

Requirements for Building Thermal Conditions under Emergency Operations in Cold Climates

Alexander M. Zhivov,^{1*} William B. Rose,² Raymond E. Patenaude,³ and W. Jon Williams⁴

¹ U.S. Army Engineer R&D Center, Champaign, IL (USA)

² William B. Rose & Associates, Inc. Urbana, IL (USA)

³ Holmes Engineering Group LLC, St. Petersburg, FL (USA)

⁴ National Personal Protective Technology Laboratory NIOSH/CDC, Pittsburg, Pa (USA)

Abstract. This paper provides recommendations on thermal and moisture parameters in different types of buildings under emergency operation in cold/arctic climates. We consider three scenarios under normal operating conditions: occupied, temporarily unoccupied, and long-term unoccupied. These thermal parameters are necessary to: (1) perform required work safely and efficiently, (2) support building processes, and (3) support long-term integrity of the building under emergency conditions (i.e., interruption of fuel, steam, hot water, and electrical service that interrupts building space conditioning). Under emergency conditions, requirements of thermal parameters for different categories of buildings may change. Mission critical areas can be conditioned to levels that support the agility of personnel who perform critical operations, but not to optimal comfort levels. Critical process requirements are given priority. This paper was developed for military applications, based on research performed under the International Energy Agency's Energy in Buildings and Communities Program, Annex 73; under the Department of Defense Environmental Security Technology Certification Program project EW18-D1-5281, "Technologies Integration to Achieve Resilient, Low-Energy Military Installations," and under the Office of the Deputy Assistant Secretary of the Army project "Thermal Energy Systems Resiliency for Army Installations located in cold climates." Results are applicable to similar public and private sector buildings.

1 Introduction

During an emergency situation, requirements of thermal parameters for different categories of buildings or even parts of the building may change. When the operation of normal heating, cooling, and humidity control systems is limited or unavailable, mission critical areas can be conditioned to the level of thermal parameters required to support the agility of personnel who perform mission critical operations, but not to the level of their optimal comfort conditions. Beyond these threshold (habitable) levels, effective execution of critical missions is not possible and mission operators have to be moved into a different location. These threshold limits of thermal parameters may be in a broader range compared to those required for thermal comfort, but not to exceed levels of heat and cold stress thresholds. However, special process requirements (e.g., with IT and communication equipment, critical hospital spaces, etc.) should be given a priority if they are more stringent. Broader ranges of air temperatures and humidity levels in building spaces surrounding mission critical areas may be used, but they need to be limited to prevent excessive thermal losses/gains and moisture transfer through walls and apertures not designed with thermal, and air/vapor barriers. Finally, noncritical standalone buildings can be hibernated, but necessary

measures should be taken, and the thermal environment should be maintained when possible to prevent significant damage to these buildings before they can be returned back to their normal operation.

2 Normal (blue sky) operating conditions

Under normal operating conditions, for any given building, factors like building envelope insulation and airtightness, ventilation rates, thermostat setpoints, plug loads, and lighting levels have a significant impact on building energy consumption and cost. These factors affect a building's energy performance in any climate, whether arctic or hot/humid.

It is important that engineers and operations and maintenance (O&M) personnel design for and use appropriate rates and setpoints to maintain these thermal conditions, which provide occupant comfort, health, and productivity, and which minimize energy usage in normal operation conditions and make thermal systems more resilient during emergency operation. Setting these rates and setpoints can be as much of an art as a science, but there are a number of standard references that are used to help in the operation of the building. The following references provide guidance on the suggested values.

* Corresponding author: Alexander.M.Zhivov@usace.army.mil

Thermal requirements include criteria for thermal comfort and health, process needs, and criteria for preventing the freezing of water pipes, growth of mold and mildew, and other damage to the building materials or furnishings. Under normal operating conditions, code compliant buildings are presumed to be free of mold and mildew problems; if these conditions do occur, they become matters for O&M intervention.

Thermal comfort and health criteria primarily involve the temperature and humidity conditions in the building. Too high a temperature means that occupants are uncomfortably hot. Too low a temperature means that occupants are uncomfortably cold. The wrong humidity (rooms typically do not have humidistats) means that occupants feel damp or sweaty or too dry. Thermal comfort is defined by ASHRAE Standard 55 [1]. When the space is unoccupied during a short period of time (e.g., few days), the room thermostat should be set back to 55 °F (12.7 °C). In spaces unoccupied for an extended period of time (e.g., weeks), temperature should be controlled at 40 °F (5 °C).

Process related criteria include temperature and humidity needed to perform the process housed in the building (e.g., spaces with IT and Communications equipment, critical hospital areas, industrial processes [painting, printing, etc.]). While new design guidance for computer systems indicates a much higher tolerance for high temperatures than previously thought, there are specialized electronic and laboratory equipment that have fairly tight temperature and humidity requirements for protection from damage caused by electrostatic discharge. Archival storage of important documents also involves relatively tight tolerances for temperature and humidity.

IT Facilities. Many mission critical facilities or dedicated spaces within these facilities (e.g., emergency operation centers, Sensitive Compartmented Information Facilities [SCIFs], Network Operations Centers [NOCs], Network Enterprise Centers [NECs]) house computer systems and associated components, such as telecommunications and storage systems. Environmental requirements for spaces with IT and Communications equipment may vary depending on type of equipment or manufacturer. According to ASHRAE [2], there are six standard classes of thermal requirements.

Class A1. Typically, a datacom facility with tightly controlled environmental parameters (dew point [DP], temperature, and relative humidity [RH]) and mission critical operations, including those housing servers and data storage.

Class A2/A3/A4. Typically, the types of products typically designed for use in an information technology space with some control of environmental parameters (DP, temperature, and RH), are volume servers, storage products, personal computers, and workstations. Among these three classes, A2 has the narrowest temperature and moisture requirements and A4 has the widest environmental requirements. (Classes A3 and A4 do not have special requirements to be considered.)

Class B. Typically an office, home or transportable environment with a little control of environmental

parameters (temperature only), including personal computers, workstations, and printers.

Class C. Typically, a point of sale or light industrial environment with weather protection.

In addition to four classes of requirements for IT and Communications equipment facilities discussed above, there are also requirements for Network Equipment-Building System (NEBS) offices housing switches, routers, and similar equipment with some control of environmental parameters (DP, temperature, and RH). Table 1 lists the recommended and allowable conditions for Class A1, Class A2, and NEBS environments.

Table 1. Recommended and allowable conditions for Classes A1-A2, and NEBS environments.

Conditions	Class A1/Class A2 [3]		NEBS [2]	
	Allowable level	Recommended level	Allowable level	Recommended level
Temperature control range				
A1	51 °F - 89 °F (11 °C - 32 °C)	64 °F - 80 °F (11 °C - 27 °C)	41 °F - 104 °F (5 °C - 40 °C)	65 °F - 80 °F (18 °C - 27 °C)
A2	51 °F - 91 °F (11 °C - 33 °C)			
Maximum temperature rate of change	9 °F/hr (31 °F/hr) ¹ (5 °C/hr [2 °C/hr])		2.9 °F/hr (1.6 °C/hr)	
RH control range				
A1	10 °F (-11 °C) DP and 8%RH to 62 °F (11 °C))DP and 80%RH	15 °F - 51 °F DP (-1 °C - 11 °C) DP and 60%RH	5%-85% 82 °F (28 °C) Max DP	Max 55%
A2	10 °F (-11 °C) DP and 8%RH to 69 °F (21 °C) DP and 80%RH			

¹ 9 °F/hr - for tape storage, 31 °F/hr for all other IT equipment and not more than 9 °F in any 15 min period of time.

Health Care Facilities. Health Care Facilities represent another group of mission critical facilities. Per NFPA 99, Health Care Facilities [3] include, but are not limited to, hospitals, nursing homes, limited care facilities, clinics, medical and dental offices, and ambulatory health care centers. This definition applies to normal, regular operations and does not pertain to facilities during declared local or national disasters. Patient Care Spaces in Health Care Facilities are described using the following four categories:

- Category 1 Space. Space in which failure of equipment or a system is likely to cause major injury or death of patients, staff, or visitors.
- Category 2 Space. Space in which failure of equipment or a system is likely to cause minor injury to patients, staff, or visitors.

- Category 3 Space. Space in which the failure of equipment or a system is not likely to cause injury to patients, staff, or visitors but can cause discomfort.
- Category 4 Space. Space in which failure of equipment or a system is not likely to have a physical impact on patient care.

Examples of requirements to thermal environment in spaces included in categories 1 and 2 are listed in Table 2.

Table 2. Thermal environment requirements for selected spaces in medical facilities [4].

Space	T °F	T °C	RH, %
Class B and C operating rooms	68-75	20-24	30 to 60
Operating/surgical cystoscopy rooms	68-75	20-24	30 to 60
Delivery room	68-75	20-24	30 to 60
Critical and intensive care	70-75	21-24	30 to 60
Wound intensive care (bum unit)	70-75	21-24	40 to 60
Radiology	70-75	21-24	Max 60
Class A operating/procedure room	70-75	21-24	20 to 60
X-ray (surgery/critical care and catheterization)	70-75	21-24	Max 60
Pharmacy	70-72	21-22	Max 60

The environmental conditions (temperature and humidity) maintained in indoor spaces determine not only the comfort of the occupants of those spaces but also the long-term condition of the building itself. Historically, only the dry bulb temperature (DBT) of indoor spaces was controlled to achieve comfortable indoor conditions for the occupants. Little attention was given to control of moisture/humidity in the spaces. As a result, many existing Army buildings have exhibited mold/mildew problems.

Arctic buildings. Eliminating mold growth from surfaces of buildings requires year-round control of both the DBT and the DP temperature (or air RH) in the indoor spaces in hot/humid climates. In arctic climates, even those humidified up to 30% RH indoors should not exhibit mold problems given the low temperature and vapor pressure outdoors. Preliminary transient hygrothermal analysis (done as a part of preparation of the Guide [5]) of common arctic building wall and roof assemblies shows no risk of mold growth except for atypical assemblies. The use of low-permeance insulating materials in wall and roof assemblies presents strong assurance of good moisture performance.

Temperature may be set back in arctic buildings during short- and long-term periods, provided measures are taken to prevent pipe bursting. See below. This may require keeping the interior of the building heated to 50 °F (10 °C). Setting back temperature does not present a mold risk in arctic climates. Of course, outdoor air to the building should be shut off during unoccupied periods.

It is important that designers and O&M personnel design and maintain the building and heating, ventilating, and air-conditioning (HVAC) systems to satisfy all three categories of requirements. In most of cases, thermal comfort requirements satisfy the process. Preventing moisture-related problems requires special attention to the design and building operation. Energy conservation should not be achieved at expense of health, occupant's wellbeing, and building sustainability. Certain strategies and technologies can minimize or eliminate premium energy use.

3 Emergency (black sky) operating conditions

Depending on the emergency situation, the objective for any mission critical area of the given building is to maintain mission critical operations as long as it is necessary or technically possible. As for other, noncritical building areas and standalone buildings, the objective is to minimize the damage to the asset. It is assumed that building processes will be kept operational only in mission critical areas and non-mission critical activities will be discontinued. In the mission critical areas/buildings, operations will continue, and processes will require people with critical skills and thought processes. While under normal circumstances, building environmental controls are designed and operated to create a thermoneutral environment conducive to optimal employee thermal environment discussed in the section under blue sky operating condition. However, should the building environmental controls fail for any reason, the thermal environment may change in such a way as to no longer be optimal for workers needing their critical skills to perform their jobs. The section below describes threshold indoor environmental conditions beyond which human physical and mental skills can no longer be maintained.

Under black sky operations, efforts should be made to maintain thermal environment to prevent significant damage to both mission critical and non-mission critical buildings before they can be returned back to their normal operation. This may include reduction of ventilation requirements; control of maximum humidity levels using a available technologies with minimum fuel consumption; allowing maximum daylight; keeping plug loads on and lowering lighting levels; in cooling constraint conditions, use window shades to minimize solar gains, reduce plug loads, and keep lighting at a minimum level.

Threshold Conditions for Human Environment.

While cold and hot stress environmental conditions are well defined for jobs performed outdoors [6,7,8], there is not much information available for such conditions when jobs are performed indoors. This section addresses the potential thermal "inflection point" when the person can no longer physiologically and behaviorally compensate for the thermal stress while on the job based on the following assumptions and considerations:

1. The building environmental control systems fail and cannot be restored over a period of hours to days.
2. The occupants of the building must stay in that building to perform their jobs (i.e., cannot leave to move to more comfortable conditions).
3. The building occupants do not have access to clothing that can provide anything more than minimal protection against either cold or hot conditions (at most a clothing insulation of $Clo \leq 1.0$).
4. The building occupants are generally healthy with the normal physiological responses to deviations in environmental conditions.
5. The workers remain inside the building and perform minimal physical work (nearly at rest, the energy generated inside the body due to metabolic activity 1.2-1.5 met). At this minimal workload, the metabolic heat produced will be minimal (slightly above that produced at rest).
6. Factors such as convection and direct radiation from the sun will be considered negligible.
7. Air movement in the building occupied zone is below 0.7 ft/min (0.2 m)/min and, as such, there is little convective heat transfer.
8. Building is lit using either fluorescent, or LED lighting, which results in a negligible radiant heat from lighting fixtures.
9. The building environmental conditions will be affected as a result of the function of the HVAC system in an indoor setting, and that the environmental stressors are the dry air temperature (dry bulb or T_{db}) and humidity or wet bulb temperature (T_{wb}) with other environmental factors such as air velocity and radiant heat being negligible.

Humans have evolved the ability to maintain a stable internal (core) temperature (T_{core}) in the face of environmental thermal extremes through physiological, biophysical, and behavioral means. Maintenance of a stable T_{core} involves a tight balance between heat gain and heat loss to the environment during exposure to either cold or hot environments. A detailed discussion of the physiological and behavioral responses to thermal extremes is beyond the scope of the present work. However, note that, although there are strong physiological and behavioral mechanisms for maintaining T_{core} , these can be overcome under severe thermal stress – especially if that thermal burden is prolonged.

The physiological responses, and the rate and magnitude that they occur, will depend on the rate and magnitude of the change in the environmental temperature and, to a greater (hot temperature) or lesser (cold temperature) extent, the RH of the air. The rate of change in the building environment in which environmental controls have failed will depend on the insulating properties of the building, i.e., the rate and magnitude of the change in temperature and RH. The physiological responses will also depend to a large extent on the degree of personal insulation (clothing) the

worker must wear to protect against the decrease in environmental temperature.

A “normal” core body temperature, T_{core} , is considered to be 98.6 °F (37 °C). It is at this temperature that optimal physiological function occurs. The physiological consequences (i.e., ΔT_{core}) from a decrease or an increase in environmental temperature can be severe. If the physiological responses to environmental temperature changes (and the ability to maintain T_{core}) are unsuccessful, then T_{core} will change (either decrease or increase); if the change is large enough, then normal function will be compromised. For example, a T_{core} of 96.8 °F (37 °C) is considered the onset of hypothermia. At $T_{core} < 95$ °F (35 °C) one becomes symptomatic (see Table 3). The physiological responses to environmental heat are an increase in blood flow to the skin and sweating, which serve to transfer heat to the environment. These responses are more successful in maintaining T_{core} in an environment with low humidity and a high capacity to accept moisture (T_{db}). If there is an increase in T_{wb} (increased RH), then sweat evaporation is reduced and a potential for an increase in T_{core} occurs. Hyperthermia occurs when T_{core} is > 100.4 °F (> 38 °C). This is normally tolerable, and the person can continue to perform well. However, as the T_{core} increases beyond 100.4 °F (38 °C), the ability to perform work begins to be compromised. Physiological/psychological signs and symptoms of hyperthermia are listed below:

- Extreme discomfort
- Numbness (tactile sensitivity, manual dexterity decreases)
- Shivering
- Skin vasoconstriction (blanching)
- Cold that becomes a distraction
- Muscle stiffness
- Cognitive changes (confusion, apathy, loss of attention, reduced memory capacity, etc.)
- Loss of sensory information (blurred vision)
- Cardiovascular effects
- Loss of consciousness.

It is important to understand that probably the first line of defense against cold is clothing that creates an insulative layer that protects the humans from cold environments. With this strategy, a human being may perform activities in a cold (41 °F [5 °C]) environment but be “exposed” to a microenvironment (the layer of air that exists between the surface of the skin and the inner surface of the clothing) that is the equivalent to a mild temperature (~71.60 °F [~22 °C]). Nevertheless, working in cold environments has demonstrable effects on humans even if wearing relatively warm clothing. Early studies of the thermal effects on human performance [9,10] focused on the frequency of industrial accidents that could be related to ambient temperature. The rate of industrial accidents could be described as a “U” curve in that the lowest frequency of accidents occurred at a temperature of ~68 °F (~20 °C) and increased as the ambient temperature either decreased or increased from 68 °F (20 °C). The

frequency of industrial accidents increased to almost 140% as the temperature decreased from 68 °F to ~50 °F (20 °C to ~10 °C) indicating cold temperatures had a significant effect on worker ability to perform their tasks safely. The decline in manual dexterity begins at a T_{sk} of 53.1 °F – 60.1 °F (12 °C–16 °C). Tactile sensitivity declines steeply below 46 °F (8 °C). This may severely limit the use of computers and other equipment that requires the use of both manual dexterity and tactile sensitivity. Similar loss of cognitive function and manual dexterity occurred in hot environments as well (starting at a T_{core} of >98.1 °F (>39 °C)).

Thermal discomfort often becomes a distraction to the person experiencing it and, hence can affect performance or the so-called “time of task” or time spent not working but addressing the thermal discomfort. The degree of distraction is affected by whether the person can leave the environment or somehow change the environment (changing a thermostat setting) to improve the thermal comfort. If the person has no control over an uncomfortable thermal environment, the degree of distraction or time off task will increase. The distraction occurs as the result of a physiological change, e.g., decrease or increase in T_{sk} , which then results in the focus of attention on that change rather than on the task before them. Distraction is also modulated by motivation such that a more strongly motivated person may be less distracted by cold stimulus than a less motivated person exposed to the same stimulus. In addition, if the person exposed to a cold stimulus perceives that they have no control over the environment and the consequence of not performing the work is high enough, then the cold environment will be less distracting from the necessary work. As can be seen from the previous discussion, the issue of distraction on cognition and job performance is complex.

Therefore, in emergency situations, reduction of indoor air temperature in spaces with mission critical buildings operation below 60.8 °F (16 °C) [8] and increase in Wet Bulb Globe Temperature (WBGT) above 87.8 °F (31 °C [6]) is not recommended since it will impair performance of mission operators.

Arctic Buildings under Emergency Conditions.

Mold growth. Arctic climates present low risk of mold growth on building surfaces. Mold does not grow at low temperatures. In addition, arctic outdoor vapor pressures are very low, so without humidification, indoor RH will be quite low. Mold growth depends greatly on the sensitivity of a surface to growth, and surfaces made of organic materials such as wood products and paper facings present the sole possibilities in arctic climates—not metal, concrete, or masonry. Preliminary modeling studies, using humidification at 30%, in U.S. DoE climate zones 6, 7, and 8, show surface RH remaining at 65% or below, while mold require surface RH above 85% in most cases.

Aside from water problems associated with roof or plumbing leaks, the greatest risk of mold growth may be from cold thermal bridges in humidified buildings. Thermal bridges may be identified using infrared (IR) thermography. Typically, in a well-insulated building the coldest surface facing the interior will be the window

surface. It is unlikely that interior temperatures at thermal bridges will be lower than the window surface temperature. Consequently, in an arctic building, the risk of interior mold growth is negligible in a building that shows no window condensation, and the presence of window condensation indicates the importance of lowering the indoor humidification.

In arctic climates, if building climate control is suspended in the short or long term, then mold growth is unlikely to occur. Normally, downward drift of temperature will occur with suspension of the operation of the air handler. This means that the indoor air temperature will decline as a function of the outdoor air temperature, the thermal insulation, the airtightness of the building, and the heat storage by the contents of the building. Also, during a heating period, the outdoor absolute humidity will be lower than the indoor absolute humidity, so it will drift downward at a rate governed primarily by the airtightness of the envelope.

Under most conditions, the downward drift of absolute humidity will be much more rapid than the downward drift of DBT, and as a consequence, the indoor RH will be low during the drift period. The downward drift of absolute humidity is considered rapid because, with each air change, assuming full mixing, the absolute humidity difference between indoors and out, is halved. Absolute humidity equilibrium with outdoors would be achieved in a matter of hours. The downward drift of temperature would be relatively slow given the low heat content of air, the thermal resistance in the envelope, and the heat storage in interior materials. It would be measured typically in days.

Modeling has provided preliminary estimates of the temperature decay rate of arctic buildings in case of a utility interruption. For a building with a average thermal resistance of R-20 (all sides), with an air tightness of 0.25 cfm (0.0001 m³/s) per 75 sq ft (7 m²), and which contains, in envelope and contents, 100 lb/sq ft (0.05 kg/cm²) of envelope, the decay half-life is approximately 1 week. By doubling the thermal resistance or the mass of contents, or by halving the air leakage, the half-life is doubled to 2 weeks. By halving the thermal resistance or the content mass, or by doubling the air leakage measure, the half-life of temperature decay is reduced to 3 to 4 days. Of course, different parts of the building will perform differently.

Pipe Burst Protection. In cold and arctic climates, hydronic heating systems typically use a glycol/water solution as the heating system fluid [11]. To reduce the risk of freezing of water pipes or wet sprinkler systems, pipes should be located in interior walls or plumbing chases. Pipes in exterior walls should be avoided. However, in the emergency situation when heat supply to the building is interrupted, the indoor air temperature can drop significantly. Research at the University of Illinois [12] has illustrated the mechanism by which water pipes burst when surrounded by cold temperatures. Cold air temperatures cause the temperature of water in pipes to decline. Water temperature may decline below 32 °F (0 °C), often to 25 °F (–4 °C). With continued cold temperatures, ice nucleates in the water, raising the temperature of the

two-phase mix to 32 °F (0 °C). With continued cold temperatures, ice begins to grow on the pipe wall, growing inward; the rate of ice growth depends on several factors such as air temperature, pipe thermal conductivity, water circulation, and effect of the air film surrounding the pipe. Through this entire process, before the formation of blockage, the pipe system is not put at risk, and with rising air temperatures the system will recover to the original condition with no ill effects.

If the ice grows inward to the point of blockage, then water pressure effects become important. The blockage can grow along the length of the pipe and act like a piston. Piston action toward the water source will generally have no ill effect, in the absence of a backflow preventer. But piston action toward the remaining liquid water confined downstream will cause the water pressure to rise. Pipe rupture or fitting failure will occur once the water pressure reaches a sufficiently high level.

There are several means to prevent pipe bursting due to freezing:

1. Avoid subzero air temperatures at the pipe.
2. Drain the water from the pipe system. Compressed air may be used for systems that do not drain entirely by gravity.
3. Provide pressure relief at any at-risk portion of the pipe system. A single pressure relief valve is usually sufficient to protect a clustered fixture group. A ballcock assembly in a typical toilet serves as a pressure relief device (which explains the greater likelihood of hot water rupture during freeze events).
4. Provide air expansion (using water hammer arresters for example) to protect piping systems where the slight water leakage from pressure relief valves is undesirable, such as in wet fire suppression systems.

It is particularly important to avoid individual sites of particularly cold temperature along the pipe length, as these are preferred sites for blockage to initiate. Such sites will occur at interruptions in pipe insulation (often at fittings such as elbows) and at air leaks in the envelope, where moving air can reduce the air film thermal resistance.

4 Thermal requirements for unoccupied spaces

Requirements for temperatures and RH discussed above are developed for occupied spaces (Table 3). Many buildings are not occupied at night or on weekends. Some military facilities including barracks, administrative buildings, and dining facilities may be unoccupied for an extended period of time due to training and deployment. So, one energy conservation strategy may be to set back temperatures for heating or set up for cooling. One source of guidance on set back or set up temperatures is ANSI/ASHRAE/IESNA Standard 90.1 *Energy Standard for Buildings Except Low-Rise Residential Buildings* [13]. This Standard does not regulate thermostat setbacks or setups, but it does regulate the capabilities of thermostats installed in

buildings. Section 6.4.3.3.2 of Standard 90.1, Setback Controls, requires that heating systems in all parts of the United States outside of Miami, FL and the tropical islands (that is, climate zones 2-8) must have a capability to be set back to 55 °F (13 °C). Heating systems in zone 1 are assumed to have minimal usage and therefore no need of setbacks. Cooling systems in hot dry areas (zones 1b, 2b, and 3b) must have the capability to be set up to 90 °F (32 °C). However, cooling systems in hot and humid climates (zones 1a, 2a, and 3a) are not required to have cooling setbacks due to potential for moisture problems. It is wasteful to cool facilities left unoccupied for an extended period of time, which are located in hot and humid climates. Significant energy savings can be achieved without damage to building materials and furnishings if a combination of measures related to the building envelope and HVAC maintain the requirements for all the air inside the building.

Table 3. Requirements of DBT and RH for occupied and unoccupied facilities to reduce the risk of moisture-related problems.

Occupancy/Use	DP (Setpoint) Not To Exceed	Maximum Dry Bulb Temp (Setpoint)	Minimum Dry Bulb Temp (Setpoint)
Occupied	61 °F (15.6 °C)	75 °F (24 °C)	70 °F (21 °C)
Unoccupied (Short term)	61 °F (15.6 °C)	85 °F (29 °C)	55 °F (13 °C)
Unoccupied (Long term)	61 °F (15.6 °C)	No Max	40 °F (4 °C)
Critical Equipment	61 °F (15.6 °C) or equip requirement if less	Equip max allowed	Equip min allowed

5 Conclusion

Requirements for thermal environmental condition in buildings are set to achieve the following purposes:

- To perform the required work in a building in a safe and efficient manner,
- To support processes housed in the building, and
- To provide conditions required for a long-term integrity of the building and building materials.

Buildings are designed to meet these three sets of requirements in normal (blue sky) operating condition. Thermal comfort requirements are defined by ASHRAE Standard 55. Different processes housed in the building (e.g., spaces with IT and Communications equipment, critical hospital areas, industrial process [painting, printing, etc.]) may have broader or narrower ranges for air temperature and RH, than those for human comfort. In normal operation conditions, environmental requirements based on sustainability of building envelope assemblies and furnishings are not a limiting factor given that the building envelope air barrier and vapor protection are designed to avoid mold growth and water accumulation within the building assembly (for cold and arctic climates requirements to the building envelope see [5]).

During an emergency situation (black sky), requirements of thermal parameters for different categories of buildings or even parts of the building may change. When normal heating, cooling, and humidity control systems operation is limited or not available, mission critical areas can be conditioned to the level of thermal parameters required for supporting a agility of personnel performing mission critical operations, but not to the level of their optimal comfort conditions. Beyond these threshold (habitable) levels, effective execution of a critical mission is not possible and mission operators have to be moved into a different location. These threshold limits of thermal parameters may be in a broader range compared to that required for thermal comfort, but not to exceed levels of heat and cold stress thresholds: in a heating mode, air temperature in spaces with mission critical operations should be maintained above 60.8 °F (16 °C) [8], and in a cooling mode, the Wet Bulb Global Temperature should be below 87.8 °F (31 °C [6]).

Special process requirements (e.g., with IT and communication equipment, critical hospital spaces, etc.) should be given a priority if they are more stringent. Broader ranges of air temperatures and humidity levels in building spaces surrounding mission critical areas may be used, but they need to be limited to prevent excessive thermal losses/gains and moisture transfer through walls and apertures not designed with thermal and air/vapor barriers.

In arctic climates, building envelope assemblies are not a limiting factor regarding how indoor climate needs to be maintained during short- or long-term outages of indoor climate control, unless water piping cannot be drained or otherwise protected against freezing.

In cases where utility supply is interrupted and the building air handler is disabled, the indoor temperature will decay to the outdoor temperature. The rate of decay has been field tested and modeled [14,15]; results show that the time it takes for indoor air temperature to reach a threshold (habitable) level or a building sustainability level will range from a few hours to several days depending on thermal resistance, airtightness, and the mass of the building envelope and contents in the building.

To avoid water damage to building materials and furnishings in cold and arctic climates, DBT should exceed 40 °F (4.4 °C) where water piping is at risk.

Finally, noncritical standalone buildings can be hibernated, but necessary measures should be taken, and the thermal environment should be maintained, when possible, to prevent significant damage to these buildings before they can be returned back to their normal operation.

References

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), *Thermal Environmental Conditions for Human Occupancy*, ASHRAE Standard 55, Atlanta, GA: ASHRAE, 2017.

- [2] ASHRAE, *Design Considerations for Datacom Equipment Centers*, ASHRAE Datacom Series Atlanta, GA: ASHRAE, 2005.
- [3] NFPA 99. 2018. Health Care Facilities Code. National Fire Protection Association.
- [4] ASHRAE, "HVAC applications," *ASHRAE Handbook*, Atlanta, GA: ASHRAE, 2019.
- [5] Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates. 2021. Editor: Alexander Zhivov. ERDC.
- [6] American Conference of Governmental Industrial Hygienists (ACGIH), *Heat Stress and Strain: TLV(R) Physical Agents*, 7th ed., Cincinnati, OH: ACGIH, 2017.
- [7] National Institute for Occupational Safety and Health (NIOSH), *Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments*, DHHS (NIOSH) Publication Number 2016-106, Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 2016.
- [8] American Conference of Governmental Industrial Hygienists (ACGIH), *Cold Stress: TLV(R) Physical Agents*, 7th ed. Cincinnati, OH: ACGIH, 2018.
- [9] E. C. Winfield, R. J. Rader, A. M. Zhivov, T. A. Adams, A. Dyrelund, C. Fredeen, O. Gudmundsson, B. Goering, Best "Practices for HVAC, plumbing, and heat supply in arctic climates," *ASHRAE Trans.*, vol. 127, Part 1, 2021.
- [10] Jeffrey R. Gordon. 1996. An Investigation into Freezing and Bursting Water Pipes in Residential Construction. Building Research Council Publication. <https://www.ideals.illinois.edu/handle/2142/54757>
- [11] K. C. Parsons, Thermal Comfort. In: Parsons KC (Editor), *Human Thermal Environments: The effects of hot, moderate, and cold environments on human health, comfort, and performance*, 2d ed., London, UK: Taylor & Francis, 2003, pp. 198-228.
- [12] P. Wargocki and D. P. Wyon, "Ten questions concerning thermal and indoor air quality on the performance of office work and schoolwork." *Building and Environment*, vol. 112, pp. 359-366, 2017.
- [13] ASHRAE, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, ASHRAE Standard 90.1, Atlanta, GA: ASHRAE, 2004.
- [14] B. K. Oberg, A. Urban, E. Leffel, J. Goebel, M. Perry, D. Vas, D. Broderson, R. Liesen, and A. Zhivov, "Thermal energy system resilience: thermal decay test (TDT) in cold/arctic climates, Part I: Data collection and protocol," *ASHRAE Trans.*, vol. 127, no. 1, 2021.
- [15] R. Liesen, B. Morton, and B. Diggs-McGee, "Thermal energy system resilience: Thermal decay test (TDT) in cold/arctic climates, Part II modeling" *ASHRAE Trans.*, vol. 127, no. 1, 2021.

© 2021. This work is licensed under
<https://creativecommons.org/licenses/by/4.0/> (the “License”).
Notwithstanding the ProQuest Terms and conditions, you may use this
content in accordance with the terms of the License.