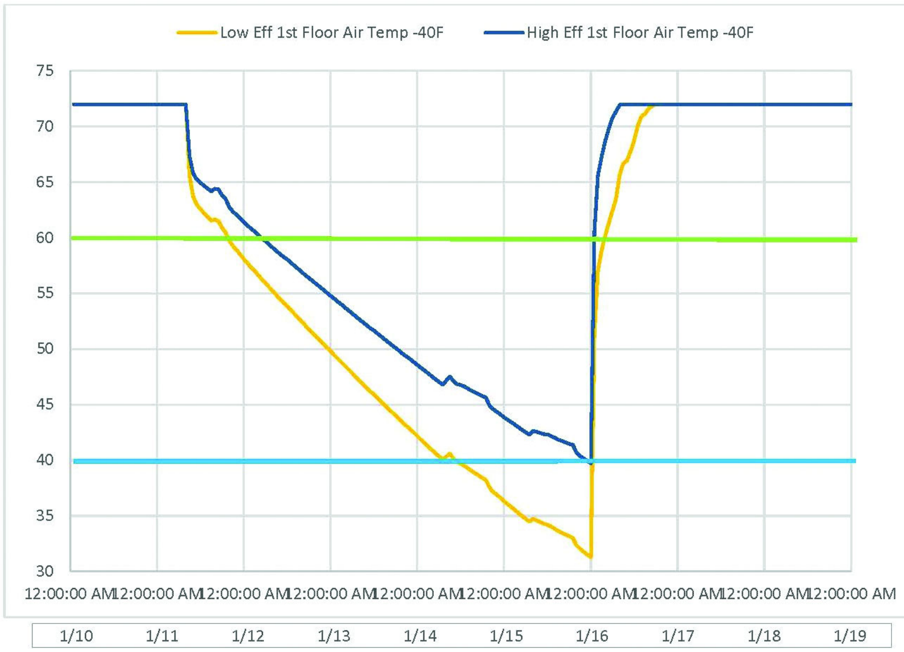


Figure 10 *Mass building comparison of high efficiency, low efficiency, and typical 1980 parameters for building heating failure results with –40°F (–40.0 °C) weather.*

heating is restored, and the buildings start to recover. The heating was restored at midnight, and the air temperature reaches set point 12 to 13 hours later, around lunchtime for this building. However, note the lag of the radiant temperature on the upper temperature graph, which does not reach its prefailure state until after three days of heating.

In the heating graph, notice the amount of heating that takes place for several days after the air temperature has reached set point. This is the amount of time it takes to recharge the building capacitance and bring it back to the prefailure building conditions.

Another area of the temperature decay chart is the slope of the decay. The slope on the air temperature decay is an indicator of the efficiency of the building envelope and the operation of the building systems and occupants as shown in the modeled scenarios. Any envelope efficiency changes, i.e., reduction in insulation levels or decrease in building airtightness, will decrease the thermal resiliency of the building. This will show how quickly operations will have to respond to certain buildings either to prevent damage or to maintain mission effectiveness.

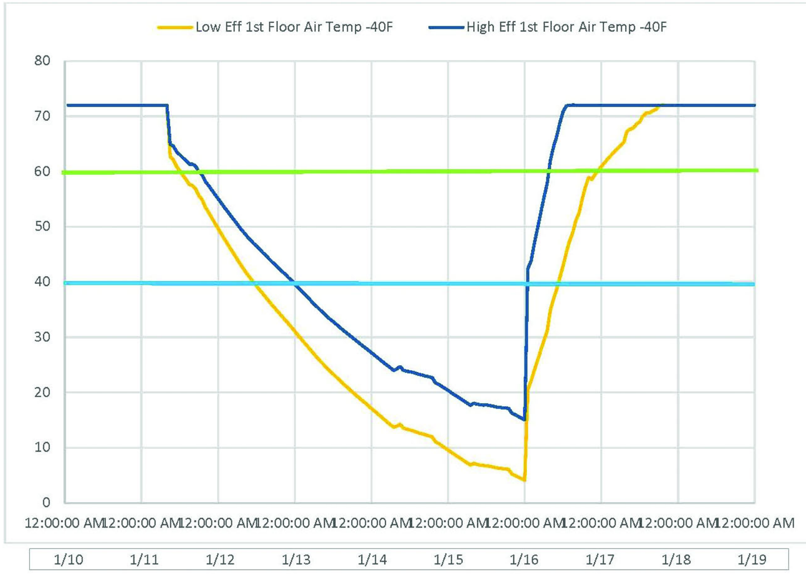
The last part of the graph indicates how long recovery takes once the heating has been restored. In the mass building scenario shown in Figure 12, it takes about half a day to recover to the normal operating air temperature in the building, with more than three days needed to recharge the thermal capacitance. The rate of temperature decay, minimum temperature, and length of recovery are all significant aspects of the building's thermal resiliency with the more efficient and capacitive structure being more thermally resilient.

CONCLUSION

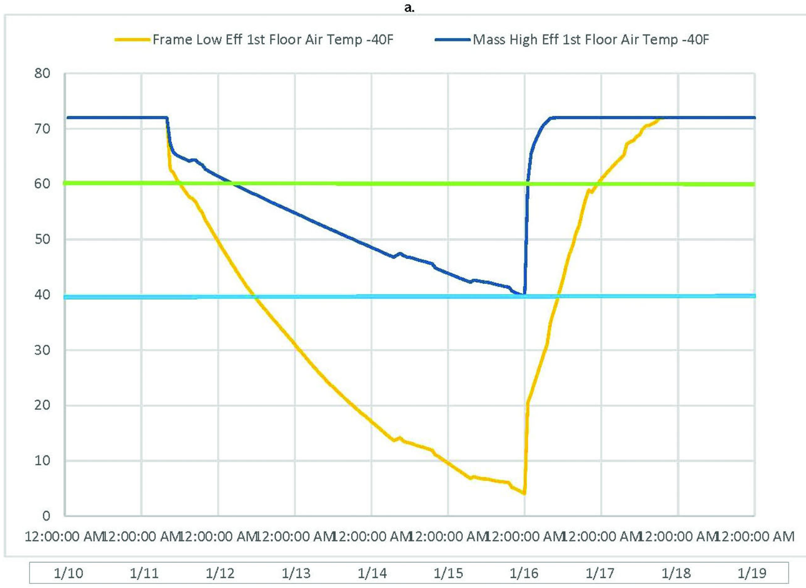
This two-part paper is a one of the first of its kind to attempt to address thermal decay in cold environments.

A team of U.S. Army Engineer Research and Development Center (ERDC) researchers in collaboration with researchers from the University of Alaska envisioned, developed, and conducted a TDT at Fort Wainwright, AK and Fort Greely, AK. These tests were performed while outdoor air temperatures ranged between –20°F and –40°F (–28.9°C and –40°C), which allowed the collection of building-specific data on temperature change in different building areas and different surfaces of tested buildings to identify critical areas with significant temperature degradation compared to other building areas.

The results of these tests indicate that air temperature in mechanical rooms located in the basement, in a semibasement, or on the first floor having openings for make-up air, fenestration, or a large open stairway column located nearby deteriorate faster than in other parts of the building; therefore, mechanical rooms can be used as representative locations to identify the length of time when a building will reach the habitability and sustainability thresholds. Typically, a building's middle floors take the longest time to achieve the habitability threshold; therefore, these locations are recommended for hosting mission-critical operations. Furthermore, the modeling of these buildings using the weather data corresponding to the test dates allowed for the calibration of building models for use in parametric studies of representative buildings.



a.



b.

Figure 11 *Comparison of a high efficiency versus a low efficiency and typical 1980 in building heating failure results at –40°F (–40.0°C) weather for a (a) frame building and a (b) mass building.*

Building indoor air temperature degradation was studied for high mass buildings (CMU and poured concrete slabs) and light-frame buildings with thermal characteristics ranging from pre-1980 code construction, current minimum energy efficiency requirements (lower efficiency), and state-of-the-art energy-efficient building characteristics (high efficiency) for buildings constructed in U.S. Department of Energy (DOE) climate zone 8. The previous section clearly shows that high mass buildings make a large contribution to the thermal resilience of buildings, as do the obvious parameters of building airtightness and controlled airflow across the building envelope.

The 40°F (4.4°C) limit is a good metric to respond to before it is reached when determining a time to repair for heating restoration. This gives time for repair while providing a safety factor before damage can occur in the structure or mechanical and water systems.

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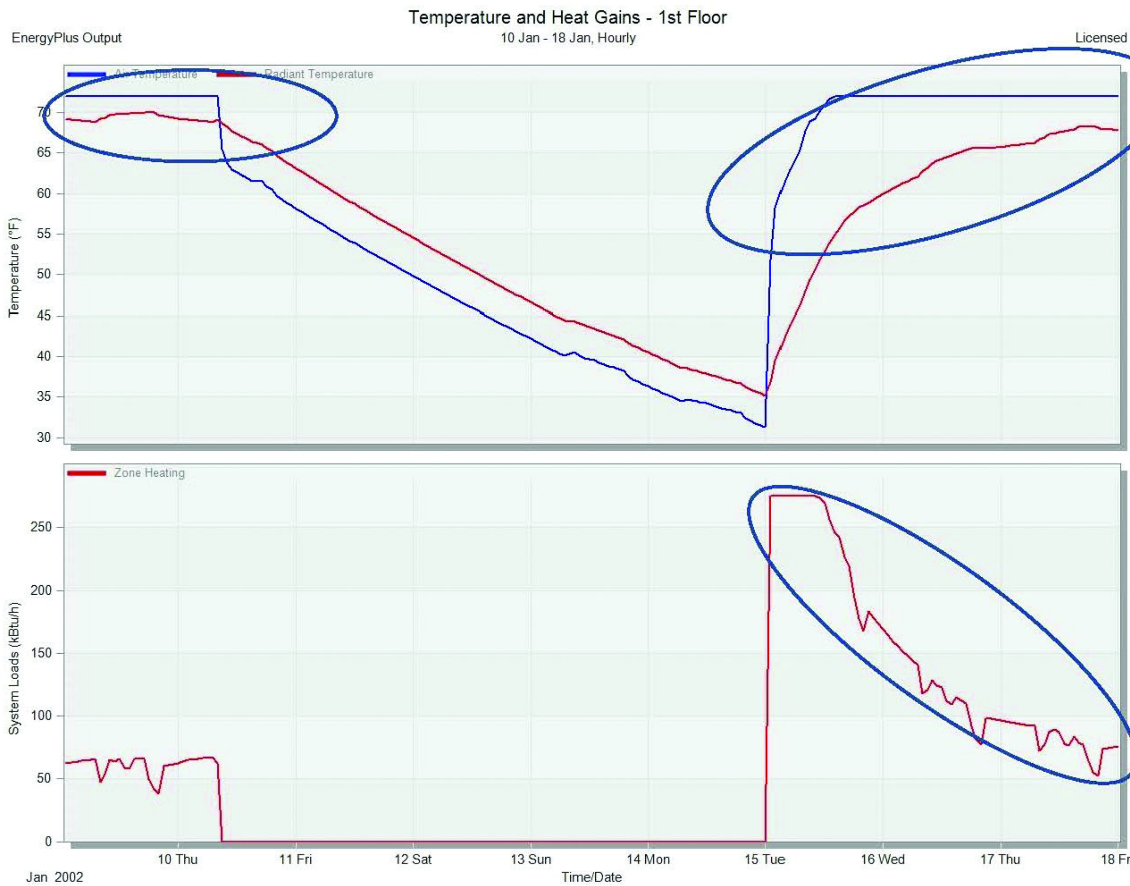

Figure 12 *Heating failure results for Bldg. 4070 in –40°F (–40.0°C) weather.*

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