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Requirements for Building Thermal Conditions under Normal and Emergency Operations in Extreme Climates

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Abstract

This paper provides recommendations on thermal and moisture parameters (air, temperature, and humidity content) in different types of buildings under normal and emergency operation conditions in extreme climate conditions, e.g., cold/arctic (U.S. Department of Energy [DOE] climate zones 6–8) and hot and humid (DOE climate zones 0–2a). Three scenarios are considered under normal operating conditions: when the building/space is occupied, temporarily unoccupied (2–5 days), and unoccupied long term (e.g., hibernated). These thermal parameters are necessary to achieve one or several of the following purposes:

- to perform 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.

Many emergency conditions may occur during the life of a building. This paper considers the emergency conditions of the interruption of fuel, steam, hot or chilled water, and electrical service leading to the interruption of space-conditioning for the building.

Information provided in this paper was developed for military applications (that include a variety of building archetypes) and was based on research performed under the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC) Annex 73, which focuses on the development of guidelines and tools that support the planning of net zero energy resilient public communities (IEA 2020); research performed under the Department of Defense Environmental Security Technology Certification Program project EW18-D1-5281, "Technologies Integration to Achieve Resilient, Low-Energy Military Installations"; and research performed under the Office of the Deputy Assistant Secretary of the Army project "Thermal Energy Systems Resiliency for Army Installations Located

in Cold Climates.” Note that results of this research are applicable to similar public- and private-sector buildings.

INTRODUCTION

During an emergency situation, requirements of thermal parameters for different categories of buildings or even parts of buildings 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 to a different location. These threshold limits of thermal parameters may be in a broader range compared to those required for thermal comfort, but should not exceed levels of heat and cold stress thresholds. However, special process requirements (e.g., for information technology [IT] and communication equipment, critical hospital spaces, etc.) should be given 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, air, or 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.

NORMAL OPERATING CONDITIONS (BLUE SKY)

Under normal operating conditions, for any given building, factors such as building envelope insulation and airtightness, ventilation rates, thermostat set points, plug loads, and lighting levels have significant impacts 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 set points 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 set points 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.

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 ANSI/ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017b).

The following dry-bulb room air temperatures (DBTs) and relative humidity (RH) values (ERDC 2010) are within the ASHRAE Standard 55 range and should not be exceeded: •

- *Cooling Period:* The DBT in occupied spaces should not be set below 70°F (21°C) with the RH maintained below 60%. When the space is unoccupied during a short period of time, the room thermostat should be reset to 85°F (29°C) with the RH maintained below 70%. In spaces unoccupied for extended periods of time, temperature should not be controlled but the building air RH should be maintained at 70%
- *Heating Period:* The RH of all building air should be maintained below 50% and above 30% at all times (unless required differently for health reasons at hospitals or daycare facilities or required by processes). Below are examples of DBTs in occupied spaces that should not be exceeded:
- Barracks and other living quarters: 70°F (21°C) Monday through Friday from 0500 to 2200 and 65°F (18.3°C) from 2200 to 0500 and 70°F (21°C) Saturday and Sunday from 0600 to 2200 and 65°F (18.3°C) from 2200 to 0600.
- Offices, warehouses, etc., where personnel work seated or in standing positions involving little or no exercise: 70°F (21°C) during working hours and not more than 55°F (12.8°C) during nonworking hours.
- Childcare facilities: 72°F (22.2°C) during working hours.

When a space is unoccupied during a short period of time, the room thermostat should be set back to 55°F (12.8°C). In spaces unoccupied for extended periods of time, temperature should be controlled at 40°F (4.4°C).

Process-related criteria include the temperature and humidity needed to perform the process housed in the building (e.g., in spaces with IT and communications equipment, critical hospital areas, 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.

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 the type of equipment or the manufacturers. According to ASHRAE (2009), there are six standard classes of thermal requirements:

- *Class A1.* Typically a datacom facility with tightly controlled environmental parameters (dew point [DP], temperature, and RH) and mission-critical operations, including those housing servers and data storage.
- *Class A2/A3/A4.* Typically a building or space that houses the types of products designed for use in IT spaces with some control of environmental parameters (DP, temperature, and RH), including 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.
- *Class B.* Typically an office, home, or transportable environment with 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.

Classes A3 and A4 do not have special requirements to be considered.

In addition to the four classes of requirements for IT and communications equipment facilities discussed above (classes A1 through A4), 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.

There are also indoor air thermal requirements for health-care facilities. Per NFPA 99, Health Care Facilities Code (2021), health-care facilities 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 regular (blue sky) operations and does not pertain to facilities designated as health-care facilities only during declared local or national disasters. Patient care spaces in health-care facilities are described using the following four categories (NFPA 2021):

- *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 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 (ASHRAE 2017a) for thermal environments in spaces included in categories 1 and 2 are listed in Table 2.

Army guidelines (ERDC 2010) provide the following recommendations for space air temperatures for industrial spaces during heating periods:

- Issue and similar rooms: 60°F (15.5°C).
- Special process rooms, such as paint shops and drying rooms: 80°F (26.6°C) allowed, or that required by the process.
- Shops, hangars, and other buildings where employees work in a standing position or exercise moderately, such as sorting or light packing/crating: 60°F (15.5°C) during the day, 40°F (4.4°C) during nighttime.
- Shops, warehouses, and the like, where employees do work involving considerable exercise, such as foundries; heavy packing, crating, and stacking; or where heat is required to protect material or installed equipment from freezing: 40°F (4.4°C). *Exception:* Localized heat, not to exceed 55°F (13°C), may be furnished in areas where the work requires medium or light personnel activity.
- Heat is not permitted in warehouse areas that do not contain materials or equipment requiring protection from freezing or condensation and where warehousing of stored goods is the only operation. Heat for the prevention of condensation on stored machinery and material should be supplied after a thorough survey of all conditions and the approval of managers.
- Buildings other than those specified above should not be heated to temperatures higher than 65°F (18°C) without approval (in writing) from managers.

The environmental conditions (temperature and humidity) maintained in indoor spaces determines not only the comfort of the occupants of those spaces but also the long-term condition of the building itself. Historically, only the DBT of indoor spaces was controlled to achieve comfortable indoor conditions for 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. Our preliminary transient hygrothermal analysis of common arctic building wall and roof assemblies shows no risk of mold growth except for atypical unwise assemblies. The use of low-permeance insulating materials in wall and roof assemblies presents strong assurance of good moisture performance.

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

Buildings in Hot/Humid Climates

There are many conditions enabling mold growth on interior building surfaces in hot/humid climates. Experience has shown that when buildings were constructed without attention to airtightness, with indoor air pressures negative, and with vinyl wall coverings, mold growth on the back side of the interior wallboard was widespread. This condition was recognized and remedied in practice. Under normal condition, with indoor humidity maintained below 70%, mold growth should not occur on interior building surfaces. Temperature setback for the short and long term should be done carefully. Indoor humidity should not be allowed to rise above 70%. In particular, short-cycling of direct expansion (DX) units should be avoided. (Short-cycling allows lowered cooling loads to be met with little or no humidity removal.)

Mold growth occurs in buildings even with moderate average air RH when cold spots exist on poorly insulated supply air ducts and chilled-water pipes or supply air diffusers, on building envelope elements that are poorly insulated and not airtight, on areas with thermal bridges, etc. Careful design and operation of the building envelope and the heating, ventilating, and air-conditioning (HVAC) and exhaust systems is required to eliminate the potential for mold growth in Army buildings. Controlling all the air inside the building above the DP will reduce potential moisture-related problems. According to *Humidity Control Design Guide for Commercial and Institutional Buildings* (Harriman et al., 2001), the suggested DP limits that meet both health and mold problem requirements are <57°F (14°C) in summer and >35°F (2°C) in winter.

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

EMERGENCY OPERATING CONDITIONS (BLACK SKY)

Depending on the emergency situation, the objective for any mission-critical area of a given building is to maintain mission-critical operations as long as it is necessary or technically possible. 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 in mission-critical areas only and that nonmission 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. Under normal circumstances, building environmental controls are designed and operated to create a thermoneutral environment conducive to an optimal employee thermal environment as discussed in the section on blue sky operating conditions. However, should building environmental controls fail for any reason, the thermal environment may change in such a way as to no longer be optimal for workers with the critical skills necessary to perform their jobs. The following subsection 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 the 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 available technologies with a minimum fuel consumption, allowing maximum daylight, keeping plug loads on, and lowering lighting levels or, in cooling constraint conditions, using 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 (NIOSH 2016: ACGIH 2001; ACGIH 2018), there is not much information available for such conditions when jobs are performed indoors. This subsection addresses the potential thermal “inflection point,” i.e., when a person can no longer physiologically and behaviorally compensate for the thermal stress while on the job, based on the following assumptions and conditions:

- The building environmental control systems fail and cannot be restored over a period of hours to days.
- The occupants of the building must stay in that building to perform their jobs (i.e., cannot leave to move to more comfortable conditions).
- 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 clo ≤1.0).
- The building occupants are generally healthy, with typical physiological responses to deviations in environmental conditions.
- The workers remain inside the building and perform minimal physical work (nearly at rest, 1.2–1.5 met). At this minimal workload, the metabolic heat produced will be minimal (slightly above that produced at rest).
- Factors such as convection and direct radiation from the sun are considered negligible.
- 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.
- Building is lit using either fluorescent or light-emitting diode (LED) lighting, which results in a negligible radiant heat from lighting fixtures.
- The building environmental conditions will be affected as a result of the function of the HVAC system in an indoor setting, and 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.

Background.—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 this 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.

Physiological Response.—The physiological responses to thermal stress, and the rate and magnitude at which 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 a building environment in which environmental controls have failed depends 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 has to protect against a 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 (36°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 the 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 person's ability to perform work begins to be compromised. Table 3 lists some of the symptoms of hyperthermia.

It is important to understand that probably the first line of defense against cold is clothing that creates an insulative layer that protects 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 (~71.6°F [~22°C]). Nevertheless, working in cold environments has demonstrable effects on humans even if they are wearing relatively warm clothing. Early studies of the thermal effects on human performance 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 workers’ ability to perform their tasks safely. The decline in manual dexterity begins at a T_{sk} of 53.6°F to 60.8°F (12°C to 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 >98.6°F (>37°C).

Thermal discomfort often becomes a distraction to the person experiencing it and hence can affect performance or the so-called “time off task,” or the 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 (e.g., change 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 itself. 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.

A compilation of the effects of temperature resulting in the decline in the ability to perform light work (1.2 met) while wearing light clothing (0.6 clo) is described in detail by Parsons (2003) and Wargocki and Wyon (2017). Briefly, this literature indicates that when indoor temperature decreases from 60.1°F to 51°F (16°C to 10°C), the rate of accidents increase sharply by 40%, manual dexterity rapidly declines by 20%, and speed and sensitivity of fingers decline by 50%—all of which suggests that the ability of workers to perform critical tasks is significantly impaired at temperatures below 60.8°F (16°C). Conversely, for workers performing sedentary work (1 met) while wearing normal indoor clothing (1.0 clo), as the ambient temperature increased from ~75°F to 77°F (24°C to 25°C), the rate of accidents rose sharply by 50%. In addition, as the ambient temperature increased from 68°F to 86°F (20°C to 30°C), mental performance decreased by 40% and, finally, as the ambient temperature increased from 61°F to 80.1°F (20°C to 27°C), the work rate declined sharply (by 55%). These data show that the ambient temperature is capable of significantly affecting the ability of workers to perform tasks if the exposure lasts long enough.

Therefore, in emergency situations, reduction of indoor air temperatures in spaces with mission-critical operations below 60.8°F (16°C) (ACGIH 2018) and an increase in wet-bulb globe temperature (WBGT) above 87.8°F (31°C) (ACGIH 2017) is not recommended because it will impair the performance of mission operators.

Arctic Buildings under Emergency Conditions

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 climate zones 6, 7, and 8, show surface RH remaining at 65% or below, whereas mold requires surface RH above 85% in most cases.

Aside from water problems associated with roof or plumbing leaks, the greatest risk of mold growth in arctic buildings 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 outdoors is halved. Absolute humidity equilibrium with the 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.

Our modeling provided preliminary estimates of the temperature decay rate of arctic buildings in case of a utility interruption. For a building with an average thermal resistance of R-20 (all sides), with an airtightness of 0.25 cfm per 75 ft^2 (0.0001 m^3/s per 7 m^2), and which contains, in envelope and contents, 100 lb/ft^2 (0.05 kg/cm^2) 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 (Winfield et al. 2021). 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 an emergency situation where heat supply to the building is interrupted, the indoor air temperature can drop significantly. Research at the University of Illinois 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 the effect of the air film surrounding the pipe. Through this entire process, prior to 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 inside the pipe 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:

- Avoid subzero air temperatures at the pipe.
- Drain the water from the pipe system. Compressed air may be used for systems that do not drain entirely by gravity.
- 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).
- 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 ideal 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.

Buildings in Hot/Humid Climates under Emergency Conditions

Mold growth is more widespread on building surfaces in hot/humid climates than in cold climates because mechanical cooling may chill surfaces to temperatures close to the DP of the indoor air. Therefore surfaces, rather than air, must become the focus of any understanding of mold growth and the attendant health risks.

Mold only grows on surfaces that retain sufficient moisture over time. But not all moisture is equally available to support mold growth. In some materials, moisture is tightly bound to the surface and cannot be used by mold. In other materials, the moisture is easily accessed to support microbial growth. The most reliable moisture-related metric that governs growth is the surface water activity, or the equilibrium relative humidity (ERH) at the surface of the material in question. Water activity can also be described as a measurement of the bioavailability of moisture in a material. It is in fact a measurement of the difference in water vapor pressure between the fungal cell and the moisture in the surface on which it is located. Therefore, criteria should focus on the more reliable risk indicator of surface water activity.

For most building professionals, the term *water activity* will be new and unfamiliar. The confusion comes from the assumption that RH in the air is the same as RH at the surface. Therefore, a short explanation is needed to clear up the confusion built up over the last 40 years about the relationship between RH, moisture content, and microbial (mold) growth risk.

The greater the mass of water vapor in the air, the greater the risk of absorption and persistent dampness when surfaces become cool. The indoor air DP is a reliable measurement of the mass of water vapor available for absorption and therefore potentially available to support microbial growth.

The RH in the air is rarely the same as the RH at the surface. This is particularly true near cold supply air diffusers. In buildings, the indoor DP stays high over months whenever AC systems are turned off. The persistent high DP allows excessive moisture absorption and mold growth on the surfaces of acoustic ceiling tiles near supply air diffusers. Keeping the indoor DP below 60°F (15.6°C) greatly reduces the amount of indoor humidity available to support mold growth. This maximum is a design requirement for systems in mechanically cooled buildings (ASHRAE 2019a).

To model the effect of an emergency shutdown of air-handling equipment in a building in a hot/humid climate, it is first necessary to select the extreme DP outdoor conditions. The DP at extreme outdoor conditions in hot/humid climates within the continental United States is below 80%, which is the critical surface ERH for the onset of mold growth on most building materials. So the building goes from a mold-safe indoor ERH and decays to a mold-growth ERH. The decay process itself may contain conditions for mold growth, however. Infiltration may bring the indoor absolute humidity to the outdoor absolute humidity level in a matter of hours, but the indoor temperature will drift upward to the outdoor temperature in a matter of days. So for several days the building may see conditions of ERH well in excess of 80% and mold growth could be expected.

If the sole concern following a power or fuel outage was mold prevention on interior surfaces, one effective strategy would be to open the building as fully as possible to the outdoors so that the interior surfaces and contents were brought to outdoor temperatures as quickly as possible. However, other concerns such as continued use of the building following an outage or security may argue to keep it closed up. A more effective method to allow the building to come to outdoor conditions would be to provide auxiliary dehumidification or auxiliary heating. The aim for either of these strategies would be to keep the indoor DP below 60°F (15.6°C).

Thermal Requirements for Unoccupied Spaces

Requirements for temperature and RH discussed in previous sections have been developed for occupied spaces (Table 4). Many buildings are not occupied at night or on weekends. Some military facilities, including barracks, administrative buildings, and dining facilities, may be unoccupied for extended periods of time due to training and deployment. So, one energy-conservation strategy may be to set back temperatures for heating or set up temperatures for cooling. One source of guidance on set-back or set-up temperatures is ANSI/ASHRAE/IESNA Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2004). ANSI/ASHRAE/IESNA Standard 90.1-2007 does not regulate thermostat setbacks or setups, but it does regulate the capabilities of thermostats installed in buildings (ASHRAE 2007). Section 6.4.3.3.2 of Standard 90.1-2004, Setback Controls, requires that heating systems in all parts of the United States outside of Miami, Florida, 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 the potential for moisture problems. It is wasteful to cool facilities left unoccupied for an extended period of time 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.

CONCLUSION

Requirements for thermal environmental conditions 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
- To provide conditions required for the long-term integrity of the building and building materials

Buildings are designed to meet the thermal, thermal comfort and health, and process-related requirements under normal operating conditions. Thermal comfort requirements are defined by ASHRAE Standard 55 (2017b). Buildings with different processes (e.g., spaces with IT and communications equipment, critical hospital areas, painting, printing, etc.) may have broader or narrower air temperature and RH ranges than those for human comfort. Under 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 climate requirements for the building envelope, see Axelarris et al. [2021]).

During an emergency situation, requirements of thermal parameters for different categories of buildings or even parts of the building may change. When normal heating, cooling, and humidity control system operation is limited or not available, mission-critical areas can be conditioned to the level of thermal parameters required for supporting the agility of personnel performing mission-critical operation 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 should not 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) (ACGIH 2018), and in a cooling mode, the WBGT should be below 87.8°F (31°C) (ACGIH 2017).

Special process requirements (e.g., for 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 (Oberg et al. 2021; Liesen et al. 2021); 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.

In hot/humid climates, mold growth on interior surfaces is a serious risk with both short- and long-term interruption of climate control. Prevention of microbial growth requires maintaining the indoor DP temperature below 60°F (15.6°C), typically requiring the use of auxiliary equipment. Table 5 gives the indoor requirements to avoid damage to building materials and furnishings.

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 to their normal operation. Tables 6 through 9 summarize the recommendations for thermal environmental conditions for buildings located in cold and hot/humid climates for normal and emergency situations. Note that the recommendations for human comfort in normal operations with regards to maximum and minimum DBT and maximum DP are based on ASHRAE Standard 55 (2017b).

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Table 1.

Recommended and Allowable Conditions for Classes A1–A4 and NEBS Environments

Conditions	ClassA1/ClassA2 (ASHRAE 2019b)			NEBS (ASHRAE 2005)	
	Class	Allowable Level	Recommended Level	Allowable Level	Recommended Level
Temperature control range	A1	59°F to 89.6°F (15°C to 32°C)	64.4°F to 80.6°F (18°C to 27°C)	41°F to 104°F (5°C to 40°C)	65°F to 80°F (18°C to 27°C)
	A2	50°F to 95°F (10°C to 35°C)			
Maximum temperature rate of change	A1, A2	50°F/h (36°F/h)* (5°C/h [2.2°C/h])	—	2.9°F/h (1.6°C/h)	—
RH control range	A1	10.4°F (−12°C) DP and 8% RH to 62.6°F (17°C) DP and 80% RH	15.8°F to 59°F DP (−9°C to 15°C) DP and 60% RH	5% to 85% 82°F (28°C) max DP	Max 55%
	A2	10.4°F (−12°C) DP and 8% RH to 69.8°F (21°C) DP and 80% RH			

* 9°F/h (5°C/h) for tape storage, 36°F/h (2.2°C/h) for all other IT equipment and not more than 9°F (5°C) in any 15 min period of time.

Table 2.

Thermal Environment Requirements for Selected Spaces in Medical Facilities

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

Table 3.

Physiological/Psychological Signs and Symptoms of Thermal Strain (List Not Comprehensive)

Hypothermia (T_{core} <96.8°F [<36°C])	**Hyperthermia (T_{core} >100.4°F [>38°C])**
Extreme discomfort	Skin vasodilation (flushing)
Numbness (tactile sensitivity, manual dexterity decreases)	Sweating (>1 $L \cdot h^{-1}$ in the extreme)
Shivering	Dehydration (thirst not a good indicator of hydration status)
Skin vasoconstriction (blanching)	Eventual decrease in sweating (hidromeiosis)
Cold becomes a distraction	Increase in heart rate
Muscle stiffness	Fatigue (heat exhaustion)
Cognitive changes (confusion, apathy, loss of attention, reduced memory capacity, etc.)	Cognitive changes (decreased situational awareness, poor judgment)
Loss of sensory information (blurred vision)	Mental confusion
Cardiovascular effects	Behavioral changes
Loss of consciousness	Collapse—heat stroke

Table 4.

Requirements to DBT and RH for Occupied and Unoccupied Facilities to Reduce the Risk of Moisture-Related Problems

Occupancy/Use	DP (Set Point) Not to Exceed	Maximum Dry-Bulb Temperature (Set Point)	Minimum Dry-Bulb Temperature (Set Point)
Occupied	60°F (15.6°C)	75°F (24°C)	70°F (21°C)
Unoccupied (short term)	60°F (15.6°C)	85°F (29°C)	55°F (13°C)
Unoccupied (long term)	60°F (15.6°C)	No max	40°F (4°C)
Critical equipment	60°F (15.6°C) or equipment requirement if less	Equipment maximum allowed	Equipment minimum allowed

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Table 5.

Indoor Requirements to Avoid Damage to Building Materials and Furnishings

Arctic climate	≥40°F (≥4.4°C) dry bulb, where water piping is at risk
Hot/humid climate	≤60°F (≤15.6°C) DP, to avoid mold growth

Table 6.

Recommended Thermal Conditions for Buildings Located in Cold/Arctic Climates—Normal Operations

	Space Occupancy						
	Occupied Normal Operations (Regular Business Hours)			Unoccupied (Short Term) Unoccupied for a Short Time Period (e.g., a Few Days)		Unoccupied (Long Term/ Hibernated) Unoccupied for an Extended Period of Time (e.g., Weeks) Building Freezing/Not Freezing	
Type of Requirement	**DP**	**Maximum Dry-Bulb Temperature**	**Minimum Dry-Bulb Temperature**	**DP**	**Minimum Dry-Bulb Temperature**	**Humidity Not to Exceed**	**Minimum Dry-Bulb Temperature**
Human comfort	<63°F (17.2°C)[1]	82°F (27.8°C)[1]	68°F (20°C)[1]	<63°F (17.2°C)[1]	55°F (12.7°C)[4]	N/A	
Process driven	Process specific—see examples in Tables 1 and 2			Process specific—see examples in Tables 1 and 2 (unless specified otherwise)		N/A	
	Humidity not to Exceed	**Minimum Dry-Bulb Temperature**		**Humidity not to Exceed**	**Minimum Dry-Bulb Temperature**	**Humidity not to Exceed**	**Minimum Dry-Bulb Temperature**
Building sustainment	80%[3]	40°F (4.4°C)[2]		< 80%[3]	40°F (4.4°C)[2]	80%[3]	40°F (4.4°C)[2] or N/A if drained

[1] ASHRAE Standard 55 (2017).

[2] To prevent water pipe rupture, with factor of safety.

[3] To prevent interior surface mold growth, with no factor of safety.

[4] To prevent longtime recovery and significant energy losses.

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Table 7.

Recommended Thermal Conditions for Buildings Located in Cold/Arctic Climates—Emergency Operations

Scenario	Emergency Space Occupancy					
	Mission-Critical Operation		Tertiary Space (Non-Mission-Critical Space Bordering Mission-Critical Space)		Hibernated Can Be Unoccupied for Extended Period of Time (from Days to Weeks) Building Freezing/Not Freezing	
Type of Requirement	DP	Minimum Dry-Bulb Temperature	Humidity not to Exceed	Minimum Dry-Bulb Temperature	Humidity not to Exceed	Minimum Dry-Bulb Temperature
Human comfort	<63°F (17.2°C)[1]	>60°F (16°C)[5]	N/A		N/A	
Process driven	Process specific—see examples in Tables 1 and 2		N/A		N/A	
	Humidity not to Exceed	Minimum Dry-Bulb Temperature	Humidity not to Exceed	Minimum Dry-Bulb Temperature	Humidity not to Exceed	Minimum Dry-Bulb Temperature
Building sustainment	80%[3]	40°F (4.4°C)[2]	80%[3]	40°F (4.4°C)[2]55°F (12.7°C)[4]	80%[3]	N/A 40°F (4.4°C)[2] or N/A if drained

[1]ASHRAE Standard 55 (2017).

[2]To prevent water pipe rupture, with factor of safety.

[3]To prevent interior surface mold growth, with no factor of safety.

[4]To prevent longtime recovery and significant energy losses.

[5]ACGIH TLV, thermal stress recommendations (ACGIH 2018).

Table 8.

Recommended Thermal Conditions for Buildings Located in Hot/Humid Climates—Normal Operations

	Space Occupancy						
	Occupied			**Unoccupied (Short Term)**		**Unoccupied (Long Term/Hibernated)**	
	Normal Operations (Regular Business Hours)			**Unoccupied for a Short Time Period (e.g., Few Days)**		**Unoccupied for an Extended Period of Time (e.g., Weeks) Building Freezing/Not Freezing**	
Type of Requirement	**Humidity not to Exceed**	**Maximum Dry-Bulb Temperature**	**Minimum Dry-Bulb Temperature**	**Humidity not to Exceed**	**Maximum Dry-Bulb Temperature**	**DP not to Exceed**	**Maximum Dry-Bulb Temperature**
Human comfort	60%[1]	82°F (27.7°C)[1]	68°F (20°C)[1]	70%[3]	85°F (29°C)[3]	N/A	
Process driven	Process specific—see examples in Tables 1 and 2			Process specific—see examples in Tables 1 and 2 (unless specified otherwise)		N/A	
	DP	**RH**		**Humidity not to Exceed**	**DP**	**DP**	**RH**
Building sustainment	≤60°F (15.6°C)[2,4]	<70%[2]		<70%[2]	<60°F (15.6°C)[2,6]	≤60°F (15.6°C)[2,4]	<70%[2]

[1] ASHRAE Standard 55 (2017).

[2] To prevent interior surface mold growth, with no factor of safety.

[3] To prevent longtime recovery and significant energy losses.

[4] ASHRAE Standard 62.1 (2019a).

Table 9.

Recommended Thermal Conditions for Buildings Located in Hot/Humid Climates—Emergency Operations

	Space Occupancy					
	Mission Critical		Tertiary Space around Mission Critical		Hibernated—Can Be Unoccupied for an Extended Period of Time (from Days to Weeks)	
Type of Requirement	WBGT		WBGT		WBGT	
Human activity broad range	<87.8°F (31°C)[3]		N/A		N/A	
Process driven	Process specific—see examples in Tables 1 and 2		N/A (unless specified otherwise)		N/A	
	DP	RH	DP	RH	DP	RH
Building sustainment	≤60°F (15.6°C)[2,4]	<70%[2]	≤60°F (15.6°C)[2,4]	<70%[2]	≤60°F (15.6°C)[2,4]	<70%[2]

[1] ASHRAE Standard 55 (2017).

[2] To prevent interior surface mold growth, with no factor of safety.

[3] ACGIH TLV, thermal stress recommendations (ACGIH 2017).

[4] ASHRAE Standard 62.1 (2019a).