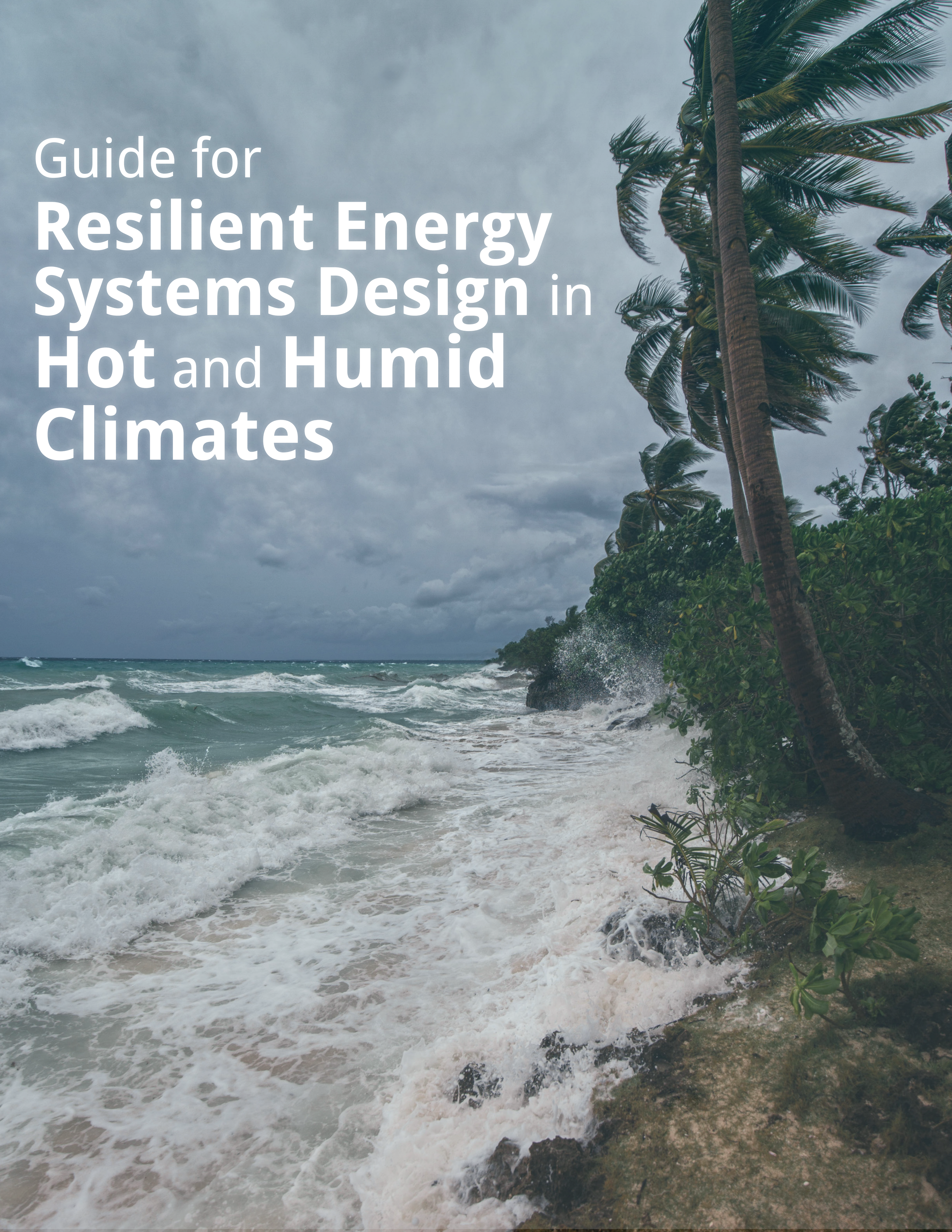
Guide for Resilient Energy Systems Design in Hot and Humid Climates



Guide for Resilient Energy Systems Design in Hot and Humid Climates

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Foreword

Resilience of thermal energy systems is critically important in extreme climates. 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 despite a clear need in the earth's hot and humid regions.

Thermal energy systems addressed in this Guide consist of both the demand and supply sides. The demand side is comprised of active and passive systems including thermal demand by the process; heating, cooling, ventilating, and air-conditioning (HVAC) systems maintaining required environmental conditions for the building's operations and comfort for people; and a shelter/building that houses them. The supply side includes energy conversion, distribution, and storage system components. Requirements to maintain thermal/environmental conditions in the building (or in a part of the building) needed for housing critical mission-related processes and occupants include criteria to maintain thermal comfort and health, to support process needs, and to prevent mold, mildew, corrosion and other conditions that can damage building materials or furnishings.

During an ***emergency (black sky)*** 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 systems operation is limited or not available, mission-critical areas can be conditioned to the level of thermal parameters required for supporting agility of personnel performing a mission-critical operation, but not to the level of their optimal comfort conditions during ***normal (blue sky)*** operations. Beyond these thresholds (habitable) levels, effective execution of a critical mission is not possible and mission operators must be moved to a different location. The Guide establishes these threshold limits of thermal parameters that may be in a broader range compared to that required for thermal comfort, but not to exceed levels of heat stress thresholds: in a cooling mode, the wet bulb global temperature (WBGT) in spaces with mission-critical operations should be maintained below 87.8 °F (31 °C) (ACGIH 2018).

Prescriptive guidelines for building energy efficiency in hot climates have traditionally been derived by a holistic consideration of climatic factors, energy policy, environmental policy, and economics. The differences in thermal barrier requirements in buildings across hot and humid regions of the world are influenced as much by the differing priorities of the governing bodies that set these requirements as they are by actual physical demands and conditions. Usually, national requirements for building envelope characteristics, e.g., thermal insulation values of its components, building envelope airtightness, vapor permeability, building mass, detailing, etc., are based on economic and environmental considerations. Thermal energy system resilience consideration brings another dimension to the optimization process of these parameters. The Guide summarizes best practice requirements pertaining to building envelope characteristics for buildings located in hot and humid climates of the United States, Republic of Korea, Japan, Singapore, Turkey, and several other countries; it also compares the effects of different levels of building envelope efficiency and building mass on indoor air temperature decay when cooling energy supply is interrupted.

Hot and humid climates present some of the most complex challenges for sustainable building design and operation to maintain high indoor air quality efficiently. Additionally, high temperatures, coupled with high humidity, create extreme comfort issues and exacerbate the potential for condensation, mold, and mildew.

Moisture control, or humidity control, is paramount in hot and humid climates. Currently, most humidity control strategies are based on relative humidity (RH) control. Extensive recent ASHRAE research has shown the benefits of controlling habitable space dewpoint, as opposed to RH, and indicated associated risks to the building above the suggested dewpoint threshold of 60 °F (16 °C). The Guide describes available control devices and subsequent building logic to control dewpoint efficiently while mitigating the potential for mold and mildew and to provide adequately conditioned supply air to satisfy the needs of space-conditioning efficiently.

Building materials in humid climates, especially in coastal locations, are also subject to rust and decay much more quickly than in other environments. In extreme situations, e.g., at Kwajalein or Okinawa, concrete elements of the building envelope break down and condenser units installed outside of the building envelope must be replaced within 2 to 3 years due to premature corrosion caused by a salt-laden ambient air. Additionally, many coastal areas located in hot and humid climates experience frequent tropical storms and hurricanes with associated heavy winds that can force water into the building and damage the building envelope.

This Guide is designed for energy systems designers, architects, energy managers, and building operators; it should prove a valuable resource for those who are involved in building planning and operation in hot and humid climates. This Guide, with its focus on the resilience of thermal energy systems, is meant to complement the ASHRAE Guide for Buildings in Hot & Humid Climates (Harriman and Lstiburek 2009).

Acknowledgments

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CHAPTER 1. INTRODUCTION

1.1. Geographical Areas

ASHRAE determines minimum requirements for building envelopes and HVAC system practices to ensure that buildings provide the greatest energy savings and environmental quality based on the building location's thermal (0 through 8) and moisture (marine, dry or humid) climate zone. A humid climate is generally defined as a region that receives more than 20 in. (50 cm) of annual precipitation (ASHRAE 2020). Thermal zones range between extremely hot (climate zone 0) and very cold (climate zone 8). This Guide addresses construction specifics in locations regarded as "extremely hot" and "warm" (see Figure 1-1 and Table 1-1).

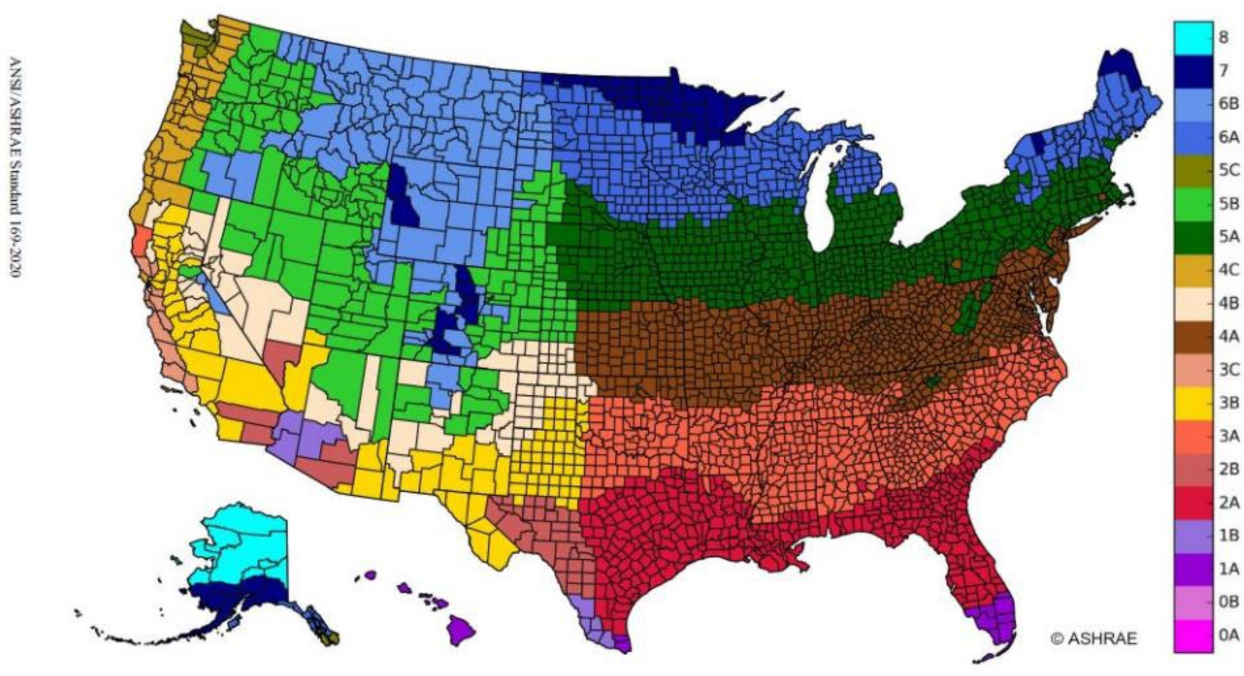


Figure 1-1. U.S. Department of Energy (DOE) climate zones.

Table 1-1. Thermal climate zone definitions (ASHRAE Standard 169-2020).

Thermal Zone	Name	I-P Units	SI Units
0	Extremely Hot	10,800 < CDD50 °F	6000 < CDD10 °C
1	Very Hot	9000 < CDD50 °F ≤ 10,800	5000 < CDD10 °C ≤ 6000
2	Hot	6300 < CDD50 °F ≤ 9000	3500 < CDD10 °C ≤ 5000
3	Warm	CDD50 °F ≤ 6300 and HDD65 °F ≤ 3600	CDD10 °C < 3500 and HDD18 °C ≤ 2000

These “extremely hot” through “warm” areas include ASHRAE climate zones 0A, 1A, 2A, and parts of 3A. This Guide will discuss construction specifics common to these “hot and humid” climate zones. When appropriate, differences in characteristics between the building envelope and HVAC system architectures will refer to specific climate zones. Note that climate zones 0A, 1A, 2A, and 3A not only experience high outdoor air temperature and moisture content but may also be located in coastal or inland areas where they can be subjected to unique weather phenomena that can rapidly deteriorate structures and mechanical systems (NAVFAC 2006).

Although this Guide focuses primarily on construction practices and HVAC systems used in the United States, the information included here may be considered for application at other international locations in equatorial regions where annual climate conditions are referenced as *rainy-dry epochs* across the year, rather than *hot-cold seasons*; i.e., at sea level, climate conditions require that air-conditioning systems operate in cooling mode year-round to meet “temperature” comfort conditions and to counter varying humidity challenges associated with *rainy-dry epochs*.

Because of the constant exposure to sunlight across the year, equatorial rain forests do not face the wide temperature or seasonal changes experienced in the southern and northern hemispheres. In the equatorial regions at sea level, dry bulb air temperature varies typically within a small range of 27 °F (15 °C) across the year. In many countries located in the equatorial region, conventional comfort HVAC systems are not required.

Table 1-2 lists examples of cities located in the equatorial region that represent ASHRAE climate zones 0A, 1A, 2A, and 3A.

Table 1-2. Examples cities located in the Equatorial region that represent ASHRAE climate zones 0A, 1A, 2A, and 3A.

Country	City	ASHRAE Climate Zone
Brazil	Barranquilla	0-A
Brazil	Manaus	0-A
Colombia	Monteria	0-A
	Providencia	0-A
	San Andrés	0-A
	Quibdo	0-A
	Recife	0-A
	Valledupar	0-A
	Villavicencio	0-A
	Neiva	0-A
Guam	Guam	0-A
India	Coimbatore	0-A
	Nagpur	0-A
Indonesia	Bali Ngurah Rai	0-A
Jamaica	Kingston-Norman Manley	0-A
Kenya	Mombasa	0-A
Malaysia	Kuala Lumpur	0-A

Country	City	ASHRAE Climate Zone
Marshall Islands	Kwajalein	0-A
Mexico	Acapulco	0-A
Nigeria	Lagos	0-A
Panama	Panama City-Tocumen	0-A
Philippines	Manila	0-A
Puerto Rico	San Juan-Luis Muñoz	0-A
Singapore	Singapore Changhi	0-A
Sri Lanka	Colombo-Bandanariake	0-A
Thailand	Bangkok	0-A
Tanzania	Dar Es Salaam	0-A
Brazil	Belo Horizonte	1-A
Colombia	Cali	1-A
Japan	Iwo Jima	1-A
Vietnam	Da Nang	1-A
Honduras	Tocontin/Tegucigalpa	2-A
Japan	Kadena	2-A
	Kumaijima	2-A
	Naha	2-A
Colombia	Bacaramanga	2-A
	Medellin	2-A
	Pasto	2-A
	Pereira	2-A
Japan	Kure	3-A
	Kobe	3-A
Mexico	Mexico City	3-A
Mexico	Tuluca	3-A
Zimbabwe	Harare	3-A

1.2. Hazards Specific to Construction in Hot, Humid Climates

1.2.1. High Ambient Temperature, Humidity, and Dewpoint

Ambient temperatures in the range of 80 °F to 100 °F (27 °C to 38 °C) coupled with relative humidity (RH) in the range of 70% to 100% for most of the year results in high dewpoints above 75 °F (24 °C), which are ideal conditions for mold and mildew, wood decay, accelerated rusting of various metals, and intensified galvanic action in many metals. Many paints in highly humid conditions do not perform well. Additionally, vapor barriers in air-conditioned buildings in highly humid locations require careful detailing. Common building materials that exhibit hygroscopic properties such as gypsum, insulation, and particle board can lose their structural and functional properties in humid climates.

1.2.2. Intense Rain Periods

Prolonged periods of rain associated with hot, humid climates increase ambient moisture content and water infiltration, which can exacerbate rust and decay and even cause building structural instability.

1.2.3. Monsoons

These are wind systems on a continental scale that seasonally reverse their direction because of a change in temperature trends over land and sea. Generally, winds blow from cold to warm regions: for example, sea to land in summer and land to sea in winter. This occurs because atmospheric pressure is high in cold regions and low in warm regions. Monsoons are one of the most important rain-producing currents on the globe. Intensity and duration are not uniform year to year. A heavy season with floods may be followed by several seasons with below-average precipitation.

1.2.4. Tropical Storms, Typhoons, and Hurricanes

Tropical storms, typhoons, and hurricanes frequently cause disastrous storm surges along the Gulf Coast of the United States that can cause fatalities and billions of dollars damage to property and infrastructure.

1.2.5. Storm Surges

In one type of storm surge, strong winds pick up water along the coast causing sea level to rise. The approximate height of this storm surge can be predicted based on wind speed and direction, fetch, water depth, and the shape of the ocean basin. Other factors, such as currents, astronomical tides, and seiches (standing waves in an enclosed or partially enclosed body of water, e.g., a lake or bay) set up by storms, complicate the calculations.

The second type of surge is a large wave that moves with the storm, typhoon, or hurricane that causes it. First comes a gradual change in water level, the forerunner, a few hours ahead of the storm's arrival. It is caused by the regional wind system and may cause sea level to fall slightly along a wide stretch of coastline.

When a typhoon or hurricane center passes, it causes a sharp rise in water level called a surge. This surge usually lasts about 2.5 to 5 hours; rises in sea level of 12 ft to 16 ft (3.7 m to 4.9 m) have been observed – usually slightly offset from the storm's center. Extremely high waves generated by the storm surges can be extremely destructive.

Following the storm, the sea level continues to rise and fall as oscillations set up by the storm pass. These more or less "free surface" waves have been termed the storm's "wake," like the wake left by the passage of a ship through the water. The sea surges can be quite dangerous, particularly because they are often not expected once the storm itself has subsided.

1.2.6. Floods

Floods happen when the water rises above a flood plain level and begins to cause damage. Flood plains can be channels, deep and wide, or many miles wide and shallow, such as an alluvial plain.

1.2.7. High Water Table

The water table lies underground at the level where the soil and gravel are completely saturated with water. There is often some seasonal change in the water table, due to rain or drought. A high water table is especially common in low-lying areas, or areas where the soil is not well-drained. High water tables can be above the level of basement floors or crawlspaces so that buildings in these areas without water protection can experience flooding or damage.

1.2.8. Seismic Considerations

Earth's lithosphere is composed of numerous plates, the boundaries of which are the source of seismic activities. Many of these plates are located in the Pacific Rim area (Figure 1-2). Though design for seismic design is beyond the scope of this Guide, selection of the building envelope and mechanical and energy supply systems design must account for applicable seismic codes.

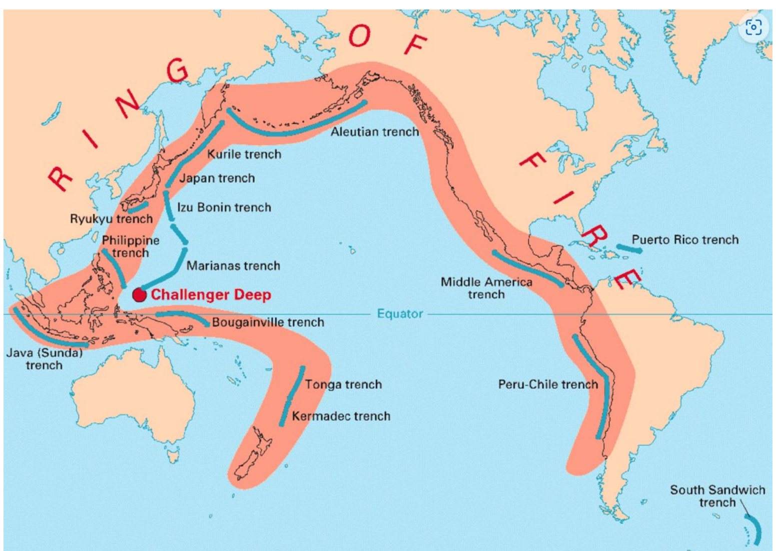


Figure 1-2. Pacific Ring of Fire.

1.3. Special Issues Related to Coastal Areas

1.3.1. Tsunamis

Tsunamis or seismic sea waves (not within the scope of this Guide) are caused by a sudden movement of the ocean bottom resulting from earthquakes or volcanic eruptions. Because of their frequent occurrence in the tropical region and their devastating effects on life and property, it is wise to design buildings and their systems using historic tsunami data. Other extreme weather events common in coastal areas include hurricanes and associated high winds and flooding that may require special features ranging from rain guards for air intakes, to platforms and safety cables to protect the unit from the extreme weather

1.3.2. Prolonged Elevated Temperatures

Elevated temperatures can adversely affect building materials such as paints, wood, and many asphalt-based products. These high temperatures combined with humidity can cause severe deterioration.

1.3.3. Salt-Laden Air

Salt rapidly accelerates wood deterioration (Jones et al. 2011) and causes galvanic action between metals, rusting of ferrous metals (including inadequately protected reinforcing steel in concrete structures and metal components of HVAC equipment and systems), and pitting of many aluminum alloys. Salt-laden air also adversely affects the application of paints, sealants, elastomeric coatings, and asphalt rooting applications. The severity of salt-laden environments varies with elevation, prevailing on-shore winds, vegetation, and rainfall. In addition, small flat coral islands with sparse vegetation (such as Kwajalein, Midway, and Diego Garcia) are characterized by a greater potential for severe corrosion than are larger volcanic islands with moderate vegetation and rainfall (such as Hawaii and Guam). Although all locations in a coastal area must address corrosion protection, projects undertaken in areas with known or suspected severely corrosive environments require additional protective enclosures, materials, and coatings.

Island nations often have all these coastal characteristics. In addition, electricity tends to be significantly more expensive, which should stimulate the use of efficiency-improving features like demand management and high efficiency dehumidification. Temperature and humidity tend to be more stable allowing equipment to be optimized for a narrower range of conditions.

1.3.4. Severe Tidal Fluctuations

Tidal fluctuations, especially large ones, can have an effect on the water table and cause additional hydrostatic pressure for below-grade building configurations. The King Tide, as defined by the U.S. Environmental Protection Agency (USEPA), is the highest predicted high tide of the year at a coastal location. It is above the highest water level reached at high tide on an average day. King tides are also known as “perigean spring tides.” In April 2017, Hawaii recorded its highest tide level of 9 in (23 cm). above the normal 24 in. (61 cm). Therefore, for projects located near the coastline, a general rule of thumb is to assume the recorded water table level will rise or fall 2 ft to 4 ft (0.6 m to 1.4 m). More details may be found at

https://www.epa.gov/cre/king-tides-and-climate-change#:~:text=The%20king%20tide%20is%20the,known%20as%20perigean%20spring%20tides

https://www.hawaii.edu/news/2017/05/19/sea-grant-king-tides/

1.4. Major Issues Affecting Building Sustainability in Hot and Humid Climates

1.4.1. Mold Considerations

In hot and humid climates, mold in buildings is a serious concern because for many months of the year, ambient outdoor temperatures are high, in the range of 80 °F to 100 °F (27 °C to 38 °C). These conditions, when coupled with RH in the range of 70% to 100% for most of the year can result in high DPs above 75 °F (24 °C), which create ideal conditions for mold growth. Micro-organisms (mold), which can damage buildings and cause health concerns for the occupants, all need moisture in their food sources. Although some need more moisture than others, they all need greater moisture levels, for longer periods, than what is considered "normal" in building materials and furnishings. Mold does not primarily (or only) favor conditions of high humidity; it favors conditions with moisture in its food source, e.g., drywall, ceiling tiles, carpets, fabrics, etc. Figure 1-3 gives a simplified illustration of the basic growth cycle of indoor mold.

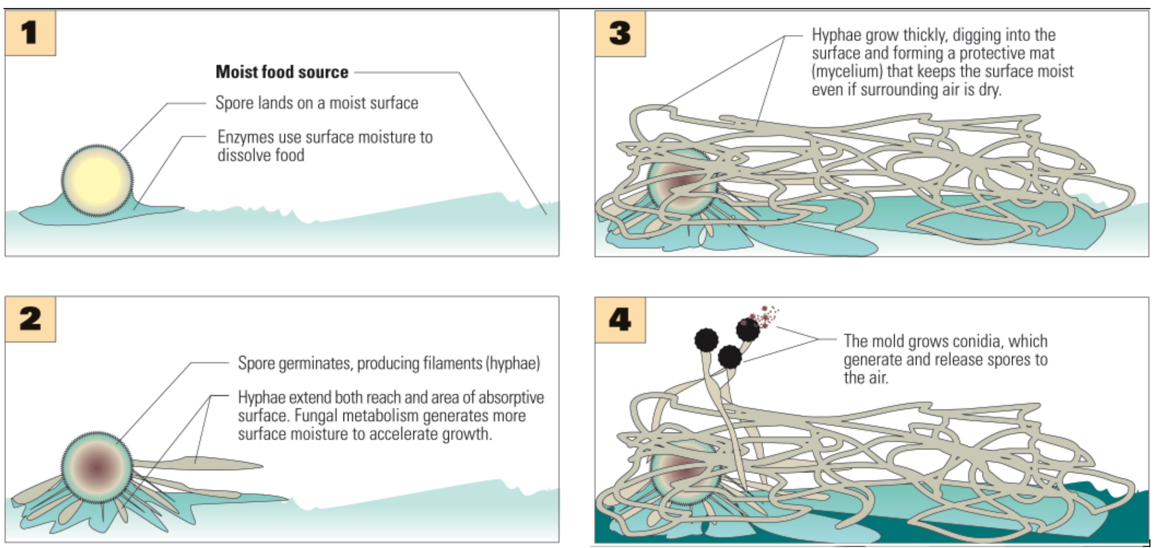


Figure 1-3. Mold growth stages (courtesy of Lew Harriman, Mason-Grant).

Mold spores are ubiquitous in the indoor environment, typically originating from the exterior environment (Figure 1-3, top left). When mold spores land on a surface, enzymes on the exterior of the mold spore combine with surface moisture to dissolve the food source (paper, wood, ceiling tile, etc.). Osmotic pressure causes liquid nutrients to diffuse across the spore wall allowing the spore to absorb the nutrients dissolved in the food source (Figure 1-3, bottom left). The spore then germinates producing filamentous hyphae that accumulate more surface moisture to accelerate growth. The hyphae grow quickly, digging into the surface and creating a protective mycelium mat that keeps the surface moist (Figure 1-3, top right). The mold then grows conidia that generate and release spores into the air, allowing more spores to land on adjacent surfaces and continue the mold growth cycle (Figure 1-3, bottom right).

In short, fungi and bacteria grow and multiply on surfaces. They may survive in the air, but they grow to problematic levels only on surfaces. Therefore surfaces, rather than air, must become the focus of any understanding of mold growth when making decisions regarding lowering the probability of mold growth in buildings.

When materials stay damp for extended periods, the probability of mold growing sufficiently to become problematic for the building and its occupants increases. To avoid these issues, the building and its contents should be kept as dry as possible. The one measurable condition that reflects the dryness of the interior of the building materials is the dewpoint. In humid climates, it is not unreasonable to find exterior DPs above 80 °F (27 °C). Maintaining the interior dewpoint (DP) low around 54 °F to 56 °F (12 °C to 13 °C) will reduce the probability of mold growth.

Excessive mold growth in buildings can have negative health effects for occupants, especially immunocompromised individuals. The level of exposure, the length of exposure time, and the health of the individual will vary based on everyone's immune system capability.

Lack of humidity control during unoccupied periods is a significant risk and one of the drivers behind the new humidity targets for unoccupied buildings in the latest ventilation standard. Cooler early morning conditions are a special risk. Low-cost solutions without reheat capability can then only control humidity at very low temperatures.

Health Effects of Toxigenic Molds and Mycotoxins.

Molds negatively impact human health. The severity of the impact depends on the nature of the species involved, the metabolic products produced by the species, the amount and duration of the individual's exposure to the actual mold or its byproducts, and the specific susceptibility or state of health of the person exposed.

Health effects generally fall into seven categories:

- Type-1 allergy or immediate type hypersensitivity
- Delayed-type hypersensitivity reaction
- Infection
- Mucous membrane and trigeminal* nerve irritation
- Adverse reactions to odor or pseudo allergy
- Toxicity or neurotoxicity by molds and mycotoxins
- Immunotoxicity induced by molds and mycotoxins.

Type-1 Allergy or Immediate Type Hypersensitivity

The most common response to mold exposure may be an allergy. Atopic people, that is, people who are genetically capable of producing an allergic response, may develop allergic symptoms when their respiratory system or skin is exposed to mold or mold products to which they have become sensitized. Sensitization may occur in atopic individuals with sufficient exposure. This reaction is immediate and occurs within minutes after exposure to molds.

* The trigeminal nerve is the largest of the 12 cranial nerves. Its main function is transmitting sensory information to the skin, sinuses, and mucous membranes in the face

Delayed-Type Hypersensitivity Reaction.

This type of reaction occurs hours or days after exposure to molds. It is mediated by IgG, IgM, IgA (antibodies), or immune complexes and is referred to as Type-2 and Type-3 allergic reaction. Finally, direct lymphocyte reaction to mold antigens may result in delayed-type hypersensitivity or Type-4 allergic reaction. This reaction is mediated by lymphocyte reaction to mold antigens.

Infection

Infection from molds that grow indoors is not a common occurrence, except in certain susceptible populations, such as individuals who have compromised immune systems resulting from disease or drug treatment. Several *Aspergillus* species that can grow indoors are known to be pathogens. *Aspergillus fumigatus* is a weak pathogen that is thought to cause infections (aspergillosis) only in susceptible individuals.

Mucous Membrane and Trigeminal Nerve Irritation

The fourth group of possible health effects from fungal exposure derives from volatile organic compounds (VOCs) produced using a fungal primary or secondary metabolism subsequently released into the air indoors. Some of these volatile compounds are continuously produced as the fungus consumes its energy source in the course of the primary metabolic processes. Such compounds, in low yet sufficient aggregate concentration, can irritate the mucus membranes of the eyes and the respiratory system.

Adverse Reactions to Odor or Pseudo Allergy.

Odors produced by molds may also adversely affect some individuals. The ability to perceive odors and respond to them is highly variable among people. Some individuals can detect extremely low concentrations of volatile compounds, while others require high levels for perception. Some people derive enjoyment from odors of all kinds. Others may develop negative symptoms, such as headache, nasal stuffiness, nausea or even vomiting to certain odors, including perfumes, cigarette smoke, diesel exhaust, or moldy odors.

Toxicity or Neurotoxicity by Molds and Mycotoxins

The spores of many molds are capable of producing secondary metabolites, such as antibiotics and mycotoxins, some of which are extremely toxic. Depending on the route of entry, they may damage the skin, lungs, gut, vascular system, urinary system, reproductive system, and neuroimmunological systems. The spores from *Stachybotrys chartarum*, a mold capable of producing some of the most toxic known substances, can survive temperatures up to 500 °F (260 °C), as well as acid, caustics, and bleach without being destroyed.

Immunotoxicity Induced by Molds and Mycotoxins

The exposure of animals to molds has shown a significant effect on the immune system. In animals, this was manifested as increased susceptibility to infectious diseases. It is important to note that almost all mycotoxins have an immunosuppressive effect, although the exact target within the immune system may differ. Many mycotoxins are also cytotoxic so their route of entry can have damaging effects on the gut, skin, or lungs. Such cytotoxicity may affect the physical defense mechanisms of the respiratory tract and can decrease the ability of the airways to clear particular contaminants (including bacteria or viruses). It may also damage alveolar macrophages, thus preventing the clearance of contaminants from the deeper lung cavity.

Conclusions

In recent years, mold in buildings with excess moisture has become a national and international concern. HVAC systems affect the humidity and the air movement through buildings. Also, the performance of the building's exterior envelope concerning airtightness and vapor penetration impacts the amount of moisture that enters the building's interior. Further, the interaction between HVAC systems and the building envelope affects the amount of moisture that collects in organic materials that act as a food source for mold.

Mold growth requires an organic food source that contains an excess of moisture. Many indoor mold problems are associated with inadequate building envelopes and HVAC systems. Other building mold problems are associated with excess indoor humidity, the hygrothermal performance of building envelopes, and microbial growth in HVAC systems.

Properly designed, operated, and maintained building systems can have a beneficial influence on maintaining a high-quality indoor environment. Preventing mold problems in buildings is a *shared* responsibility among all parties involved in the design, specification, construction, commissioning, maintenance, and use of buildings. The concept of a well-integrated building design and maintenance program can reduce the probability of mold growth. Mold problems often seem to occur where the responsibilities of these groups overlap, or where involved individuals are unaware of this responsibility.

Mold growth in buildings should be avoided through the use of design, construction, and maintenance practices that limit the accumulation of moisture indoors and that swiftly eliminate accumulated moisture. Even under normal (blue sky) conditions, small amounts of moisture may collect periodically in building assemblies and HVAC systems. In organic materials, any such moisture accumulation must be removed quickly to avoid mold problems.

1.4.2. Water Control

Buildings should shed rainwater and prevent rainwater from entering the building envelope or into closed building cavities. At the roof, water control is achieved at the roof surface and overhangs. Stormwater drainage from the roof should not be allowed to accumulate at the building foundation. A water-resistive barrier (WRB) is usually applied to the sheathing behind the cladding to prevent moisture intrusion into the walls. This WRB should be detailed correctly at windows and other openings. At the foundation, below-grade spaces—basements and below-grade crawl spaces—are strongly discouraged in hot-humid climates since they have an elevated risk of moisture problems even when waterproofing measures are taken. In general, a discharge site for roof rainwater should be determined—away from the building foundation—and measures taken to provide a path to direct the water there. Such a proactive approach is more effective than such reactive measures as the application of coatings and flashing.

1.4.3. Vapor Control

The water vapor control layer—often called a vapor barrier or vapor retarder—affects conditions within the envelope assembly. It has no impact on moisture conditions at the inside and outside faces of the envelope, which are affected by temperature conditions at the surface and humidity conditions in the surrounding air.

Most wall assemblies that meet current energy requirements in hot and humid climates contain a thickness of relatively impermeable rigid thermal insulation such as extruded or expanded polystyrene or polyisocyanurate board. Such material forms an ideal vapor control layer in that it separates the air cavity on either side both thermally and for vapor pressure. Walls with these materials show uniformly good vapor performance. Use of these materials is strongly encouraged.

In cold climates, the need for vapor control appears because there is a clear difference between indoor and outdoor vapor pressure, with higher vapor pressure occurring on the interior. Therefore, in cold climates vapor barriers may have a place. However, in hot-humid climates, indoor and outdoor vapor pressures are typically in the same range so there is no consistent direction of vapor drive. Where there is no consistent direction for vapor drive, an effective membrane vapor control layer cannot be designed. While thermally insulating materials that are relatively vapor impermeable perform very well in all climates, we make no such claim for membrane vapor retarders in hot-humid climates.

One exception to the general rule regarding semi-equivalent indoor and outdoor vapor pressures arises with the use of claddings capable of storing large quantities of water such as thick stucco or soft masonry (adhered veneers). These claddings are subject to solar vapor drive, where sunshine on wetted and saturated materials may drive large quantities of moisture inwards. A relatively impermeable rigid insulation layer of sheathing resolves this problem. In the absence of a rigid insulation layer, with reservoir claddings, a vapor barrier material may need to be applied outboard of the structure.

1.5. Corrosion

1.5.1. Introduction

Buildings in humid climates, especially in coastal locations, experience rust and decay of materials much more quickly than in other environments. Corrosion causes problems across a wide array of infrastructure components, but three building systems that need further investigation are building envelopes; HVAC systems; and cooling energy generation, storage, and distribution systems. In extreme situations, e.g., at Kwajalein or Okinawa, premature corrosion caused by salt-laden ambient air can break down concrete elements of the building envelope, and damage condenser units installed to the exterior of the building so they must be replaced every 2 to 3 years. Under such conditions, systems are most effective and easiest to maintain when they are designed to have minimal exposure to the corrosive environment, are built of corrosion-resistant materials, and use corrosion-resistant coatings.

Facilities located in highly corrosive environments are especially vulnerable to accelerated corrosion degradation. An analysis of the collected data indicates that corrosion rates decrease significantly when an installation is located more than 2 miles (3 km) from the ocean. Corrosion maintenance is most often based on finding and fixing the damage before it becomes a structural or safety concern. This approach is inadequate to meet mission criticality, e.g., the availability of equipment and facilities to support deployment, training, and readiness. There has been little emphasis on the development of engineering tools needed to manage these corrosion and associated maintenance and repair actions. Because the benefits and longevity of corrosion prevention and control measures have not been quantified, it has not yet been possible to optimize these actions. As fleets and facilities have aged, and as the costs of corrosion maintenance have dramatically risen, the life-limiting degradation mechanisms have shifted from those associated with usage to those associated with time. Furthermore, the concerns for corrosion, which previously focused on cost, have begun to include structural integrity and safety. This shift has dictated a change to a prediction and management approach beyond just simply reactive "finding and fixing."

1.5.2. Effect of Distance to the Ocean on Corrosion Rates

There is a sharp (and expected) decrease in chloride levels and corrosion rates as the distance from the ocean increases. Most of that decrease occurs well within the first mile, more generally within the first one-quarter mile (0.4 km). Attenuation factors are in the range of 7:1 to 8:1. The chloride contribution to corrosion is an important factor in atmospheric corrosion rate, but it should be recognized that this is only one part of a complex, synergistic relationship between chlorides and other critical environmental variables. Various measures of moisture in the atmosphere play a very important role. For example, high time of wetness (TOW) in combination with high chloride concentration produces a higher corrosion rate than would be expected from either effect individually (Akhoondan and Sagüés 2012).

When documenting corrosion rates at buildings located near a coast, it is very important to include the location's distance from the ocean, especially within the first one-half mile (0.8 km) and even within the first mile (1.2 km). Beyond the 2-mile (3-km) range, the effects of distance appear to be negligible. It is therefore very important, when possible, to position equipment and structures beyond about 2 miles (3 km) from the coastline to significantly reduce the impacts of corrosion.

Corrosion causes problems across a wide array of infrastructure components but building envelopes, HVAC, as well as cooling energy generation, storage, and distribution are growing concerns that must be investigated.

The atmospheric corrosion resistance of materials is predictable if the environmental aggressiveness is well known. Therefore, the classification of atmospheric corrosivity is important because it forms the basis of the information necessary for the design of good corrosion protection. The International Organization for Standardization (ISO) approved a Standard, ISO 9223:2012, that determined the three factors that can be used for this purpose: annual metal corrosion rate (I_{corr}), TOW, and the level of corrosive impurities in the atmosphere (SO_2 and airborne salinity as chloride ion).

The I_{corr} value depends strongly on the initial exposure period, e.g., a dry or a rainy season, which is very marked in the tropical hot-humid climate.

The TOW is defined as the time that it takes for an electrolyte film and pollution contaminants on a metal surface to cause corrosion. The TOW can be calculated from the meteorological data for atmosphere temperature (T) and RH according to ISO 9223:2012 or measured by appropriated sensory devices. RH and T are often described as the temperature-humidity index, (THI).

It is very important to note that in a tropical hot-humid climate the TOW occurs in high temperature ranges. For example, in the marine coastal (MC) sites 64-73% of TOW is in the T ranges of 73 °F to 86 °F (23 °C to 30 °C); in the rural-urban (RU) site 54% to 64% of TOW occurs in a low range of 68 °F to 77 °F (20 °C to 25 °C).

There is a great difference between the TOW in MC and RU sites at 30 km or more from the seashore. For example, in the Peninsula of Yucatan the calculated TOW for the RU regions is about 4500 h, while for the MC regions it is 8400 h. This difference is due to two effects: (1) extensive airborne salinity in the MC environments and (2) the presence of the sea, the greatest thermal source, which maintains a constant daily, monthly and annual RH average of 77% to 78%.

It is recommended to study the TOW distribution in different T ranges to explain metal corrosion and material degradation processes and rates. The effect of the temperature is not included in ISO 9223:2012. The accelerated corrosion in humid tropical atmospheres probably results from the higher annual temperature ranges. Moreover, the standard proposes to collect the RH and T monthly or annual average values as complementary data for characterization of a site.

In fact, the daily RH and T values in a marine environment are very constant due to the influence of the sea, and RH is usually above a critical value. However, in the RU zone the TOW occurs only at night when the RH value is higher that the critical value (RH > 80%) and therefore during the day the corrosion is interrupted (TOW does not occur). Thus, the corrosion products formed in the RU atmosphere support both dry and wet cycles, while in the MC sites it is wet during the day and night.

It is recommended that measures to protect exposed metallic surfaces be implemented where any building, project, or installation is within 2 miles of a body of salt water.

1.5.3. Building Envelopes

Nearly all building enclosure-related failures in hot-humid climates are related to decay and corrosion associated with water: rainwater, groundwater, airborne water, and water already in the building materials. Regular maintenance and repair of coatings are routinely deferred because of the expense and time constraints imposed by mission-required facility operations. The lack of routine coating maintenance results in the development of rust, pitting, and under-film corrosion. Such coating failures, if not repaired for an extended period, will cause significant damage and will ultimately increase the cost and time requirements for facility maintenance or rehabilitation.

Figure 1-1 shows the corrosion of the studs and fasteners on a seven-story concrete and metal-framed building in a hot-humid climate, 7 years after the building was completed. The exterior water and air control layer of this building was a mechanically fastened building wrap that was neither detailed to be sufficiently airtight, nor sufficiently water vapor impermeable to counteract high moisture drive from the exterior to the interior.

Figure 1-2 shows oriented strand board (OSB) sheathing saturated due to insufficient drainage and insufficient vapor control behind stucco on a three-story townhouse in a hot-humid climate, 8 years after construction. The stucco cladding was installed over two layers of the mechanically fastened building wrap. While this wall assembly complies with the current building code and the windows and penetrations were flashed correctly, two layers of building wrap do not provide enough air space behind the stucco to: (1) relieve hydrostatic pressure, (2) act as a capillary break and receptor for capillary water, and (3) facilitate hydric redistribution and moisture removal by air change. In hot-humid climates, a drainage mat paired with a water and air control membrane with a water vapor permeance of between 5 and 10 perms is recommended to control wetting, while still permitting drying to the exterior. The additional drainage and water vapor control is especially important for buildings with higher moisture risk factors such as those constructed in wet climates (more than 20 in. [51 cm] of rain per year), those that are multistory (exposed to higher wind and moisture loads), and those that are architecturally complex. Where continuous exterior insulation is used in high moisture conditions, is recommended that the drainage mat be placed on the interior of the insulation, between the insulation and the water control layer. In lower moisture load conditions, a textured building wrap can be used in place of the drainage mat.

Figure 1-4. Example of corroded fasteners.

Figure 1-5. Example of saturated-oriented strand board (OSB) sheathing.

Doors and Windows

Doors and windows are an area of weakness for a building envelope and can be the cause of corrosion because of defective design, materials, construction, or a combination of those elements that allows moisture to enter through the external building envelope. This then causes corrosion and decay to the internal structure of the building. Coatings are generally recognized as the “first line of defense” for protecting building envelopes. However, coatings applied to steel structures for corrosion protection are routinely subjected to cuts and scratches during normal (blue sky) operations or maintenance (Figure 1-6).

Figure 1-6. Door damage by machinery impact.

Concrete

All concrete structures are subject to the destructive effects of alkali-silica reaction (ASR). This form of concrete corrosion slowly deteriorates concrete from the inside by forming highly expansive gels that cause swelling and cracking of the concrete matrix. ASR is a heterogeneous chemical reaction that takes place between aggregate particles (e.g., chert, quartzite, opal, strained quartz crystals) and the alkaline pore solution of the cement paste. All Portland cement contains alkalis, and many are highly alkaline.

The alkali content of concrete is also likely to increase with the use of additives and admixtures. The infusion of chlorides in the form of seawater or pavement de-icing salts may also increase alkalinity. Water in the pore fluid is imbibed into the reaction sites and eventually, alkali-calcium silica gel is formed. When this substance absorbs water, it expands in volume and imposes internal stresses on the concrete matrix causing spalling (Figure 1-7). Studies have shown that ASR typically develops and continues in concrete when internal RH exceeds 80% to 85%.



Figure 1-7. Common spalling of concrete.

Corrosion of Steel-Reinforced Concrete in Coastal and Inland Environments

This section presents corrosion control methods that are applicable to structures made of steel-reinforced Portland cement concrete. Reinforcing steel is compatible with concrete not only because of similar thermal expansion properties, but also because the highly alkaline pore solution in Portland cement pastes allows a stable, protective oxide film to form on the surface of the encased steel.

The major cause of deterioration of reinforced concrete structures is corrosion of the reinforcing steel (rebar) and attack by acidic materials. The rebar in a new properly constructed concrete structure is protected from immediate corrosion by the alkaline (pH 13) concrete cover (about 2 in.).

The corrosion process can damage concrete in several ways, including cracking, loss of bond, and localized corrosion (see NACE 2017):

- **Cracking.** The corrosion products of steel often occupy several times the volume of the base metal. The expansive pressure because of this volume increase exerts a significant tensile force on the surrounding concrete. Resulting cracks propagate toward either the concrete surface or nearby reinforcing steel, causing delamination.
- **Loss of Bond.** Minor corrosion at the metal surface of the reinforcing steel can be sufficient to crack the concrete cover and cause loss of bond.
- **Localized Corrosion.** Localized corrosion typically occurs at construction joints, non-corrosion-related cracks (e.g., from early removal of formwork or from concrete shrinkage), or where the structural steel exits the concrete.

Environmental pollutants greatly influence the corrosion of reinforcing steel embedded in concrete. However, it is not easy to find direct correspondence between them because of the concrete cover. Therefore, the corrosion phenomena of reinforced concrete are different from those occurring in atmospheric exposed steels. For example, airborne salinity affects the metals exposed to the atmosphere immediately, but in the case of reinforcing steel, that salinity must be transported by absorption, diffusion, or both processes through the concrete to cause corrosion.

Time of wetness (TOW) and pluvial precipitation (PP) are other atmospheric variables that influence the corrosion mechanism of steel. This influence is not direct on reinforced concrete due to its specific structural characteristics: water/cement ratio (w/c), time of curing (tc) and the initial passive state of the embedded steel. For example, a large TOW can produce water saturation in concrete. However, if the concrete is dense enough, the humidity will remain only on the concrete surface. On the other hand, if the concrete is not dense, and the atmospheric humidity and chloride are sufficiently high, the interface steel/concrete will remain humid. Consequently, the steel corrosion rates will differ in reinforced concrete from those in free atmospheric exposure. Figure 1-8 shows the main factors responsible for reinforcement corrosion, Carbonation induces a generalized corrosion while the presence of chloride ions in the material surrounding the steel leads to localized corrosion.

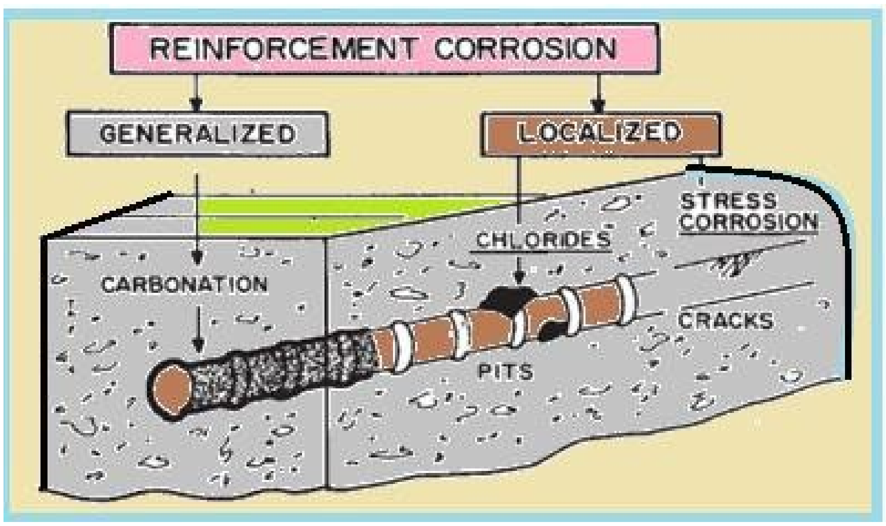


Figure 1-8. Schematic for localized corrosion of reinforcing steel in presence of chloride.

Tuutti (1982) suggested that the deterioration process in reinforced concrete structures is divided into two distinct time phases: the initiation phase and the propagation phase. During the initiation phase, the aggressive agents such as Cl^- and the carbonation front ingress and depassivate the steel rebars. The initiation phase usually lasts a long time, 15–20 years (Yuan et al. 2007). The propagation phase encompasses the actual corrosion process, which results in spalling, cracking, and in some cases, collapse. The remaining life of a reinforced concrete structure is drastically reduced when there is severe corrosion of the rebar. Hence, the durability of reinforced concrete structures is controlled by the initiation phase, which depends on the concrete quality and severity of the environmental conditions. It is essential to understand these conditions to improve the design requirements and better predict the service lifetimes.

Chloride Distribution within the Concrete Cover

To provide an example of chloride distribution within a concrete cover, concrete and steel samples were obtained from a bridge in a hot and humid environment in an investigation of chloride-induced steel corrosion (Liu et al. 2020). Two different bridge zones were considered: the atmospheric zone and the tidal zone. The bridge deck was considered for the atmospheric zone. Pier columns within a range of altitudes were subjected to periodic wetting and drying and were considered in the tidal zone.

Ten concrete samples were cored out, with a diameter of 3 in. (70 mm) and a height of 2 in. (50 mm) as shown in Figure 1-9. Figure 1-9a shows how five concrete samples (A1–A5) were cored out along the western half of the bridge deck, representing the concrete exposed to the atmospheric environment. Four of them were close to the deck side and the other was in the middle of the deck half. Another five concrete samples (T1–T5) were cored out in the tidal zone on the columns of pier #1 (Figure 1-9b).

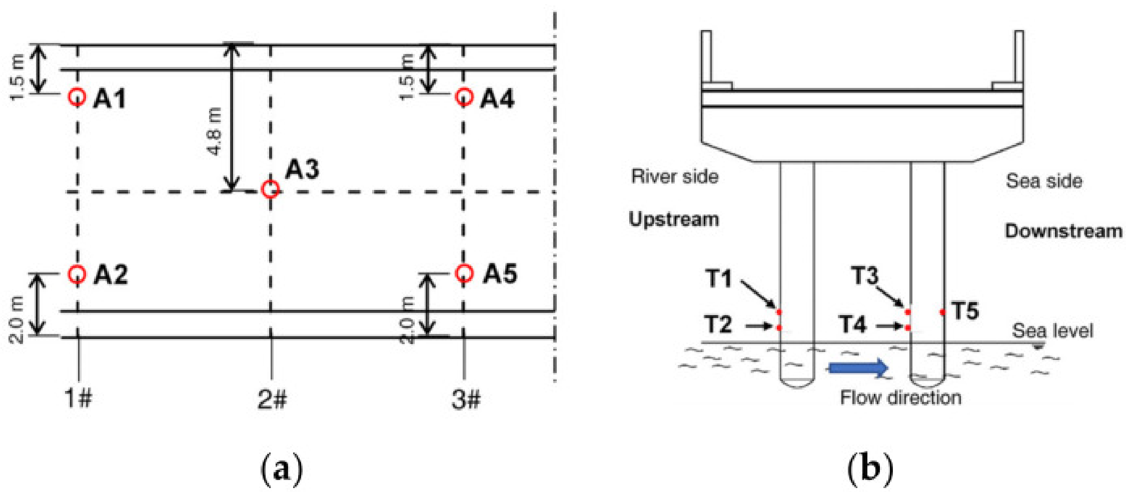


Figure 1-9. Locations of concrete samples: (a) Bridge deck; (b) Pier #1.

Figure 1-10 shows the distributions of chloride ions within the concrete in the atmospheric and tidal zones. Chloride ion content first increased to a peak value and then decreased with the distance from the exposed surface. This was due to the periodic wetting and drying conditions. It was noted that the wetting period for the deck concrete was mainly caused by rainfall. During the wetting period, chloride ions in the external water were brought into the concrete rapidly, along with water absorption, resulting in a peak near the exposed surface. During the drying period, chloride diffused from the high chloride content region near the exposed surface to the deeper region with the low chloride content. The external seawater with chloride ions moved into the concrete and chloride diffused into the deeper concrete throughout the wetting-drying cycles.

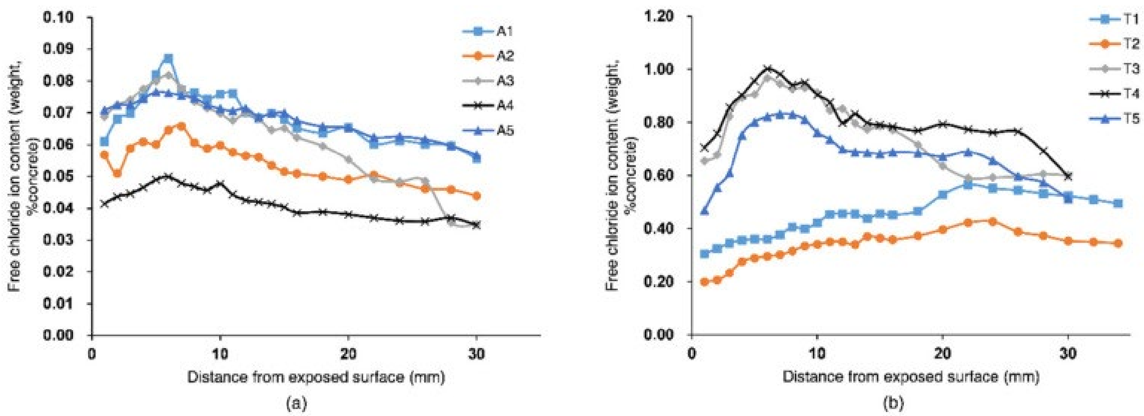


Figure 1-10. Chloride profiles within the concrete: (a) in the atmospheric zone and (b) in the tidal zone.

A comparison of the chloride profiles shown in Figure 1-10 shows significantly higher chloride content in the tidal zone than in the atmospheric zone; in the tidal zone, the lowest level of free chloride ion (0.20%) is more than twice as high as the highest level in the atmospheric zone (0.09%). This was due to different boundary conditions for the chloride transport. Chloride ion was absorbed from seawater continually under cyclic wetting-drying conditions in the tidal zone, while in the atmospheric zone, surface chloride accumulated from chloride in the atmosphere and then diffused into the concrete. The results also showed that the chloride profiles for T1 and T2 were lower than the profiles for other pier concrete samples. This was because the concrete samples T1 and T2 were closer to the river water, where ambient chloride concentrations were lower. The chloride content for T5 was also lower than T3 and T4's, even though these concrete samples were located next to each other and had similar boundary chloride concentrations. This could be explained by the lower porosity of T5. The lower porosity led to a decreased number of pathways for chloride transport within the concrete.

Causes of Chloride Attack on Concrete Structures

The attack of chloride on concrete structures can happen either from inside of the concrete or through the ingress of chloride from outside to the inside of concrete structures.

The chlorides exist in concrete during the casting process for the following reasons:

- Use of seawater for the concrete mixing process
- Use of calcium chloride as an additive to increase the setting time
- Use of aggregates for mixing that were not washed, and that contained chlorides
- Aggregates with chloride content more than the limit stated in the specification.

The chlorides enter the concrete from the exterior environment to concrete interior for the following reasons:

- Exposure of concrete to seawater
- Chloride content in atmosphere
- Temperature
- Annual average RH
- Annual average rainfall
- Prevailing wind direction

- Annual average wind speed
- Cyclic wetting and drying (TOW) conditions can significantly accelerate chloride penetration in concrete.

A comparison of the two ways chlorides can affect concrete clarifies that the chances of exterior chloride action are high. Most offshore structures are subjected to extreme chloride attacks, which induces corrosion of the concrete reinforcement in the structures. The action of chloride in inducing corrosion of the reinforcement is more serious than other corrosive effects. For example, sulfates attack the concrete, but chloride attacks the steel reinforcements.

Carbonation Attack

The carbonation of concrete is another factor that causes corrosion in reinforced concrete structures. Carbon dioxide (CO_2) from the environment reacts with calcium hydroxide ($Ca[OH_2]$) in the hardened concrete. This reaction results in the formation of calcium carbonate ($CaCO_3$), which fills the pores of the concrete and makes the concrete environment less alkaline, lowering the concrete pH from a typical value of 13 to around 8. This more acidic environment destroys the passive layer at the steel surface and initiates the corrosion of the rebar.

Causes of Carbonation of Concrete Structures

The microstructure of concrete is such that it has capillary pores (up to 28%). The extent of pores depends on the quality of the concrete and the presence of water at the time of mixing of concrete. These pores are created due to evaporation of excess free water during strengthening of concrete mass and are interconnected and go from surface of concrete structures to the inside of the concrete mass. Making more dense concrete with a lower ratio of water to cement reduces the number of pores (Sohail et al. 2015).

Carbonation of concrete is a process by which carbon dioxide from the air penetrates concrete through pores and reacts with calcium hydroxide to form calcium carbonates. The conversion of $Ca(OH)_2$ into $CaCO_3$ by the action of CO_2 results in a small shrinkage.

We shall see another aspect of carbonation, as CO_2 by itself is not reactive. In the presence of moisture, CO_2 changes into dilute carbonic acid, which attacks the concrete and reduces the alkalinity of concrete (i.e., pH value reduces).

Air contains CO_2. The concentration of CO_2 in rural air may be about 0.03% by volume. In large cities the content may go up to 0.3% or exceptionally it may go up to even 1.0 per cent. In poorly ventilated tunnels, the concentration may be much higher.

The pH value of pore water in the hardened concrete is generally between 12.5 to 13.5 depending upon the alkali content of cement. The high alkalinity forms a thin passivating layer around steel reinforcement and protects it from the action of oxygen and water. If steel is placed in a highly alkaline condition, it is not going to corrode. Such a condition is known as passivation.

In actual practice, CO_2 in the atmosphere in smaller or greater concentrations permeates and carbonates the concrete and reduces the concrete's alkalinity. The pH value of pore water in the hardened cement paste, which is commonly around 13, will be reduced to around 9.0. When all the $Ca(OH)_2$ has become carbonated, the pH value will reduce up to about 8.3. In such a low pH, the protective layer gets destroyed and the steel is exposed to corrosion.

The carbonation of concrete is one of the main reasons for corrosion of reinforcement. Of course, oxygen and moisture are the other components required for corrosion of embedded steel. Figure 1-11 shows the reinforcement corrosion process.

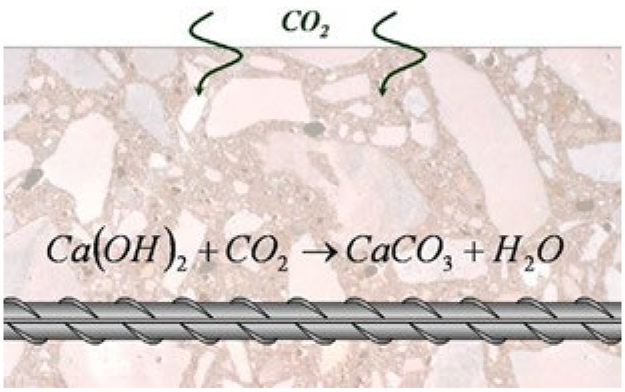


Figure 1-11. The process of corrosion of reinforcement from carbonation of concrete structures.

Sulfate attack on concrete is a chemical breakdown mechanism where sulfate ions attack components of the cement paste (Figure 1-12). The compounds responsible for sulfate attack on concrete are water-soluble sulfate-containing salts such as alkali-earth (calcium, magnesium) and alkali (sodium, potassium) sulfates that are capable of chemically reacting with components of concrete.

Figure 1-12. Spalling due to a sulfate attack.

Sulfate Attack

Causes of Sulfate Attack

Sulfate attack on concrete might show itself in different forms depending on

- The chemical form of the sulfate
- The atmospheric environment to which the concrete is exposed
- When sulfates enter concrete
  - It combines with the C-S-H, or concrete paste, and begins destroying the paste that holds the concrete together. As sulfate dries, new compounds are formed, often called ettringite.

- These new crystals occupy empty space, and as they continue to form, they cause the paste to crack, further damaging the concrete.

Sources of Sulfate Attack

The sources of sulfates responsible for sulfate attack are

1. Internal Sources. This is rarer but originates from such concrete-making materials as hydraulic cements, fly ash aggregate, and admixtures.
   a. Portland cement might be oversulfated.
   b. Presence of natural gypsum in the aggregate.
   c. Admixtures also can contain small amounts of sulfates.
2. External Sources. External sources of sulfate are more common and usually are a result of high-sulfate soils and ground waters or can be the result of atmospheric or industrial water pollution.
   a. Soil may contain excessive amounts of gypsum or another sulfate.
   b. Groundwater is transported to the concrete foundations, retaining walls, and other underground structures.
   c. Industrial waste waters.

Reactions of Sulfate Attack on Concrete

Nature of reaction: Chemical and physical reactions of the sulfate attack process decrease the durability of concrete by changing the chemical nature of the cement paste and by changing the mechanical properties of the concrete.

There are two forms of chemical reaction that occur depending on concentration and source of sulfate ions, and composition of cement paste in concrete.

Some considerations regarding physical process of sulfate attack include

- The complex physicochemical process of “sulfate attack” is interdependent as is the resulting damage.
- Physical sulfate attack is often evidenced by a “bloom” (the presence of sodium sulfates) at exposed concrete surfaces).
- Sulfate attack is not only a cosmetic problem; it is the visible symptom of possible chemical and microstructural problems within the concrete matrix.
- Since both the chemical and physical reactions of a sulfate attack manifest themselves simultaneously, their separation is inappropriate.

A sulfate attack on concrete is usually diagnosed when the concrete surface displays visible spalling.

HVAC and Controls

HVAC components in volatile environments are particularly vulnerable. For example, the warm, humid island climate of Hawaii creates a high demand for AC; meanwhile, Hawaii’s ocean coastal location creates a high chloride salt environment that is highly corrosive to the aluminum components of AC systems as well as to the steel components of the associated machinery and housing (Figure 1-13). Extending the service life of HVAC units could reduce and control the costs of AC maintenance, repair, and replacement due to corrosion.

Figure 1-13. Exfoliation of a bare aluminum coupon after 24 months of exposure in a hot and humid climate.

The Department of Public Works at Schofield Barracks, Hawaii estimates that a new AC system will have a 15–20-year service life; however, actual average service life in a highly corrosive environment is closer to 7 to 10 years.

Cooling Energy Generation, Storage, and Distribution

Accelerated corrosion of critical steel infrastructure components in hot, humid environments includes the corrosion of steel utility piping in mechanical rooms and steel pump housings used in cooling tower systems. A prime example of such serious problem surfaced as accelerated corrosion of exposed union joints in the mechanical rooms at Fort Bragg's newly constructed 16th Military Police Barracks (Figures 1-14 and 1-15). These problems can be attributed to the use of a corrosion-vulnerable mild steel alloy in the lower pump housings. These housings are typically exposed to highly oxygenated turbulent water, which effectively consumes the metal through extensive pitting and flaking. Ineffective or improper system water treatment may also contribute to the accelerated corrosion of these pump components, further aggravating the problem.

The use of mixed metals (stainless steel and carbon steel) in pump fabrication will result in internal galvanic corrosion. The stainless-steel components must be electrically isolated from the carbon steel components. The environmental conditions in the mechanical rooms resulted in heavy amounts of condensation accumulating on the supply line insulation and metal brackets that support the pipes. In addition to causing accelerated corrosion, there is also concern about the potential for the growth of mold, which can create health hazards and safety issues.

Figure 1-14. Mechanical room at Fort Bragg.

Figure 1-15. Corroded union joints on piping in a mechanical room.

Coating systems can reduce the amount of corrosion on the fittings in the mechanical rooms as compared with uncoated fittings. Because this corrosion is attributed to continual condensation on the cold-water lines, it appears that a combination of effective dehumidification, with constant air circulation to remove humidity uniformly throughout the rooms, and with either of the coatings could cost-effectively arrest corrosion on mechanical room union joints and pipe fittings.

1.6. Conclusions

To meet the requirements associated with extreme weather conditions in a hot and humid climate, special attention must be paid to the selection and design of the building envelope structure, and of the HVAC and energy supply systems

Resilient infrastructure requires planning well beyond the typical resiliency planning for infrastructure in more moderate locations. Building envelopes are the first defense against harsh climates; they can be designed and built to increase building resiliency. Mechanical systems must be designed with the hot and humid and corrosive climate in mind; some equipment simply does not last long in this environment and getting repairs in remote locations is not quick or easy. Resilient mechanical and energy systems for hot and humid climates usually require backup equipment and (in some cases) thermal storage.

CHAPTER 2. REQUIREMENTS FOR BUILDING THERMAL CONDITIONS UNDER NORMAL (BLUE SKY) AND EMERGENCY (BLACK SKY) OPERATIONS IN HOT AND HUMID CLIMATE

2.1. Introduction

This chapter provides recommendations on thermal and moisture parameters (air, temperature, and humidity content) in different types of buildings under normal (blue sky) and emergency (black sky) operation conditions in hot and humid climate conditions (DOE climate zones 0-3a). Three scenarios are considered under normal (blue sky) operating conditions: building/space is occupied, temporarily (2-5 days) unoccupied, and long-term unoccupied (e.g., when a building is hibernated). These thermal parameters are necessary to achieve one or several purposes:

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

Many emergency (black sky) conditions may occur over the life of a building. This chapter will limit the emergency (black sky) conditions to interruption of electrical service, chilled water, and fuel, leading to the interruption of space-conditioning for the building.

During an emergency, the 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 optimal comfort conditions. Beyond this threshold (habitable) level, effective execution of critical missions is not possible and mission operators must 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, non-critical standalone buildings can be hibernated, but necessary measures should be taken, and the thermal environment should be maintained (at sustainability threshold level) when possible, to prevent significant damage to these buildings before they can be returned to their normal (blue sky) operation.

2.2. Normal (Blue Sky) Operating Conditions

Under normal (blue sky) operating conditions, for any given building, factors like building envelope insulation and airtightness, ventilation rates, thermostat setpoints, plug loads, and lighting levels significantly impact building energy consumption and cost.

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 (blue sky) operation conditions and make thermal systems more resilient during emergency (black sky) operation. Setting these rates and setpoints can be as much of an art as a science, but several standard references are used to help in the operation of the building. The following references guide the suggested values:

- **Thermal requirements** include criteria for thermal comfort and health, process needs; criteria for preventing the growth of mold and mildew; and criteria for preventing other damage to the building materials or furnishings. Under normal (blue sky) 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. If temperatures are too high, occupants will be uncomfortably warm. If temperatures are too low, occupants will be uncomfortably cold. The wrong humidity (rooms typically do not have humidistats) will make occupants feel damp or sweaty or too dry. Thermal comfort is defined by ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017a).

The following dry bulb room air temperatures and RH values (IMCOM 2010) are within the ASHRAE Standard 55 range and should not be exceeded:

- ***Cooling Period*:** The dry bulb temperature (DBT) in occupied spaces should not be set below 70 °F (21 °C) with the RH maintained below 60%. When the space is unoccupied for a brief period (e.g., a few days), the room thermostat should be reset to 85 °F (29 °C) with the RH maintained below 70%. In spaces unoccupied for an extended period (e.g., weeks), the temperature should not be controlled but the building air RH should be maintained at 70%
- ***Heating period:*** 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). In hot and humid climates, there is rarely a need for humidification in non-medical facilities. Examples of DBT in occupied spaces not to be exceeded include:
    - Barracks and other living quarters: 70 °F (21 °C) Monday through Friday from 5 a.m. to 11 p.m. and 65 °F (18.3 °C) from 11 p.m. to 5 a.m. Temperature settings for barracks Saturday and Sunday 70 °F (21 °C) from 6 a.m. to 11 p.m. and 65 °F (18.3 °C) from 11 p.m. to 6 a.m.
    - Offices, lecture halls, meeting spaces, etc., where personnel work seated or in a standing position involving little or no exercise: 70 °F (21 °C) during working hours and not more than 55 °F (12.8 °C) during non-working hours.
    - Childcare facilities: 72 °F (22.2 °C) during working hours.
    - When the space is unoccupied during a brief period (e.g., a few days), the room thermostat should be set back to 55 °F (12.8 °C).
    - Warehouses and in spaces unoccupied for an extended period (e.g., weeks), the temperature should be controlled at 40 °F (4.4 °C) with the capability of being warmed to 55 °F (12.8 °C) when occupancy is required.

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, some specialized electronic and laboratory equipment has precise constraints on 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.

2.2.1. Data and Electronic Equipment Centers

Environmental requirements for spaces with IT and Communications equipment may vary depending on the type of equipment or manufacturer. According to ASHRAE (2005), there are six standard classes of thermal requirements.

Class A1. Typically, a datacom facility with tightly controlled environmental parameters (dewpoint, temperature, and 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 (dewpoint, 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 have no special requirements to consider.

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 (dewpoint, temperature, and RH). Table 2-1 lists the recommended and allowable conditions for Class A1, Class A2, and NEBS environments.

Table 2-1. Recommended and allowable conditions for Classes A1-A2, and NEBS environments.

	ClassA1/ClassA2 (ASHRAE 2019a)			NEBS (ASHRAE 2005)
Conditions	**Allowable Level**	**Recommended Level**	**Allowable Level**	**Recommended Level**
Temperature control range		64 °F-80 °F (18 °C–27 °C)	41 °F-104 °F (5 °C–40 °C)	65 °F-80 °F (18 °C–27 °C)
A1	51 °F - 89 °F (11 °C – 32 °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)	

Conditions	ClassA1/ClassA2 (ASHRAE 2019a)			NEBS (ASHRAE 2005)
	Allowable Level	Recommended Level	Allowable Level	Recommended Level
RH control range		15 °F - 51 °F dewpoint (-9 °C - 11 °C) dewpoint and 60% RH	5%-85% 82 °F (28 °C) Max dewpoint	Max 55%
A1	10 °F (-12 °C) dewpoint and 8% RH to 62 °F (17 °C) dewpoint and 80%RH			
A2	10 °F (-11 °C) dewpoint and 8% RH to 69 °F (21 °C) dewpoint and 80%RH			
[1] 9 °F/hr (5 °C/hr) for tape storage, 31 °F/hr (2 °C/hr) for all other IT equipment and not more than 9 °F (5 °C) in any 15 min period.				

2.2.2. Healthcare Facilities

Health care facilities represent another group of mission-critical facilities. Per NFPA 99, 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 normal, regular operations and does not apply 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 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.

Table 2-2 lists examples of requirements (ASHRAE 2017) to thermal environment in spaces included in categories 1 and 2.

Table 2-2. 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 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 (burn 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 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.

Building related criteria. 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 dewpoint 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 (i.e., 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 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 past 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 adsorption and persistent dampness when surfaces become cool at or below the dewpoint of the air. The indoor air dewpoint (DP) is a reliable measurement of the mass of water vapor available for adsorption, and therefore potentially available to support microbial growth.

The RH in the air is rarely the same as RH at the surface. This is particularly true near cold supply-air diffusers. In buildings, the indoor dewpoint stays high over months whenever air-conditioning systems are turned off. The persistent high dewpoint allows excessive moisture adsorption and mold growth on the surfaces of acoustic ceiling tiles near supply-air diffusers. Keeping the indoor dewpoint below 60 °F (16 °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 Standard 62.1-2019b, *Ventilation for Acceptable Indoor Air Quality*).

To model the effect of an emergency (black sky) shutdown of air-handling equipment in a building in a hot-humid climate, it is first necessary to select the extreme dewpoint outdoor conditions. The dewpoint at extreme outdoor conditions in hot/humid climates within the Continental United States (CONUS) 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-unsafe ERH. However, the decay process itself may contain conditions for mold growth. 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 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 and dewpoints as quickly as possible. However, those with concerns for continued use of the building following an outage, or with concerns for security may argue that the building should remain closed.

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 dewpoint below 60 °F (16 °C). A more detailed discussion of the logic for setting 60 °F (16 °C) dewpoint as a prudent limit for "normal" indoor humidity (and as a reasonable compromise with respect to energy use to maintain building dryness) can be found in the ASHRAE Humidity Control Design Guide, and Chapter 62 of the USEPA Handbook, *Moisture Control Guidance for Building Design, Construction and Maintenance* (Harriman et al. 2001; Harriman and Lstiburek 2009; ASHRAE 2015; USEPA 2013).

2.3. 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, non-critical building areas and standalone buildings, the objective is to minimize the damage to the assets. It is assumed that building processes will be kept 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 (blue sky) circumstances, building environmental controls are designed and operated to create a thermoneutral environment conducive to optimal employee comfort or, at least, performance. 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 who need 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 emergency (black sky) operations, efforts shall be made to maintain a thermal environment to prevent significant damage to both mission-critical and non-mission-critical buildings before they can be returned to their normal (blue sky) operation. This may include reducing ventilation requirements; controlling maximum humidity levels using available technologies with a minimum fuel consumption; allowing maximum daylight; keeping plug loads low and lowering lighting levels; and in cooling constraint conditions, using window shades to minimize solar gains.

Threshold Conditions for Human Environment. While stressful cold and hot environmental conditions are well defined for jobs performed outdoors (NIOSH 2016, ACGIH 2018), there is not much information available for such conditions when jobs are performed indoors. This section addresses the potential thermal "inflection point," i.e., when a person can no longer physiologically and/or behaviorally compensate for the thermal stress while on the job, based on the following assumptions and conditions:

1. The building environmental control systems fail and cannot be restored for 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 are generally healthy with the normal physiological responses to deviations in environmental conditions.
4. The workers remain inside the building and perform minimal physical work (nearly at rest, the energy generated inside the body due to metabolic activity [MET] of 1.2-1.5 MET).[*] At this minimal workload, the metabolic heat produced will be minimal (slightly above that produced at rest).
5. Factors such as convection and direct radiation from the sun will be considered negligible.
6. 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.
7. Building is lit using either fluorescent or LED lighting, which results in negligible radiant heat from lighting fixtures.
8. The building environmental conditions will be affected by the function of the HVAC system in an indoor setting; 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.
9. Other considerations are indirect radiation, which occurs when the sun heats the building mass, allows the building mass to radiate this heat inward to the occupants; and air movement such as by ceiling fans, which can often alleviate some of the thermal stresses of a warmer than optimal work area.

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 following discussion will focus on the physiological responses to heat stress as the result of the prolonged failure of the building HVAC system in a building situated in a hot and humid locale.

Physiological response. The physiological responses, 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 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, and in some cases, on solar heat gain. The physiological responses will also depend to a large extent on the degree of personal insulation (clothing) surrounding the worker during exposure to an increase in environmental temperature.

[*] A MET, or "Metabolic Equivalent of Task," is a ratio of an individual's working metabolic rate relative to resting metabolic rate.

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 an increase in environmental temperature can potentially be severe. If the physiological responses to environmental temperature changes (and the ability to maintain T_{core}) are unsuccessful, then T_{core} will change (increase); if the change is large enough, then normal function will be compromised. For example, a T_{core} of 100.4 °F (38 °C) is considered the onset of hyperthermia. At T_{core} >100.4 °F (38 °C) one becomes symptomatic. Physiological/Psychological Signs and Symptoms of hyperthermia are:

- Feelings of subjective discomfort due to heat
- Sweating (leading to loss of body fluid that must be replaced by drinking fluids)
- Increased heart rate from decrease in body fluids
- Increased perception of thirst (**not** a good indicator of the level of dehydration)
- Dark colored urine (indicating dehydration)
- Heat cramps
- Altered cognitive function
- Dizziness or lightheadedness (especially getting up from seated position)
- If prolonged exposure to severe enough heat – heat exhaustion.

It is important to understand that probably the first line of defense against heat is behavioral, that is, removal of outer clothing that can create an insulative layer that may decrease heat transfer to the environment under hot conditions or under high metabolic rates (i.e., high level of physical activity). With this strategy, a human being may even perform strenuous (high metabolic rate) 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 hot temperatures (86 °F [30 °C]) that can potentially cause heat stress and illness (Parsons 2003). Nevertheless, working in hot, and especially humid, environments have demonstrable effects on humans even if wearing relatively light 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). Altered cognitive function in hot environments may severely limit the performance of intellectually demanding tasks (Gaoua et al. 2018; Aljaroudi et al. 2020). For example, passive heating (i.e., not due to exercise or an increase in metabolic rate) reduces the accuracy of the number of problems solved and an increase in the latent response that seems to be due to an increase in thermal discomfort in subjects whose T_{core} ~102 °F (~39 °C) (Gaoua et al., 2018). This may severely limit the use of computers and other equipment that requires the ability to accurately solve problems occurred since a loss of cognitive function and manual dexterity occurred in hot environments (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 of the so-called "time off 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., increase in T_{sk}, which then results in the focus of attention on that change rather than on the task before them.

Separately, Parsons (2003) and Wargocki and Wyon (2017) have described in detail 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). Briefly, the literature indicates that when indoor temperature increased from ~75 °F (~24 °C) to 77 °F (25 °C), the rate of accidents rose sharply by 50% in workers performing sedentary work (1 MET) while wearing normal indoor clothing (1.0 Clo).

Therefore, from the above discussion, in emergency (black sky) situations that increase indoor air temperature alone (not WBGT) in spaces with mission-critical buildings operation above ~75 °F (~24^{o}C) may lead to an increase in the rate of accidents or in decreased focus on the critical tasks required for the job. Increasing WBGT inside the building above 87.8 °F (31 °C [ACGIH 2017]) is not recommended since it will significantly impair the performance of mission operators.

2.4. Thermal Requirements for Unoccupied Spaces

The requirements for temperatures and dewpoint discussed above were developed for occupied spaces (Table 2-3). 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 due to training and deployment. So, one of the energy conservation strategies 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 90.1-2004 *Energy Standard for Buildings Except for Low-Rise Residential Buildings* (ASHRAE 2004). Standard 90.1-2007 (ASHRAE 2007) 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 90.1-2004, *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 for 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. In hot and humid climates, it is wasteful to cool facilities located that are left unoccupied for an extended period of time. 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 maintains the requirements for *all* the air inside the building.

Table 2-3. DBT and RH requirements for occupied and unoccupied facilities to reduce the risk of moisture-related problems.

Occupancy/Status	Dewpoint (Setpoint) Not to Exceed	Maximum Dry Bulb Temp (Setpoint)	Minimum Dry Bulb Temp (Setpoint)
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 equip requirement if less	Equip max allowed	Equip min allowed

2.5. Recommendations

Requirements for the 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 the long-term integrity of the building and building materials.

Buildings are designed to meet these three sets of requirements in normal (blue sky) operating conditions. Thermal comfort requirements are defined by ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017). 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 (blue sky) operation conditions, environmental requirements based on the sustainability of building envelope assemblies and furnishings are not a limiting factor given that the building envelope air barrier and vapor protection are (or should be) designed to avoid mold growth and water accumulation within the building assembly.

During an emergency (black sky) 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 systems operation is limited or not available, mission-critical areas can be conditioned to the level of thermal parameters required for supporting 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 must 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 °F (15.6 °C) [ACGIH 2018], and in a cooling mode, the WBGT should be below 87.8 °F (31 °C [ACGIH 2017]).

To prevent significant damage to both mission-critical and non-mission-critical buildings before they can be returned to their normal (blue sky) operations, mechanical systems and controls in conditioned spaces should maintain indoor dewpoint < 60 °F (< 15.6 °C). Mold will not grow under these conditions. In the case of unconditioned buildings, modeling strongly suggests that, in hot-humid climates, mold will not grow on interior surfaces of unconditioned buildings. This finding must be confirmed by observation or further research.

For example, at the weapons of mass destruction (WMD) facility at Eglin AFB, FL, the urban assault trainers (pseudo buildings used for soldiers to perform house-to-house combat tactics training exhibited minor mold growth after some particularly large temperature swings in the spring). The pseudo buildings are not conditioned in any way but did sustain some condensation and resulting mold growth after a series of cold (40 °F to 50 °F [104 °C to 122 °C]) nights followed immediately by a change in wind direction resulting in warm humid days.

If electricity service to a building is limited but not absent, the building may be partially conditioned, with the zone of mission-critical facilities conditioned. To prevent mold growth at the interface between the conditioned and unconditioned space these strategies may be adopted:

1. Maintain interior dewpoint < 60 °F (< 15.6 °C) for the whole building. This may require the operation of the air handler for long periods of time. It may require ensuring air exchange between the conditioned and unconditioned parts of the building. If a low dewpoint can be maintained in the building, then building surfaces of whatever temperature should remain mold-free.
2. If the separation between conditioned and unconditioned parts of the building is anticipated at design time, then the separation should be designed and constructed as an exterior assembly with a continuous air barrier and sufficient vapor control, e.g., a 4-in. (10.2cm) concrete masonry unit (CMU) with exterior-insulated finish system (EIFS) on the exterior (unconditioned) and drywall at the interior (conditioned).
3. If the separation between the conditioned and unconditioned parts of the building is not anticipated, then the separation should be reconfigured as if it were an exterior assembly. Drywall should be removed from any partitions that serve as an interface. An assembly consisting of a vapor barrier and mold-resistant materials should be used.
4. 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 cases where the utility supply is interrupted and the building air handler is disabled, the indoor temperature will decay to the outdoor temperature. The rate of decay analysis described in Chapter 7 shows that the time it takes for the 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 the space function and location within the building, and on the building mass.

Finally, non-critical 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 2-4 and 2-5 summarize recommendations for thermal environmental conditions for buildings located in hot and humid climate for normal (blue sky) and emergency (black sky) situations.

Table 2-4. Recommended thermal conditions for buildings located in hot and humid climate – Normal (blue sky) operations.

Type of Requirement	Space Occupancy						
	Occupied			Unoccupied (Short Term)		Unoccupied (Long Term/ Hibernated)	
	Normal (blue sky) operations (Regular Business Hours)			Unoccupied for a Short Period (e.g., Few Days)		Unoccupied for Extended period (e.g., Weeks) Building Freezing/ Not Freezing	
	Humidity Not to Exceed	Maximum Dry Bulb Temp	Minimum Dry Bulb Temp	Humidity Not to Exceed	Maximum Dry Bulb Temp	Dewpoint Not to Exceed	Maximum Dry Bulb Temp
Human Comfort	60%[1]	82 °F (28 °C)[1]	68 °F (20 °C)[1]	70%[4]	85 °F (29 °C)[4]	N/A	
Process Driven	Process specific. See examples in Tables 1-1 & 1-2			Process specific. See examples in Tables 1-1 & 1-2 (unless specified otherwise)		N/A	
	Dewpoint		RH	Humidity not to exceed	Dewpoint	Dewpoint	RH
Building Sustainment	≤60 °F (16 °C)[3,6]		< 70%[3]	<70%[3]	<60 °F (16 °C)[3,6]	≤60 °F (16 °C)[3,6]	<70%[3]

Table 2-5. Recommended thermal conditions for buildings located in hot and humid climate – Emergency (black sky) operations.

Type of Requirement	Space Occupancy					
	Mission-Critical		Tertiary Space around Mission-Critical		Hibernated Can Be Unoccupied for Extended period (from Days to Weeks)	
	WBGT		WBGT		WBGT	
Human Activity Broad Range	< 87.8 °F (31 °C)[5]		NA		N/A	
Process Driven	Process specific – see examples in Table 1-1		N/A (unless specified otherwise)		N/A	
	Dewpoint	RH	Dewpoint	RH	Dewpoint	RH
Building Sustainment	≤60 °F (16 °C)[3,6]	< 70%[3]	≤60 °F (16 °C)[3,6]	< 70%[3]	≤60 °F (1.6 °C)[3,6]	<70%[3]

[1]ASHRAE Standard 55 (2017).

[2]To prevent water pipe rupture, with a factor of safety, a building must be reliably maintained above 40 °F (5 °C) during the winter season if design temperatures can fall below 32 °F (0 °C) regardless of how infrequently this may occur.

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

[4]To prevent long time recovery and significant energy losses.

[5] ACGIH TLV, Thermal stress recommendations (ACGIH 2017, 2018).

[6]ASHRAE Standard 62.1 (2019b).

CHAPTER 3. PARAMETERS FOR THERMAL ENERGY SYSTEM RESILIENCE

3.1. Introduction

The resilience of thermal energy systems is especially important for extreme climates, including hot and humid environments. To be able to provide a design that is robust, adaptable, and affordable, it is important to understand the aspects of the geographic location that will impact equipment selections, operating hours, and maintenance needs. Another consideration is the ability of a building to withstand a cooling plant outage, either locally or from a centralized source. This chapter defines the term “resiliency” as the ability of a nonresidential building to withstand an interruption of its internal environmental control system during hot and humid outdoor ambient conditions. Buildings with a fast rate of temperature degradation during environmental control system loss have low resiliency, while buildings with a slower rate of temperature degradation have higher resiliency.

In hot and humid climates, resiliency plays an integral role in maintaining mission-critical operations as long as it is necessary or technically possible and in preventing significant damage to both mission-critical and non-mission-critical buildings during the outage before they can be returned to their normal (blue sky) operation. Emergency shutdown of air-handling equipment in a building in a hot-humid climate can result in mold growth on most building materials, which can cause enormous damage that can be very expensive to repair. In addition, mold growth can also impact occupants' wellbeing and morale, and result in negative health effects that affect productivity.

Therefore, it is necessary not only to look at building HVAC installations but also on the building envelope and the whole energy infrastructure. A more resilient low carbon system (as compared to a building-level HVAC system) can be achieved by taking advantage of the large thermal capacity of concrete and brick walls, and by using critical system redundancy, thermal energy storage, a reasonable layer of outside insulation without weak points, airtight building envelope and a centralized controlled chilled-water supply.

In addition to traditional hot-and-humid-climate building parameters, thermal resilience is a parameter of growing importance, especially for medical and university campuses, and for military and government installations that house mission-critical operations. Resilient energy systems (both electric and thermal) are those that can prepare for and adapt to changing conditions and recover rapidly from disruptions including deliberate attacks, accidents, and naturally occurring threats (PPD-21 [White House 2013, HQDA 2015]). A quantitative approach described in Zhivov and Lohse (2021) allows for evaluation of both resilience metrics: the ability of a system to absorb the impact of a disruption (robustness) with minimal failure, and its ability to recover.

3.2. Energy System Resilience Metrics

For some critical missions where any amount of interruption from an event is unacceptable, it is assumed that power quality requirements and a short-term uninterruptable power supply to mission-critical equipment are handled using building-level energy systems. Other critical missions can withstand small disruptions as long as the system can recover quickly. This can be quantified as a deviation in mission availability from baseline operations to the degraded system state following a disturbance.

Electric and thermal energy delivery may be visualized as having three delivery mechanisms or layers (Figure 3-1). The first delivery mechanism resides internal to the facility; it is the building-level power infrastructure for electric energy systems and building envelope and its mechanical systems for thermal energy supply. The second delivery mechanism is the emergency, or backup, energy systems directed to the facility from outside of the building but sourced from local infrastructure power and thermal energy generation. The third delivery mechanism is the full load delivered to the facility under normal (blue sky) operating conditions; this is commonly comprised of prime power or power delivery from an electric utility for electric systems; and steam, hot water, and/or chilled water delivered from the campus, building cluster, or some location outside the campus plant.

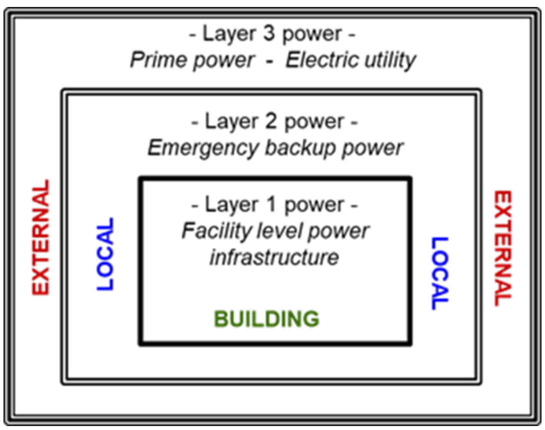


Figure 3-1. Layers of energy supply to mission-critical facilities.

Two facility load levels are defined. The full electric and thermal power load is provided by a layer three system and serves the entire electrical/thermal load of the facility. The critical electrical load is provided by layers one and two also referred to as backup power, and only serves the facility's critical infrastructure. The facility's critical infrastructure load results from the load shedding of all power-connected equipment that is not critical for the continuity of the mission or missions housed in the facility. Layer one power for a facility is the electrical backup power that resides inside of the facility. Common components are an uninterruptable power supply (UPS) and an automatic transfer switch (ATS). Layer one backup power is the shortest duration of electrical power capacity of the three layers. The power delivery capacity can typically be from several minutes to several hours.

Layer two power for a facility is the electrical backup power that resides outside of the facility, but at a minimum is partially dedicated to supplying the facility. Common components are generator sets and renewable energy systems such as solar arrays. Layer two backup power is of variable duration. The electrical power delivery capacity can range from several hours to days in duration. The electrical power delivery capacity is limited only by factors such as fuel storage capacity, battery rectifier capacity, etc. The layer two power can also be supplied for an installation-wide or campus microgrid system. In such a case, the facility power is supplied from a microgrid system that also provides power to other facilities that reside at the same location as the facility in question.

Layer three for a facility is the electrical power that resides in the infrastructure of the prime power utility. Common components of the utility that serve electrical power to the facility are substations and the medium voltage power distribution system. Layer three is a supplier of electrical power under normal (blue sky) conditions. Unlike layers one and two, layer three is not maintained or repaired by the facility. An exception would be when an installation or campus uses distributed power generation in conjunction with connection to the prime power utility; the primary goal is a lower cost of the distributed power generation or opportunities to sell energy to the utility grid to achieve a positive cost differential. Failure at layer three requires reliance on layers one and two for continuity of mission operations.

In the case of thermal energy systems, layer one can include the building envelope and the building-level thermal storage, while level two-layer may include an emergency or mobile boiler and chiller, or an electric backup thermal system.

A variety of energy system options can be used to supply power, heating, and cooling to campuses; these options vary by the architectures and technologies used, and by whether they apply to individual buildings, building clusters, campuses, or even entire communities. Design and evaluation of these system resilience measures should be based on requirements established by mission operators, which are currently not well understood.

A quantitative approach to the resilience of energy system that supplies energy to the building can include (but is not limited to) the following metrics:

- Energy System Robustness
- Energy System Recovery time
- Energy Availability
- Energy Quality.

The first three parameters are critical for the selection of the energy supply system architecture and of the technologies that comprise the system, and to satisfy requirements related to energy system resilience. As described by Zhivov and Lohse (2021), requirements to Energy Availability and Energy System Recovery Time depend on

- Criticality of the mission being served by the system,
- System repairability, which has significant dependence on the remoteness of the facility hosting the mission, and
- Redundancy of facilities that can serve the same critical function.

Energy Robustness requirements depend on the value of the mission-critical load. Energy Robustness requirements can be (1) measured as the percentage of the load that is available to the mission in degraded state from the total mission-essential load requirements (Figure 3-2), and (2) related to the overall building energy load under normal (blue sky) conditions.

Energy Quality is another important quantitative metric for the energy system serving critical functions and should be considered as a design parameter for internal building energy systems.

Most mission-specific energy quality requirements can be handled by the building-level energy systems. Building-level electric systems (nano-grids) generally include redundant or backup components and infrastructure for power supply, UPS, automatic transfer switches, data communications connections, environmental controls (e.g., air-conditioning, fire suppression), and various security devices. These electrical systems can be designed to provide power with a severe demand on the stability and level of the frequency, voltage, and waveform characteristics of the uninterruptable electrical power to mission-critical equipment and can operate in an islanded mode between 15 minutes and several hours.

For resilient thermal energy system planning, a well-insulated and airtight building envelope of a massive building can maintain habitable indoor air temperature for several hours after heat or cooling supply to the building is interrupted. See Chapter 7 for more details.

These internal electrical and thermal systems are designed based on the class or tier of such facilities. Therefore, requirements for Energy Availability, Energy Recovery Time, and Energy Quality to be specified for energy systems providing energy to the building will differ from those required by the critical equipment and personnel.

Energy Robustness is defined as “the ability to absorb shocks and continue operating” (NERC 2018). For many critical facilities, there may be many mission assets that are considered uninterruptible, critical but interruptible, and life and safety related. Since it is imperative to the mission that these assets remain online, any undelivered load to such facilities or assets would be considered mission failure and the shock would have caused the failure. Energy Robustness is a metric that shows the power availability, P (in kW and/or kBtu/hr) to satisfy critical mission loads over time immediately following the event, measured as a fraction of the mission-critical requirement or as a fraction of the baseline energy requirement.

Using the Energy Robustness metric, we can quantify the overall resilience of a system in two phases: ***absorption*** of the event, and ***recovery***. Consider an event occurring as shown in Figure 3-2. Immediately following the event, there is a sharp drop in the load available to the mission. For electric energy systems, the duration of phase one is much shorter than for thermal energy systems, unless thermal systems are used for processes using steam or hot water. This change from the baseline to the degraded state represents the robustness of the system to that particular event. The time required to restore the system to its baseline state is referred to as recovery. The smaller the change in load available to the mission and the shorter the recovery time, the more robust the system.

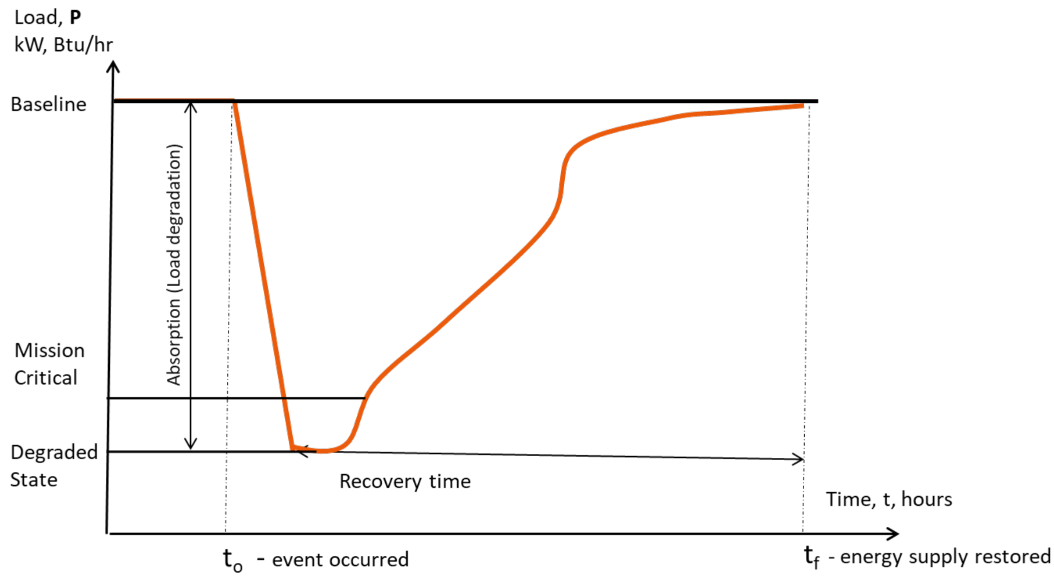


Figure 3-2. System Response to a disruptive event.

The robustness, R of the system to any particular event can be quantified using Equations 3-1 and 3-2. The smaller the area between the baseline and the curve, the more resilient the system. Energy Robustness will be measured on the scale between 0 and 1, where 1 is the most resilient system:

$$ER_{m.c.} = \frac{E_{event}}{E_{m.c.}} \tag{3-1}$$

$$ER_{baseline} = \frac{E_{event}}{E_{baseline}} \tag{3-2}$$

where, $ER_{m.c.}$ and $ER_{baseline}$ are energy system robustness measured against the mission-critical load and the baseline load; E_{event}, $E_{m.c.}$, and $E_{baseline}$ are energy supplied to the building during the period of time between t_o and t_f with the baseline load, mission-critical load, and degraded due to event load. This can be illustrated by the area between the line showing the baseline mission availability and the curve representing the actual mission performance over time (Equation 3-3):

$$\boldsymbol{E} = \int_{t_o}^{t_f} \boldsymbol{P}(\boldsymbol{t})\boldsymbol{dt} \tag{3-3}$$

Depending on mission needs, it may be more important to prioritize either absorption or recovery. For example, Figure 3-3 shows two systems with different levels of absorption. The two systems have the same recovery time, but System 2 has a lower initial decrease in power available to the building. System 2 is more resilient to the postulated event and is more robust than System 1 despite having the same recovery time.

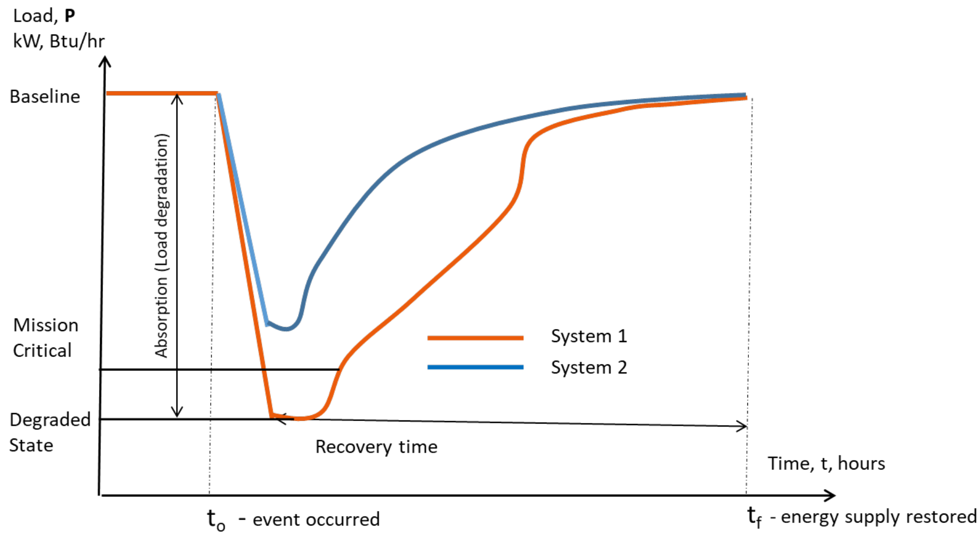


Figure 3-3. Two systems with different absorption.

In other cases, it may be more important to prioritize recovery from an event as opposed to absorption. Figure 3-4 shows two systems with similar absorption to an event, but different recovery times. Though both systems have the same ability to absorb the shock from the event, the shorter recovery time for System 2 yields a larger area under the curve. Accordingly, System 2 can be said to be more resilient than System 1.

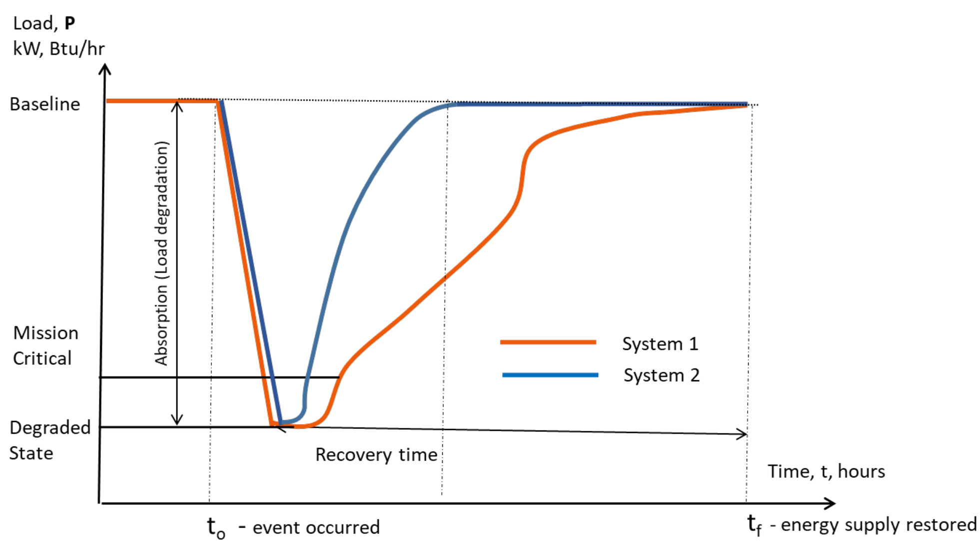


Figure 3-4. Two systems with different recovery times.

In the recovery phase, the system is stabilized, and no further damage or degradation is expected. The system may be operating in alternate or emergency (black sky) modes with a reduced load. At the beginning of this phase, energy may be provided to critical systems using an internal building system with the power storage capacity followed by standby generators, emergency boilers, alternate utility feeds, or distributed energy resources. In this phase, the emphasis is on restoring the system to its baseline operation.

As previously discussed, the shorter the recovery time, the more robust the system. Recovery time is determined by the average length of time required to return damaged components to service. In general, the availability of energy for the mission increases as assets are recovered. For large or complex systems, availability during the recovery phase may change continuously. For smaller systems, or where fewer redundant paths exist, it can be more useful to consider the change in availability during the recovery phase as a step function. That is, there are discrete step changes in availability as components or success paths are returned to service.

Figure 3-5 shows an example of this concept for an electric energy system. In this example, an event has disabled both the onsite generation as well as one of two redundant utility feeders resulting in a significantly reduced power supply to the mission (degraded state). The onsite generators are quickly returned to service, resulting in a large step increase in availability to support mission-critical loads. During generator unavailability, power to mission-critical assets is provided by UPSs integrated into the nano-grid. After some time, the redundant utility feed is returned to service, resulting in a second step increase in availability. It is important to note that for a single success path to be restored, all series components must be fully restored before improvements in availability are realized. For example, if an event disables a backup generator, its associated fuel tank, and fuel lines, all these assets must be repaired before that feed is considered back online.

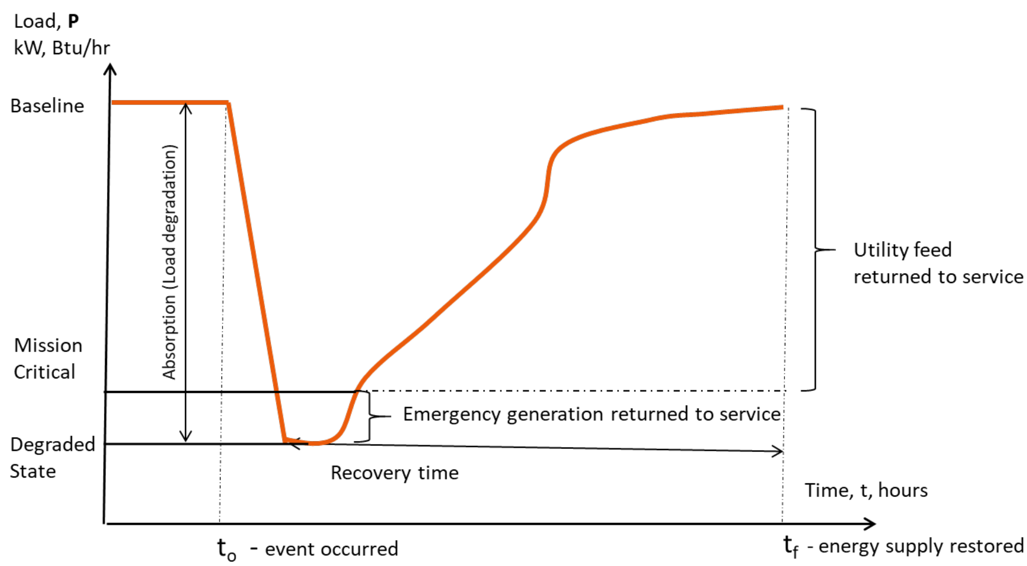


Figure 3-5. Stepped recovery of power system assets.

If one considers the step-change model illustrated in Figure 3-5, it becomes apparent that the recovery time for the system can be approximated using the mean time to repair (MTTR) for the various affected components. However, designers, planners, and facility managers must use caution when using MTTR to anticipate recovery time following a contingency event. MTTR data is typically based on failure modes that occur during normal (blue sky) operation. Contingency events may cause different failures to occur, and additional logistics delays must be considered based on the nature of the event and the location of the site. To determine the recovery time for a system, Maximum Time to Repair (MaxTTR) data should be used as an input to an evaluation of the disaster recovery plan.

3.3. Maximum Allowable Downtime

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

While much discussion and research have focused on the resilience of electric energy systems, the resilience of thermal energy systems is especially important for extreme climate locations. Resilience requirements for a thermal system comprised of energy conversion, distribution, and storage components depends on the thermal parameters necessary for one or several of the following purposes:

- Performance of required work in a building in a safe and efficient manner (habitability),
- Support for processes housed in the building, and
- Provision of conditions required for long-term “health” of the building itself (sustainability).

MaxTTR of thermal systems serving a building can be defined in terms of how long the process can be maintained or the building remains habitable or protected against damage to water pipes, sewer, fire suppression systems, sensitive content, or mold damage during the extended loss of energy supply from extreme weather events. The analysis presented in Chapter 8 shows that major factors that affect the time when the internal temperature reaches the threshold of building habitability or sustainability include

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

Also, the thermal mass of building structures composed of concrete, masonry, or stone materials that constitute high levels of embodied energy enables the building to absorb and store heat to provide “inertia” against temperature fluctuation and allows an increase in the time allowed for the thermal system to be repaired. Thermal Energy Storage (for cooling and heating) can add a few more hours or even days.

National requirements for building envelope characteristics, e.g., thermal insulation values of its components, building envelope airtightness, vapor permeability, building mass, detailing, etc., are usually based on economic and environmental considerations. Thermal energy system resilience consideration brings another dimension to the optimization process of these parameters.

CHAPTER 4. BUILDING ENCLOSURE

4.1. Introduction

The hot-and-humid-climate zone encompasses a broad swath of the world, from coastal to inland, and island to mainland locations. As explained in Chapter 1, hot and humid climates have some unique construction and enclosure-related challenges, that can be summarized in the following four categories:

- High ambient temperature, humidity, and associated dewpoint
- Long and intense rainy periods, including tropical storms or hurricanes/typhoons
- Tidal flooding, tsunamis
- Corrosion caused by salt-laden, moist sea air.

Historically, buildings have been built to respond to and address local climate conditions through the use of locally available materials and passive strategies. For example, Pacific Islanders used palm trees and other available materials to build elevated shelters on stilts to leverage locally abundant materials and mitigate high water and flooding issues. In the southern United States, buildings were built of lumber and brick to leverage the locally abundant forests and clay. Before air-conditioning was introduced for cooling, buildings in this climate were designed to leverage natural ventilation. Passive design techniques such as large openings for increased ventilation, towers to support stack effect, protruding eaves for shading, and positioning on the site were incorporated to reduce solar heat gain and maximize prevailing winds.

As air-conditioning became available and adopted as common practice across these climates, passive cooling principles that increased the construction cost were deemed unnecessary and new issues began to emerge. To sustain the supply of cool conditioned air in interior spaces, the building envelope became increasingly closed off to limit natural ventilation. Cool conditioned air within these buildings, in parallel with other design changes, created temperature gradients between the interior and exterior and as a result, issues with indoor air quality (IAQ) and mold/mildew increased. These issues were a result of a combination of factors, particularly condensation due to inadequate improvements to the existing building enclosure to account for the decreased interior temperatures and general lack of an airtight enclosure.

Old unimproved, and even some new building enclosures allowed for infiltration of moist unconditioned outside air into the conditioned interior spaces. In these instances, where humid unconditioned air met interior cold surfaces (cooler than the exterior dewpoint), condensation occurred. This condensation resulted in water trapped in organic construction materials that then supported the growth of mold. Mold and mildew issues continue to plague modern buildings even with better methods of condensation control and moisture management. Mold and moisture within buildings are discussed further in Section 1.4.1.

High ambient temperatures coupled with ultraviolet (UV) radiation have been found to accelerate the physical and chemical breakdown of many construction materials, thereby decreasing the building's expected lifespan. To address this, climate-appropriate materials for roofing membranes, sealants, etc., need to be specified in the design and used in construction.

The site grading and enclosure design can minimize the exposure of exterior walls to rain by diverting stormwater runoff on the surface away from the building and deflecting falling water with deep overhangs and drip edges. The incorporation of a drainage plane and ventilation space within the wall between the cladding and the water control layer, also called a "rain-screen system," helps minimize the risk of water infiltration.

When bulk water enters the building in the event of flooding, it brings with it all manner of salt, particulates, sand, waste, etc. For this reason, construction in areas designated at high risk of flooding should avoid designing occupied spaces below grade and may consider elevating the structure above grade. Construction materials should be carefully considered in flood-prone areas, for example, following flooding, surfaces often need to be abrasively cleaned or power washed. Wall assemblies that are not moisture sensitive, such as cast-in-place concrete and concrete block, are easier to clean and should be used instead of steel or wood framing and exterior gypsum sheathing products.

Corrosion-related issues are discussed in Chapter 1 (section 1.5). The solutions offered in this chapter help to increase the building's life and prevent the early replacement of certain elements of the enclosure.

Many of the conditions that affect these climates are similar, predominantly high humidity and temperatures, along with extreme weather events (although these conditions may manifest differently across these locations). This climate zone also represents many different architectural building solutions that have been developed and adapted to the local climates by local inhabitants, explorers, and immigrants over many years.

Good building science principles are best practices that must be followed by building designers, contractors, and operators to successfully solve these issues. This is especially critical as more stringent energy and IAQ requirements are being introduced. This chapter summarizes the best practice recommendations for the building enclosure characteristics of buildings located in hot and humid climates. The outlined recommendations are provided to direct the designer toward paths that better manage moisture and durability concerns unique to these climates and toward approaches to design and improve buildings to resolve the issues discussed in Chapter 1 with particular attention to improving IAQ by reducing mold and mildew and improving building energy performance, durability, efficiency, and resiliency.

4.2. Typical Construction Archetypes

Significant experience regarding building archetypes specific to hot and humid climates has been collected from the U.S. Army Corps of Engineers (USACE). Throughout the years USACE has designed, improved, and maintained buildings adapted to local conditions and developed best practices through lessons learned. USACE Mobile (SAM) and USACE Honolulu (POH) Districts contributed their unique experience and knowledge of installations within hot and humid climates to this Guide and provided information on building archetypes that are the most suitable for this climate.

USACE outlined three types of primary structural systems per their best practices to be used as common construction strategies in hot and humid regions based on their physical characteristics, ease of construction, availability, cost, and durability (see Appendix A):

- Concrete (CMU, cast-in-place, ICF, precast)
- Steel-framed with infill steel stud walls
- Pre-engineered metal buildings.

Note that, within this climate, cellulose-based materials such as wood have been avoided because historically, they have resulted in durability issues related to mold, rot, and damage from insects. This does not mean that wood-based materials should not be used. To its credit, it is readily available, cost-effective, and can be used in a wide variety of ways. However, in a tropical climate, the material's inherent properties make it a less than ideal choice, and therefore construction with wood materials is not included in this Guide. Occasionally, retrofits of existing wood structures are identified. In these cases, with good design and building science principles, wood buildings can be retrofitted as energy-efficient durable buildings.

The three superstructures that are reviewed in this Guide still require careful design for hot and humid climates, as the high risk of wetting, and typical salt-laden air of the coastal areas can still cause issues such as corrosion of concrete reinforcement and exposed steel. Unfortunately, with the challenging demands of hot and humid climates and coastal environments, none of these typical archetype superstructures are low carbon.

A series of schematic construction details presented in section 4.10 illustrates the key details at enclosure penetrations and transitions for all three superstructure options. Each detail focuses on the continuity of the control layers for rain, air, vapor, and heat (thermal), and includes building science notes to explain the design intent. The cladding will not be the focus of the details, because with correct detailing any cladding can be placed on any superstructure. In many of the provided details, all critical design information pertains to the exterior of the structure. Therefore, the specifics of the superstructure are not as relevant to the overall enclosure design strategy concerning the control of rain, water, air, and vapor.

4.3. Building Energy Requirements

Understanding the development and purpose of energy codes over the years allows designers and planners to better visualize an installation's existing building portfolio, which will assist in the development of retrofit approaches, local best practices for O&M, and the design of new high-performing buildings. This evolution is visible through the development of the ASHRAE Standard 90.1 (ASHRAE 2016a).

For many years, energy and operation costs were a major driver behind requirements to the building design, its operations, and maintenance. Before the 1970s, building energy usage was less of a concern due to low energy costs and abundant supplies of fossil fuels. The oil embargo of 1973 changed all that and ushered in a new era of energy conservation when the Organization of Petroleum Exporting Countries (OPEC) oil embargo pushed oil prices up by nearly 350%. Oil shortages and subsequent cost increases were felt across all energy sectors, especially gas and electricity. As a result, energy conservation in a buildings' performance and construction began in earnest as the era of "cheap fuel" was coming to an end across the United States and the rest of the world. Demand reduction was necessary. This is even more important today as climate concerns around the world increase.

To achieve reductions in energy usage, better-performing building enclosures and mechanical systems were needed. To regulate the design and retrofit of buildings, energy and building codes and associated standards were developed by governing bodies and organizations to specify new building performance requirements. These new standards outlined the increased performance of the building enclosure concerning thermal requirements, airtightness, and fenestration. One of the first publications of ASHRAE's Standard 90 in 1980 (ASHRAE 90a-1980) provided minimal U-values (prescriptively or by calculation) for the enclosure and for slabs on grade as listed in Table 4-1. The typical air leakage rate of buildings built at that time (per information provided by the National Institute of Standards and Technology [NIST]) was about 1.2 cfm/ft^2 at 0.01 psi (75 Pa) (17 m^3/h/m^2 at 50 Pa) of pressure difference across the building envelope.[*] Solar heat gain coefficients were also specified for fenestration.

Table 4-1. Minimum requirements to thermal properties of the building envelope in hot and humid climates (adapted from ASHRAE90a-1980).

Pre-1980	0A[*]	1A	2A	3A
Insulation Above Deck	R-9.22 ci	R-9.22 ci	R-9.22 ci	R-9.22 ci
Mass wall	U 0.58 / NR	U 0.58 / NR	R 3.498 ci	R 3.594 ci
Steel-Frame Wall	R-7	R-7	R-7	R-7
Windows	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22
where SHGC is "Solar Heat Gain Coefficient"				

ASHRAE Standard 90a-1980 (ASHRAE 1980) was just one of the first efforts to improve building performance. These standards undergo continual revision to push building performance further and capture current knowledge. This process was highlighted in the more recent revisions to ASHRAE Standard 90.1 in 2013 (ASHRAE 2013) currently referred to by *Energy Efficiency Standards for the Design and Construction of New Federal Commercial and Multi-Family High-Rise Residential Buildings* (10 CFR-433) (Table 4-2) and in the latest version published in 2019 (ASHRAE 2019b) (Table 4-3). In this version of the standard, insulation requirements for hot and humid climate have not changed much over the years since the 2013 standard, but airtightness and fenestration requirements have evolved due to a better understanding of the effects of air leakage on the building performance and issues with IAQ as well as heat gain through the fenestration. However, there was a significant evolution of requirements for fenestration (both for U-value and solar heat gain coefficient (SHGC) in hot and humid climates (Table 4-3).

[*] Cubic Feet per Minute (CFM)

Table 4-2. Minimum requirements for thermal insulation in hot and humid climates (adapted from ASHRAE Standard 90.1-2019c, Tables 5.5-0 to 5.5-3).

Recommended Thermal Insulation								
Climate Zone	**0**		**1**		**2**		**3**	
	Min. (R-value)	**Max. (U-value)**	**Min. (R-value)**	**Max. (U-value)**	**Min. (R-value)**	**Max. (U-value)**	**Min. (R-value)**	**Max. (U-value)**
Roof								
Ventilated Attic	R-38	U-0.027	R-38	U-0.027	R-38	U-0.027	R-38	U-0.027
Exterior Continuous Insulation	R-20 c.i.[2]	U-0.048	R-20 c.i.[2]	U-0.048	R-25 c.i.[2]	U-0.039	R-25 c.i.[2]	U-0.039
Metal Building[1]	R-10 c.i.[2] + R-19	U-0.41	R-10 c.i.[2] + R-19	U-0.41	R-10 c.i.[2] + R-19	U-0.41	R-10 c.i.[2] + R-19	U-0.041
Walls								
Mass (concrete)	NR	U-0.580	NR	U-0.580	R-5.7 c.i.[2]	U-0.123	R-7.6 c.i.[2]	U-0.123
Metal Building	R-9.8 c.i.[2]	U-0.094	R-9.8 c.i.[2]	U-0.094	R-9.8 c.i.[2]	U-0.094	R-9.8 c.i.[2]	U-0.094
Steel-framed	R-13	U-0.124	R-13	U-0.124	R-3.8 c.i.[2] +R-13	U-0.084	R-5 c.i.[2] +R-13	U-0.077
Wood-framed and other	R-13	U-0.089	R-13	U-0.089	R-13	U-0.089	R-13	U-0.089
Below-Grade Walls	NR	U-1.140	NR	U-1.140	NR	U-1.140	NR	U-1.140
Slab on Grade								
Unheated	NR	F- 0.730	NR	F- 0.730	NR	F- 0.730	NR	F- 0.730
Heated	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.	F-1.020	R-10 for 24 in.	F-0.900	R-15 for 24 in.	F-0.900

[1]When using the R-value compliance method for metal building roofs, a thermal spacer block is required (See ASHRAE Standard 90.1-2019, section A2.3.2)

[2] "c.i." denotes continuous insulation without significant thermal bridging of structure

Table 4-3. Window specifications from different ASHRAE 90.1 standards.

Year of Construction	Climate Zone			
	0A	1A	2A	3A
Pre-1980	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22
2010	SHGC 0.25 / U 1.2	SHGC 0.25 / U 1.2	SHGC 0.25 / U 0.7	SHGC 0.25 / U 0.65
2013	SHGC 0.25 / U 0.57	SHGC 0.25 / U 0.57	SHGC 0.25 / U 0.57	SHGC 0.25 / U 0.50
2016	SHGC 0.22 / U 0.50	SHGC 0.25 / U 0.57	SHGC 0.25 / U 0.54	SHGC 0.25 / U 0.49
2019	SHGC 0.22 / U 0.50	SHGC 0.23 / U 0.50	SHGC 0.25 / U 0.45	SHGC 0.25 / U 0.42

Exceeding current energy performance standards is an integral component in the effort to create better buildings, improve IAQ, and provide longer-lasting, more sustainable buildings. Moreover, 10CFR 433 currently directed the U.S. Department of Energy (DOE) to develop requirements for commercial and low-rise multi-family residential buildings to realize energy consumption levels at least 30% below those established by ASHRAE Standard 90.1-2013 to achieve a life-cycle cost-effectiveness. To put high-performance buildings on a path to net zero, a building would need to be designed to perform at least 30% better than ASHRAE 90.1-2019 (Table 4-4)

Table 4-4. Minimum requirements for thermal insulation in hot and humid climates.

Recommended Thermal Insulation*								
Climate Zone	0		1		2		3	
	Min. (R-value)	Max. (U-value)	Min. (R-value)	Max. (U-value)	Min. (R-value)	Max. (U-value)	Min. (R-value)	Max. (U-value)
Roof								
Ventilated Attic	R-38	U-0.027	R-38	U-0.027	R-38	U-0.027	R-38	U-0.027
Exterior Continuous Insulation	R-25 c.i.[2]	U-0.039	R-20 c.i.[2]	U-0.048	R-25 c.i.[2]	U-0.039	R-25 c.i.[2]	U-0.039
Metal Building1	R-10 c.i.[2] + R-19	U-0.41	R-10 c.i.[2] + R-19	U-0.41	R-10 c.i.[2] + R-19	U-0.41	R-10 c.i.[2] + R-19	U-0.041
Walls								
Mass (concrete)	NR	U-0.580	NR	U-0.580	R-5.7 c.i.[2]	U-0.151	R-7.6 c.i.[2]	U-0.123
Metal Building	R-9.8 c.i.[2]	U-0.094	R-9.8 c.i.[2]	U-0.094	R-9.8 c.i.[2]	U-0.094	R-9.8 c.i.[2]	U-0.094
Steel-framed	R-13	U-0.124	R-13	U-0.124	R-3.8 c.i.[2] +R-13	U-0.084	R-5 c.i.[2] +R-13	U-0.077
Wood-framed and other	R-13	U-0.089	R-13	U-0.089	R-13	U-0.089	R-13	U-0.089
Below-Grade Walls	NR	U-1.140	NR	U-1.140	NR	U-1.140	NR	U-1.140
Slab on Grade								
Unheated	NR	F- 0.730	NR	F- 0.730	NR	F- 0.730	NR	F- 0.730
Heated	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.	F-1.020	R-10 for 24 in.	F-0.900	R-15 for 24 in.	F-0.900

*Adapted from ASHRAE Standard 90.1 – 2019 Tables 5.5-0 to 5.5-3)

[1] When using the R-value compliance method for metal building roofs, a thermal spacer block is required (See 90.1 Section A2.3.2)

[2] "c.i." denotes continuous insulation without significant thermal bridging of structure

4.4. Building Science Primer – Review of the Building Enclosure

The building enclosure, sometimes referred to as the building envelope, is a system of materials, and assemblies that physically separates the exterior environment from the interior occupied space. The enclosure is comprised of several assemblies, including roofs, above-grade walls, soffits, windows, doors, below-grade walls, and slabs on grade. All the assemblies that form the enclosure must work together to control elements between the exterior and interior such as water, air, heat, water vapor, fire, smoke and embers, sound, insects, and others. A series of control layers within the enclosure assemblies to perform these functions, each intended to serve one or more functions within the building enclosure. By controlling all the necessary exterior elements, the durability of the enclosure and hence the sustainability of the enclosure can be maximized to greatly increase the serviceable life cycle of the building.

The four critical control layers to consider for enclosures in hot and humid climates are

- Water Control Layer*
- Air Control Layer*
- Vapor Control Layer
- Thermal Control Layer.

Due to the importance of water and air control, Unified Facilities Criteria (UFC) 3-101-01, *Architecture* (NAVFAC 2021a), Appendix 6.1 includes, as best practice, mockup testing of the air and water control layers in large facilities (above 50,000 ft [4,650 m^2] for common buildings, and

* The water and air control layers are the most critical of the four in hot and humid climates for long-term durability and building performance.

above 25,000 ft [2,325 m^2] for unique buildings). Mockups can be constructed separately from the building, but more commonly, an area of the building is closed off to perform air and water testing. Successful tests will set installation standards for the rest of the building. Another best practice included in UFC 3-101-01 states that a representative wall and window mockup be tested for air and water infiltration. Specifically, each system that contributes to moisture control and the air barrier must be included in the mockup. The installed fenestration must be field-tested using American Society for Testing and Materials (ASTM) E783 (2020) to determine their airtightness. ASTM E1105 (2016) can then be used to determine if fenestrations and their connections to walls are watertight.

4.4.1. Water Control

Water control is critical in every assembly of the enclosure, and at every transition between assemblies (i.e., roof to wall, wall to floor, etc.), and at other transitions (i.e., wall to window, roof to a skylight, etc.) and between different types of construction. Failure of the water control layer is often the reason for premature enclosure failure as a result of mold, rot, decay, corrosion, etc.

Water can affect the enclosure in different ways and different forms. The most common regular source of water is wind-driven rain, especially in coastal climates that can experience frequent heavy rain events. Liquid water can also affect the enclosure at and below grade as a splashback, surface runoff, flooding, and groundwater. Control of water in vapor form is also critical to the enclosure performance, although water vapor is typically handled by the air and vapor control layers. Lastly, plumbing-related failures can be a source of water in the enclosure, and while these can be significant, they are not considered in this Guide.

At a fundamental level, water control and increased enclosure durability start by minimizing exposure to water. At the roof level, this starts with ensuring a minimum slope of 2% on low-slope (flat roofs) or using a pitched-roof assembly to avoid standing water on the roof membrane. Overflow scuppers on flat roofs should be well designed and integrated into the roofing system and should not direct water onto the exterior of the wall assembly below the scupper. Overhangs should be used whenever possible to decrease exposure and concentration of water on the walls below. Collecting and draining as much water as possible away from the building through gutters and downspouts also minimizes water against the surfaces of the enclosure. Other strategies include landscaping and soil grading that directs surface runoff water away from the enclosure at grade, minimizing penetrations in the enclosure as much as possible, and avoiding below grade or sometimes even at grade construction (i.e., basements/crawlspaces or raising structure above grade) in new construction depending on the risk of flooding in an area.

At above-grade walls, the water control starts with the cladding, which is often referred to as the water-shedding surface. There are two main types of cladding, perfect barrier and rain screen. A perfect barrier system is designed to function as both the cladding and water control layer. In a rain-screen cladding system, the cladding is not expected to stop all the water, but typically stops a large percentage of the driving rain from passing further into the enclosure. The remainder of the water is stopped by the drainage space combined with the water control layer behind the cladding and a system of integrated flashings. In above-grade wall assemblies, this is typically a system of materials installed on the exterior of the structure that direct any water that reaches the water control layer (also sometimes referred to as a WRB, but should not be referred to as the more ambiguous “weather-resistive barrier”), to drain to the bottom of the wall or the head of penetration such as a window or a door where the water is directed to the exterior of the cladding by a flashing. The most durable wall design consists of a drained and ventilated cavity (sometimes referred to as a rain screen) behind the cladding to direct any water to the bottom of the drainage cavity, and back to the exterior. UFC 3-101-01, *Architecture* (NAVFAC 2021a), sections A-5.3.2 and A-5.3.4 (in Appendix A) requires an underlying drainage plane or WRB behind all claddings with flashings to lead water out from behind the cladding. The water control layer must be continuous across the entire building, including windows, doors, assembly transitions, and enclosure penetrations.

For large projects, it is recommended to specifically test the water control of transitions and penetrations at windows and doors early in the construction process (i.e., before cladding installation) at a performance mockup either separate from the building, or as part of the building under construction to ensure that the details used in construction are effective at controlling rainwater. Additional water tests as the construction progresses may be prudent depending on expected exposure, detail complexity, type of building, and consequences of failure.

Generally speaking, it appears from a review of provided construction details from U.S. Army projects that the water control layer on the walls is typically a self-adhered or fluid-applied membrane on the exterior of the sheathing in framed wall or metal building type structures, or directly against the concrete in CMU or cast-in-place concrete walls.

4.4.2. Air Control (Airtightness)

Overview

The air barrier, or air control layer, is a system of materials that control airflow between the interior conditioned space and the external environment and vice versa. The transition detailing between components is essential to the performance of the air barrier. Air leakage, infiltration or exfiltration, plays a large role in the movement of moisture in the enclosure, and also negatively impacts the energy performance of buildings.

It is well recognized that while the airtightness of individual enclosure elements is important, this alone is not sufficient to ensure that an airtight building enclosure is achieved. This is because critical air leakage locations are typically found at the interfaces between these elements and are highly dependent on design coordination and quality control throughout the construction process. As a result, more modern codes and standards have developed a preference for whole-building airtightness testing as a quality assurance measure to evaluate the adequacy of the as-built air barrier system.

The control of infiltration in hot and humid climates reduces the risk of interstitial condensation, and energy consumption for cooling and humidity control. Airtightness can also impact thermal comfort, IAQ, resistance to chemical attack, acoustic separation, and mechanical ventilation performance. (For more information about the effect of airtightness on HVAC sizing and performance, see Chapter 5.) Of increasingly noted importance is also the contribution of airtightness to thermal energy systems resiliency (see Chapter 7 for more details).

Airtightness testing of large buildings in cold climate regions has been used for research purposes since the early 1970s in Canada by the National Research Council, and later in the mid-1980s in the United States by the National Bureau of Standards, and in Great Britain by the Building Services Research and Information Association (Potter 1998). Since then, airtightness testing, called air permeability testing in Europe, has developed into a robust building enclosure commissioning industry and is used in conjunction with other commissioning tools to verify the airtightness of the building enclosure components and assemblies.

Whole-building airtightness testing is a functional way to quantify the building's air leakage rate, which is important for enclosure durability, energy efficiency, and thermal resiliency. However, air leakage testing only reveals the air barrier's overall performance, so individual air leaks that can cause localized moisture damage can still be present in a building that receives very good airtightness test results. Therefore, airtightness testing should be used as only one part of a comprehensive quality control/quality assurance program, which also includes air barrier design review, air barrier inspections, and diagnostic airtightness testing in combination with infrared thermography.

Air barrier design reviews should be performed to ensure that the construction documents are complete and correct regarding the construction of a continuous air barrier across the entirety of the building enclosure as well as specifications that will ensure that appropriate and compatible materials will be installed. Missing, incomplete, incorrect, or unconstructible air barrier details are very common in design and can lead to poor air barrier installations. Air barrier inspections should occur during construction to ensure that proper materials and installation techniques are being used, and they should follow Air Barrier Association of America (ABAA) guidelines. Inspections should include the observation and testing of a significant sample of details that cover the typical weaknesses in the air barrier, including all transitions in geometry and materials. Finally, additional tools such as infrared thermography and theatrical smoke should be used, when possible, to locate and qualitatively ascertain the magnitude of air leaks. While it is not possible to have a perfect air barrier, a high-performance air barrier (necessary for enclosure durability) is very much possible with proper design and construction quality control measures.

Requirements for the Air Barrier

Since 2009, USACE has implemented an airtightness requirement in all new construction and building envelope renovation projects. Engineering and Construction Bulletin (ECB) 2012-16 (USACE 2012) set levels of airtightness for building envelopes at the material, assembly, and system-level having a maximum air leakage of 0.25 cfm/ft^2 at 0.3 inches of water column (in. wc) (4.6 m^3/h/m^2 at 75 Pa) for the six-sided building envelope (Zhivov et al. 2014). This airtightness requirement is comparable to England's H.M. Government Non-Dwelling Building Code Regulation, 2010-16 L2a, which currently requires 0.21 cfm/ft^2 at 0.3 in. wc (3.8 m^3/h/m^2 at 75 Pa). USACE Engineering and Construction Bulletin (ECB) 2012-16 references many ASTM, International Organization for Standardization (ISO), and other related publications as the basis for how USACE projects are to use air leakage testing and thermal imaging for building envelope commissioning requirements. The implementation of these building envelope airtightness requirements over the past several decades for Department of Defense projects has drastically improved the level of understanding, design considerations, and construction methods of air barriers in the United States. Improvements in design, air barrier products, and installation practices have occurred during each construction cycle since 2009, resulting in a progressive learning curve for all parties involved (Leffel 2021).

Zhivov et al. (2014) reported that the average for the first 200 USACE building envelope tests was as low as 0.17 cfm/ft^2 at 0.3 in. wc (3.1 m^3/h/m^2 at 75 Pa). These test results combined with additional data from PIE (2021) show that the average air leakage of a small sample of tested military facilities located in hot and humid climates to be as low as 0.15 cfm/ft^2 at 0.3 in. wc (2.8 m^3/h/m^2 at 75 Pa).

A review of test results conducted in hot and humid climates shows examples of projects with air leakage results below 0.25 cfm/ft^2 at 0.3 in. wc (4.6 m^3/h/m^2 at 75 Pa) more specifically, close to 0.15 cfm/ft^2 at 0.3 in. wc (2.8 m^3/h/m^2 at 75 Pa) that had observable air leakage pathways at major air barrier transitions. Thermal images shown in Figure 4-1 show thermal images of multiple buildings that achieved a test result better than 0.15 cfm/ft^2 at 0.3 in. wc (2.8 m^3/h/m^2 at 75 Pa), and which still experience significant air leakage signatures.

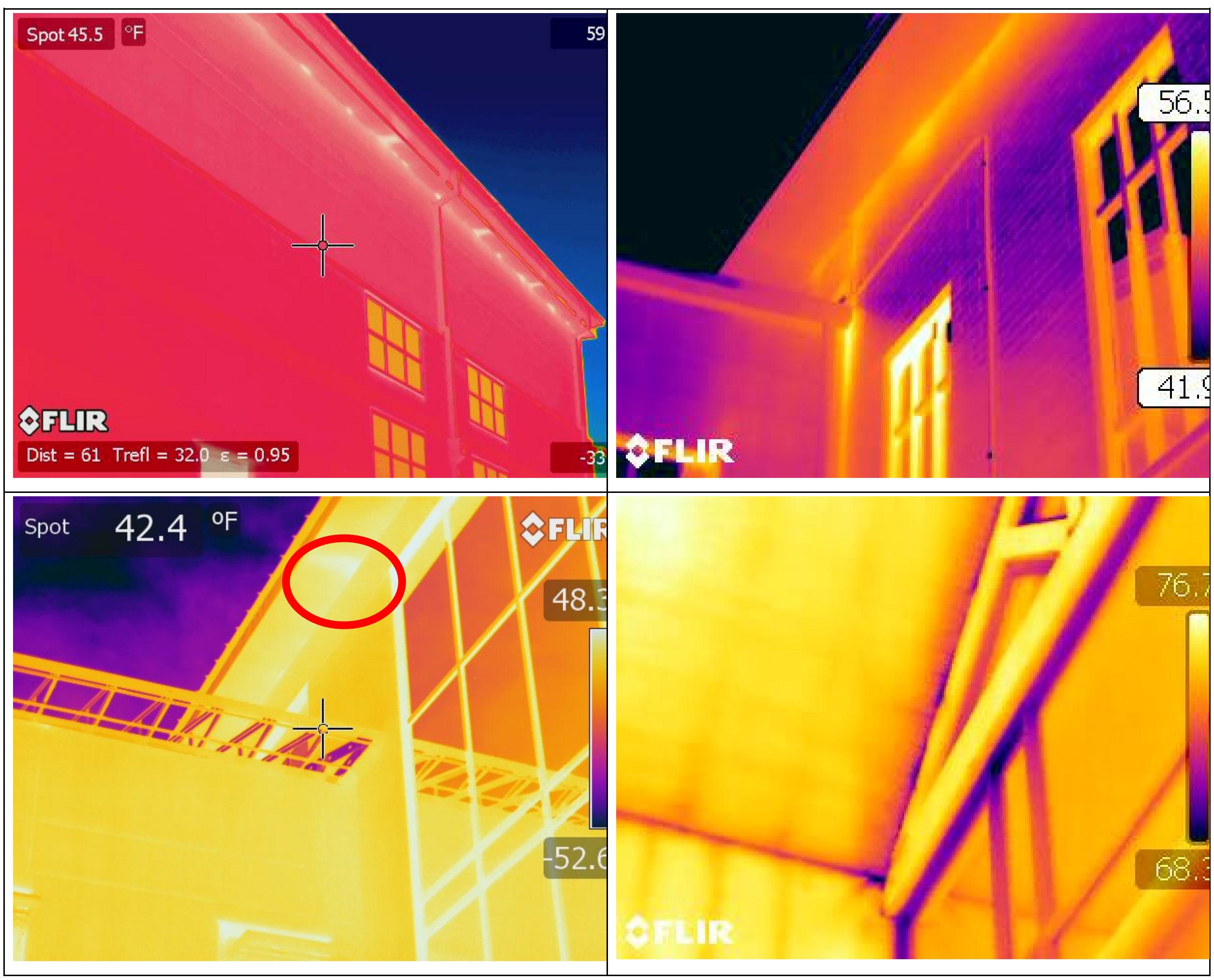


Figure 4-1. Examples of air leakage observed at soffit transition: from outside (top left, top right, bottom left), and from interior (bottom right).

Soffits create a difficult air barrier transition because the primary air barrier of the roof system is above the roof deck and must continue past the wall air barrier as far as the roof does. This leaves two options, adding additional sheathing to provide a substrate for an air barrier material to wrap the underside of the soffit or the air barrier at the wall must be terminated to the underside of the roof deck, which is not where the roof air barrier is located. In some instances, such as fluted metal decks, the flutes can be individually filled with sprayed polyurethane foam, which may transition the air control from the wall to the roof depending on the specific details.

While not as common as air leakage through soffits, parapet transitions have also been observed to be a source of air leakage when the roof membrane is not properly wrapped over the face of the wall to the air barrier on the exterior.

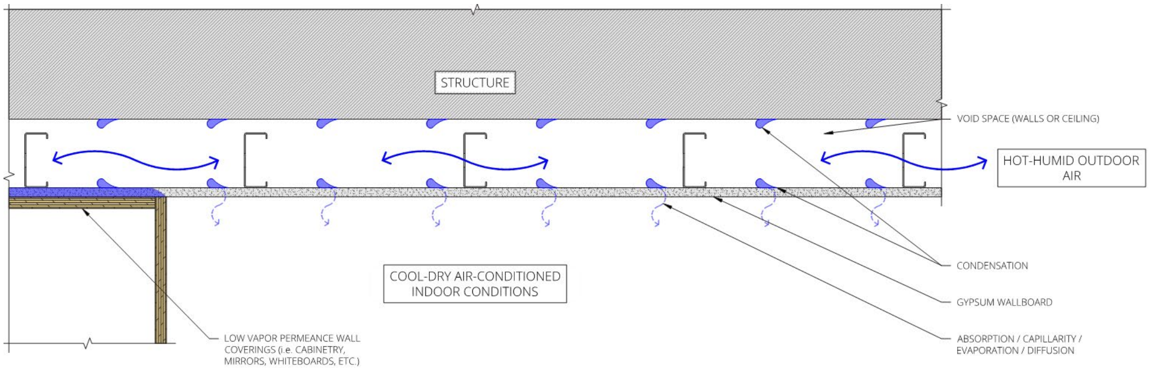
Building durability, IAQ, energy savings, and thermal resilience justify the need for more airtight building enclosures in hot-and-humid-climate regions, and highlight the need for more stringent requirements for building airtightness. For these reasons, it is recommended that the maximum airtightness requirement for hot-and-humid-climate regions be reduced to 0.15 cfm/ft^2 at 0.3 in. wc (2.8 m^3/h/m^2 at 75 Pa) for normal indoor RH conditions. Table A-4 lists a sample of test results of buildings located in a hot and humid climate, conducted in accordance with ASTM E779 (ASTM 2019b). It includes results from 28 buildings tested by PIE Consulting and Engineering between 2012 and 2021 alongside 18 additional building results previously published in (Zhivov et al. 2014).

Ensuring Airtightness in Hot and Humid Climates

Typically, several different materials, joints, and assemblies are combined to provide an uninterrupted plane of primary airflow control. Regardless of how air control is achieved, the air barrier system (ABS) should meet the following five criteria:

1. **Continuity.** This is the most important and most difficult criterion.
2. **Strength.** The ABS must be designed to transfer the full design wind load to the structural system.
3. **Durability.** The ABS must continue to perform for its service life. Exposure can be minimized by protecting the ABS with exterior continuous insulation.
4. **Stiffness.** The ABS must be stiff enough so that deformations do not change the air permeance and/or distribute loads through unintentional load paths.
5. **Impermeability.** The ABS must be impermeable to air.

In hot and humid climates, the common risk of air enclosure leakage is that exterior air will infiltrate through the air barrier of the enclosure into the void spaces in the walls and ceilings to the cooler air-conditioned side of the enclosure, which can be below the dewpoint of the exterior air for most of the year. This means that the air infiltrating through the enclosure will reach elevated sustained RH levels and is likely to reach 100% RH as it cools, resulting in condensation on the surfaces and components (Figure 4-2). Since this can result in durability issues with any enclosure system, airtightness on the exterior side of the enclosure is critical to avoid these issues. Figure 4-3 shows a photo of an investigation of a tall building in a hot and humid climate with substantial deficiencies in the ABS. The hot-humid air was drawn into the void spaces in the walls, and moisture accumulated in the void space, and the interior drywall resulted in unpleasant odors. The wall cavity had significant moisture staining and organic growth, and the accumulated moisture on the interior was visible once the cabinetry was removed (Figure 4-3).



Source: RDH Building Science Inc.

Figure 4-2. Schematic of air infiltration moisture problems in a hot-humid climate.

Source: RDH Building Science Inc.

Figure 4-3. Air leakage moisture damage in a hot-humid climate.

High-performance airtightness begins at the initial design stage. The UFC 3-101-01 requires that all air barrier components be clearly identified for each enclosure assembly on the construction documents, including the details at the joints, interconnections, and penetrations of the air barrier components. Detailed inspection and testing requirements and acceptance criteria must be included in the project specifications. Include United Facilities Guide Specification (UFGS) section 07.05.23 as part of the project specification when testing of the air barrier is required.

When possible, the barrier system should be tested using building pressurization and depressurization before the installation of interior and exterior finishes so improvements and repairs can be made in the ABS as required by the testing results.

Existing buildings, constructed before there was a focus on making buildings airtight, will most likely be very leaky and would benefit the most from energy and durability retrofits to reduce the air leakage to meet the energy, durability, and occupancy comfort requirements. On federal projects, a cost-benefit analysis is required to determine if the installation of an air barrier is feasible. The challenge with cost-benefit analysis is that it is difficult to assign costs to occupancy comfort and potential health improvements. Improving airtightness is one of the critical areas that retrofits should focus on to achieve both increased building durability and energy efficiency.

4.4.3. Thermal Insulation Control Layer

The thermal insulation layer controls heat flow across the enclosure and is important for the energy efficiency of the building and comfort within the building. Identifying the components of the thermal control system such as roof insulation, wall insulation, windows, etc. makes it easier to avoid thermal bridges and to ensure that the insulation aligns as well as possible across the different building assemblies, windows, doors, etc. Thermal bridges are less of an issue in hot and humid climates than they are in cold climates because the temperature gradients across the enclosure are typically less, although thermal bridges should still be minimized where possible. Hot and humid climates require less enclosure insulation for the following primary reasons.

1. The temperature gradient across the enclosure in hot-humid climates is generally much less than in cold climates, and the heat loss is directly proportional to the temperature gradient across the enclosure.
2. The main source of heat on the interior of most typical buildings in hot-humid climates is a result of solar heating through windows. This represents a much higher portion of the cooling demand than the heat through the opaque wall areas, even with minimal wall insulation.

Various methods for establishing minimum required insulation values in buildings exist. The simplest guidelines are those that establish a single minimum insulation value for buildings by climate zone, differentiating only between the walls, roof, and floor, with additional guidelines for windows and doors. Table 4-4 shows the minimum required R-values, or maximum required U-values for different enclosure components as per ASHRAE 90.1-2019. Changes to insulation requirements over time are less likely to be a result of a climate change (e.g., more or fewer degree days per year over time) as they are to be as a result of a change in priorities associated with environmental, energy, comfort, economic, or societal parameters. As a general trend, guidelines for minimum insulation values have increased and continue to do so. This increase in insulation values impacts both new construction and retrofits.

The range of prescriptive thermal insulation values considers energy guidelines, economic factors, and construction realities. It does not, however, address thermal resiliency. Thermal resilience as an input variable in the setting of insulation guidelines is a relatively new field that brings its own priorities. The effect of improved thermal insulation on thermal system resilience is addressed in Chapter 7.

Generally speaking, all research, building science knowledge, and hygrothermal simulations indicate that the best strategy for insulating a building is to install the insulation to the exterior of the structure and the other control layers. Wrapping the structure in insulation ensures that the insulation is continuous and that the structure and its control layers do not experience large temperature swings, thereby increasing its durability and longevity, and minimizing most thermal bridges. If the insulation is installed on the exterior of the structure, other important elements to consider are thermally broken cladding supports, flashings, and other penetrations. Note that installing exterior continuous insulation on buildings in hot and humid climates is not a historically typical insulation location, especially in CMU or concrete structures. It has been more common historically to install continuous insulation directly on the interior surface of the structure and coat the exterior of the concrete against water intrusion. However, a review of some recent architectural drawings from USACE locations has demonstrated that exterior insulation has become more common in hot and humid climates for improved enclosure durability and longevity.

The thermal control layer or insulation is conceptually easy as part of the opaque enclosure, walls, roof, slab, etc. However, other large areas of the enclosure such as fenestration must also provide thermal control for the interior space. In hot and humid climates, the window specifications generally play a more significant role in the thermal control because, depending on the window to wall ratio, windows are often a much larger source of interior heating as a result of convection across the window, and solar energy passing through the window to the interior. Windows are a very necessary component of the enclosure but can lead to overheating in most climate zones for large portions of the year. Window specifications are also reviewed and discussed below in section 4.6.

4.4.4. Vapor Control

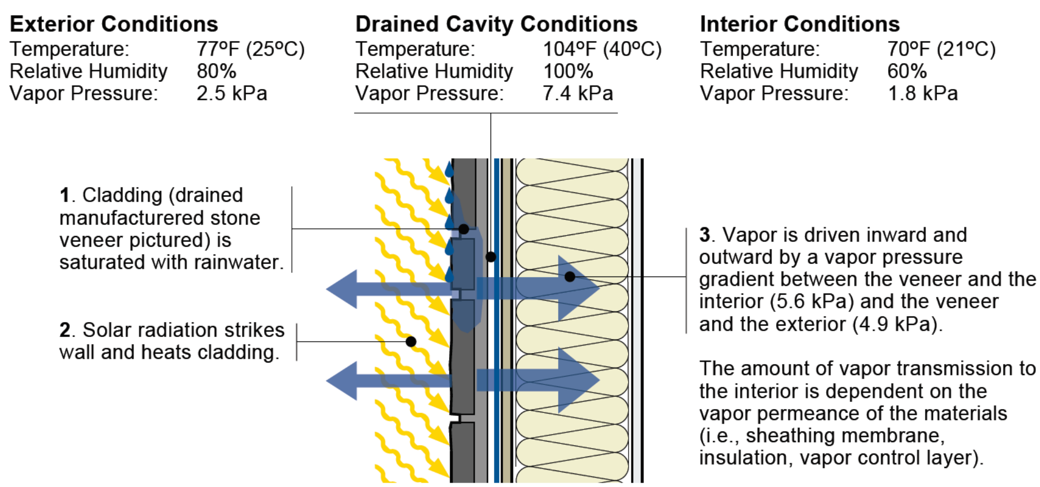
Vapor control must be considered when designing a building in a hot and humid climate, although a vapor barrier/retarder may not be required, depending on the enclosure materials chosen for each assembly. To clarify, a vapor retarder/barrier is defined by the 2021 International Building Code, , as a material or assembly's ability to limit the amount of moisture that passes through it. It divides vapor retarders into three classes, Class I (0.1 perm of less), Class II (0.1<perm≤1.0 perm) and Class III (1.0<perm≤10 perm). Only Class I is considered a vapor barrier. Recent improvements to the code provide options for use of specific vapor retarder classes at the interior side of walls based on climate zone. This is especially useful when designing in hot and humid climates because, IBC Table 1404.3(2) "Vapor Retarder Options," for example, clearly states Class I and II vapor retarders are not permitted to be installed on the interior side of frame walls for climate zones 1 and 2. Alternatively, air barrier materials could be used in this instance, because it would allow vapor to escape the wall assembly. According to IECC 2021, C402.5.1, the air barrier is made up of materials with an air permeability not greater than 0.004 cfm/ft^2 and can be located on the inside or outside of the building thermal envelope. In comparison to vapor retarders, an air barrier is a material with a perm rating greater than 10 perms.

Table 4-5. Vapor retarder options.

Climate Zone	Vapor Retarder Class: I	II	III
1, 2	Not Permitted	Not Permitted	Permitted
3, 4 (except Marine 4)	Not Permitted	Permitted	Permitted
Marine 4, 5, 6, 8	Permitted	Permitted	See Table 1404.3(3)

Source: Table 1404.3(2) at https://codes.iccsafe.org/content/IBC2021P1/chapter-14-exterior-walls (also see at Table 1404.3[3]).

As mentioned previously in section 4.4.2, air leakage across the enclosure can move orders of magnitude more water vapor than vapor diffusion, but vapor diffusion in hot and humid climates can still cause enclosure durability issues. The primary concern in hot climates for water vapor in the enclosure is solar-driven moisture resulting from water absorbed into absorptive cladding such as brick veneers and adhered masonry. When a cladding becomes wetted and is then heated by the sun, the vapor pressure of the cladding or the space behind the cladding can increase significantly, and moisture is driven toward the interior. For example, in the simplified schematic shown in Figure 4-4, the vapor pressure in the masonry reaches 7400 Pa, which is significantly higher than the interior conditions of 1800 Pa, so there will be a significant gradient and vapor pressure drive from the masonry to the interior space, and the amount of vapor that diffuses through the enclosure will be determined by the vapor permeance of the layers. Because of the typical frequency of alternating wetting, and sunny periods in hot and humid climates, this relatively constant source of water can be a concern. If there is a vapor barrier installed on the interior side of this type of assembly, moisture will collect at that layer, resulting in moisture-related deterioration issues. This has been a well-known and documented issue in hotels with vinyl wallpaper in the southern United States. However, other low-permeance materials installed on the interior of the assembly such as cabinetry, mirrors, and whiteboards have also resulted in moisture accumulation and mold in the interior space in hot-humid climates. As such, the best practice is to install any interior low-permeance items such as cabinetry, etc. on vertical strapping over the interior drywall of enclosure walls to allow natural ventilation to remove the moisture between the drywall and interior finishes.



Source: RDH Building Science Inc.

Figure 4-4. Solar inward vapor drive schematic with an absorptive cladding.

It is important to always have a continuous air control layer in the enclosure in all climate zones, but it is more common to construct a wall assembly in a hot and humid climate without a vapor barrier, provided that none of the building materials are moisture sensitive and all the materials are sufficiently vapor permeable to allow the vapor to flow through easily and not accumulate within the enclosure. Figure 4-5 shows moisture trapped by an interior vapor barrier. Of course, vapor moving to the interior still must be removed from the HVAC system, and there are risks associated with future programming changes to the space without consideration for the existing enclosure design. Therefore, it is a long-term lower-risk alternative to install a low vapor permeance layer near the exterior of the enclosure to minimize the moisture within the enclosure for the life of the building. This low-permeance layer is often a vapor impermeable self-adhered membrane but could also be a fluid-applied membrane or even certain types of continuous exterior insulation such as closed-cell medium-density spray foam, extruded polystyrene (XPS), or foil-faced polyisocyanurate (polyiso).

Figure 4-5. Moisture trapped by an interior vinyl wallpaper vapor barrier.

Section 4.5 discusses special considerations regarding the vapor barrier for internal walls separating mission-critical spaces with cooling requirements from other building spaces during emergency (black sky) situations.

4.5. Roof, Wall, and Floor Assemblies

As stated earlier, the building enclosure is a system of materials, components, and assemblies that physically separates the exterior and interior environments. It comprises various elements including roofs, above-grade walls, windows, doors, skylights, below-grade walls, and floors, which in combination must control water, air, heat, and water vapor (and which were all discussed in detail earlier). The enclosure must also control other things that are not included in this book such as fire, smoke, insects, sound, etc. Additionally, the building enclosure is an aesthetic element of the building. Each of these functions must be included in the design of the building enclosure assemblies discussed in the following sections.

Figure 4-6 shows some simplified schematics of a slab on grade, wall assembly, and roof assembly illustrating the principle of exterior continuous insulation on the exterior of the structure and the control layers for increased energy efficiency, durability, and resiliency.

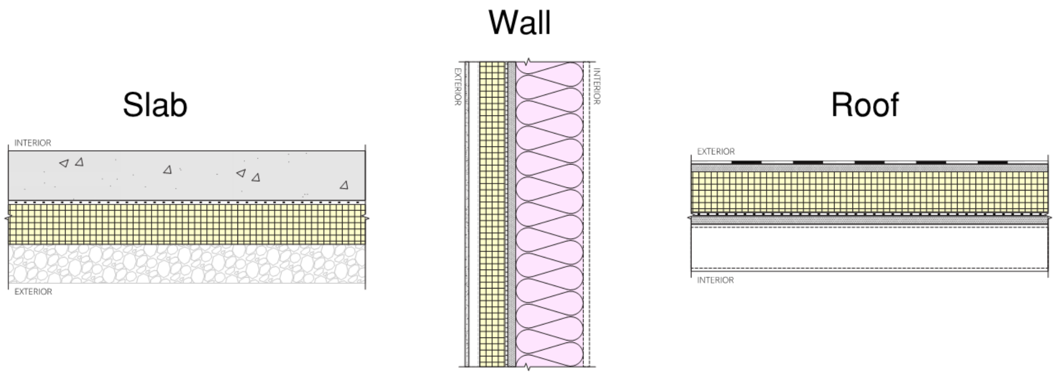


Figure 4-6. Schematics for continuous exterior insulation in the enclosure.

4.5.1. Roofs

For all buildings, there are two main roof types, sloped (or pitched) and flat (low-slope, approximately 2% slope). The type of roof on a building is dependent on the type of superstructure, and the architectural design of the building. Both types of roof assemblies can be designed and constructed to be durable and high performance, although sloped roof assemblies, by their nature, drain away the water by gravity at a higher rate and are therefore less risky than a flat or low-slope roof assembly, where water often remains on the roof membrane for long periods. High levels of UV radiation, as well as potentially corrosive coastal environments, can accelerate the aging and deterioration of roof membranes and should be inspected regularly for degradation. The design of roof assemblies in hot and humid climates is not much different from code-compliant roof designs in all other parts of the country.

In many parts of the country, pitched roofs are ventilated, which means that the thermal control layer (insulation) is installed across the horizontal ceiling plane, such that there is a large volume of unconditioned air between the underside of the roof deck and the ceiling insulation. Per local building code, vents are installed at the eave soffits and near the ridge to allow air to move through the attic to remove moisture and heat from the attic. In hot and humid climates, particularly in coastal areas, or where storms are expected, ventilated attics are not recommended because the air being brought into the attic can be very humid and corrosive, which can result in risks of moisture accumulation, deterioration, and decay of wood structures as well as corrosion of metal systems and fasteners. To avoid this, it is recommended to include the attic space in the conditioned space. Moreover, the attic space is a common location for HVAC equipment and ductwork to distribute conditioned air. By keeping the equipment within a conditioned attic and therefore within the thermal control layer of the enclosure, the HVAC will have significantly less energy loss to the environment, and will not be exposed to highly humidity and potentially salt-laden air.

If possible, the best option for an unvented roof assembly is to install the insulation on the exterior of the structure to protect the structure and the air control layer. Figure 4-7 shows schematics for both a low-slope and pitched-roof assembly with exterior continuous insulation. The low-slope roof assembly would be essentially the same installed over a concrete deck instead of a metal deck. The cladding attachment for the pitched-roof assembly would depend on the design, roofing choice, and expected wind loads of the building.

Alternatively, if exterior insulation is not practical or possible, then an unvented roof assembly can be constructed with spray foam installed directly to the underside of the steel or concrete roof deck as illustrated in the construction details section (section 4.10).

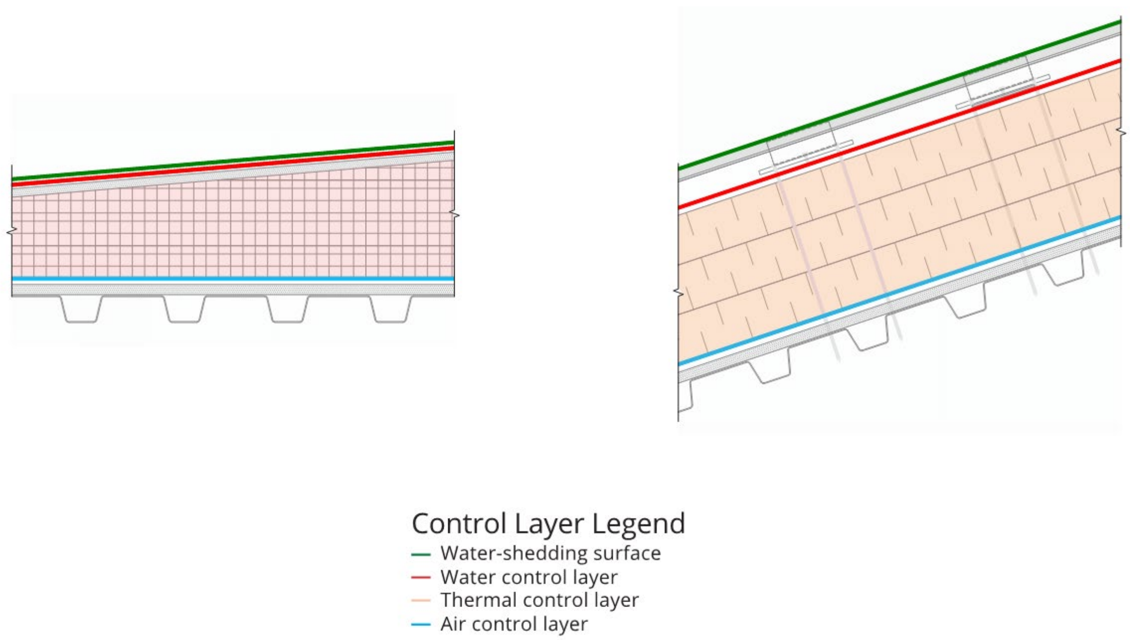


Figure 4-7. Exterior-Insulated "flat" and sloped roof assemblies.

The roof membrane in a low-slope roof assembly is the primary water-shedding layer and the water control layer of the roof assembly, and as such is also installed to be air and vapor impermeable. In most roofing assemblies, an interior air control layer is also recommended to minimize air movement between the roofing space and the interior space. This assembly is suitable for all building archetypes in this book. An alternate approach is to use a protected membrane assembly, sometimes called inverted roof membrane assembly (IRMA), which has the benefit of protecting the membrane from extreme exterior environmental conditions and results in longer expected lifespans of roof assemblies. However, a protected membrane roof is not recommended for use in high wind regions as it is designed to allow some amount of drainage below the insulation. The assembly typically relies on weighing the insulation down with a load on the top surface, and the insulation is not adhered to or fastened to the structure, which may limit its design and use. In combination with the air and vapor control of the roof membrane, a secondary interior membrane should limit the air movement into the roof assembly. This secondary air barrier near the interior of the roofing assembly should be vapor permeable to minimize risks of condensation and moisture accumulation as it is typically on the cooler side of the enclosure.

The roofing membrane must be compatible with extreme heat and solar exposure and oftentimes, white, or brighter and more reflective roof colors are used to minimize solar heating of the roofing assembly. This can reduce temperatures in the roof assembly, but in some hot climates, the unintended side effect has been moisture accumulation in the roof assembly related to night sky radiative cooling, followed by lower than typical drying potential throughout the day, especially if the air barrier on the interior of the roof assembly is not continuous. Avoiding the use of air and vapor permeable insulation within the roof assembly will minimize this risk. The roof system must be designed and constructed for the anticipated wind loads in coastal regions including extreme wind events.

Sloped roofs should pursue similar exterior-insulated unvented strategies to reduce thermal bridging through the assemblies, and to bring moisture-sensitive structural elements within the conditioned space. This will reduce the moisture exposure and temperature cycling of these materials and contribute to building durability and maximum service life. Alternatively, if exterior insulation is not possible in a roof assembly, medium-density closed-cell spray polyurethane foam (SPF) could also be installed in a continuous manner directly to the underside of the roof sheathing to form an unvented high-performance roof assembly. The primary advantage of exterior insulation is that it minimizes thermal bridging and protects the structure from thermal cycling.

Unvented sloped roof assemblies in hot and humid climates have several other advantages compared to vented sloped roof assemblies:

- It is easier to make an unvented roof part of the airtight enclosure compared to the ceiling plane of a vented roof assembly.
- Vented roof assemblies bring high humidity, and potentially corrosive air, into the space that is likely to result in condensation and potential corrosion on colder surfaces such as ducts, or the roof sheathing at night.
- Rainwater may enter the roof vents during extreme weather events.
- HVAC and ductwork in a vented attic will result in energy losses compared to an unvented conditioned attic space.

Some specific recommendations for roofs in hot-humid climates that use either a concrete or steel superstructure are shown in Appendix A, Table A-1 based on the experience from USACE.

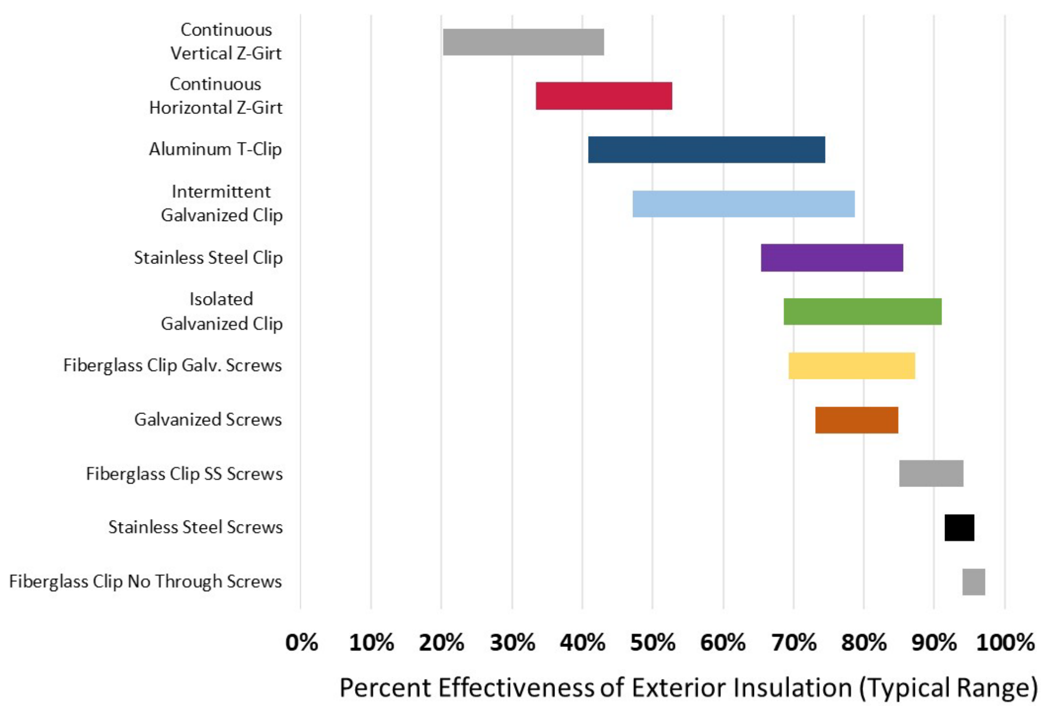
4.5.2. Walls

An exterior-insulated wall assembly is recommended to increase enclosure durability and energy efficiency as this approach protects moisture-sensitive structural elements from elevated humidity conditions and maximizes durability and service life. This also protects the structure from movement related to thermal changes. A key consideration for these assemblies is the support of the exterior finish (i.e., cladding). In some cases, this can be incorporated as part of insulation products (i.e., EIFS or insulated metal panel [IMP]) and in others, specific cladding support designs will need to be considered, such as thermally broken cladding attachment clips or long fasteners through the insulation. The attachment system of the cladding must withstand gravity loading as well as wind loading. Figure 4-8 shows the thermal effectiveness of different cladding attachment options through exterior insulation. As the thermal performance of the cladding attachment decreases, the effectiveness of the exterior insulation also decreases. For example, installing a continuous horizontal Z-girt through R10 continuous exterior insulation will result in an effective R-value for that exterior insulation of approximately R3 to R5.

Airtightness in this assembly can be achieved using a membrane applied to the sheathing or other continuous substrate. This membrane also typically performs the function of the water control layer (WRB). The vapor control could be performed by a low vapor permeance continuous exterior insulation, or the water and air control membrane. Consideration should be given to draining any condensation that occurs on the outboard side of this air/water/vapor barrier (AWVB). In systems with cladding independent of the insulation, a drained and vented cavity should be provided behind the cladding. Corrosion-resistant cladding attachments (i.e., fasteners, clips, rails, etc.) should be employed as these components will see continuous high humidity service conditions, potentially with corrosive characteristics.

In steel-framed walls, it makes sense to put all the insulation on the exterior since there will be a loss of effective R-value of at least 50% of the installed insulation R-value within the steel framing. Sometimes due to economic or practical constraints, a split-insulated wall is recommended to make efficient use of the cavity space created by the wall structure. This approach can be particularly beneficial when using structural systems with relatively low thermal conductivity (i.e., wood), where the insulation effectiveness is better realized. Similar to the exterior-insulated wall described above, a variety of insulation and cladding attachment strategies are available.

Vapor control layers should not be provided on the interior side of any assemblies in this climate since they limit the ability of the wall to dry inwards. Consideration should also be given to unintended interior vapor barriers such as interior finishes (e.g., paints, wallpapers, tiles, etc.) and furnishing (e.g., mirrors, cabinet linings, etc.) as highlighted in section 4.4.4.



Source: RDH Building Science Inc.

Figure 4-8. Cladding support thermal performance.

Interior Walls between Mission-Critical Spaces

Walls between non-occupied spaces that are adjoined to critical spaces, which will continue to receive air-conditioning during emergency (black sky) events, should be given special consideration. These interior walls must contain a continuous and effective air control layer and thermal control layer designed and constructed as if it were an exterior wall assembly to control the flow of more warm humid air to the cooler side of the interior partition wall. Recall that air leakage can move orders of magnitude more moisture than vapor diffusion under similar operating conditions. This can be difficult with the typical interior electrical penetrations on both sides of most interior partition walls. As the event progresses, the non-mission-critical interior spaces will begin to acclimate to the exterior temperature and thus may be expected to be warmer and more humid than the cooler, conditioned mission-critical spaces. A vapor control layer should be considered at the warmer side of the wall (in combination with essential air control) so it is above the dewpoint and minimizes the risk of condensation.

4.5.3. Slabs on Grade

Slabs on grade are constantly in direct contact with the ground, which is a source of moisture, both liquid and vapor, and soil gases. Slab-on-grade scenarios must be sufficiently protected from the water in the ground, and airtight to prevent high humidity air and soil gas from infiltrating into the interior. It is critical that the control layers for water, air, and vapor be continuous below the slab. In addition, concrete is “capillary active,” which means that concrete has the ability, due to its physical properties, to wick liquid water significant distances by capillarity. This means that, if concrete that is in contact with the ground is not sufficiently protected from liquid water, it will wick or transport liquid water along with the concrete until it evaporates from the surfaces above grade. This means that any concrete in contact with the ground should be protected from water in the ground either by a membrane, SPF, or other capillary inactive material. Special attention is required to the connection between the footing and below-grade concrete walls as shown in the below-grade detailing. Capillary water movement presents a far lower risk than movement by gravity associated with a high water table but can still represent a constant source for water into the enclosure and interior space for the life of the structure.

Concrete floors should not be installed lower than grade in areas that have high water tables or that are prone to flooding so that water will drain away from the building by gravity following a flood event. Water, air, vapor, and thermal control are all required below a floor system (in a conditioned space) that borders an unconditioned space. In coastal regions where high tidal fluctuations or floodwater is anticipated, it is recommended to lift buildings off the ground (with stilts for example) to minimize the risk of moisture damage, to lower flood insurance cost, and to increase the expected lifespan of the building. Figure 4-9 shows an example of a house in a hurricane-prone coastal region of the southeast United States. The Federal Emergency Management Agency (FEMA) Homeowner’s Guide to Retrofitting, Chapter 5 “Elevating Your House” explains the importance and past success of lifting homes off the ground in flood-prone areas (FEMA 2014).

Lifting buildings off the ground creates a floor above unconditioned (exterior) space that requires all the considerations of the other areas of the enclosure plus possible fire separation between building occupancy types. It must have continuity of all the control layers with the adjacent walls.

Figure 4-9. Raised construction is recommended where flooding is expected.

Existing buildings may have below-grade spaces for use or mechanical equipment. In major renovation, these spaces may be abandoned, or they may be waterproofed against water entry. In both cases, engineering services are required because of the wide variety of buildings, their uses, and their hydrological and geotechnical conditions.

To abandon below-grade spaces, assuming relocation of uses and services, the space may simply be filled with sand or gravel and then considered part of the exterior environment so thermal, air, and water control layers will be required between the abandoned below-grade space and the interior space. The remaining floor should meet the characteristics of good slab construction—wood floors should be replaced with concrete floors. This approach should be considered only in cases where the added material is balanced by soil at the exterior; adding sand or gravel behind walls exposed to the exterior provides lateral loads for which walls are not designed.

Additional sub-surface drainage to alleviate hydrostatic pressure would consist of additional pumps and collector piping for evacuation of any water that enters. Sizing such a system depends heavily on the conditions of the building and site.

Other Measures to Prevent or Reduce Water from Entering at or Below Grade

All reasonable attempts should be made to minimize the exposure of below-grade enclosure components to liquid water, especially hydrostatic pressure. Some strategies include

- Ensuring a positive sloping grade away from the building enclosure to direct surface runoff away from the enclosure.
- Berms or other features may help direct overland water flow away from the enclosure, but care must be taken to ensure that water does not become trapped between the building and the water management feature.
- Installing drainage to move all surface water and roof runoff away from the structure.
- Porous pavement may be used to reduce the water on the ground surface provided it is not directed toward the below-grade enclosure.

- Excavating grade around the basement perimeter and replacing the below-grade waterproofing system.
- Injecting below-grade waterproofing closed-cell polyurethane grout system behind foundation walls.

4.6. Fenestration

Selection of a fenestration system and how much glazing to use is of particular importance as solar gains represent a significant portion of the conditioning load in hot and humid climates. Furthermore, fenestration typically represents the lowest performing element of the building enclosure from the perspective of thermal control, and thus the most likely cause of energy, comfort, and durability challenges. Key performance considerations include structural capacity, water penetration resistance, airtightness, SHGC, visible light transmission (VLT), thermal conductance (U-value), and temperature index (I). Beyond how much glazing to install, there are two primary components of any fenestration system that must be considered: the frame and the glazing. ASHRAE 90.1-2019 sets some recommended maximum fenestration areas (Tables 5.5-0 through 5.5-8 in the ASHRAE standard). However, choosing to decrease the window-to-wall ratio from the maximum allowed by the code in the design will have both cost and energy advantages whenever possible. In addition to carefully specifying the window parameters to minimize solar gains, exterior shading can be used to better block light during the hotter parts of the day or hotter times of the year. Exterior shading devices often present their own challenges, such as providing thermal bridging through insulation layers, penetrating the control layers of the enclosure, adding materials susceptible to corrosion and staining, and providing roosting locations for birds. In some areas, passive shading strategies such as trees can help shade the enclosure and reduce solar impact, and enclosure surface temperatures.

UFC 3-101-01, *Architecture* (NAVFAC 2021a) states that fenestration must meet both code and UFC 4-010-01 (NAVFAC 2021b) requirements, with material limitations in Environmental Severity Classifications (ESC) of C4 or C5. Current UFC requirements for antiterrorism and code requirements (USACE 2020a, NAVFAC 2019), should be reviewed during the design process for wind-borne debris regions and requirements for the impact-resistant class.

4.6.1. Frame

While the thermal performance of the window frame may be less of a concern in hot and humid climates than in cold climates, the air and water tightness of the frame and associated dry (i.e., gasket) and wet (i.e., sealant) seal components are fundamental to the fenestration product's overall performance.

All window materials are potentially applicable to hot and humid climates; however, care must be taken when using moisture or UV sensitive base materials such as wood or plastic to achieve other design objectives. Where aluminum frame materials are used it is important to ensure that a well thermally broken product is selected.

The key frame consideration is the durability of finishes in potentially corrosive environments as explained in detail in the Kwajalein Atoll Installation Design Guide (CITE) and the corrosion-related sections of this Guide. Other considerations include internal water control strategy (drained strategies are recommended), hardware type and durability (i.e., multi-point locking hardware improves compression on air seal gaskets for operable units), and integration with the surrounding building enclosure.

4.6.2. Glazing

The glazing of the fenestration is typically the greatest source of heat into a building in a hot and humid climate and dominates the cooling demand of the HVAC system. The maximum recommended glazing surface area is reported in ASHRAE 90.1. By reducing the percentage of window area, the energy required for space-conditioning is also decreased, although windows are important for practical and aesthetic reasons. The SHGC controls the measurement of solar energy transmitted through the window, so it is a measure of how good or bad a window is at blocking heat from the sun. The scale used for SHGC is 0 to 1, where 1 equals the maximum amount of solar heat allowed through a window, and 0 equals the least amount possible allowed through. A SHGC of 0.25 or 25% means that 25% of the available solar heat can pass through the window. Tables 4-6 and 4-7 show the prescriptive U-values and max SHGC according to ASHRAE 90.1 in 2013 and 2019 respectively. The hotter the climate, the lower the SHGC required to reduce the cooling demand. Spectrally selective coatings can be used to permit some portions of the solar spectrum while blocking others to admit as much daylight as possible while preventing transmission of as much solar heat as possible. Appendix A, Table A-4 lists the recommended window specifications for some of the USACE Pacific Ocean Division bases based on their experience. Some values in the table exceed the prescriptive requirements of Table 4-6.

Insulated glazing units should minimally be double glazed and may require structural resistance to various impact forces. Laminated glass with polyvinyl butyl (PVB) layers is one of a number of options for large and small missile impact resistance in storm regions, or blast resistance in some buildings.

Table 4-6. Window specifications from ASHRAE 90.1-2019.

Climate Zone	0*		1		2		3	
	Max. U-value [1]	Max. SHGC	Max. U-value	Max. SHGC	Max. U-value	Max. SHGC	Max. U-value	Max. SHGC
Nonmetal Framing	U-0.50	0.25	U-0.50	0.25	U-0.40	0.25	U-0.35	0.25
Metal Framing - Fixed	U-0.57		U-0.57		U-0.57		U-0.50	
Metal Framing - Operable	U-0.65		U-0.65		U-0.65		U-0.60	
Metal Framing - Entrance Door	U-1.10		U-1.10		U-0.83		U-0.77	

* Adapted from ASHRAE 90.1 – 2013 (cf. Tables 5.5-1 to 5.5-3); Climate Zone (CZ) 0 not included in 2013 AHSRAE 90.1, so CZ 1 specifications were used.

[1] For locations with a cooling design temperature of 95F and greater, U-values are U-0.32 for nonmetal, U-0.50 for fixed, U-0.65 for operable metal, and U-0.83 for entrance door metal framing

Table 4-7. Window specifications from ASHRAE 90.1–2019.

Climate Zone	0*		1		2		3	
	Max. U-value	Max. SHGC	Max. U-value	Max. SHGC	Max. U-value	Max. SHGC	Max. U-value	Max. SHGC
Fixed	0.5	0.22	0.5	0.23	0.45	0.25	0.42	0.25
Operable	0.62	0.2	0.62	0.21	0.6	0.23	0.54	0.23
Entrance Door	0.83	0.2	0.83	0.21	0.77	0.23	0.68	0.23
*Adapted from ASHRAE 90.1 – 2019 (cf. Tables 5.5-0-5.5-3).								

4.6.3. Water and Air Control at Fenestration

Window installations are common locations for both rainwater and air leakage in the enclosure, and as such require attention to detail to avoid enclosure issues such as mold and rot resulting from water ingress, and air leakage condensation. In general terms, every opening in the enclosure should be flashed so that any water in the opening is drained to the bottom of the assembly and then directed to the exterior. Figure 4-10 shows the best practice for flashing window rough openings with a back dam and end dams built into the windowsill to help ensure that any water in the rough opening is directed to the exterior. This is further enforced in UFC Architecture 1404.4.3 -Sill Pan Flashing, which states

> *Penetrations such as windows and louvers in the exterior wall assemblies must have pan flashing installed in the rough opening sill. This pan sill flashing must have end dams at both jambs a minimum of 2 in. (50 mm) high and a rear dam of 2 in. (50 mm) high.*

All the control layers for water, air, vapor, and insulation must be continuous across all aspects of the enclosure, e.g., fenestration, transitions between enclosure elements, and other penetrations. During construction, it is always a good idea to have the onsite trades involved in the mockup for window installation that includes water and air testing of the installed window, as discussed previously. This mockup can be done separately from the building or could be the first window that is installed in the building. Installing and testing the first window as a mockup ensures that the workers understand the required standard of quality control for the remainder of the window installations.

In construction projects that do not require an official standardized spray rack test, the water test could be as simple as spraying a hose at the window transition and watching the interior to see if water enters the building.

A summary of window specifications used by the USACE Pacific Ocean Division can be found in Appendix A, Table A-4. All the recommended assembly U-values and SHGC values in the provided information match the specifications in ASHRAE 90.1-2019. However, some useful notes related to the pros and cons of the window assemblies based on experience are noted in the table as are some material recommendations such as storm shutters, marine-grade aluminum, etc., that will be useful in specifying windows in these and other regions.

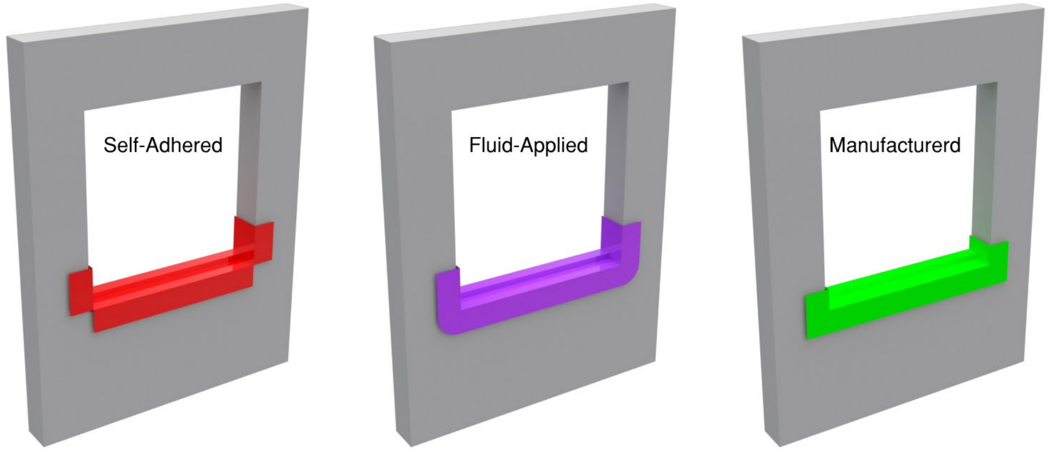


Figure 4-10. Examples of sill pan flashing technologies, installed with back dam and end dams.

4.7. Building Enclosure Design Considerations for Corrosion Prevention

Particularly in facilities located in highly corrosive environments, facilities are vulnerable to accelerated corrosion degradation. Corrosion maintenance is most often based on finding and fixing the damage before it becomes a structural or safety concern. The Department of Defense (DOD) has identified this approach as inadequate to meet mission criticality, e.g., equipment and facilities availability to support deployment, training, and readiness. As the DOD fleets and facilities have aged, the life-limiting degradation mechanisms have shifted from those associated with usage to those associated with time. The costs of corrosion maintenance have risen drastically. Furthermore, the concerns for corrosion, which previously had centered around cost, have now begun to include structural integrity and safety. This shift has dictated a change to a prediction and management approach beyond just simply finding and fixing.

Chlorides and particularly corrosion rates show a sharp (and expected) decrease in chloride levels and corrosion rates as the distance from the ocean increases. The sharpest portion of that decrease is well within the first mile (1.2 km) and more generally within the first one-quarter mile (0.4 km). Attenuation factors are in the range of 7:1 to 8:1. The chloride contribution to corrosion is an important factor in atmospheric corrosion rate, but it should be recognized that this is only one part of a complex, synergistic relationship between chlorides and other critical environmental variables. Various measures of moisture in the atmosphere play a very important role. The high TOW of a corroding surface in combination with high chloride concentration produces a higher corrosion rate than would be expected from either effect individually.

Corrosion causes problems across a wide array of infrastructure components but building envelopes, HVAC, as well as cooling energy generation, storage, and distribution are growing concerns that must be investigated.

4.7.1. Geometries

Designs should be detailed to prevent accelerated deterioration of facility components. Design geometries should be developed that prevent the collection of debris, allow water to readily drain in all situations, incorporate sealed joints between components, maintain protection from mechanical coating damage, and avoid dissimilar materials in direct contact with each other. Follow best engineering and design practices to prevent galvanic corrosion. Slope all possible surfaces such as windows sills, parapets, and pavements to drain away from the structure.

Avoid designs that tend to direct corrosive elements to any specific area of a structure. Minimize the flow of water, airborne contaminants (for example, salts and pollutants), and humid air over susceptible materials when designing facility components, systems, and assemblies. Minimize damage and avoid dissimilar materials in direct contact with each other. As stated previously, one key design principle to protect the structure is to wrap the structure in a continuous air/water barrier, as well as the thermal control (insulation) layers so the exposure to the structure is significantly decreased.

4.7.2. Coatings

Coatings are generally recognized as the "first line of defense" for protecting building envelopes as they protect metallic structures from corrosion and are an integral part of corrosion control. Proper coating selection, application, inspection, and maintenance are critical steps to the performance of all coating systems. General guidelines for the use of protective coatings are listed below:

- Each facility, system, and structure should be evaluated for the application of a high-performance industrial protective coating system.
- All new steel structures should have a high-performance industrial protective coating system that is specifically designed to withstand the characteristics of the environment that they will be subjected to.
- Protective coating systems shall be shop applied to the maximum extent possible. Shop coated materials should be safely stored and carefully transported to protect the protective coating system from damage, including UV degradation.
- Shop and field application of protective coating systems shall be performed by a qualified and experienced industrial coating contractor in strict accordance with the manufacturer's instructions and applicable project coating specifications. The coating contractor shall have a minimum of 5 years of experience applying similar high-performance industrial coatings.
- A NACE Certified Level 3 Coating Inspector shall provide onsite inspection and testing for all coating applications other than minor maintenance coating activities. The coating inspector shall have a minimum of 5 years of experience inspecting similar high-performance industrial coatings.
- For each new facility, system, and structure that is provided with a protective coating system, specific maintenance requirements shall be specified for the protective coating system.

Protect water and wastewater systems, fire water systems, and other piping from internal and external corrosion. Design factors include water quality and composition (for example, pH, alkalinity, and dissolved oxygen), ferric scale, flow conditions, biological activity, and the presence of disinfectants and corrosion inhibitors.

4.7.3. Material Selection

All materials need to be carefully selected for the intended applications defined as “exterior,” “non-conditioned interior,” and “conditioned interior.” In many applications, specialty materials that exhibit superior corrosion resistance in marine environments are required and can exceed the minimum requirements of applicable UFC documents:

- Non-metallic materials should be considered instead of metallic materials if design conditions permit.
- Use materials that can withstand high humidity or incorporate efforts to eliminate humidity in humid locations.
- 316 or 316L stainless steel and marine-grade aluminum (5052, 5083, 6061, etc.) are the preferred metals of choice and should be used if design conditions permit.
- 304 stainless steel should NOT be substituted for 316 or 316L stainless steel.
- 316 or 316L stainless steel fasteners (bolts, nuts, washers, rivets, etc.) should be used for exterior and non-conditioned interior applications unless dissimilar metal contact requires the use of marine-grade aluminum fasteners.

When two different types of metal are in electrical contact, galvanic corrosion can occur in the presence of moisture. Galvanic corrosion due to dissimilar metal contact is evident in fasteners and other metallic components throughout several facilities nationwide. A comprehensive review of materials, equipment, and construction methods is required to prevent dissimilar metal contact.

Sufficient drainage and insufficient vapor control should also be considered in enclosure design. Enough air space must be left to (1) relieve hydrostatic pressure, (2) act as a capillary break and receptor for capillary water, and (3) facilitate hydric redistribution and moisture removal by air change. In hot-humid climates a drainage mat paired with a water and air control membrane with a water vapor permeance of between 5 and 10 perms is recommended to control wetting, while still permitting drying to the exterior. However, if there is a significant risk of solar inward vapor drives depending on the location and cladding type, then a more vapor impermeable membrane may be required.

The additional drainage and water vapor control is especially important for buildings with higher moisture risk factors such as those constructed in wet climates (more than 20 in. [50.8 cm] of rain per year), those that are multistory (exposed to higher wind and moisture loads), and those that are architecturally complex. Where continuous exterior insulation is used in high moisture conditions, the drainage mat is recommended to be placed on the interior of the insulation, between it and the water control layer. In lower moisture load conditions, a textured building wrap can be used in lieu of the drainage mat.

Vapor barriers such as polyethylene sheeting, foil-faced batt insulation, reflective radiant barrier foil insulation, and any impermeable wall coverings should be avoided on the interior of air-conditioned spaces in any climate, but especially hot-humid climates where buildings experience increased vapor drive from the exterior to the interior. Interior vapor barriers provide both a cold condensing surface for water vapor and restrict interior drying.

For hardware and fasteners specify galvanized ferrous metals, stainless steel, brass, bronze, copper, aluminum, or other corrosion-resistant metals for hardware and fasteners. Do not use ferrous metal as finishing strips or as components of other securement systems, even if a protective coating is provided.

4.7.4. Dissimilar Metals

Protect against galvanic corrosion when dissimilar metals are in close contact. Metals such as magnesium, steel, zinc, and aluminum (anodes) tend to corrode when in contact with copper, stainless steel, and nickel (cathodes). When relatively incompatible metals must be assembled in the design, apply the following methods to minimize or prevent galvanic corrosion.

Design metal couples where the surface area of the cathode is smaller than the surface area of the anode metal and only when the anode metal can afford loss due to local corrosion. For example, only use stainless steel bolts to fasten carbon steel parts when bolt removal is frequent and necessary, and when the loss of carbon steel at the bolt hole is acceptable. Interpose of a non-absorbing, inert gasket or washer between the dissimilar materials before connecting them. This is applicable to couples that are not to serve as electrical conductors.

Seal faying edges to preclude the entrance of liquids.

Apply corrosion-inhibiting pastes or compounds under the heads of screws or bolts inserted into dissimilar metal surfaces, whether or not the fasteners had been previously plated or otherwise treated, in addition to applying an organic coating to the faying surfaces before assembly. In situations where large faying surfaces are involved, it may be feasible to insert a thicker barrier such as dried adhesive or sealant material. This applies to joints that are not required to be electrically conductive.

Where practicable or where it will not interfere with the proposed use of the assembly, coat the joint externally with an effective paint system or sealant.

4.7.5. Design Methods for Corrosion Prevention and Control in Steel-Reinforced Concrete Structures in Hot-Humid Coastal and Inland Environments

The designer should consider corrosion standards and criteria during the design and construction of the steel-reinforced concrete structure. The standards and criteria in this Guide give the designer several alternative methods of controlling the corrosion of atmospherically exposed, submerged, or buried reinforced concrete structures. Throughout this Guide, references will include American Concrete Institute (ACI) and ASTM standards, which are applicable to design and construction of national and international steel-reinforced concrete structures. During the design and construction phases of a reinforced concrete structure where corrosion is a major factor, the services of a qualified registered engineer, or Advanced Materials and Processing Program (AMPP) certified corrosion specialist specializing in concrete structures shall be obtained so that proper materials selection and engineering practices for corrosion control are included in the design (see NACE 2017).

4.7.6. Achieving Service Life by Design

- **Service Life Requirements:**
  Different structures have different service life requirements. Some service lives are implied by construction codes; some are specified by owners during construction; some become apparent during the life of the structure. Service life is also greatly influenced by environmental exposure and microclimates (see NACE 2017).
- **Environmental Exposures:**
  Environmental aggressiveness must be taken into consideration during the design phase. Some have divided hot climates into three sub-divisions (based on the magnitude of the average relative humidities in the region) as follows: (a) hot-humid (RH usually above 85%), (b) hot-moderate (RH 50-65%), and (c) hot-dry (RH usually below 40%). In the present report this classification of hot climates is used (see also a recent review by the author). Hot-humid climate (tropical), as encountered in Africa, Asia and South America, is characterized by a high temperature of 86 °F to 104 °F (30 °C to 40 °C), high RH and intense precipitation (usually more than 59 in. (1500 mm) annually). Diurnal temperature variation is not very high (average about 14 °F [8 °C]). On the other hand, hot-dry (desert) climate is distinguished by its high daytime temperature 104 °F to 122 °F (40 °C to 50 °C), very low RH, and intense solar radiation. The diurnal variation in temperature is pronounced (average about 29 °F (16 °C); twice that of hot-humid climate). It has been reported that surface temperatures of exposed concrete elements such as pavements, walls etc., may reach 158 °F to 176 °F (70 °C to 80 °C) during the day, and during the night such surface temperatures may drop 9 °F to 18 °F (5 °C to 10 °C) lower than ambient temperature (Berhane 1992).

It has been shown on bridges in the Florida Keys (Sagüés et al. 1999) that the most aggressive corrosion environment is in the region 3 ft to 6 ft (1 m to 2 m) above the high tide level, with negligible corrosion below the water line because of oxygen starvation, and above the 6 ft (2 m) level because of lower chloride exposure out of the splash zone.

An example of categorization of exposure classes for the purposes of this standard is presented in Table 4-8, adapted from European Standard EN 206-15 and used with permission of the European Committee for Standardization (CEN) (2000). The examples of structures are included for their informative value; they are not meant to be taken as definite or exclusive.

Table 4-8. Exposure classes related to environmental conditions (NACE 2017).

Class Designation	Description of the Environment	Informative Examples of Reinforced Concrete Structures or Elements Where Exposure Classes May Be Found
1 Low risk of corrosion or attack		
X0	Low risk of corrosion of reinforcement or attack of concrete, very dry	Concrete inside buildings on very low air humidity
2 Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in nonaggressive water
XC2	Wet, rarely dry	Concrete completely buried in nonaggressive soil Concrete subject to long-term water contact

Class Designation	Description of the Environment	Informative Examples of Reinforced Concrete Structures or Elements Where Exposure Classes May Be Found
XC3	Moderate humidity	External concrete surfaces sheltered from direct rain Concrete inside structures with high air humidity (e.g., bathrooms. kitchens)
XC4	Cyclic wet and dry	Concrete surfaces exposed to alternate wetting and drying
3 Corrosion Induced by chlorides other than from seawater		
XD1	Moderate humidity	Concrete surfaces in parts of bridges away from direct spray containing deicing salts
XD2	Wet, rarely dry	Swimming pools Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Parking garage Slabs Pavements
4 Corrosion Induced by chlorides from seawater		
XS1	Exposed to airborne salt but not in direct contact with seawater	Structures in coastal areas more than 100 m (110 yd) from the sea
XS 2	Permanently submerged	Pans of marine structures completely submerged more than 1m (3 ft) below lowest water level
XS3	Tidal, splash and atmospheric zones	Concrete structures in seawater down to about 1 m (3 ft) below lowest water level External Concrete surfaces less than 100 m (110 yd) from the sea
Source: European Committee for Standardization (CEN). Management Center: Rue de Stassart, 36, B-1050 Brussels, BE		

4.7.7. Site History and Environmental Survey

A survey should be conducted at the proposed construction site to determine the environmental conditions that could affect the durability of a reinforced concrete structure (see Table 4-8). Samples of soil, stream water, and concrete (from existing structures at the proposed site, if applicable) should be obtained and tested to determine corrosiveness of the environment. Local observations should be made and data collected to determine their effect on the service life of the proposed structure. The possibility of interaction risk from externally generated stray currents should also be evaluated. Other environmental issues that should be considered are weather conditions and atmospheric pollution.

The detailed descriptions of the following properties/conditions are described in NACE (2017):

- Soil properties
- Water properties
- Marine environment.

4.7.8. Design Considerations

Methods to isolate the steel reinforcement from corrosive environments include increasing the concrete cover, improving the quality of the concrete, and avoiding aggressive microenvironments (NACE 2017, section 5).

4.7.9. Selection of Construction Materials

The concrete selected and produced shall be of the type best suited for the conditions. Concrete materials shall be selected to provide the least permeable concrete and crack-free matrix. The materials being used for construction should be durable, with no adverse reactions, e.g., alkali-aggregate reaction. All concrete materials shall meet appropriate industry standards. The relevant ASTM standards for the U.S. are included in NACE (2017, section 6).

4.7.10. Preventive Measures Applied to Concrete

There are a number of preventive measures that can be applied to the concrete mix and post cured hardened surfaces (NACE 2017, section 7).

4.7.11. Preventive Measures for Reinforcing Steel

There are a number of preventive measures that can be applied to reinforcing steel, as well as the use of higher corrosion-resistant steels and non-metallic alternatives (see NACE 2017, section 8; and Stephenson et al. 2009).

4.7.12. Concrete Compaction (Recast from App C)

During construction, certain procedures should be followed and precautions taken to ensure the production of a durable concrete structure. These procedures apply to concrete, steel, and the cathodic protection (CP) system, if used, and are discussed in NACE (2017), section 11, and Stephenson et al. (2009).

4.8. Hot Weather Concrete Construction – Things To Consider about Hot Weather Concreting

When the temperature of freshly mixed concrete approaches approximately 77 °F (25 °C) adverse site conditions can impact the quality of concrete. Ambient temperatures above 90 °F (32 °C) and the lack of a protected environment for concrete placement and finishing (enclosed building) can contribute to difficulty in producing quality concrete.

The precautions required to ensure a quality end product will vary depending on the actual conditions during concrete placement and the specific application for which the concrete will be used. In general, if the temperature at the time of concrete placement will exceed 77 °F (25 °C), a plan should be developed to negate the effects of high temperatures.

The precautions may include some or all the following:

1. Moisten subgrade, steel reinforcement, and form work before concrete placement.
2. Erect temporary wind breaks to limit wind velocities and sunshades to reduce concrete surface temperatures.
3. Cool aggregates and mixing water added to the concrete mixture to reduce its initial temperature. The effect of hot cement on concrete temperature is only minimal.
4. Use a concrete consistency that allows rapid placement and consolidation.

5. Protect the concrete surface during placement with plastic sheeting or evaporation retarders to maintain the initial moisture in the concrete mixture.
6. Provide sufficient labor to minimize the time required to place and finish the concrete, as hot weather conditions substantially shorted the times to initial and final set.
7. Consider fogging the area above the concrete placement to raise the RH and satisfy moisture demand of the ambient air.
8. Provide appropriate curing methods as soon as possible after the concrete finishing processes have been completed.
9. In extreme conditions consider adjusting the time of concrete placement to take advantage of cooler temperatures, such as early morning or nighttime placement.

With proper planning and execution concrete can be successfully placed and finished to produce high-quality durable concrete at temperatures of 95 °F (35 °C) or more.

4.8.1. Setting Time

The effect of high ambient temperatures and high temperature concrete component materials have on the setting time of concrete mixtures is a topic of concern due to the reduced time in which concrete must be placed, consolidated and finished; increased potential for plastic shrinkage cracking, thermal cracking and cold joints; potential strength reduction due to high water demand and high curing temperatures; difficulty in controlling air content; and increased urgency for applying appropriate curing method at an early age.

As a general rule of thumb an increase of 20 °F (-7 °C) will reduce the setting time of a concrete mixture by as much as 50%. As an example, a concrete mixture that reaches final set in 3 hours at 60 °F (16 °C) may reach final set in as little 1½ hours at 80 °F (27 °C). As the concrete temperature increases the setting time is further reduced. The actual temperature of the concrete mixture as delivered is affected by the temperature of the materials used in the mixture, the cementitious content of the mixture, the temperature of the equipment used to batch and transport the concrete, and the ambient temperature and conditions at the project site. Concrete applications may be considered hot weather concrete at temperatures ranging from 77 °F to 95 °F (25 °C to 35 °C) depending on the specific application. Precautions should be planned in advance to counter the effects of high temperature well in advance of execution to counter these effects.

Precautions may include use of materials with a good performance history in high temperature conditions, cool concrete materials or concrete mixture, provide concrete consistency and placement equipment and crew for rapid placement, reduce time of transport, schedule placement to limit exposure to atmospheric conditions (night time placement or more favorable weather), plan to limit rapid moisture loss (sun screens, wind screens, misting, or fogging), and consider the use of an evaporation retarder. Schedule a preconstruction meeting including all the participants to discuss the plan to control the effects specific to the project and expected conditions (PCA 1979).

4.8.2. Rehabilitation/Prevention of Rebar Corrosion in Existing Concrete Structures Located in Hot-Humid Coastal/Inland Environments

The corrosion of steel rebar in reinforced concrete structures is a pervasive and expensive problem for DOD. The maintenance and repair costs for affected structures and equipment amounts to hundreds of millions of dollars each year, and the degradation negatively impacts military readiness and infrastructure safety. This section provides details of repair technologies to prevent further rebar corrosion. They are a corrosion inhibitor system and a liquid galvanic coating that provides a type of sacrificial cathodic protection for steel-reinforced concrete. These corrosion prevention technologies were applied to critical infrastructure in a highly corrosive environment located at U.S. military facilities in Okinawa. In addition to these corrosion prevention technologies, this section also provides details for different types of sacrificial and impressed current CP systems for steel-reinforced concrete and a system to prevent water ingress into submerged or direct buried steel-reinforced concrete structures.

Corrosion Assessment of Existing Concrete Deterioration

The first step in solving a corrosion problem is to identify the root cause, mechanism and rate. This can be done by measurement of the surrounding environment (pH and chloride concentration) visual inspection (pitting or uniform), and rate (half-cell potential, polarization resistance and coupons). Inspection to determine the amount of metal loss is also done to determine if the structure is beyond the point of being saved even if the rate of corrosion is reduced (Stephenson et al. 2009).

The presence of corrosion in the selected structures is typically determined by observing the presence of concrete spalls and corroded rebar. The following properties should be tested to evaluate the status of the rebar corrosion rate and cause of corrosion before treatment:

- pH of cement at the rebar level
- Total and water-soluble chloride content in cement at the rebar level
- Corrosion current and rate measured in micrometers of steel loss per
- Year (to calculate an average corrosion rate)
- Half-cell potential
- Concrete resistance or conductivity.

Stephenson et al. (2009) includes detailed technical information on Galvapulse and GWT Metrics Technologies.

Figures 4-11 through 4-15 show examples of corrosion failure of atmospherically exposed concrete structures in a hot and humid environment such as Okinawa.

Rebar was exposed where concrete had been spalled in four areas. The exposed rebar was used for measurements with the GalvaPulse. Figure 4-11 shows representative exposed rebar. Corrosion is readily apparent on the exposed rebar (nominally ⅜-in. [19 mm] diameter), though it was difficult to quantify the metal loss. The spalled areas were repaired by Surtreat during the rehabilitation and re-opened in July to facilitate future measurements.

Figure 4-11. Exposed rebar on culvert.

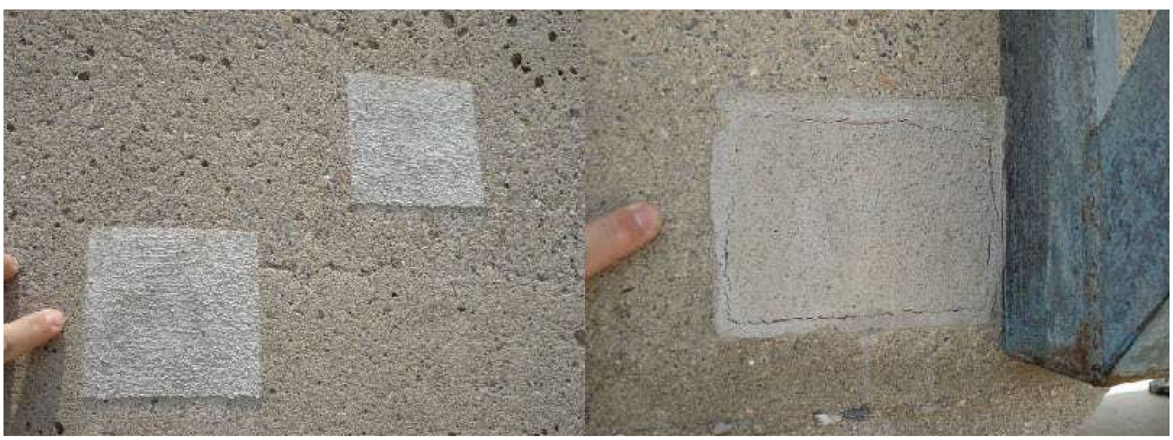


Figure 4-12. Typical repairs using a cementitious material. The patch material has a rough appearance and failed within months of installation.

Figure 4-13. Shows a typical corroded steel rebar that has delaminated from the concrete.

Figure 4-14. Overview of a steel-reinforced concrete beam inside a building.

Figure 4-15. Shows a typical section of exposed corroded rebar.

Corrosion Prevention Technologies for Existing Concrete Structures

The first type of corrosion prevention technologies is a surface applied corrosion inhibitor (Surtreat corrosion protection system) which consists of (1) an ionic-anodic type of inorganic migratory corrosion inhibitor (TPS II), (2) an organic vapor phase migratory corrosion inhibitor (TPS XII), and (3) a reactive silicone surface protection agent (TPS XVII). The combined application of these three corrosion-inhibiting formulations provides a durable and multifunctional corrosion-inhibiting environment along with a reduction in water penetration rate.

Appendix B shows the Detailed Description of the surface applied corrosion inhibitor Application Procedure (Stephenson et al. 2009, UFGS-09 97 23.17 [August 2016], Change 1 - 11/16 corrosion inhibitor coating of concrete surfaces [NAVFAC 2016]).

The second type of corrosion prevention technologies is a sacrificial cathodic corrosion protection coating developed by the National Aeronautics and Space Administration (NASA). The cathodic coating system consists of an inorganic silicate vehicle containing zinc, aluminum, magnesium, and indium metal powders. The coating is applied to a reinforced concrete surface along with titanium mesh strips that are connected to the rebar to conduct cathodic current produced by the coating.

The third type of corrosion prevention technologies is cathodic protection. For buried or submerged structures or systems, include a combination of CP systems (see Figure 4-16), protective coatings, proper material selection, encasement, or other methods of overall corrosion protection of buried or submerged structures.

For buried structures, design for the corrosivity of the soil, including soil pH, resistivity, moisture content, and presence of chlorides, sulfides, and bacteria.

For immersed structures, consider the corrosivity of the water (primarily the salinity of the water but also affected by pH, dissolved oxygen, temperature, and current). Tidal and splash zones will experience higher corrosion than continuously immersed or atmospherically exposed zones.

For submerged or partially submerged structures, account for the differences in corrosion potential associated with each zone.

CP systems can be one of two types. This includes galvanic systems and impressed current systems. Galvanic systems utilize galvanic or sacrificial anodes while impressed current systems utilize impressed current anodes. Galvanic CP systems, also sometimes referred to as sacrificial CP systems, employ galvanic anodes such as specific magnesium or zinc-based alloys, which are anodic relative to the ferrous structure they are installed to protect. Impressed current systems use direct current (DC) applied to an anode system from an external power source to drive the structure surface to an electrical state that is cathodic in relation to other metals in the electrolyte (HQDA 2021).

For information on cathodic protection design, evaluation, maintenance, and rehabilitation of reinforcing steel in concrete, refer to NACE (2017, 2018, 2019a,b). Cathodic protection of reinforcing steel in atmospherically exposed concrete is described in NACE (2019c, 2016).

The fourth type of corrosion prevention technologies is Concrete Dewatering.

Electro-Osmotic Pulse (EOP) technology offers an alternative to conventional water control techniques as well as preventing the destructive effects of ASR. This form of concrete corrosion slowly deteriorates concrete from the inside by forming highly expansive gels that cause swelling and cracking of the concrete matrix (Marshall 2009).

It mitigates water-seepage problems from the interior of affected areas without excavation. EOP reduces corrosion damage to indoor materials and equipment and eliminates mold problems caused by moist or highly humid environments. EOP technology is based on the phenomenon of electro-osmosis, the directed migration of an electrically charged liquid using an external electric field. A system has been developed to apply electro-osmosis for control of water intrusion within concrete structures by applying a pulsed electric field, at cost savings of over 50% compared with conventional waterproofing methods.

Electro-osmosis is not a new technology, but new applications are still being developed. Research has shown that flow is initiated when *cations* (positively charged ions) in the pore fluid of a porous medium such as concrete migrate toward a *cathode*, carrying the surrounding water with them (McInerney et al. 2002). Electro-osmosis has been used in civil engineering to dewater dredged material and other high water-content waste solids (O'Bannon 1977). It also has been used to consolidate clays, strengthen soft, sensitive clays, and increase the capacity of pile foundations (Chew et al. 2003). Electro-osmosis has also received significant attention as a method for removing hazardous contaminants from groundwater or to arrest water flow (Probstein et al. 1991).

An EOP system was developed by ERDC-CERL and DryTronic, Inc., to apply electro-osmosis commercially within concrete structures using a pulsed electric field. This system uses two sets of electrodes — one set embedded just below the surface of concrete floors, walls, or ceilings, and the other set placed either in the surrounding soil or, if the wall is thick, deep within the concrete. Pulsed DC voltage is applied between the electrodes to produce an electric field in the walls. The field moves water from inside of a concrete structure toward the outside, reversing or preventing moisture seepage toward the interior space. A positive electrical pulse causes cations (e.g., Ca++) and surrounding water molecules to move from the dry side (anode) toward the wet side (cathode) against the direction of flow induced by the hydraulic gradient, thus preventing water penetration into a buried or submerged concrete structure (Figure 4-16).

EOP technology can dry concrete to below 55% RH and keep it dry. The model of EOP installed in a concrete basement wall and floor (Figure 4-17). By making moisture unavailable to support formation of the ASR gel, EOP could be capable of greatly reducing the rate of concrete deterioration caused by ASR in DOD infrastructure.

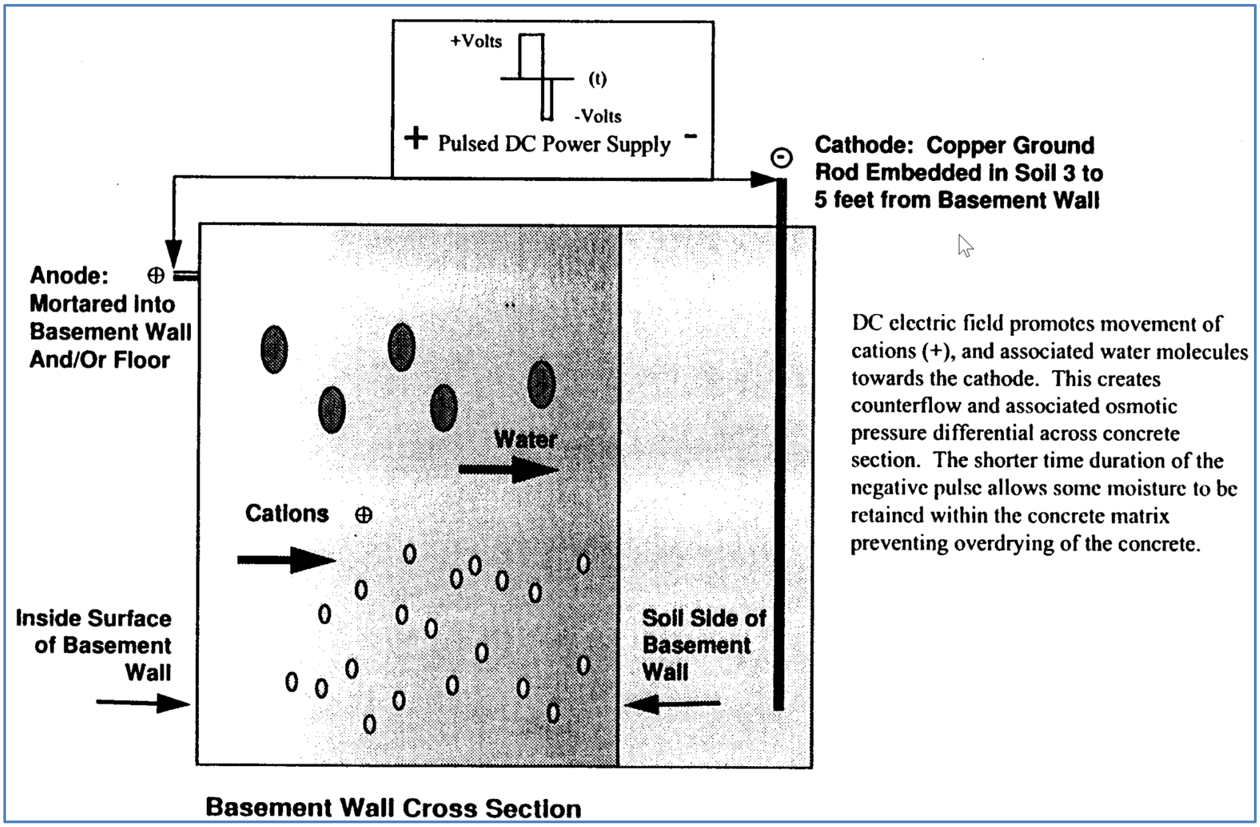


Figure 4-16. Schematic diagram of the EOP system.

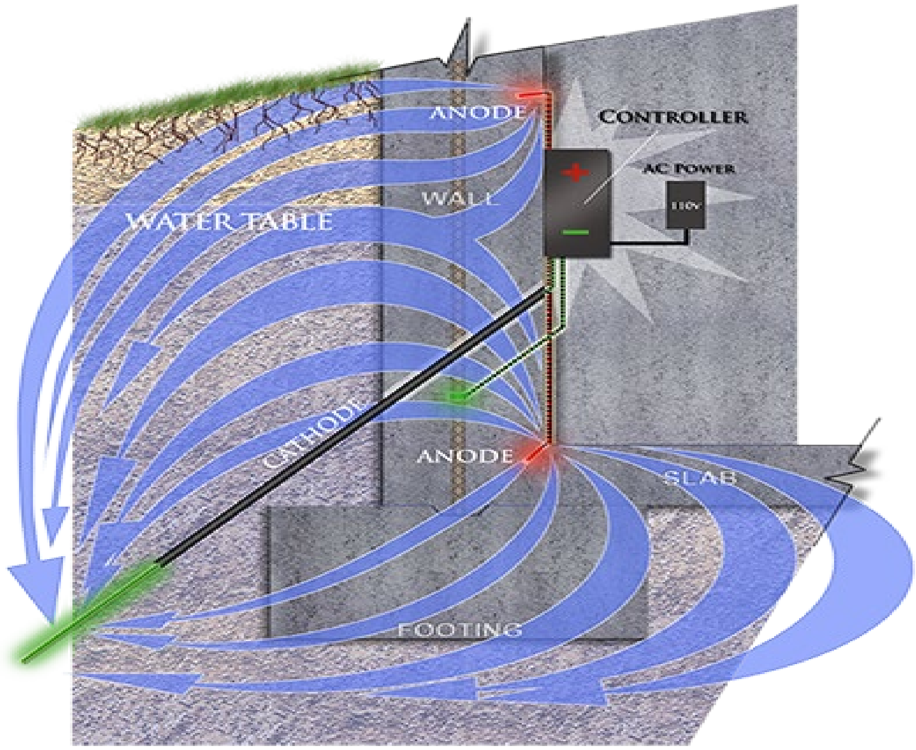


Figure 4-17. EOP Diagram and model.

Conclusions

The degradation of reinforced concrete structures in a hot-humid coastal and inland environment is related to physical and chemical processes including chloride penetration, sulfate attack, and carbonation. Among these factors, chloride penetration is the most concerning for the durability of concrete structures.

Chloride ions move into concrete by the mechanisms of diffusion and convection. Diffusion is caused by differences in chloride ion concentrations in pore water while convection is due to water transport carrying chloride ions. During the chloride transport process, some chloride is dissolved in pore water and the rest is bound by cement hydrates, i.e., free chloride and bound chloride, respectively. The free chloride is responsible for destroying the passive layer of steel and initiating steel corrosion

A protective oxide film is present on the surface of the steel reinforcement due to the concrete alkalinity. This layer is called passivity. The process of carbonation will affect this protective passivity layer. This layer can also be affected by the presence of chlorides in water or in oxygen. The reinforcement corrosion process (Figure 4-18).

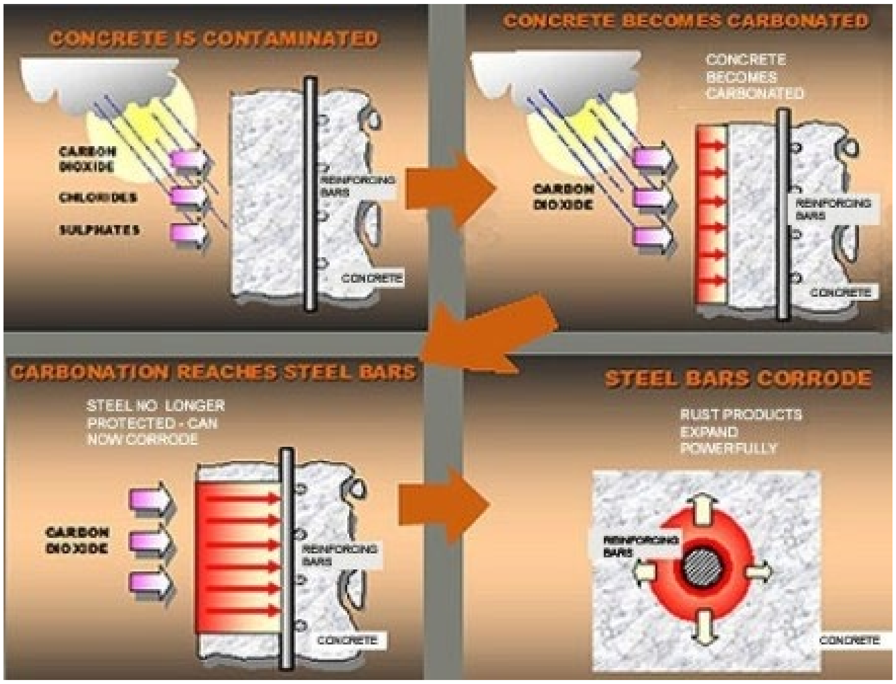


Figure 4-18. The process of corrosion of reinforcement from chloride attack.

4.9. Retrofits for Energy and Durability

Most of the discussion in this chapter applies to new construction and major renovation projects. It is relatively easy to design, and construct durable, energy-efficient, and resilient new buildings and to make significant changes to the building undergoing a major renovation with the scope of work, which can be either energy- or non-energy-related. Timing a deep energy retrofit to coincide with a major renovation is best since the building is typically evacuated and gutted; scaffolding is installed; single pane and damaged windows are scheduled for replacement; building envelope insulation is replaced and/or upgraded; and most of mechanical, electrical lighting, and energy conversion systems (e.g., boiler and chillers) along with connecting ducts, pipes, and wires will be replaced. A significant sum of money covering the cost of the energy-related scope of the renovation designed to meet the minimum energy code is already budgeted anyway. For more information regarding how to combine major renovation of building with deep energy, retrofit is provided in (Zhivov and Lohse 2017, 2019, 2021). However, most renovation projects have a limited scope of work that does not include the gutting of the whole building, and there may be only a limited opportunity to improve the building envelope and vertical chases. Regarding the building envelope, there are three primary areas of focus in a hot-humid climate:

- *Reducing Air Leakage* by increasing the airtightness of the building is critical for controlling humidity in the building, which can reduce the required size of mechanical equipment, reduce energy consumption, and reduce the risk of mold.
- *Improving Window Specifications* to improve energy efficiency and to decrease the risk of air and water leakage at window penetrations, and to reduce exposure to direct solar radiation. Shading can be added to the exterior of the building to decrease the solar gains through windows.
- *Corrosion Mitigation* of roofs, doors, windows, and fastenings.

Other measures for retrofit could include adding more insulation to the enclosure and replacing HVAC systems components and controls with more efficient and potentially smaller equipment, after making improvements to air leakage, windows, and insulation, and after making improvements to the lighting system.

4.9.1. Improving Airtightness

In existing buildings airtightness is often poor, mainly due to imperfect joints between the panels, blocks, building components (especially around windows), and services penetrating the wall. Improving the airtightness of existing buildings can be challenging to find the holes that require sealing. Before starting a minor renovation or energy-focused project, a building enclosure assessment may be performed to determine the existing paths of air leakage in the predesign or planning phase to establish if the scope and overall goals of the project would benefit from envelope improvements to mitigate airflow and reduce energy loss through the envelope. An entire building air tightness test is often a good starting point for establishing a scope for a potential renovation or retrofit project, particularly if there is no existing air barrier within (or as a component of) the building envelope. However, depressurization of buildings in hot-humid climates for lengthy periods may be risky as it introduces hot/humid air into the enclosure, which may result in condensation, so pressurization is typically preferred. Other diagnostic methods combined with building pressurization, such as using a smoke tracer, using either a hand-held unit or theatrical smoke fog machine, can be helpful in locating and determining the magnitude of leakage in a particular location.

If there is a sufficient temperature gradient across the enclosure, then thermal imaging will help identify leakage areas with depressurization, as the thermal scans should show the increased temperature on the interior as a result of infiltration of the hot exterior air. For more details in improving airtightness with minor renovation projects (see Zhivov and Lohse 2017).

4.9.2. Window Retrofits

Window retrofits of older buildings should significantly improve the comfort and energy efficiency of the building, and in the case of corrosive environment, take care of corroded frames and fastenings. When window replacement is included in the scope of work, installing better energy-efficient windows (e.g., those listed in Table 4-3 or better) might have an only incremental cost increase due to higher initial cost with the labor cost remaining the same. For the life-cycle cost analysis (LCCA), consider the effect of not only energy savings, but the impact of better windows on the overall building energy resilience (see modeling results in Chapter 7).

4.9.3. Enclosure Retrofits

The building science and construction technology for enclosure retrofits of the opaque enclosure follow the same guidelines as new construction regardless of the type of superstructure. Exterior insulation strategies are the most durable and energy-efficient retrofit solution in buildings where the exterior cladding can be covered. There are many old buildings on different military bases that are considered historic and cannot be retrofit on the exterior of the cladding. Each of those buildings requires an individual assessment and plan when considering an energy retrofit.

In general, the approach to an enclosure retrofit should be similar for most older buildings and do not typically depend on the structure or the cladding type.

1. Remove the existing cladding.
2. Install, or repair the air/water barrier system on the exterior of the structure, ensuring continuity with all penetrations, windows, roofs, foundations, etc.
3. Conduct a building air leakage test to confirm the performance of the ABS.
4. Install exterior continuous insulation over the air/water barrier of a type and R-value chosen for the project location.
5. Install the cladding over a drained and ventilated cavity using a cladding attachment method that is appropriate considering the thermal performance.
6. In some cases, shading can also be installed on the exterior of the building to minimize solar gains through windows. This may also reduce the exposure to driving rain on the window.
7. Following these improvements, it can be possible to reduce the capacity of the mechanical equipment when they next require replacing, which often leads to less expensive equipment and more efficient operation.

One potential technology that could be useful for exterior enclosure retrofits is to install a drained EIFS system over the exterior wall assembly, correctly integrated at all penetrations. This can be a durable, efficient, and affordable solution. EIFS has a reputation for being easy to damage but specifying the correct reinforcement mesh in the system results in a very durable finish with many aesthetic options depending on the geographic location.

4.10. Construction Details

This section includes schematic details of many key elements of the enclosure for the three archetype buildings with building science notes to explain any key points, and also includes alternatives that could be implemented.

These details focus on the problem areas of the enclosure where it has been challenging to maintain continuity of the key control layers, such as at transitions between different components and penetrations of the enclosure.

In many cases with these schematic details, the choice of the superstructure is not important because all the important details are related to construction on the exterior of the structure, and the building science and construction principles are the same regardless of the building's structure.

4.11. Window Details

Windows are a key component of the enclosure, but the transition between the window and the enclosure is typically one of the greatest sources of both water and air leakage. Care must be taken to ensure that the water and air control layers are continuous across the transitions. The schematics shown in Figures 4-19 to 4-27 illustrate details for the windowsill, jambs, and head of a window in structures of either concrete or steel to achieve a high-performance window installation. The principles are the same for other types of windows in punched openings, doors, and other penetrations.

The air control transition must be continuous around the entire perimeter of the window. This is typically done from the interior so that the rough opening can still drain to the exterior, and the air control sealant layer is not subjected to UV or large swings in temperature.

The rough opening should be flashed for nearly every window type (Figure 4-10) with a sill pan flashing that has a back dam, and end dams so that any water in the rough opening that leaks through or around the window are directed back to the exterior. This is a requirement of UFC 3-101-01, *Architecture*, section 1404.4.3 (NAVFAC 2021), which states

> *Penetrations such as windows and louvers in the exterior wall assemblies must have pan flashing installed in the rough opening sill. This pan sill flashing must have end dams at both jambs a minimum of 2 in. (50 mm) high and a rear dam of 2 in. (50 mm) high.*

In the following window details, the sill pan flashing is formed with the self-adhered membrane but could use different technologies as long as it is fully integrated. Figure 4-19 shows an example of a metal angle installed to support the self-adhered membrane at the back dam location.

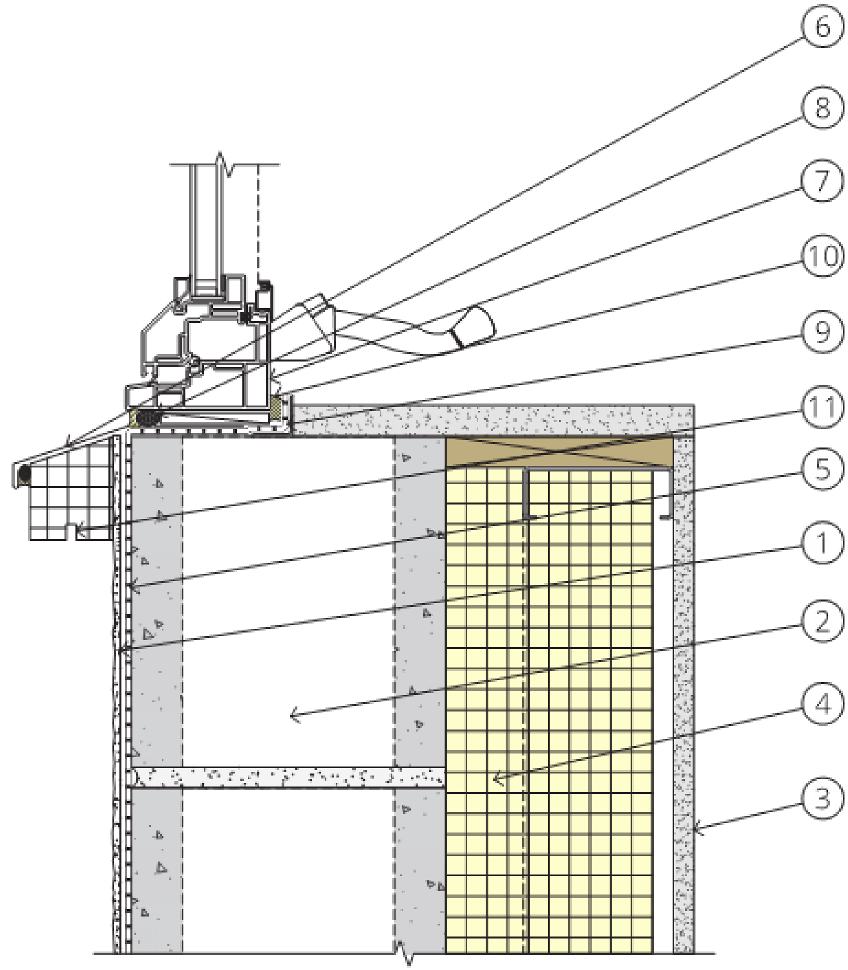
Figures 4-17 and 4-21 show a curtain wall windowsill. It is less common to install a sill pan flashing with a curtain wall because of the structural attachment requirements and interior finish of the curtain wall frame. The recommended air/water control transition at a curation wall is to mechanically secure the transition membrane inside the shoulder of the curtain wall frame to ensure that it is continuous around the perimeter of the curtain wall frame Figure 4-22. Mechanically attaching a transition membrane is typically more reliable than using a sealant; however, it is possible to install backer rod and sealant as the water control layer (Figures 4-17 and 4-21).

Head flashings above windows and sill flashings below windows should have a drip edge to help minimize water concentrations on the window and cladding. This will also decrease the risk of cladding staining over time.

Figures 4-19 and 4-15 show interior continuous insulation on the CMU wall assembly based on provided drawings by USACE. This strategy has been historically typical of concrete and CMU walls in hot-humid climates, although it is recommended to use exterior continuous insulation, when possible, based on the discussion earlier in this chapter.

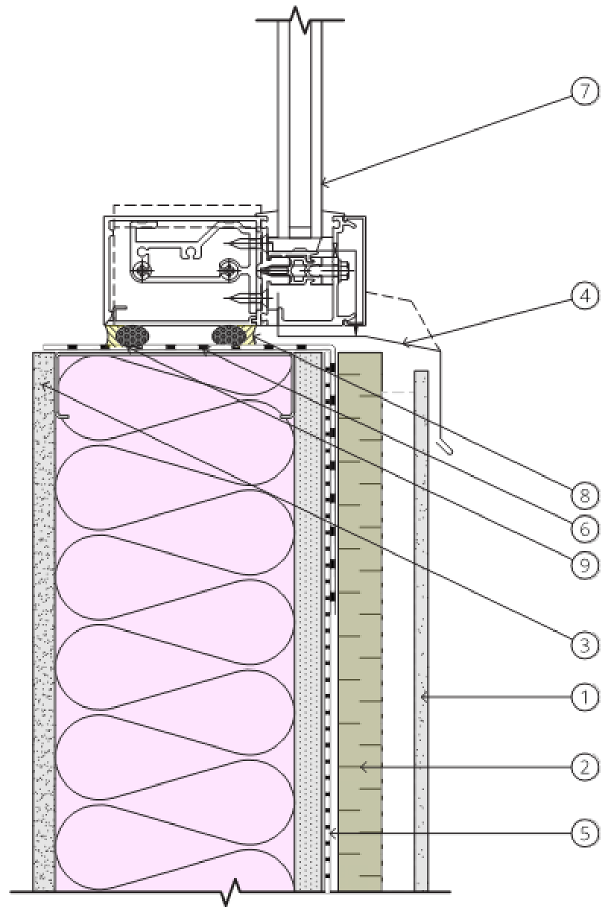
Curtain wall construction and installation are different from typical punched open window assemblies. This is because the structural component of the assembly is inside the water control and thermal control layers of the assembly. The recommended air/water control transition at a curation wall is to mechanically secure the transition membrane inside the shoulder of the curtain wall frame to ensure that it is continuous around the perimeter of the curtain wall frame as shown in Figure 4-22. Mechanically attaching a transition membrane is typically more reliable than using a sealant.

Alternatively, it is possible to use backer rod and sealant around the curtain wall as an effective water/air control layer as shown in Figures 4-17 through 4-27. Since all the drainages of the curtain wall system are designed to drain to the exterior of the exterior backer rod and sealant.



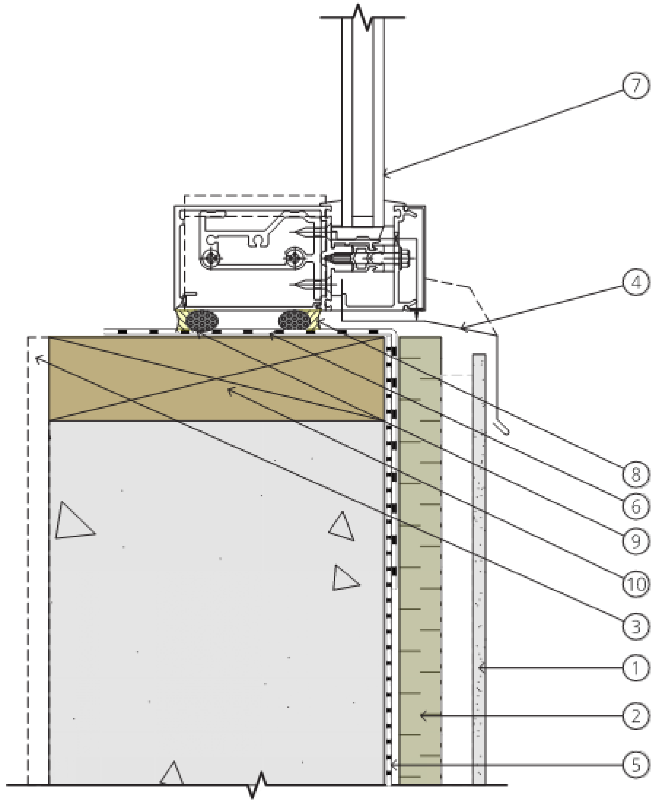
1. Cladding as per architectural – drained and vented cladding is recommended (water shedding layer)
2. Structure, CMU in this case
3. Interior finish as per architectural – avoid low vapor permeance wall coverings in hot and humid climates
4. Continuous insulation on interior of CMU. Exterior continuous insulation is preferred, but historically, interior continuous insulation is more common in hot and humid climates on concrete and CMU structures
5. Water and air control layer – self adhered or fluid applied over CMU surface
6. Bent metal drip edge under window to exterior
7. Window frame – ideally window frame aligns with insulation in wall to minimize thermal bridging, but that is not always practical
8. Exterior backer rod and sealant, discontinuous at window sill to allow drainage of water from sill flashing to the exterior
9. Water and air control layer continues from exterior into rough opening for transition of water and air control to window.
10. Interior sealant between back dam and window continuous around entire perimeter of window as air control layer.
11. Groove in underside of window sill trim detail as drip edge to prevent run back and concentration of water on the cladding below the window.

Figure 4-19. Windowsill detail in a CMU structure.



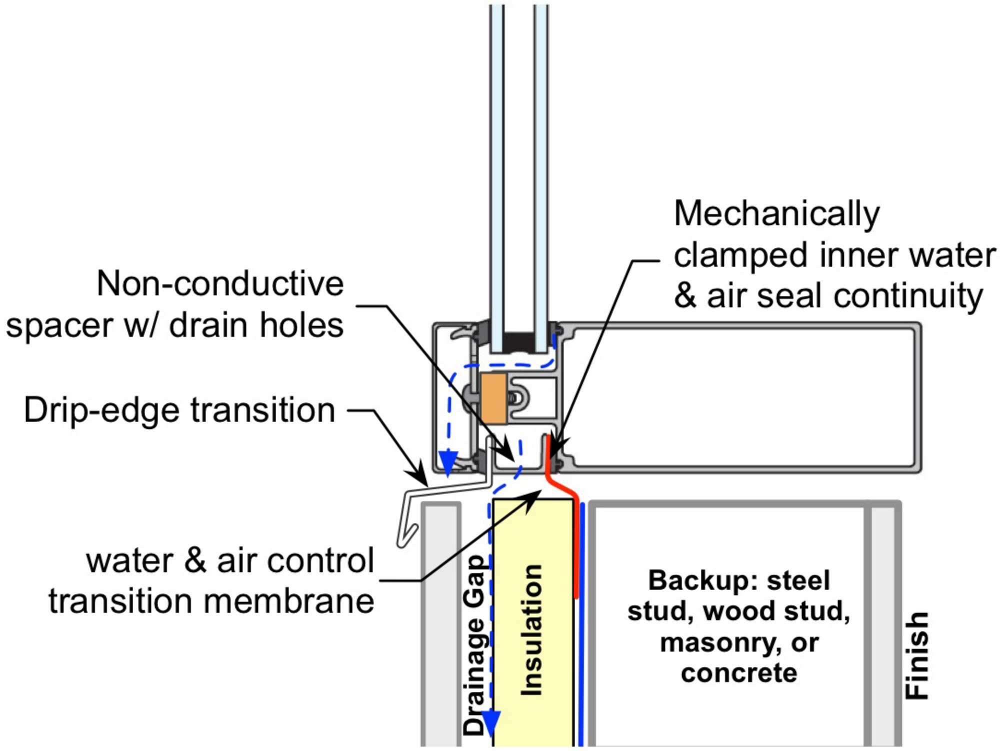
1. Cladding as per architectural – rain shedding layer for water control
2. Exterior continuous insulation depending on climate for thermal control
3. Interior finish on wall and rough opening as per architectural (Avoid low vapor permeance materials, coatings and coverings)
4. Bent metal sill pan flashing clamped into curtain wall frame. Alternatively, flashing could be flat on window sill and overlapped with transition membrane.
5. Water and air (and likely vapor) control layer. Self-adhered is recommended for performance and durability.
6. Continuous transition flashing wraps into window rough opening around the entire perimeter for continuity of air and water control from the window to the air and water control layer on the face of the wall.
7. Window – align windows so that the thermal break of the window lines up with thermal control of the wall assembly as much as possible.
8. Backer rod and sealant may be installed as air control if the sealant is continuous around the perimeter of the window. Alternatively, it is common to clamp a transition membrane from the air and water barrier of the wall into the shoulder of the curtain wall frame.
9. Backer rod and sealant is often installed at the interior surface of the window around the entire perimeter as the air control transition between the frame and the transition membrane on the rough opening. This sealant also can perform as the interior finish on the joint.

Figure 4-20. Windowsill detail in a steel building.



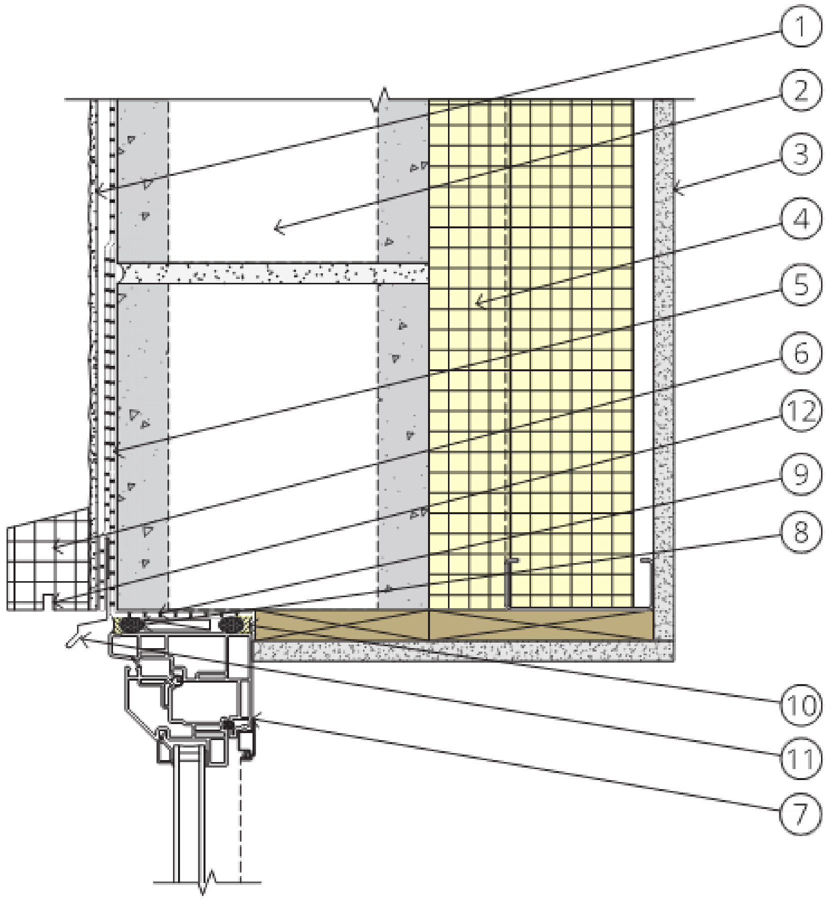
1. Cladding as per architectural – rain shedding layer for water control
2. Exterior continuous insulation depending on climate for thermal control
3. Interior finish on wall and rough opening as per architectural (Avoid low vapor permeance materials, coatings and coverings)
4. Bent metal sill pan flashing clamped into curtain wall frame. Alternatively, flashing could be flat on window sill and overlapped with transition membrane.
5. Water and air control layer (not required to be vapor barrier over concrete substrate). Self-adhered is recommended for performance and durability.
6. Continuous transition flashing wraps into window rough opening around the entire perimeter for continuity of air and water control from the window to the air and water control layer on the face of the wall.
7. Window – align windows so that the thermal break of the window lines up with thermal control of the wall assembly as much as possible.
8. Backer rod and sealant installed as air control if the sealant is continuous around the perimeter of the window. Alternatively, it is common to clamp a transition membrane from the air and water barrier of the wall into the shoulder of the curtain wall frame to act as the air and water control transition.
9. Backer rod and sealant is often installed at the interior surface of the window around the entire perimeter as the air control transition between the frame and the transition membrane on the rough opening. This sealant also can perform as the interior finish on the joint.

Figure 4-21. Windowsill detail in a concrete building.



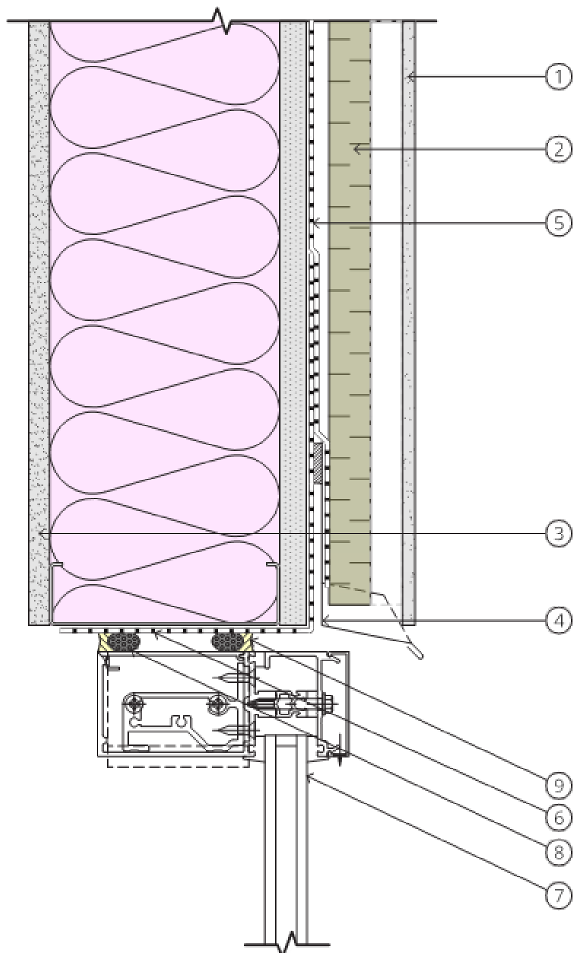
Source: High-Performance Building Enclosure, John Straube

Figure 4-22. Curtainwall sill detail with a mechanically clamped water and air control transition membrane between the structure and the curtain wall assembly.



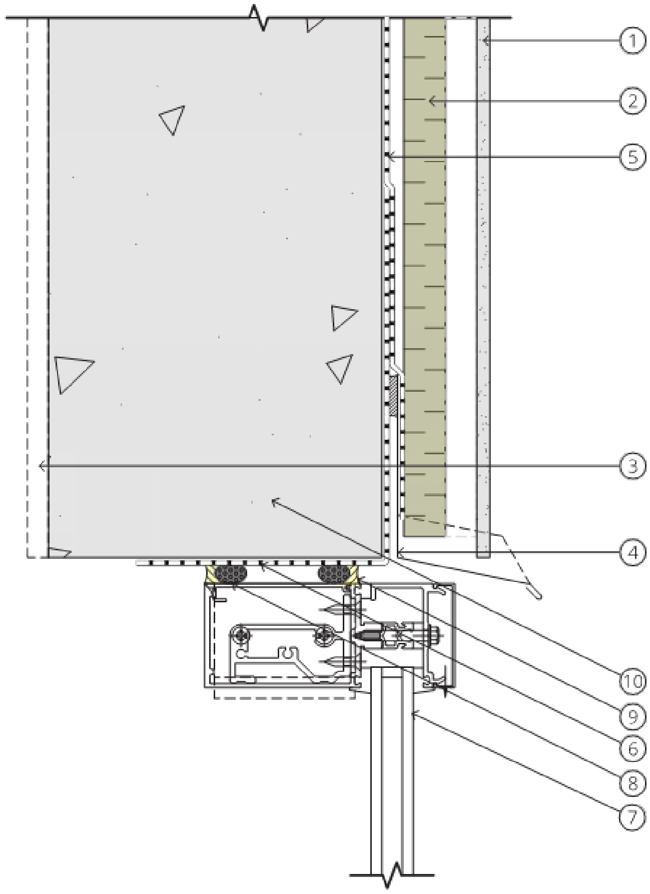
1. Cladding as per architectural – drained and vented cladding is recommended (water shedding layer)
2. Structure, CMU in this case
3. Interior finish as per architectural – avoid low vapor permeance wall coverings in hot and humid climates
4. Continuous insulation on interior of CMU. Exterior continuous insulation is preferred, but historically, interior continuous insulation is more common in hot and humid climates on concrete and CMU structures
5. Water and air control layer – self adhered or fluid applied over CMU surface
6. Window head trim to minimize water on window surface from wall runoff
7. Window frame – ideally window frame aligns with insulation in wall to minimize thermal bridging, but that is not always practical
8. Exterior backer rod and sealant continuous around head and jambs to minimize water penetration (water shedding layer), requires inspection and maintenance.
9. Water and air control layer continues from exterior into rough opening for transition of water and air control to window.
10. Interior backer rod and sealant, continuous around the perimeter of the window transitions between window frame and air control layer in rough opening, air control in rough opening
11. Bent metal drip edge sealed to water control layer on the exterior, directs any water in the drainage cavity to the exterior away from the window
12. Groove in underside of window head trip as drip edge to prevent run back of water to the window.

Figure 4-23. Window head detail in a CMU structure.



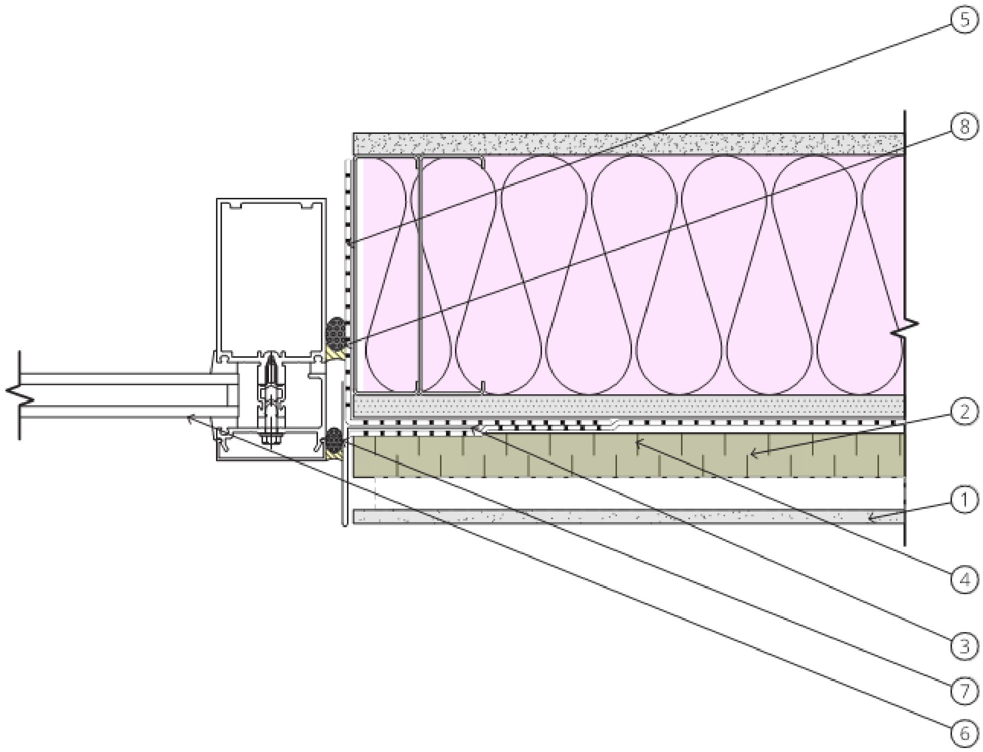
1. Cladding as per architectural – rain shedding layer for water control
2. Exterior continuous insulation depending on climate for thermal control
3. Interior finish on wall and rough opening as per architectural (Avoid low vapor permeance materials, coatings and coverings)
4. Bent metal head flashing directs any water from the enclosure above the window to the exterior to minimize concentrations of water on the window surface resulting from rundown. Flashing must be correctly overlapped with air and water barrier from the wall.
5. Water and air control layer (Vapor barrier not required over concrete wall assembly). Self-adhered is recommended for performance and durability.
6. Continuous transition flashing wraps into window rough opening around the entire perimeter for continuity of air and water control from the window to the air and water control layer on the face of the wall.
7. Window – align windows so that the thermal break of the window lines up with thermal control of the wall assembly as much as possible.
8. Backer rod and sealant is often installed at the interior surface of the window around the entire perimeter as the air control transition between the frame and the transition membrane on the rough opening. This sealant also can perform as the interior finish on the joint.
9. Backer rod and sealant at this location is acting as air and water control and must be continuous around the perimeter of the window.
10. 5.5 inches of fiberglass batt – effective R-value in a steel stud enclosure is approximately R7.

Figure 4-24. Window head detail in a steel building.



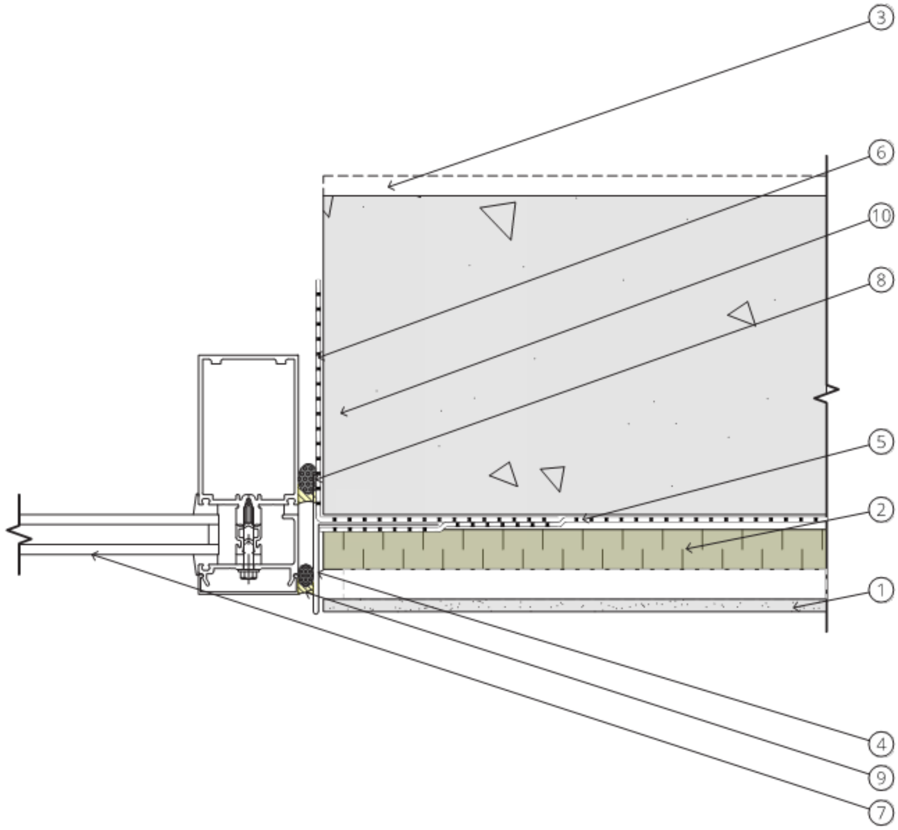
1. Cladding as per architectural – rain shedding layer for water control
2. Exterior continuous insulation depending on climate for thermal control
3. Interior finish on wall and rough opening as per architectural (Avoid low vapor permeance materials, coatings and coverings)
4. Bent metal head flashing directs any water from the enclosure above the window to the exterior to minimize concentrations of water on the window surface resulting from rundown. Flashing must be correctly overlapped with air and water barrier from the wall.
5. Water and air control layer (Vapor barrier not required over concrete wall assembly). Self-adhered is recommended for performance and durability.
6. Continuous transition flashing wraps into window rough opening around the entire perimeter for continuity of air and water control from the window to the air and water control layer on the face of the wall.
7. Window – align windows so that the thermal break of the window lines up with thermal control of the wall assembly as much as possible.
8. Backer rod and sealant is often installed at the interior surface of the window around the entire perimeter as the air control transition between the frame and the transition membrane on the rough opening. This sealant also can perform as the interior finish on the joint.
9. Backer rod and sealant at this location is acting as air and water control and must be continuous around the perimeter of the window.
10. Treated wood framing may be installed in the opening to make window installation easier. Need to ensure the wood is not exposed on the exterior, and is wrapped with the transition membrane into the rough opening

Figure 4-25. Window head detail in a concrete structure.



1. Cladding as per architectural – rain shedding layer for water control
2. Exterior continuous insulation depending on climate for thermal control
3. Correctly overlap bent metal flashing
4. Water and air (and likely vapor) control layer. Self-adhered is recommended for performance and durability.
5. Continuous flashing wraps into window rough opening around the entire perimeter for continuity of air and water control from the window to the wall.
6. Window – align windows so that the thermal break of the window lines up with thermal control of the wall assembly
7. Exterior bead of sealant on a two stage drained joint acts as the water shedding surface and exterior aesthetic finish
8. The interior bead of sealant must be continuous around the entire perimeter of the window without any gaps, and must transition between the window frame and the water/air control layer of the wall. Alternatively, with curtain wall, the water/air control from the wall could transition into the frame and get clamped by the curtain wall frame.

Figure 4-26. Window jamb detail in a steel building.



1. Cladding as per architectural – rain shedding layer for water control
2. Exterior continuous insulation depending on climate for thermal control
3. Interior finish on wall and rough opening as per architectural (Avoid low vapor permeance materials, coatings and coverings)
4. Bent metal jamb trim is an aesthetic finish, but overlapped with the water/air control barrier on the wall ensures water does not get behind it.
5. Water and air control layer (Vapor barrier not required over concrete wall assembly). Self-adhered is recommended for performance and durability.
6. Continuous transition flashing wraps into window rough opening around the entire perimeter for continuity of air and water control from the window to the air and water control layer on the face of the wall.
7. Window – align windows so that the thermal break of the window lines up with thermal control of the wall assembly as much as possible.
8. Backer rod and sealant is often installed at the exterior edge of the frame as the air and water control layer must be continuous around the perimeter of the window.
9. Backer rod and sealant at this location adjacent to the curtain wall pressure cap is acting as a water shedding surface to minimize water into the rough opening.
10. Treated wood framing may be installed in the opening to make window installation easier. Need to ensure the wood is not exposed on the exterior, and is wrapped with the transition membrane into the rough opening

Figure 4-27. Window jamb detail in a concrete structure.

4.11.1. Roof to Wall Transition Details

Roof to wall transition details have often been a location of excessive levels of air leakage as construction sequencing and timing can lead to discontinuities between the air control of the roof and the wall. If the building does not have an overhang, then the deck level air barrier from the roof should be continuous from the roof over the wall to ensure continuity at the detail as shown in Figures 4-28 and 4-29.

Often the air and water control details are independent of the structure, which means that the details can be used on any of the archetype superstructures so the structure in the detail is not significant.

Air barrier continuity can be more challenging with overhangs, but the detailed schematics in Figures 4-30 and 4-31 show a couple of options for overhangs on both sloped and low-slope roofs. It is recommended to make the connection of the air barrier components at the thermal insulation layer as well to avoid increased risks of condensation. For example, wrapping the air barrier around the overhang will result in heating of the air in the overhang, and the air will exchange with the interior potentially resulting in condensation and additional energy for space-conditioning. In situations where a structural metal deck extends beyond an exterior wall, the deck flutes are potential air leakage paths, even if the air barrier is tight to both the top and bottom of the metal deck. The individual flutes require sealing, typically by drilling holes in each flute and filling the flutes with expanding foam. Alternatively, in a large building, it may be more cost-effective to wrap the metal deck extension in an air barrier, and with insulation to avoid thermal bridging of the steel and convective looping within the steel between the interior and exterior environments.

In a building with a low-slope roof and parapet, it is recommended to continue the deck level air barrier/temporary roof under the parapet, to seal the parapet space off from the rest of the building and to ensure air barrier continuity between the roof and wall as shown in Figure 4-32. It may be possible to design buildings without parapets at all, which would be the preferred choice, if possible, as the added complexity of integration, and construction sequencing only increases the risks of water and air infiltration.

In any roof assembly with a space between the unvented roof assembly, the ceiling space should have some conditioning added by the mechanical equipment to avoid the risk of moisture accumulation and related issues in the space between the roof and the ceiling (Figures 4-28, 4-30, and 4-31).

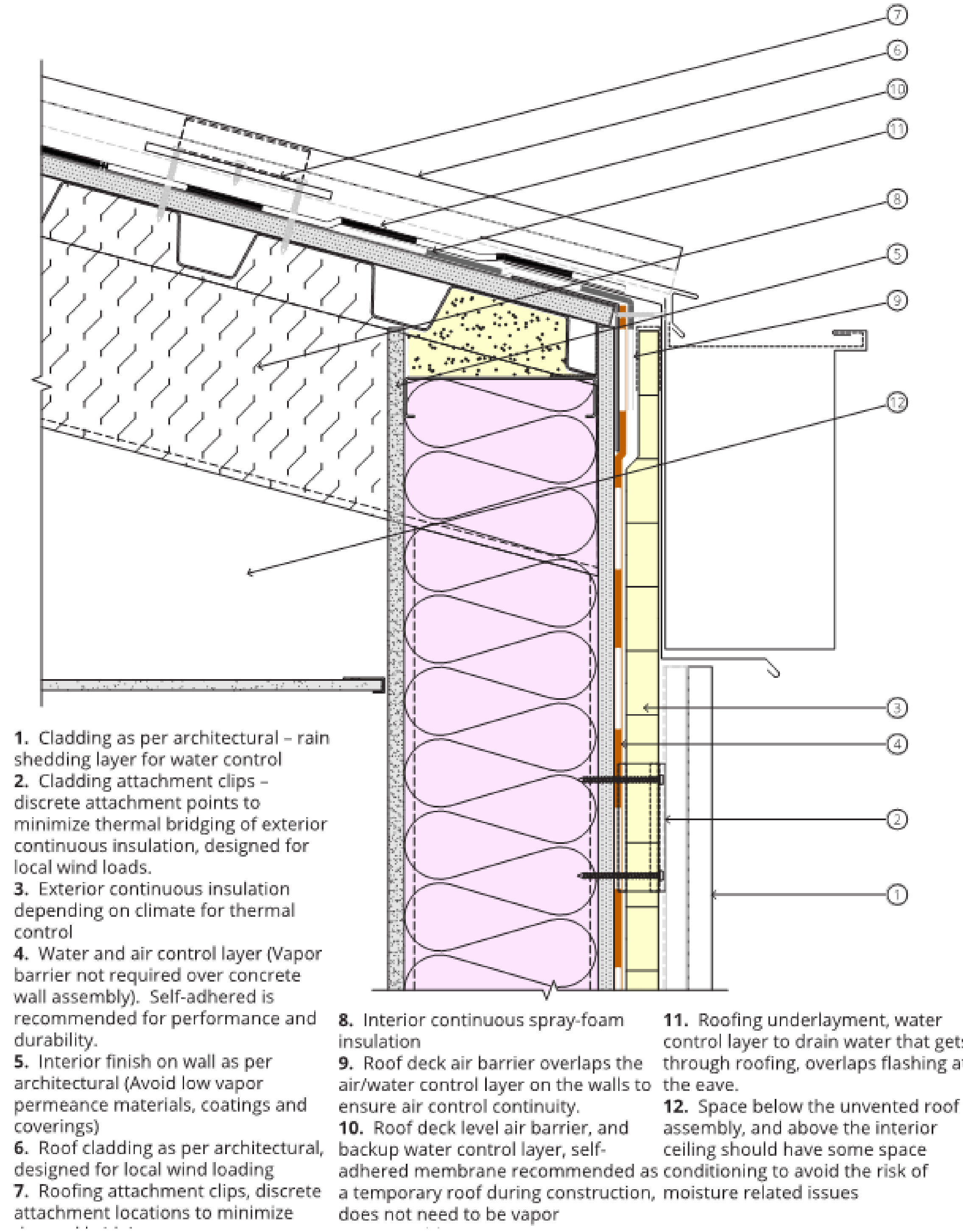
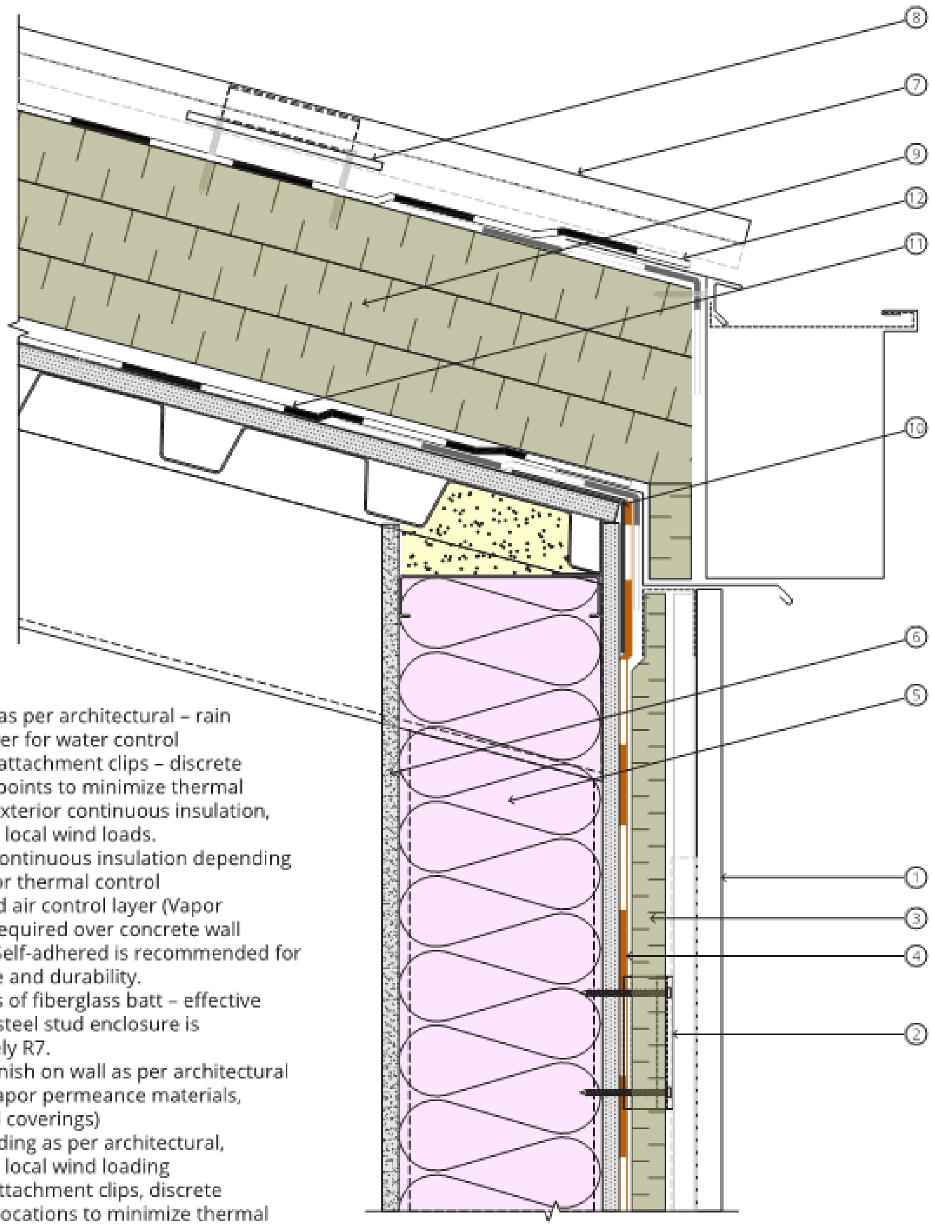
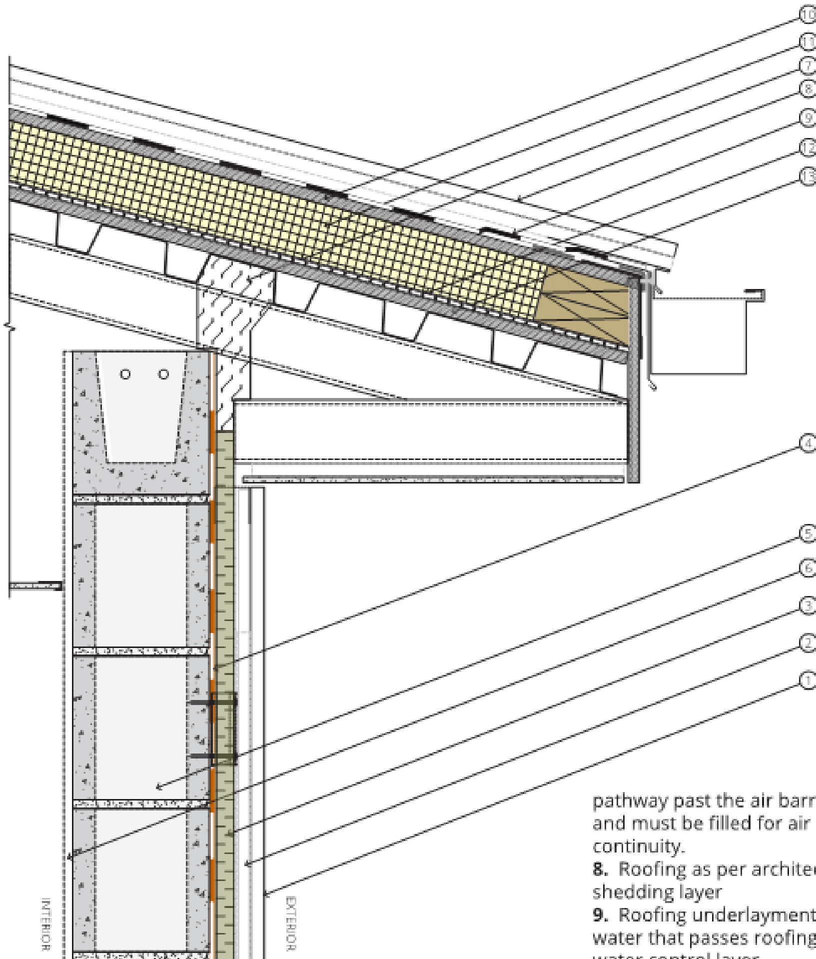


Figure 4-28. Sloped roof with interior insulation and attic space.



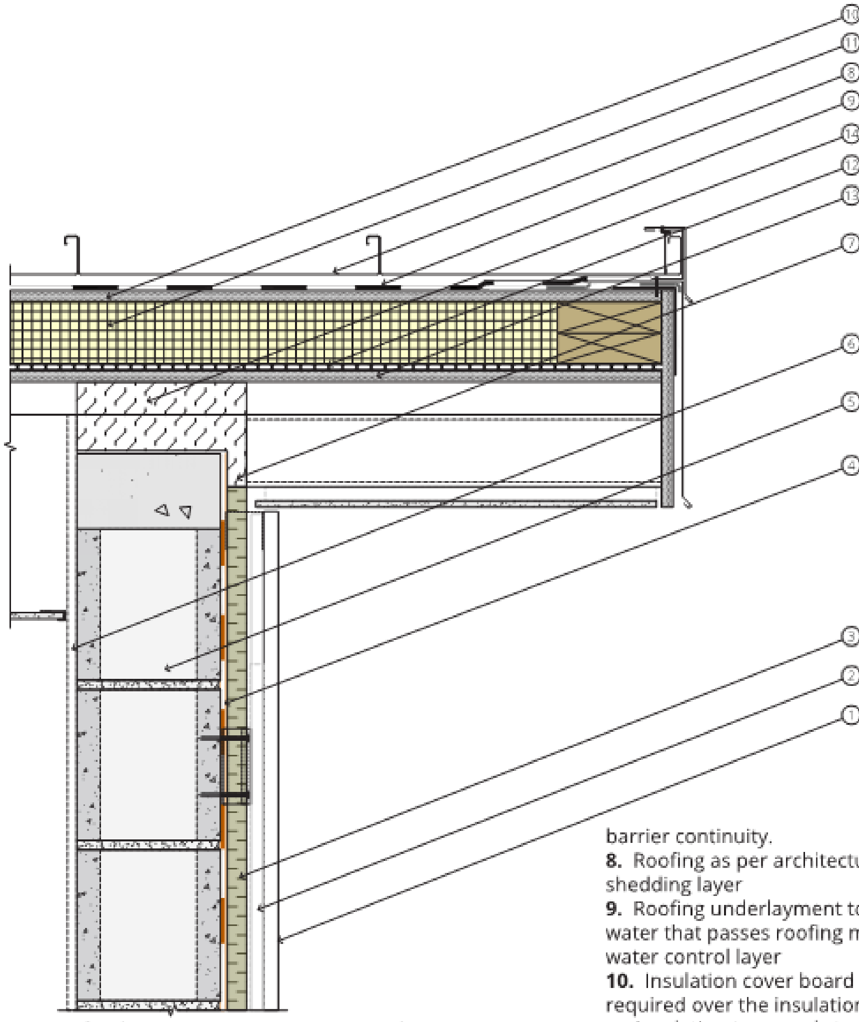
1. Cladding as per architectural – rain shedding layer for water control
2. Cladding attachment clips – discrete attachment points to minimize thermal bridging of exterior continuous insulation, designed for local wind loads.
3. Exterior continuous insulation depending on climate for thermal control
4. Water and air control layer (Vapor barrier not required over concrete wall assembly). Self-adhered is recommended for performance and durability.
5. 5.5 inches of fiberglass batt – effective R-value in a steel stud enclosure is approximately R7.
6. Interior finish on wall as per architectural (Avoid low vapor permeance materials, coatings and coverings)
7. Roof cladding as per architectural, designed for local wind loading
8. Roofing attachment clips, discrete attachment locations to minimize thermal bridging.
9. Exterior continuous roofing insulation, multiple layers, joints offset
10. Roof deck air barrier overlaps the air/water control layer on the walls to ensure air control continuity.
11. Roof deck level air barrier, and backup water control layer, self-adhered membrane recommended as a temporary roof during construction, does not need to be vapor impermeable
12. Roofing underlayment, water control layer to drain water that gets through roofing, overlaps flashing at the eave.

Figure 4-29. Sloped roof with continuous exterior roofing insulation and exposed interior roof.



1. Cladding – exterior finish as per architectural. Water shedding layer
2. Drainage and ventilation space behind cladding is important to minimize water progressing further into enclosure, and to assist with ventilation drying of the surfaces in the cavity
3. Exterior continuous insulation as thermal control depending on climate zone
4. Water and air control layer applied to the structure. Recommended self-adhered membrane or fluid applied membrane
5. Structure – in this case is CMU, but could be cast in place concrete. The choice of structure does not significantly affect the installation of the control layers.
6. Interior finish as per architectural
7. Critical transition detail between the air control layer of the wall and the air control layer of the roof. Spray foam is a good choice for this transition if applied correctly and surfaces of clean of oil and other impurities. Because the flutes in the deck run perpendicular to wall, each flute represents an air leakage pathway past the air barrier transition, and must be filled for air barrier continuity.
8. Roofing as per architectural – water shedding layer
9. Roofing underlayment to drain water that passes roofing material – water control layer
10. Insulation cover board may be required over the insulation depending on insulation type, and structural requirements
11. Continuous exterior insulation thermal control. R-value depending on climate zone.
12. Self-adhered membrane installed on sheathing as air control layer in roof assembly, and as temporary roofing membrane during construction.
13. Gypsum sheathing installed over metal deck to support air control layer.

Figure 4-30. Sloped unvented roof assembly with overhang.



1. Cladding – exterior finish as per architectural. Water shedding layer
2. Drainage and ventilation space behind cladding is important to minimize water progressing further into enclosure, and to assist with ventilation drying of the surfaces in the cavity
3. Exterior continuous insulation as thermal control depending on climate zone
4. Water and air control layer applied to the structure. Recommended self-adhered membrane or fluid applied membrane
5. Structure – in this case is CMU, but could be cast in place concrete. The choice of structure does not significantly affect the installation of the control layers.
6. Interior finish as per architectural
7. Critical transition detail between the air control layer of the wall and the air control layer of the roof. Spray foam is a good choice for this transition if applied correctly and surfaces of clean of oil and other impurities. If the metal deck was perpendicular to detail, all of the flutes would require filling to maintain air barrier continuity.
8. Roofing as per architectural – water shedding layer
9. Roofing underlayment to drain water that passes roofing material – water control layer
10. Insulation cover board may be required over the insulation depending on insulation type, and structural requirements
11. Continuous exterior insulation thermal control. R-value depending on climate zone.
12. Self-adhered membrane installed on sheathing as air control layer in roof assembly, and as temporary roofing membrane during construction.
13. Gypsum sheathing installed over metal deck to support air control layer.
14. In assemblies where the metal deck flutes pass through the air conrol layer, the individual flutes should be sealed with spray foam

Figure 4-31. Roof overhang detail.

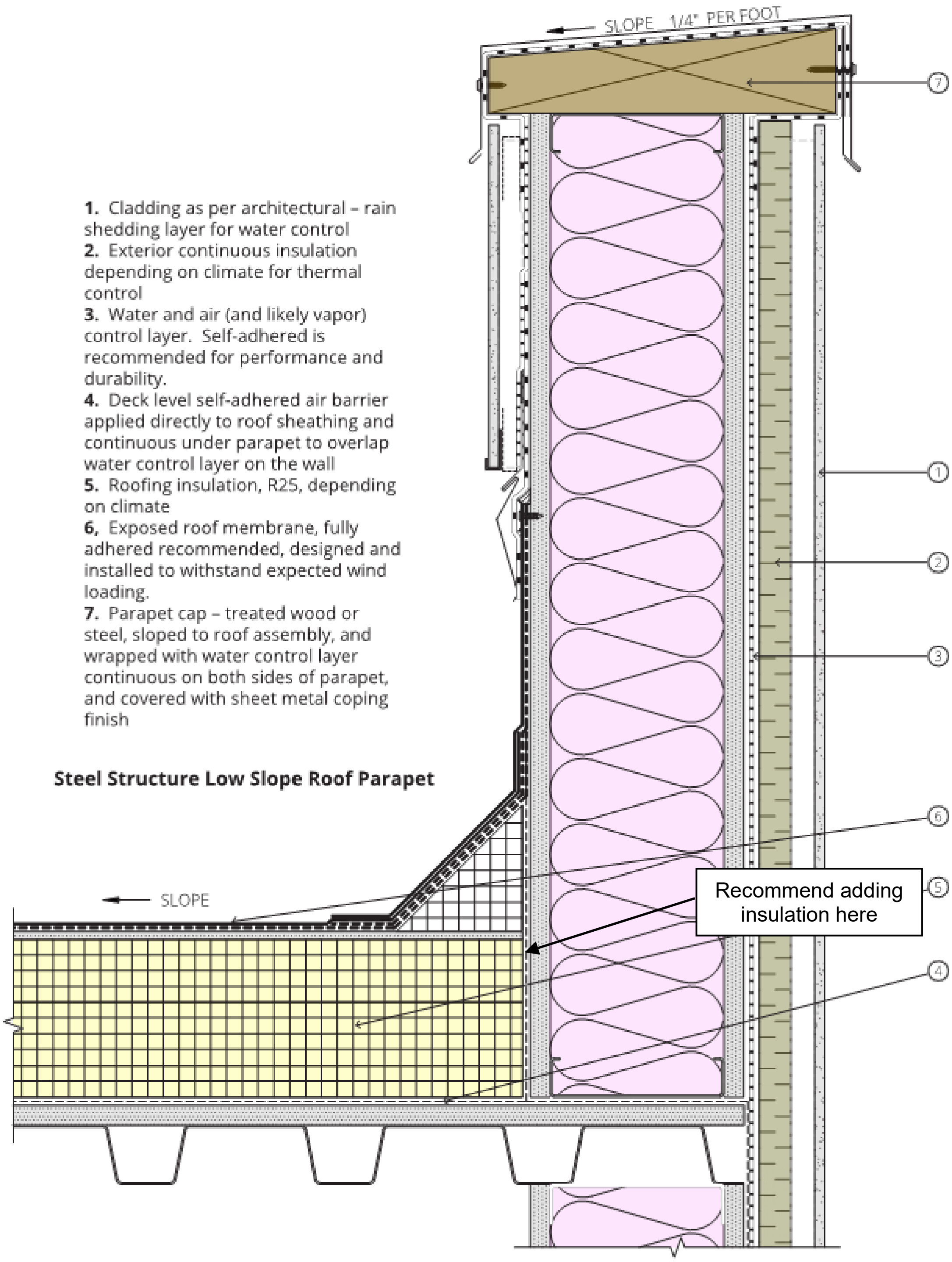


Figure 4-32. Low-slope roof and parapet detail.

4.11.2. Concrete Slab/Foundation to Above-Grade Wall Transition

The transition between the below-grade portion and the above-grade portion of the enclosure is often a combination of materials and construction trades that can make it difficult to ensure continuity. Figure 4-33 shows an example of a concrete slab on grade with a structural concrete footing and an above concrete wall provided by a USACE base. This detail shows the brick veneer cladding continuing below grade. This is not typically recommended as moisture movement into and out of the brick veneer can result in efflorescence and eventual deterioration of the brick. Figure 4-34 shows the recommended method of extending the concrete footing wall above grade and constructing the above-grade wall (steel stud, CMU, concrete, etc.) on top of the concrete wall to minimize contact with groundwater. Also, note that the interior finished floor level is higher than the exterior grade, which is always recommended in flood-prone areas.

Figure 4-33 shows the control layers for a CMU wall, however, the air and water control for the steel-framed above-grade wall would be virtually identical with an exterior water/air control self-adhered membrane installed on the surface of gypsum sheathing instead of CMUs.

The important concepts in Figure 4-33 are relevant to any concrete structure below grade either with the slab at grade, or the slab below grade in a crawlspace or basement construction. As noted previously, constructing space below grade is not recommended in coastal areas, or areas prone to flooding, but in some of the hot climates covered by this Guide, the ground may be well-drained, with essentially no risk of flooding.

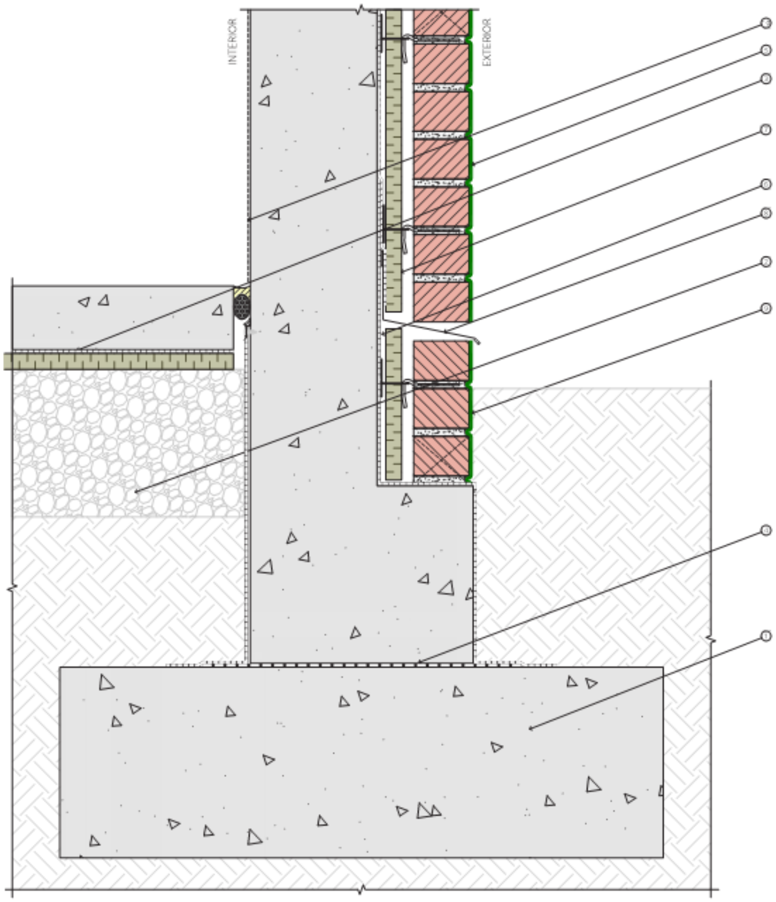
Because concrete can readily absorb liquid water and move it through the concrete pores by capillarity action, concrete should be protected whenever it is below grade to minimize the movement of water through the concrete into the enclosure and interior space.

A capillary break between the footing and the vertical concrete wall is recommended. This can be accomplished with products specifically marketed as footing capillary breaks or with sufficient below-grade waterproofing installed on the top of the footing. The surfaces of the concrete wall should be protected by a fluid-applied water control layer or self-adhered membrane intended for this use. If the concrete is expected to be below the water table at any time, more specialized waterproofing materials specifically intended for long-term submersion and water head should be used.

The slab on the grade should be installed over free-draining gravel, and directly on top of an air/vapor barrier and capillary break (typically polyethylene sheet), to minimize the water moving through the concrete from the ground. The polyethylene sheet should be sealed at all laps, penetrations, and around the edge to minimize air movement from the ground, which would increase the moisture load on the interior space, and potentially increase intrusion by soil gases such as radon. Several vapor barrier manufacturers have systems of materials, transition membranes, and details to accomplish these functions.

In all cases, the following guidelines apply:

- Where material options are provided in a UFGS, use the most durable options.
- Provide a higher level of corrosion protection as defined in the appropriate corresponding UFGS.
- Do not use unprotected ferrous metal unless there are no alternatives.
- Coat galvanized steel with an industrial coating.
- Use Type 316L, 304L, 304, or 316 stainless steel or duplex stainless steels where stainless steels are used.
- Coat aluminum with an industrial protective coating or a heavy-duty anodized coating.
- Isolate dissimilar metals (for example, aluminum and steel, stainless steel and carbon steel, and zinc-coated steel and uncoated steel) by appropriate means to avoid the creation of galvanic cells that occur when dissimilar metals come in contact.
- For structures proximate or at the waterfront, in addition to atmospheric corrosion, design for the presence of hydrostatic forces, wind, salt spray, currents, tides, waves, ice, marine borers, insects, and pollution from waterfront operations. Some common grades of stainless alloy such as Type 304 or 316 are susceptible to corrosion when immersed in salt or brackish water.



1. Footing as per structural
2. Free draining fill below slab
3. Air/water control layer directly below slab to minimize contact of water to slab, and minimize transmission of soil gases including radon into interior space. Must be sealed at all edges and penetrations.
4. A capillary break is recommended between the footing and the concrete wall to stop the wicking of water into the above grade portion of the concrete wall
5. Structure – concrete wall shown, but could be CMU, or steel structure sitting on concrete stem wall.
6. Water control layer applied to the exterior of the concrete wall, should be continuous all the way to the surface of the footing.
7. Exterior continuous insulation as thermal control depending on climate zone
8. Through wall flashing sealed to the water barrier on the concrete, sloped towards the exterior to allow any water behind the insulation, or in the drainage cavity to drain to the exterior through weep holes in the masonry.
9. Below grade masonry is not recommended as it often leads to efflorescence as a result of capillary movement of water, and evaporation from the surfaces leaving salts. Brining the concrete wall above grade before starting masonry is recommended in all climates
10. Interior finish as per architectural
11. Water barrier on the interior of the concrete wall below grade to the interface with the footing to minimize capillary movement of water into the interior space.

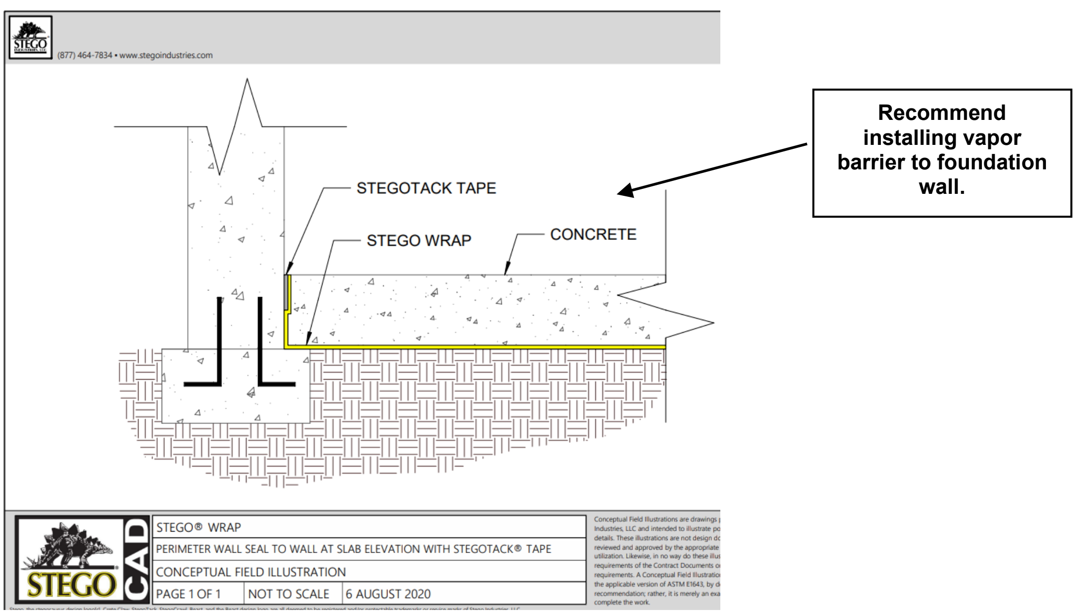


Figure 4-33. Concrete slab to above-grade wall schematic.

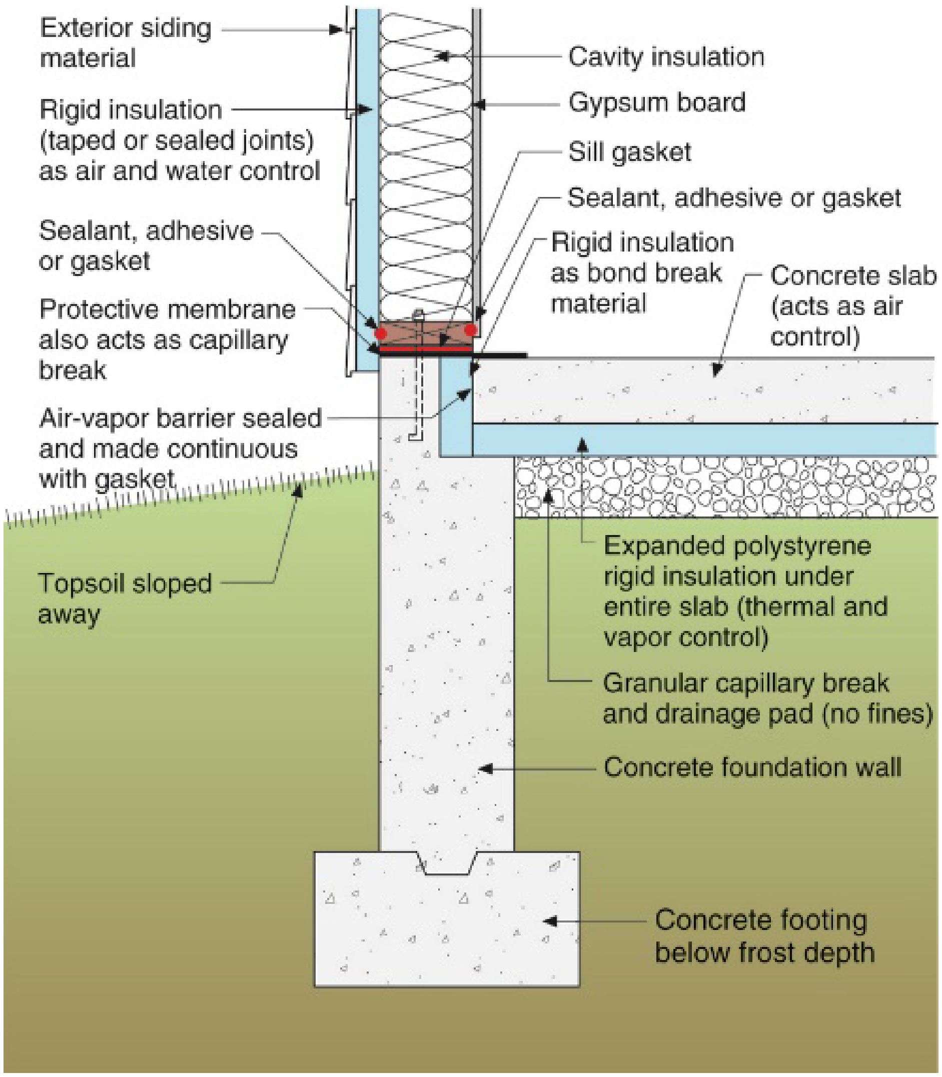


Figure 4-34. Schematic of slab-on-grade transition with a recommended concrete curb above grade and the interior floor above exterior grade.

4.12. Conclusions

The degradation of reinforced concrete structures in a hot-humid coastal and inland environment is related to physical and chemical processes including chloride penetration, sulfate attack, and carbonation. Among these factors, chloride penetration is the most concerning for the durability of concrete structures.

Chloride ions move into concrete by the mechanisms of diffusion and convection. Diffusion is caused by differences in chloride ion concentrations in pore water while convection is due to water transport carrying chloride ions. During the chloride transport process, some chloride is dissolved in pore water and the rest is bound by cement hydrates, i.e., free chloride and bound chloride, respectively. The free chloride is responsible for destroying the passive layer of steel and initiating steel corrosion

A protective oxide film is present on the surface of the steel reinforcement due to the concrete alkalinity. This layer is called passivity. The process of carbonation will affect this protective passivity layer. This layer can also be affected by the presence of chlorides in water or in oxygen. The reinforcement corrosion process is shown in Figure 4-18.

°The details and discussion in this chapter are critical for the long-term durability, energy efficiency, and resilience of buildings in hot and humid climates. The critical enclosure design criteria from this chapter can be summarized related to the enclosure can be summarized in a few key points.

The airtightness of the enclosure is critical to both moisture and energy performance of the enclosure and building. As such, the airtightness of all new and renovated buildings in hot and humid climates should be limited to a maximum air leakage of 0.15 cfm/ft^2 at 75 Pa (2.10 m^3/h/m^2 at 50 Pa). All the enclosure drawings must show the specified air barrier layer of all enclosure assemblies, and across every transition and penetration. Larger scale drawings should be used whenever necessary to accurately describe the layering of materials to the construction team. The air barrier in hot and humid climates should be located as close as possible to the exterior to minimize the risk of hot and humid air infiltrating the enclosure and interacting with the colder surfaces below the dewpoint of the outdoor air.

The prescriptive requirements of ASHRAE 90.1-2019 must be met as a minimum for new construction, and whenever possible, depending on the scope of retrofit work. It is unlikely that these requirements will be sufficient to construct net zero energy buildings; to exceed the requirements of 90.1-2019 for the enclosure and windows, it will likely be required to meet higher performance requirements.

The most critical component of the enclosure with respect to overheating and cooling loads (assuming the enclosure is relatively airtight) is the fenestration within the enclosure. Solar heat gains through windows are typically the largest source of heat within a building in typical buildings in hot and humid climates. Solar gains must be minimized as much as practically possible through the use of low-E coatings, decreased SHGC, reducing window to wall ratios, and shading strategies where appropriate.

Construction of below-grade spaces should be avoided in areas with high water tables and with a risk of flooding. It may be prudent to install structures off the ground in some areas where surface water is expected to impact the building. Mechanical and electrical services should be placed in locations within the enclosure to avoid expected flooding.

Because of the risks of roof ventilation in hot and humid climates, both low-slope (flat) and pitched-roof assemblies should be designed and constructed as unvented assemblies, ideally with exterior layers of insulation, although a reasonable alternative to install spray foam on the underside of the roof deck.

All the control layers for water, air, vapor, and insulation must be continuous across all aspects of the enclosure, i.e., fenestration, transitions between enclosure elements, and other penetrations.

CHAPTER 5. HEATING, VENTILATION, AND AIR-CONDITIONING CONSIDERATIONS FOR HOT AND HUMID CLIMATES

5.1. Introduction

Hot and humid climates (HHC) pose serious design challenges for HVAC systems. However, with proper design, resilient equipment specification, communication of operational requirements, operation in accordance with the design requirements, and maintenance that always restores the systems to as-designed condition, building HVAC systems can provide a level of protection to the interior of the building that envelope design alone may not provide.

This chapter is not intended to duplicate the wealth of information on HVAC systems available from ASHRAE and other reputable sources; rather, it describes specifics of HVAC systems that address issues specific to HHC, i.e., mold and corrosion control, and HVAC systems features that make them more resilient to major threats specific to locations with HHC conditions. Proper selection and good design of HVAC systems will not be able to mitigate the issues described above unless close attention is paid to specifics of design and construction of the building envelope in a hot and humid environment as described in Chapter 4, regarding airtightness, especially in the corrosive environment of coastal areas.

Also, this chapter addresses HVAC systems operations during normal (blue sky) and emergency (black sky) operations (described in section 5.4.2) and methods of adjusting system performance to meet requirements to thermal conditions in occupied and unoccupied buildings and their areas described in Chapter 2. Finally, this chapter's content is complemented by the information about air barriers found in Chapter 4 and resilient district cooling systems that can be found in Chapter 6.

5.1.1. Issues of Importance that Are Not HHC Specific

In general, the following topics will only be discussed minimally:

- General energy efficiency requirements are thoroughly addressed by current design standards in UFC 3-410-01, *Heating, Ventilating, and Air-Conditioning Systems* (NAVFAC 2021b).
- Sustainability/green building design requirements are thoroughly addressed by current design standards in UFC 1-200-02, *High Performance and Sustainable Building Requirements* (NAVFAC 2022).
- Indoor sources of humidity that must be designed for but that are common to all climate zones will only be addressed with respect to their mitigation and how it relates to HHC HVAC systems.

5.1.2. Issues of Importance to HHC

Issues of Importance to HHC include

- The airtightness of the building envelope can directly dictate how much outside air is required to pressurize a building to prevent infiltration. Infiltration of unconditioned outside air can lead to condensation on cold surfaces, damage to building elements and finishes, and the creation of surfaces with high potential for growth of mold and mildew leading to sick-building syndrome and a myriad of indoor-air-quality-related health problems for the building occupants.

- Building pressurization, using conditioned outside air, provides fresh air to the spaces, replaces air removed by exhaust systems, and pressurizes the building to resist the infiltration of hot, humid air due to wind and pressure differences.
- Indoor dewpoint temperature control will be shown as a much better control parameter for inside air humidity control than RH for normal occupancy conditions and thus is one of the primary parameters of monitoring and control in conditioned buildings.
- For HHC, dehumidification or latent cooling control should be decoupled from space comfort or sensible cooling control. This may require separate dehumidification equipment to pretreat the outdoor air stream, which introduces the vast majority of the dehumidification load into buildings, or can be accomplished using specialized energy recovery designs in the air handlers discussed below.

5.2. HVAC Issues Related to Hot and Humid Climates

5.2.1. Definitions of Terms Used in Chapter 5

Building Envelope. The roof, walls, windows, doors, and floor of a building that are exposed to the outside air environment and separate the indoor air from the outdoor air (atmosphere).

Dewpoint Temperature. The temperature at which a body of air, when cooled, will begin to precipitate moisture out of the airstream. Dewpoint temperature is very closely aligned with the air humidity ratio.

Dry Bulb Temperature (DBT). The temperature of the air measured with a dry bulb thermometer (with no water on the sensing bulb to evaporate). Most commonly referred to as “the Temperature.”

Exfiltration. Air leakage from inside a building to the outside through cracks or joints in the building envelope.

Humidity Ratio. The mass of moisture (water vapor) in a body of air divided by the mass of the dry air contained in the same body.

Infiltration. Air leakage into a building from the outdoors caused by wind effects, negative pressurization, vapor pressure, and other transport mechanisms.

Latent Cooling. Removal of water from the air by means of condensing water vapor from the air through cooling that results in a reduction in dewpoint temperature of the airstream.

Sensible Cooling. Removal of heat from an airstream that does not result in a change in water vapor content and that results in a decrease in the measured DBT of the air with no change to dewpoint temperature.

Wet-Bulb Temperature. The air temperature is measured with a thermometer, the sensing bulb of which is covered with a wick fabric that has been immersed in warm water. When exposed to a fast-moving air stream, the evaporating moisture in the wick material will cause the bulb to sense an equilibrium temperature of the air moving over the wick-covered bulb that is at some value between the air's DBT and its dewpoint temperature. The more humid the airstream, the closer the wet-bulb temperature will be to the DBT.

5.2.2. Infiltration and Building Pressurization

Buildings are never 100% airtight. A solid piece of glass or metal fascia or even block and masonry walls (if painted and sealed correctly), as well as roofs, are fairly impervious to air passing through them. However, the joints and cracks created where these surfaces meet will allow significant quantities of air to pass from inside to outside (exfiltration) or outside to inside (infiltration). While the exfiltration leaks conditioned room air to the outside and should be minimized, infiltration of hot and humid outside air into a conditioned space should be avoided wherever reasonably and practically possible. Infiltration of warm, moist outside air increases the dewpoint temperature of the space. This can cause condensation on cold surfaces and create moist areas on porous building materials creating environments that are favorable for mold and other biological growth.

The causes of infiltration can be narrowed to one basic condition: a slightly lower atmospheric pressure inside the building relative to the outside of the building. Pressure difference drives air movement through the cracks in a resisting barrier. The two main causes of low pressure inside a building are wind outside the building and building exhaust systems in the building that have not been provided enough makeup outside air to replace the exhaust.

Air infiltration can occur due to pressure differences between the internal and external environments of the building caused by (1) wind pressure, (2) stack pressure caused by a difference in atmospheric pressure at the top and bottom of a building due to differences in air temperature inside and outside the building, and (3) a negative pressure caused by fans when the exhaust airflow rate exceeds the supply airflow rate.

Wind creates lower pressure zones outside the building on the leeward or downwind side(s) of the building while higher pressure conditions exist on the windward or upwind side(s) of the building. This sets up a situation where conditioned air is exfiltrating the building on the leeward side of the building while infiltration is occurring on the windward side. If the outside air conditions are warm and moist, the indoor conditions will be changed toward being warm and moist as well. For this issue, the tighter or lower leakage the building air barrier can be made, the easier it is to overcome the infiltration issue.

Building exhaust that is replaced by the building air-conditioning system (and not by conditioned outside air) will also result in general infiltration of unconditioned outside air. This situation must be overcome by correctly designing the building HVAC to supply makeup outside air into the building to replace the exhausted air.

In buildings that are taller than six stories or 80 ft (24.4 m), stack effect can begin to introduce a buoyancy pressure difference between the inside air and the outside air at the bottom of the building. The pressure difference will tend to cause exfiltration during hot and humid times of year and only produce infiltration when the outside air is cooler and dryer than inside. For buildings greater than 80 ft (24.4 m) in height, care should be taken with respect to these pressure differences as door opening forces can be affected.

Building pressurization and makeup airflow is the solution to infiltration issues. The building HVAC system must supply sufficient, conditioned replacement or makeup air to replace the air exhausted by the various exhaust systems in any building. In addition, to resist infiltration due to wind, the outside air system should supply a sufficient flow of conditioned outside air to produce a 0.1-in. water column (0.036 psi) of pressure differential higher inside air pressure relative to the outside air pressure. This pressure difference will resist the effects of up to a 12 knot (22.2 kph) wind speed impinging on the building. While the pressure difference could be increased for higher wind speeds, it is preferable to limit the building pressurization to 0.1 in. water column (0.036 psi) so that building door-opening-closing forces do not exceed 5 lbs (22 Newtons).

The relationship between a building's airtightness or air barrier allowable leakage comes into play when calculating the required airflow for building pressurization. For DOD buildings, UFC 3-101-01 (NAVFAC 2021a) requires the air barrier to be tested during construction (for new buildings and major renovation) by holding the building pressurized to 0.3-in. water column (0.0108 psi) higher pressure inside than outside. The airflow into the building is measured. When compared to the exposed area of the building, the airflow should not exceed the allowable airflow per unit area (cfm/ft^2, m^3/h/m^2) set forth in the UFCs and standards referred to therein.

Given that the majority of the leakage through the air barrier is at the joints or cracks, the leakage rate can be estimated assuming orifice flow and be considered to be proportional to the square root of the pressure differential across the air barrier. Given the test pressure of 0.3-in. water column (0.0108 psi) and a desired building pressurization of 0.1-in. water column (0.0036 psi), the allowable leakage rate (cfm, L/s) can be multiplied by the square root of the pressure ratio $\sqrt{(0.1/0.3)}$ to obtain the required pressurization flow into the building. The net pressurization airflow should be approximately 58% of the allowable leakage rate of the building. If one knows the outside surface area, A_{AB}, of any building being designed and also knows the allowable leakage rate per unit of surface area, q_{Al}, then a pressurization airflow can be calculated for the building. The pressurization, conditioned airflow into the building, Q_{Press}, will be calculated as:

$$Q_{Press} = AAB * q_{Al} * 0.58 \qquad (5\text{-}1)$$

The total outside airflow into the building is currently set by ASHRAE 62.1 and this minimum must be maintained.

However, in cases where the outside airflow for 62.1 compliance is lower than that required to pressurize the building, it is recommended that the outside airflow be increased to overcome all required exhaust airflows and provide building pressurization. In other words, total design outside airflow should be

$$Q_{OA} = Q_{Press} + Q_{Exh} \tag{5-2}$$

where Q_{Exh} is the required exhaust airflow from the building

OR

$$Q_{OA} = Q_{A62.1} \tag{5-3}$$

where $Q_{A62.1}$ is the required airflow of the ventilation rate procedure of ASHRAE 62.1, whichever is larger.

For example, consider an office building that is 100 ft wide by 100 ft long by 20 ft high (30.5 m wide by 30.5 m long by 6.1 m high). In its simplest form the air barrier is composed of the bottom floor, the roof, and the four walls. The total air barrier area would be 28,000 ft^2 (2601 m^2). For Air Force buildings, the allowable air barrier leakage is 0.4 cfm/ft^2 (0.12 m^3/min/m^2). For Army buildings, the allowable leakage rate is 0.25 cfm/ft^2 (0.076 m^3/min/m^2). The design recommendation is that allowable leakage be reduced to 0.15 cfm/ft^2 (0.046 m^3/min/m^2). Table 5-1 shows the required pressurization airflow reduction produced by improving the airtightness of the building. From this we see the motivation for improving airtightness. Chapter 4 discusses methods of achieving improved airtightness.

Table 5-1. Allowable leakage and pressurizing outside airflow – Sample building.

Office Building 100 ft (l) x 100 ft (w) x 20 ft (h) (30.5 m wide by 30.5 m long by 6.1 m high)	**Allowable Leakage (cfm/ft^2 [m^3/h/m^2]) Test pressure 0.3-in. w.g.**	**Building Allowable Airflow Leakage (cfm [L/s]) (28,000 ft^2 air barrier)**	**Building Pressurization Airflow Required (cfm [L/s]) at 0.1-in. w.g. building pressure**
Air Force	0.40 (5.7)	11,200 (5286)	6,496 (3066)
Army	0.25 (0.29)	7,000 (3304)	4,060 (1916)
Proposed	0.15 (0.18)	4,200 (1982)	2,436 (1150)

Again, minimum IAQ is established by ASHRAE Standard 62.1 (2019b); designers are usually required to follow the ventilation rate procedure of this ASHRAE standard. For our example office building above, there could be as many as 100 occupants. ASHRAE 62.1 would require a minimum of 1,375 cfm (649 L/s) of outside air to be supplied to the space to provide an acceptable IAQ. Since this flow rate is less than that required to pressurize the building, the rate from Table 5-1 would be required. If, however, the sample building contained a large auditorium or other assembly space, the ASHRAE 62.1 required outside air could become dominant (perhaps requiring 2600 cfm (1,227 L/s) for 300 people in the building) and building pressurization would be satisfied by the ASHRAE 62.1 required airflow.

In terms of outside air quantity, outside airflow rates are generally fairly constant and only vary based on the requirements in the list above. In HHC, the conditioned, dehumidified, outside airflow rate should be the largest between those calculated using Equations 5-4 and 5-5:

$$Q_{OA} = Q_{A62.1} \tag{5-4}$$

$$Q_{OA} = Q_{Exh} + Q_{Press} \qquad (5\text{-}5)$$

where:

Q_{OA} = Total outside airflow supplied to the building,

$Q_{A62.1}$ = Sum of outside airflow rates required by the Ventilation Rate Procedures chapter of ASHRAE 62.1 (2019b) to be supplied in all building's zones,

Q_{Exh} = Sum of all exhaust airflows from the building, and

Q_{Press} = AAB x qAl x (0.1/0.3)0.5, same as Equation 5-4 where:

- Q_{Press} = Required net airflow to the building that will produce a 0.1-in. (25 Pa) net pressure in the building relative to the outside. (The '0.1/0.3' term is the required actual pressure divided by the required test pressure of the building air barrier.)
- A_{AB} = The Area of the building air barrier, and
- q_{Al} = The allowable airflow (leakage) rate per unit of area of the air barrier at the required test pressure of the building air barrier (0.3 in. water column [0.036 psi])

The HVAC controls should continually monitor the occupancy of the building, the total of all exhaust airflows, and the actual outside airflow and adjust the outside airflow to meet the minimum building pressurization (Equation 5-5) at all times and the minimum ventilation for IAQ (Equation 5-4) when it becomes the greater airflow requirement. If scheduling shuts down certain exhaust fans, the airflow for pressurization may also be reduced. However, the net conditioned airflow into a building should never be reduced to less than that required for pressurization (Q_{Press}) in HHC when the outside conditions include a dewpoint temperature greater than 55 °F (13 °C).

Figure 5-1 includes three charts for a sample building, shown with an assembly space and a commercial kitchen.

The first (Chart A) represents the outside airflow required to comply with ASHRAE 62.1 Ventilation for Acceptable Indoor Air Quality (ASHRAE 2019b). Notice that, for most of the day, the outside air requirements represent a typical business occupancy and are less than the requirements for building pressurization in Chart B. However, at 17:00 an assembly occurs that drives the outside air requirements for IAQ much higher because the number of people in the assembly area increases. Chart A represents Equation 5-4 for a sample building.

The second (Chart B) represents the outside airflow required to provide building pressurization and offset exhaust airflows. Notice that, in the pre-morning and throughout the regular business day, the exhaust level is high, possibly due to the kitchen exhaust requirements. Chart B represents Equation B (above) for a sample building. Also, notice that the basic requirement for building pressurization airflow (the purple block) never goes away in a hot and humid climate. The only way to lower this airflow is to improve the building's airtightness. Specifying, requiring, and testing to confirm proper installation of the building air barrier is critical in reducing this continuous airflow volume. Conditioning outside air requires a ton of refrigeration for every

150 cfm (71 L/s) of outside airflow during summer season conditions that can occur from January to December.

> … the basic requirement for building pressurization airflow … never goes away in a hot and humid climate. The only way to lower this airflow is to improve the building's airtightness. Specifying, requiring, and testing to confirm proper installation of the building air barrier is critical in reducing this continuous airflow volume. Conditioning outside air requires a ton of refrigeration for every 150 CFM of outside airflow during summer season conditions, which can occur from January to December in hot and humid climates!

Chart C shows the overall requirements for outside air based on either Chart A or Chart B requirements, whichever is higher. Chart C also includes the required relief air to offset outside air brought into the building to maintain IAQ, but which is not being exhausted and which could cause pressure issues with opening or closing exterior doors if not relieved. As will be discussed later, the relief air can be passed through an energy recovery device to capture some cooling or heating that might otherwise be lost.

Next, we will discuss the control requirements for the building HVAC system.

Figure 5-1. Building outside airflow requirements: Sample building with assembly spaces and commercial kitchen.

5.2.3. Control of Indoor Air Dewpoint Temperature

While most current methods of controlling the humidity levels (and possible condensation) are based on holding the RH of spaces typically at around 50%, the property of RH can be quite elusive.

Dewpoint Temperature and Specific Humidity

The Psychrometric Chart (Figure 5-2) is one of the easiest tools used to determine the properties of air containing water vapor. The horizontal lines on the chart represent the specific quantity of water vapor in the air or specific humidity. Moving up the chart represents an increase in the amount of moisture in the air. Moving down the chart represents a decrease in moisture. Moving from left to right represents sensible heating without adding moisture. Moving right to left represents sensible cooling as long as the saturation curve (100% RH curve) is not reached.

Typical HVAC design practice sets a target indoor condition at or near a temperature of 75 °F (24 °C) and a RH of 50%. This means that most designers' intended indoor dewpoint is at or near 55 °F (13 °C). For HHC, a design point of 72 °F (22 °C) at 50% RH will provide a target room dewpoint temperature of 52.5 °F (11 °C). This provides some margin to accommodate facility operations that may not be exactly as envisioned – such as doors that are propped open to "let fresh air in," non-optimal envelope conditions, and other unforeseeable situations. Designing for even lower target dewpoint temperatures will also help to accommodate climate change and equipment wear and performance degradation over time. Additionally, spaces with lower dewpoint temperatures can achieve thermal comfort satisfaction at higher dry bulb temperatures, which can lead to significant energy savings with proper HVAC system design (see ASHRAE 55 [2017]). In any case, the design should result in spaces that have air with a dewpoint temperature that is lower than the coldest surfaces to be expected in the space.

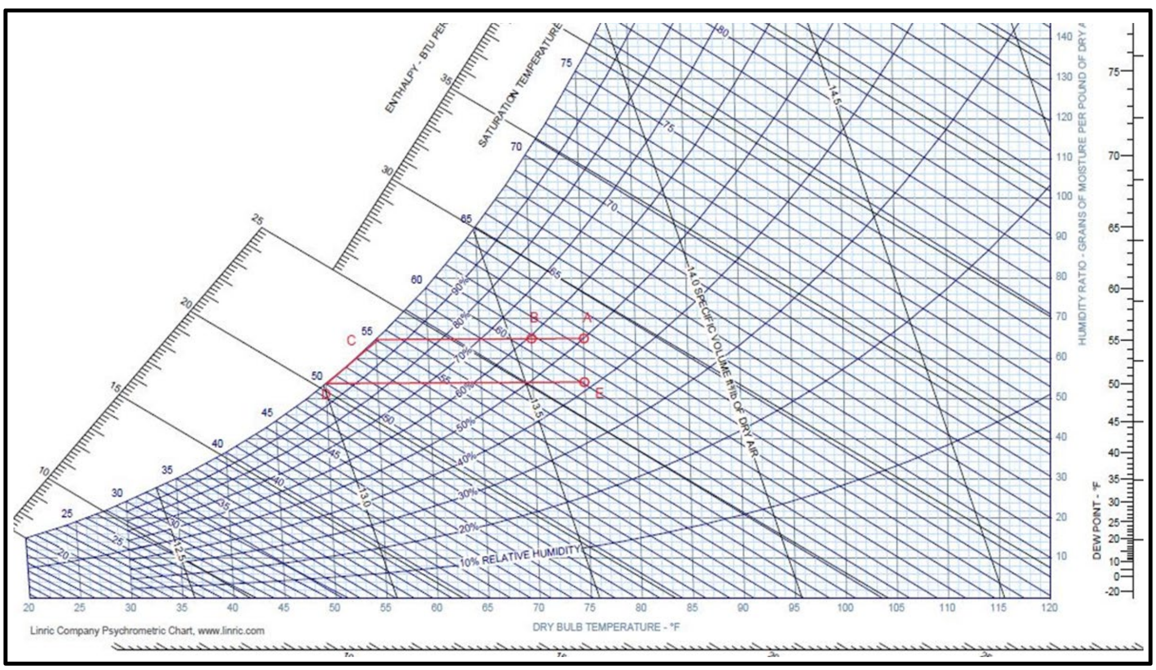


Figure 5-2. Psychrometric Chart. Note process points A, B, C, D, and E.

Since the late 1980s in North America and increasingly around the world, moisture and humidity problems in buildings have caused concerns about mold growth in buildings. For example, a detailed survey of federal buildings during the late 1990s noted that more than 85% of buildings surveyed had experienced moisture or humidity problems over their lifetime, and at the time of the investigation 45% were experiencing problems.

The chart in Figure 5-2 shows that the relative humidity of a space with an initial dry-bulb or room temperature of 75 °F (24 °C) and 50% RH (relative humidity - state point A), which is then cooled to 70 °F (21 °C) (state point B) with no air exchange, will see a rise in the relative humidity to 59%.

If the room is cooled to 55 °F (13 °C) (state point C), the RH will rise to 100% and any further cooling will cause condensate to appear at the source of the cooling. In this case, 55 °F (13 °C) is the dewpoint temperature.

Further cooling of the room (without circulation of air in or out) will precipitate water vapor out of the air, lowering the room (dry bulb) temperature and dewpoint temperature with it (state point D).

Adding heat back to the air in the room without adding moisture will raise the dry-bulb temperature, in this case back to the original dry-bulb temperature of 75 °F (24 °C) – state point E) and lower the relative humidity, but the dewpoint temperature of the room will be lowered to the value at state point D and does not go back up to 55 °F (13 °C) but remains at 50 °F (10 °C).

Also note that, if the air is again cooled to 55 °F starting from state point E, the temperature change will not produce any condensation because the dewpoint temperature is at 50 °F (10 °C). The psychrometric chart shown in Figure 5-2 illustrates the described state points. From line D to E in Figure 5-2, one can see that heating the air sensibly, without adding moisture, will raise the dry-bulb temperature but will not change the dewpoint temperature so the resulting state point E will have a lower relative humidity than did state point A even though the dry-bulb temperature is the same for each. The psychrometric chart clearly shows that tracking and controlling dewpoint temperature can provide a better control parameter for space humidity concerns.

In the past 20 years, researchers and ASHRAE have become aware of the risk of mold growth in buildings usually caused by dampness. It became clear that the risk for mold growth was related to the buildings surface RH and not necessarily the RH of the air within the occupied spaces.

In August 2019, the ASHRAE Board of Directors approved the 2019 revision of Standard 62.1. In mechanically cooled and ventilated buildings, the new standard requires that designs include equipment and controls that are always capable of keeping the indoor air dry, including periods when the building is not occupied. The standard defines dry as a dewpoint temperature of 60 °F (15 °C) or below.

In August of 2019, ASHRAE Standard 62.1, the Board of Directors approved the 2019 revision of Standard 62.1. Section 5.10 from the standard states:

Maximum Indoor Air Dewpoint in Mechanically Cooled Buildings. Buildings or spaces equipped with or served by mechanical cooling equipment shall be provided with dehumidification components and controls that limit the indoor humidity to a maximum dewpoint of 60 °F (15 °C) during both occupied and unoccupied hours whenever the outdoor air dewpoint is above 60 °F (15 °C). The dewpoint limit shall not be exceeded when system performance is analyzed with outdoor air at the dehumidification design condition (that is, design dewpoint and mean coincident dry bulb temperatures) and with the space interior loads (both sensible and latent) at cooling design values and space solar loads at zero.

Exceptions to section 5.10 include:

1. *Buildings* or spaces that are neither equipped with nor served by mechanical cooling equipment.
2. *Buildings or spaces equipped with materials, assemblies, coatings, and furnishings that resist microbial growth and that are not damaged by continuously high indoor air DPs.*
3. *During overnight unoccupied periods not exceeding 12 hours, the 60 °F (15 °C) dewpoint limit shall not apply, provided that indoor RH does not exceed 65% at any time during those hours.*

Some informative notes follow:

1. Examples of spaces are shower rooms, swimming pool enclosures, kitchens, spa rooms, or semi-cooled warehouse spaces that contain stored contents that are not damaged by continuously high indoor air DPs or microbial growth.
2. This requirement reduces the risk of microbial growth in buildings and their interstitial spaces because it limits the mass of indoor water vapor that can condense or be absorbed into mechanically cooled surfaces. The dewpoint limit is explicitly extended to unoccupied hours because of the extensive public record of mold growth in schools, apartments, dormitories, and public buildings that are intermittently cooled during unoccupied hours when the outdoor air dewpoint is above 60 °F (15 °C).

Water Activity and Equilibrium Relative Humidity

For most building professionals, the term “water activity” will be new and unfamiliar. Therefore, a short explanation is needed, to clear up the confusion built up over the past 40 years about the relationship between RH, moisture content, and microbial growth risk.

Mold and bacteria only grow on surfaces that retain sufficient moisture over time to support said growth. But not all moisture is equally available to support growth. In some materials, moisture is tightly bound to the surface, and cannot be used by bacteria and fungi. In other materials, the moisture is easily accessed to support microbial growth. Microbiologists have found that the most reliable moisture-related metric that governs growth is the water activity 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 or bacterial cell and the moisture in the surface on which it is located. It is also known by the technical name equilibrium relative humidity (ERH).

The confusion comes from the assumption that the air’s RH in a room’s free space is the same as RH at a surface. In fact, they are rarely the same, because of three factors: the difference between surface and air temperatures, the presence of sub-surface moisture, and the changes in all the variables inside complex building assemblies. In buildings, moisture and heat is constantly moving around within, as well as into and out of materials in small or large amounts. So, the traditional use of RH in the air as a threshold of concern is both incorrect and misleading (Harriman et al. 2001; ASHRAE 2015; Harriman and Lstiburek 2009; USEPA 2013). Instead, HVAC criteria should focus on the more reliable risk indicator of surface water activity.

Documents and logic that support this suggested threshold of concern include ANSI/ASHRAE Standard 160 (2016), which recommends that in the absence of more specifically known parameters for risk of mold growth. Those who model the hygrothermal behavior of building systems should be aware that risks of mold are higher when the 24-hour moving average of the ERH (the water activity) at the surface of organic material or coating stays above 80% for 30 days.

The problem with this criterion is how, in a functioning building, to practically monitor the conditions at all locations where they may occur given there are so many such locations. The current thinking is to provide space humidity sensors and to calculate the dewpoint temperature from the DBT and RH sensed and control the space dewpoint temperature such that the ERH will not be above 80% for any significant length of time.

Outdoor Design Conditions

As discussed, the building needs to be pressurized with conditioned outside air so that conditioned space air will exfiltrate to the environment instead of having unconditioned outside air infiltrate into the conditioned space. To begin designing the system to accomplish this, it is necessary to determine the most extreme conditions of the outside air that the cooling equipment will have to accommodate. Contrary to intuitive thought, the hot sunny day peak dry bulb and mean coincident wet-bulb temperature tabulated by ASHRAE is NOT the most demanding for the system cooling outside air before supplying it to the building. The peak dehumidification (or peak dewpoint) temperature (and not peak sensible temperature) must be used for design of these systems. In HHC, the peak dehumidification day typically requires significantly higher cooling capacity than the peak sensible day (even though the DBT may be significantly lower than at peak dry bulb conditions).

> … the hot sunny day peak dry-bulb and mean coincident wet-bulb temperature tabulated by ASHRAE is NOT the most demanding condition for the system that must cool outside air before supplying it to the building. The peak dehumidification (or peak dewpoint) temperature must be used for design of these systems …

For example, in the City of Mobile, Alabama, USA, a Dedicated Outdoor Air System will require 6.4 tons (76.6 kBtu) of refrigeration to cool 1,000 cfm (472 L/s) of outside air from the ASHRAE 0.4% sensible design dry bulb and mean coincident wet-bulb temperatures (94.1 °F/76.8 °F (35 °C/25 °C) to 56 °F (13 °C) dry bulb and 55 °F (13 °C) wet-bulb temperature. Whereas, outside air at the ASHRAE 0.4% dehumidification design wet-bulb and mean coincident DBT (80.1 °F/88.5 °F [27 °C/31 °C]), a Dedicated Outside Air System (DOAS) cooling the same 1,000 cfm (472 L/s) will require 7.7 tons (92 kBtu) of refrigeration. A system sized based on the 0.4% dry bulb outside air temperature would be undersized by approximately 17%.

The outside air dehumidification should always be designed based on the larger of either the design dry bulb and mean coincident wet-bulb, design wet-bulb and mean coincident dry bulb, or the design wet-bulb temperature and mean coincident dry bulb temperatures for the outside air entering the system.

5.2.4. Corrosive Environments

As discussed in Chapter 1, many hot-and-humid-climate communities are located in areas close to the ocean and as such require special provisions for dealing with the corrosive, moist environments in which they operate. Additional care should be taken that all exposed surfaces be properly coated to prevent corrosion.

Exterior surfaces exposed to the seacoast or saltwater-laden air should be provided with phenolic coatings or other treatments of the metal surfaces. This applies to rooftop units, condensers, air-cooled chillers, exhaust fans, etc. located outside. It is recommended that units with more than 50% outside air be constructed with marine-grade aluminum or stainless steel, especially if located outdoors. Exposed fasteners should be at a minimum of 316 stainless steel or similar alloy. Heat exchange coils must be provided with coatings that prevent bare metal from being directly exposed to the corrosive sea air. All exposed surfaces and coils should be required to have coatings that pass a minimum 3,000-hour salt spray test.

Cooling coils should include fin-and-tube type coils constructed of seamless copper tubes and copper fins (although aluminum fins can be used if properly coated) with phenolic coating applied by immersion. Casing and tube support sheets that are not lighter than 16-gauge stainless steel, formed to provide structural strength should be provided. Coils with more than 50% outside airflow shall be provided with a phenolic coating for corrosion protection. Coatings like phenolic, Blygold, and E-coat provide a method to mitigate corrosion and extend the service life of HVAC coils and condensers in corrosive environments. In corrosive environments, copper tubing far outperforms aluminum and steel for condenser units and corrosion of copper will be delayed by the application of a coating system. The best protection for an expensive piece of equipment is to locate that equipment indoors. In performing life-cycle cost analyses, metallic equipment located outdoors within 2 miles (3.2 km) of the ocean, sea, gulf or other saltwater body, should only be expected to survive for approximately 7 years before requiring replacement.

When it is necessary to locate equipment on the exterior of the building, all mechanical equipment should be ground-mounted on reinforced concrete pads, surrounded by solid 6 in. (152 mm) reinforced concrete walls, or 8 in. (203 mm) reinforced fully grouted CMU walls with gate(s) that protects mechanical equipment from hurricane flying debris.

The life of condenser units and cooling towers located in a corrosive environment must have corrosion protection per ASME B-117 salt spray testing based on 5000 hours-tests. Consider alternate methods of heat rejection such as geo-exchange fields, water-to-water loops in the adjacent body of water (see Chapter 6), water-cooled condensers with condenser-water energy recovery to be used immediately (e.g., for air reheat or for domestic water heating, or be stored in thermal energy storage [TES] for future use see Appendix C, section C.3, “Condenser-Water Energy Recovery”). These approaches reduce replacement and operational cost, save energy use and cost, reduce greenhouse gas (GHG) emissions, and increase energy systems’ resiliency.

Air intakes in marine environments should be designed with stainless steel or non-metallic ductwork for the first 5 ft (1.52 m) from the outside air louver to the air-handling equipment. Smaller capacity systems are preferred in corrosive environments due to the ease of replacement and maintenance as well as the availability of parts.

If exterior ductwork is used, it should be stainless steel 316L. Galvanized sheet metal ductwork is allowed for exterior-insulated ducts that do not have bare steel exposed to the environment. Exterior-insulated ducting shall be provided with a 316 stainless-steel jacket. All exterior ducting should be insulated unless the duct is used for non-conditioned fresh air.

During construction, all ductwork openings should be taped closed to prevent construction dust from entering the ductwork. The installer must clean the ductwork and replace the filters after construction and just before the turnover of the facility.

Mechanical filtration can be used to reduce the amount of salt introduced into air-handling systems. This works best when using outdoor air pretreatment solutions, which allow the outdoor air to be filtered before entering downstream air-handling units. Decoupling of the outdoor air filtration from the recirculated air filtration gives designers more flexibility to respond to the location and space-based needs of the HVAC system.

In marine environments, the size of salt aerosol particles can vary widely based on proximity to the coast, wind speed, irradiation, and local air pollution, but salt aerosols typically range from 0.05 to 0.5 microns. MERV 14 and higher filters can be used to effectively reduce (not eliminate) the amount of salt being introduced into HVAC systems. This can extend the lifetime of HVAC systems by reducing corrosion associated with salt deposition on cooling coils, fans, casings, and other metallic equipment. In addition, intake louvers designed to admit large volumes of air while capturing and draining liquid water via drainable blades and stainless-steel bird screens must always be used in seacoast environments.

5.3. Design Solutions for HVAC in HHC

5.3.1. Determining Pressurization Requirements and Outside Airflow

The building HVAC system must pressurize the building as discussed in section 5.2.2 with outside air-conditioning to lower its dewpoint temperature as discussed in section 5.2.3.

5.3.2. Determining Required Outside Air Supply Conditions

Current design requirements in UFC 3-410-01 (NAVFAC 2021) require that the HVAC system be able to accommodate the total building load at the design (near worst-case) conditions. Whatever means is used to deliver the outside airstream to the building, the systems involved must have adequately sized coils and cooling coil temperatures (chilled-water temperature and refrigerant evaporation temperatures) that are well below the required temperature of the air leaving the coil.

When the outside airstream can be separated from the space in a DOAS configuration, the dewpoint temperature of the outside air being conditioned should be suppressed to lower than the dewpoint temperature desired in the space and reheated sensibly to a temperature that is neutral in the space to which it is supplied, typically 68 °F to 78 °F (20 °C to 26 °C). It is recommended that this reheat value be inversely related to the unconditioned, outside air temperature. For example, if the outside air is 32 °F (0 °C) (dry bulb) or colder, set the outside air system to deliver 75 °F (24 °C) to the space. If the outside air is warmer than 80 °F (27 °C) (dry bulb) then only deliver the outside air to the spaces at 68 °F (20 °C) dry bulb. Exact values should be determined based on the system type and design details. Reheating cooled and dehumidified air should be minimized when the zone has a net cooling load. Section 6.5.2 of ASHRAE Standard 90.1-2019 limits simultaneous cooling and heating (i.e., reheat). For dehumidification systems, Subsection 6.5.2.3 states that "Where humidity controls are provided, such controls shall prevent reheating, mixing of hot and cold airstreams, or other means of simultaneous heating and cooling of the same airstream." Where there is no net cooling load, reheat is needed but should be provided through process heat in the DOAS unit. Options to achieve that include the use of recovered heat, such as an air-to-air energy recovery device, a hot-gas reheat coil, a hot-water coil that uses condenser heat from a chiller plant, or pre-cooling/post-heating and the use of solid and liquid desiccants. Limitations on the use of reheat as well as exceptions will be discussed in more detail in the 2023 update to the ASHRAE DOAS design guide (ASHRAE 2017c).[*]

Certain everyday processes and activities that occur in various spaces within the building can produce increased space humidity or latent loads for the building HVAC to deal with. These processes include cooking, laundry, showering/bathing, physical activity, and others. When there are internal loads in the spaces that produce latent loads, air supplied to the space must have a lower specific humidity ratio and dewpoint temperature such that when it mixes with the air in the space, the latent load is continually absorbed by the supplied airstream. When the outside air is supplied by a separate system, this separate system can be designed for better dewpoint suppression and dehumidification than the space (comfort) conditioning system. Some space-conditioning systems (such as radiant cooling) cannot be used for latent cooling and dehumidification at all because there is no means for dealing with condensate. The system dedicated to the outside airstream's conditioning must offset ALL the internal latent (humidity) loads by further depression of outside air dewpoint temperature. The use of a DOAS adds better capabilities to the building systems.

5.3.3. Outside Air-Conditioning and Delivery to Building and Building Zones/Spaces

Given that the outside air latent loads are fairly constant over a day while the building sensible load varies significantly, separating outside air loads from space sensible loads (conduction, convection, and internal loads) becomes desirable for better control. In many instances, in HHC, the outside air load on the cooling system will be nearly half of the total load. Using a separate airstream and associated conditioning can vastly improve the selection of the outside air system's cooling coils, filtration, and controls while allowing the use of much simpler cooling systems for the space loads. Refer to Appendix C, section C.2, "Dedicated Outside Air System (DOAS)" for more information.

[*] *ASHRAE Design Guide for Dedicated Outdoor Air Systems*. 2nd ed. RP 1712. Anticipated publication, 1st Quarter 2023.

Figure 5-3 illustrates a potential solution for separating outdoor air and building loads. The outdoor air is pretreated and dehumidified down to a low enough dewpoint before entering the air-handling unit (AHU) to handle all latent loads in the system (outside air plus space latent loads). This allows the AHU to respond solely to the sensible cooling demands that vary significantly throughout the day based on solar radiation, occupancy, and other use factors.

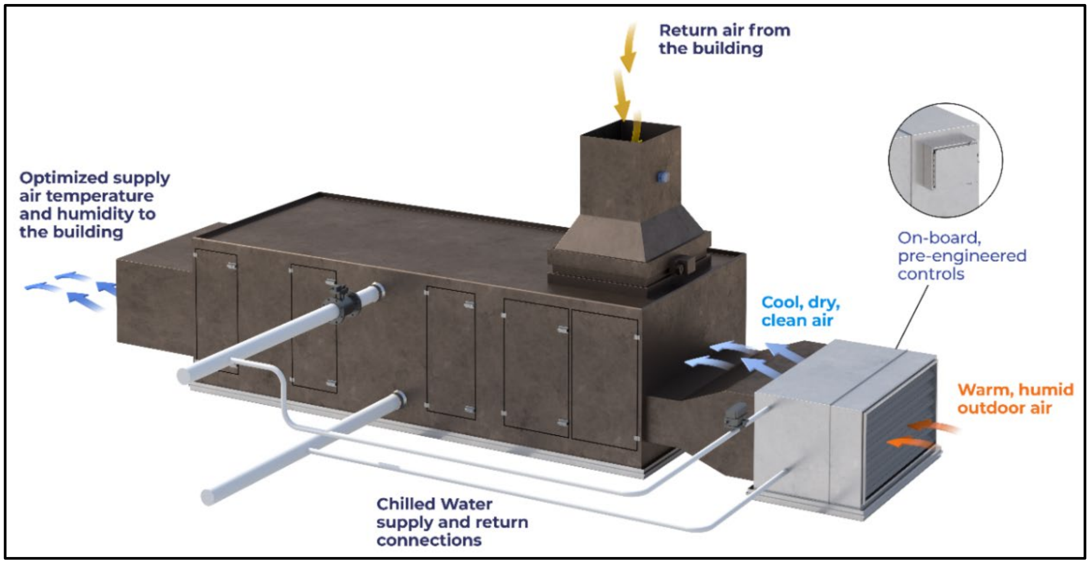


Image courtesy Altaire Systems, LLC (www.altairesystems.com).

Figure 5-3. Example outdoor air pretreatment device that decouples latent and sensible cooling loads.

Conventional systems can consist of small, single-zone air-handling units (conditioning one or more spaces having similar loading over the course of the day) all the way up to large, variable-air-volume, multizone air-handling units with satellite terminal damper-and-reheat boxes (terminal units) that modulate cooling and provide local heating in response to local temperature and humidity sensors in each zone of the building. Typically, only the larger of these system types perform well in HHC. This is because there is usually a requirement for continuous outside air intake through the unit, and the cooling coil must operate continuously to deal with the outside air sensible and latent loads.

In smaller systems, the cooling may cycle on and off in response to the space load and (when the cooling is off) unconditioned outside air is drawn into the space, increasing the space dewpoint temperature and RH. Where smaller systems are to provide space-conditioning, a DOAS should be provided unless the space outside air demands are negligible. However, in HHC, the outside airflow required to pressurize the building is almost never negligible.

DOASs introduce additional flexibility to building HVAC. The DOAS unit may be designed to deal with hot and humid outside air conditions, seacoast air/corrosive environmental conditions, and provide resiliency with respect to tropical weather and emergency (black sky) operating conditions. Where a DOAS provides all outside air-conditioning and additional space latent load removal, the space-conditioning systems can have very simple controls including on-off fan cycling with cooling coil operation. The DOAS unit can respond to outside air conditions and supply a set dewpoint temperature in the conditioned outside air such that as space latent loads increase, the DOAS dewpoint can be lowered to counteract the space loads.

For example, a barracks building with room-level, cooling and heating, fan-coil units will have a temperature and humidity sensor in each room. The control system can calculate the dewpoint temperature based on the space DBT and humidity in each room. If any room's dewpoint temperature rises above the room setpoint, the DOAS cooling coil's discharge air temperature can be lowered to reduce the DOAS supply-air dewpoint temperature to counteract the rise in the space. If all spaces' calculated dewpoint temperatures are much lower than required, the DOAS cooling coil may have the leaving air temperature setpoint set higher. If the ambient outside air dewpoint temperature is lower than the setpoint required for the DOAS leaving air, the unit can totally stop mechanical dehumidification and take advantage of the favorable outside conditions.

The control of the DOAS can also become variable volume in nature. In buildings with assembly spaces (large conference rooms and small auditoriums), when the building is occupied but these assembly spaces are not, occupancy sensors can direct the DOAS to reduce the total outside airflow (provided building pressurization is maintained) to save on cooling load at the DOAS.

Pretreatment of Outdoor Air for Centralized Air Handlers. As discussed, it is critical to decouple the latent load control from the sensible load control in HHC. A primary way to accomplish this is to use DOASs or outside air pretreatment units for the outdoor ventilation air streams upstream of the air handlers. By pretreating the outdoor air before it enters the AHUs, the air can be adequately dehumidified to handle the entire latent load of most building uses since the vast majority of the latent load comes from the ventilation air.

> Many DOAS units are designed to provide a constant volume of ventilation air at constant pressure. Therefore, use caution when connecting the DOAS to any part of a system where airflows and pressures will vary. Any change in pressure at the point of connection will alter the amount of outdoor air delivered by the DOAS unit.

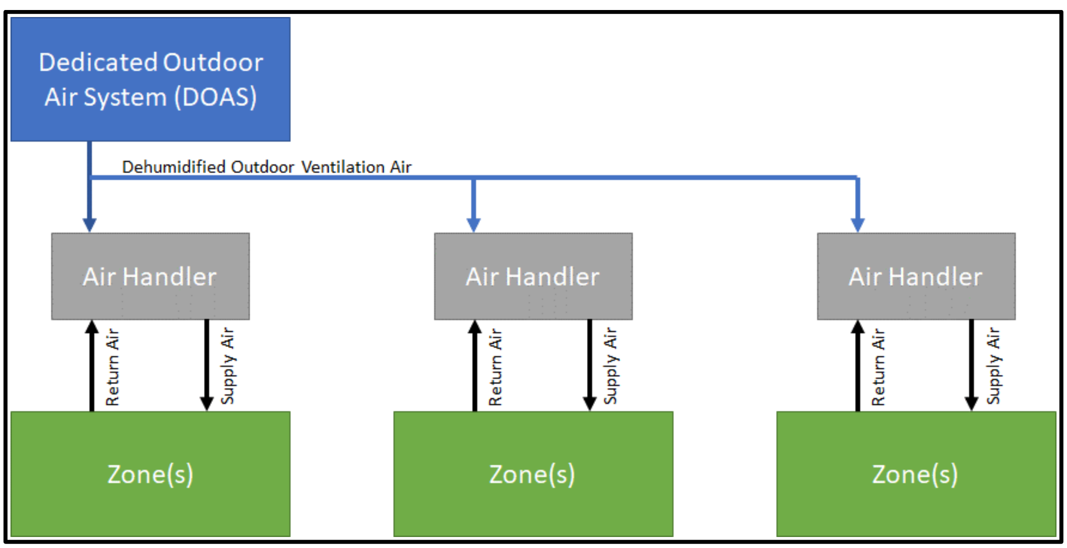


Figure 5-4. Centralized dedicated outdoor air supply (DOAS).

Using a centralized DOAS system to pretreat the outdoor air has the advantage of reducing the equipment count for the building, which can significantly reduce maintenance costs. However, using a centralized DOAS approach introduces some important design considerations.

Some design consideration for centralized DOAS for OSA pretreatment are

1. Centralized DOAS equipment must be able to deliver air at a low enough dewpoint to provide all dehumidification for all downstream systems under all operating conditions – part load, full load, and unoccupied. This needs to be considered not only for the equipment selection, but also for the control sequence design. If the DOAS equipment cannot provide adequate latent control for each AHU, then latent and sensible loads cannot be decoupled at the AHU, which will result in significant control issues, a potential to require additional reheat, and an increased potential for mold and other microbiological growth in the downstream AHUs, ducts and the space.
2. Select centralized DOAS equipment with adequate capacity to meet worst-case OSA dewpoint conditions AND ensure the system has adequate and stable turndown to support all modes of operations and part-load conditions. Part-load and alternative operating modes (i.e., nighttime setback operations, emergency [black sky] modes, etc.) should be shown on the mechanical schedules and equipment providers should be required to show performance at these conditions.
3. Air delivered by the DOAS system should be tempered before being delivered to downstream air-handling equipment. For cooling-based dehumidification technologies, delivery of very cold saturated air from the dehumidification process can result in potential condensation and fogging when mixed with the return air at the air-handling equipment. This requires the leaving air from the DOAS to be reheated using some type of energy recovery process, as using new sources of energy are not allowed by ASHRAE 90.1 (2016, section 6.5.2.3). Chilled-water energy recovery, exhaust energy recovery, and condenser energy recovery (either condenser-water for chilled-water] systems or hot-gas reheat for direct expansion [DX] systems) can all be used to temper supply air from the DOAS.
4. Supply-air ducts from the DOAS to the air handlers must be adequately insulated to ensure there is no condensation that will significantly shorten the life of the ductwork. Care should be taken at the transitions of the ductwork to equipment to ensure there are no areas of potential condensation.
5. Downstream AHU equipment should be sized based on the new entering conditions delivered by the DOAS. This allows the downstream AHUs to use smaller coils, higher face velocities, and smaller air ductwork, which reduces overall system cost and footprint. This can provide a significant overall design advantage by reducing the AHU system size and cost.
6. Airflow control devices should be used to supply the pretreated OSA to each AHU, such as simple variable air volume (VAV) boxes or flow rings with an airflow control damper. This allows the airflow to be modulated to each AHU based on actual space demand from feedback such as demand control ventilation (DCV) systems or occupancy sensor-based feedback. This also allows the total ventilation airflow to be modulated to meet space demands, significantly reducing the energy associated with ventilation air. However, care should be taken to ensure adequate building pressurization control (that is, more OSA than exhaust airflow) while ventilation airflow is modulated. Note that full cutoff VAV boxes or dampers are not required as buildings in HHC typically require ventilation dehumidification systems to run continuously to provide positive pressurization of the building envelope. In other climate zones, full cutoff capability could be used.

Where centralized outside air pretreatment is not possible, decoupling of the latent and sensible loads can happen at the individual AHUs through dedicated pretreatment equipment. In this configuration, a treatment unit without a fan could be used due to the close coupling with the AHU system (Figure 5-5).

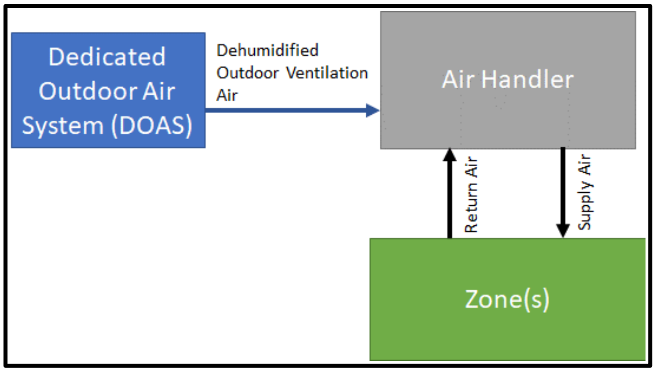


Figure 5-5. DOAS using close coupling with the AHU system.

This approach has the disadvantage of increasing the amount of equipment in the building compared to a centralized DOAS approach and retains many of the same design considerations discussed above. Additionally, a distributed OSA pretreatment approach makes it difficult to combine with exhaust energy recovery systems to further increase energy efficiency. However, this approach also has the following advantages.

1. The leaving air dewpoint from the pretreatment unit can be optimized for each AHU, which can result in enhanced controllability and energy efficiency.
2. The fan count can be reduced by relying on the individual AHU supply fans to support the airflow through the outdoor air pretreatment unit. The pretreatment unit pressure drop can be figured into the supply fan selection, thus reducing fan count and electrical distribution costs, while significantly simplifying the controls for the system.
3. The amount of duct work between the pretreatment unit and AHU can typically be reduced significantly, which can save both space and cost.

The 2023 update to the DOAS design guide will discuss the option to provide outdoor air to each zone directly through a dedicated duct system in which local cooling is provided via split units, or via an air handler that uses an existing ducting system as well as indirectly via the intake duct of existing air handlers. Chapter 3 of the update ("System Selection") will evaluate a number of additional configurations including their impacts on installation and operational costs.

Energy Recovery from Exhaust

DOAS units offer an opportunity for energy recovery. DOAS units can be provided with parallel exhaust fan systems (Figure 5-6). The exhaust stream can be used to precool the outside air in summer and preheat it in winter. Heat pipes, crossflow heat exchangers, and total energy wheels can serve the purpose of reducing the required cooling (and heating) coil loads (see Figure 5-7). However, each technology has its own set of disadvantages as well:

- Heat pipes require careful installation to allow natural convection to move the refrigerant sealed within them. If piping is misaligned, they may not function.
- Crossflow heat exchangers and energy wheels require additional filtration on the exhaust airstreams and if not maintained, will become less and less effective.
- Wheels have small motors and fragile belts to rotate them and failure of either stops the energy transfer.

All these systems can significantly increase the fan energy of the system; moreover, they require fairly sophisticated maintenance personnel and operators to provide successful performance and energy savings over the whole life of the systems.

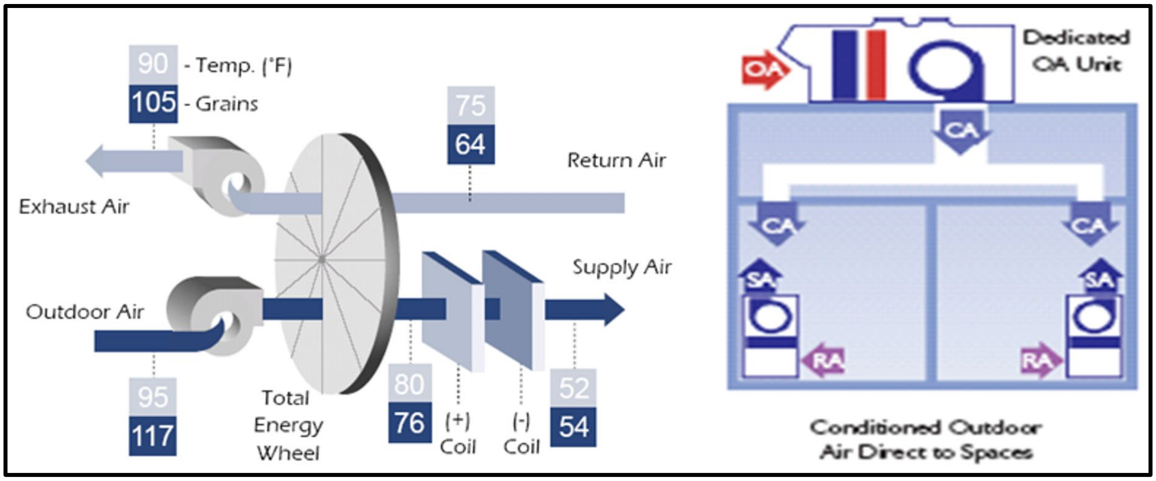


Figure 5-6. A total energy recovery wheel DOAS.

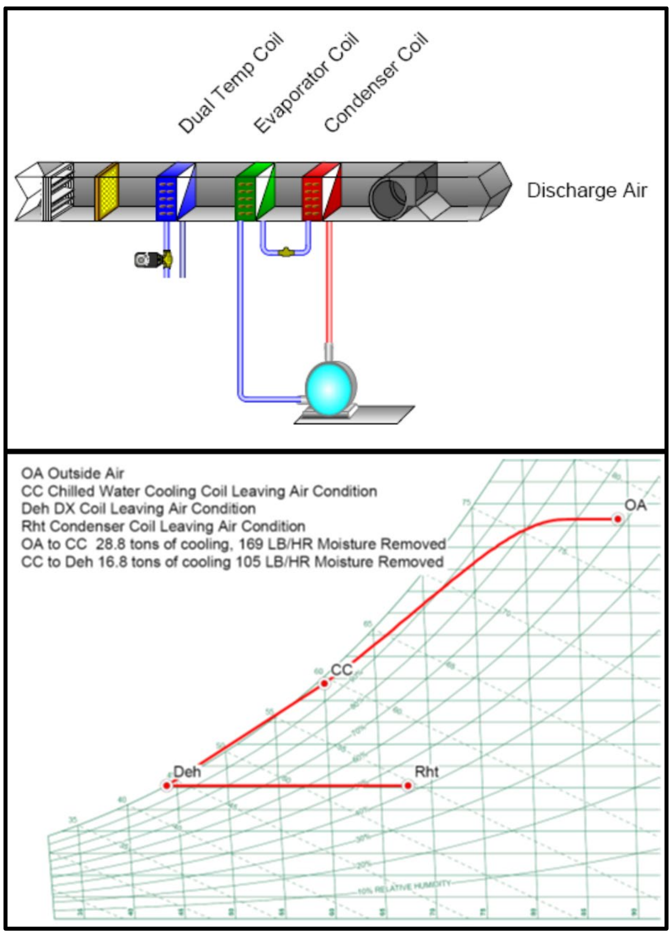


Figure 5-7. Example DOAS with hot water heating, and DX unit evaporator coil cooling and condenser coil reheat. Additional condenser coil outside is omitted in this graphic.

Chilled-Water Energy Recovery

Note that most exhaust energy recovery designs, while potentially reducing inlet cooling and heating loads, do not address the significant energy penalty associated with reheat for dehumidification control in HHCs. There are currently new technologies on the market that use the low-grade waste heat from the chilled water (CHW) return of a dehumidifying coil to reheat the sub-cooled and dehumidified air. This enables on-board reheat without the use of additional natural gas, electric, or steam heating energy. This works particularly well in HHCs where incoming outdoor air temperatures are relatively high most hours of the year.

Energy recovery from other sources may be available. Condenser heat from the refrigerant circuits may be used to provide reheat of the outside airstream, regeneration of desiccant wheels, or in buildings with large domestic hot water demand (such as for showers or kitchens), condenser heat can be captured to provide hot water preheating (see Figure 5-8) However, a designer must be aware of possible times or seasons when mechanical cooling may not be available and the source for the energy recovery may not be available. Backup sources of heating may be required. Other sources of heating may be available as well such as district cooling and heating plants (see Chapter 6), solar systems, ground-source heat exchangers, and adjacent bodies of water will be addressed in more detail in the 2023 update to the ASHRAE *Design Guide for Dedicated Outdoor Air Systems (DOAS)* (ASHRAE 2017c).

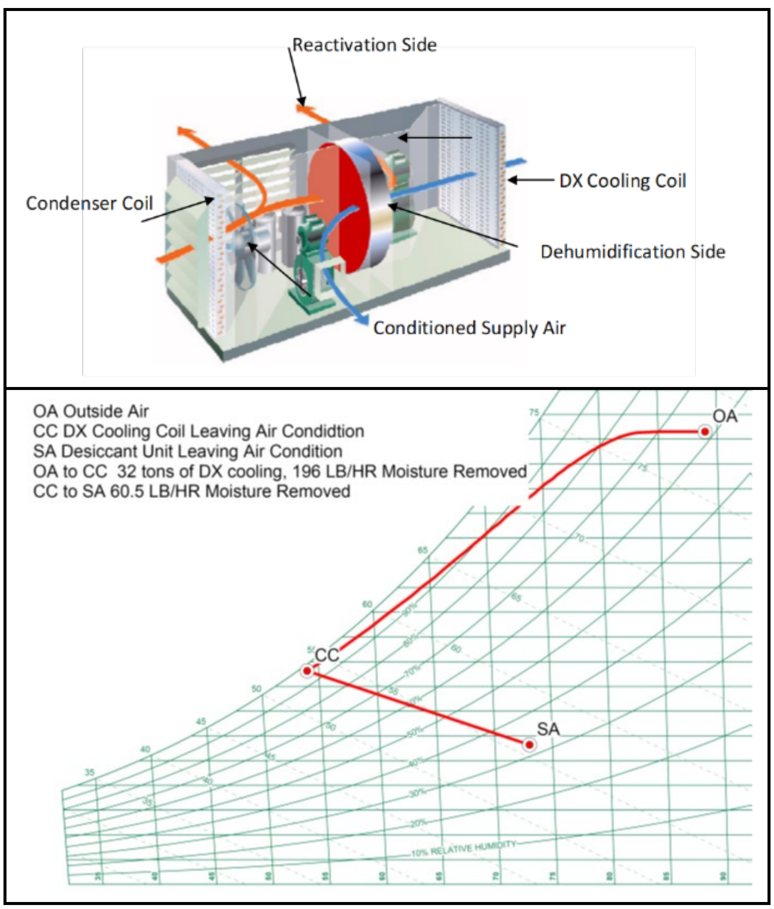


Figure 5-8. Example desiccant wheel system.

Liquid Desiccant Dehumidifier

Liquid desiccants have been used for dehumidification for decades, primarily in the food industry and in other industrial applications where precise humidity control is critical. Advances in membranes and plastic technology have resulted in a new generation of equipment that differs significantly from earlier desiccant technologies and from applications that use solid desiccants.

Newer liquid desiccant dehumidifiers simultaneously cool and dehumidify the air using a three-way heat exchanger that employs a concentrated desiccant, which itself is cooled using a heat transfer fluid. Panels are covered with a membrane, behind which the desiccant flows over sheets that are cooled internally (Figure 5-9). The desiccant is regenerated using condenser heat, which lowers condenser airflows and temperatures.

The equipment controls cooling capacity by adjusting compressor capacity to change the water temperature used for cooling, and controls dehumidification capacity by varying the desiccant concentration via adjusting the water flow rate through the condenser. This provides independent control of both humidity and temperature. In extremely humid and dry conditions, air-cooled coils can be added to increase or reduce the concentration of the desiccant. The concentration of the desiccant directly determines the RH of the supply air. Managing the concentration of the desiccant

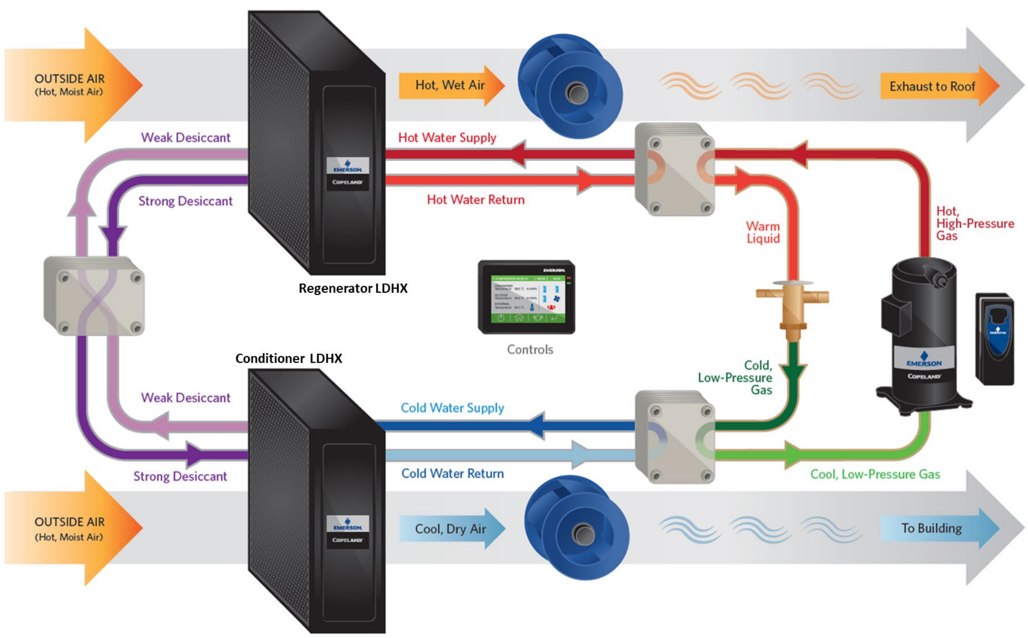


Image used courtesy of Emerson Climate Systems (2021).

Figure 5-9. Example liquid desiccant dehumidification system.

Liquid desiccant systems are more efficient than solid desiccant dehumidifiers since they avoid the load required to condensate humidity out of the air and operate at a lower lifts with higher avoid the overcooling associated with dehumidification using a cold coil (Figure 5-10), and allow for the use of warmer evaporator temperatures that reduce compressor lift.

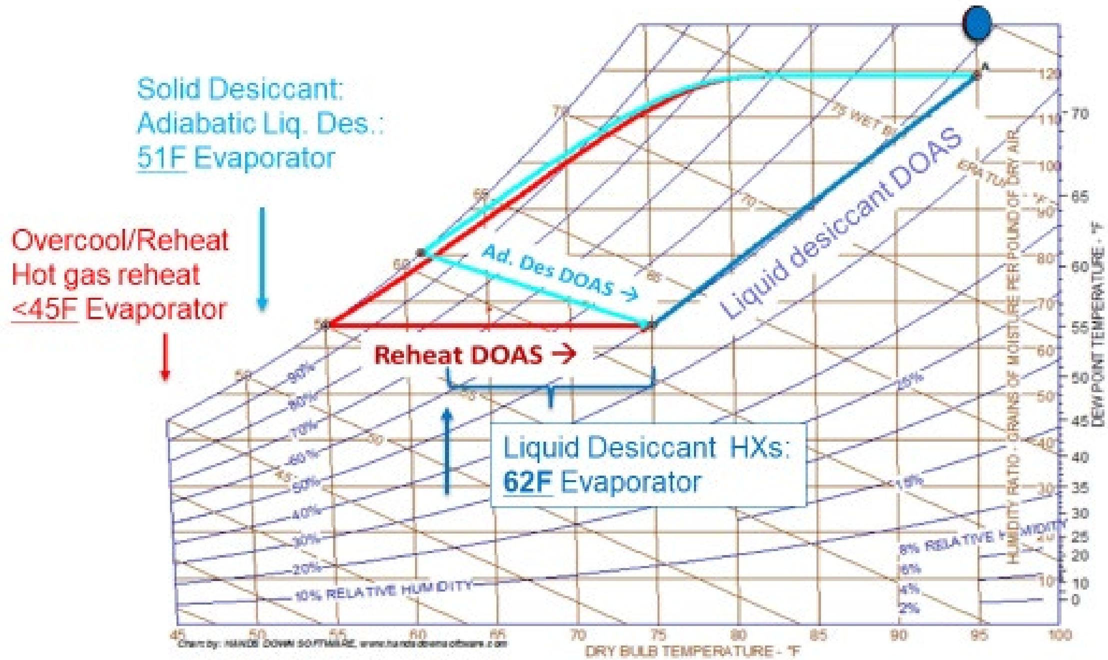


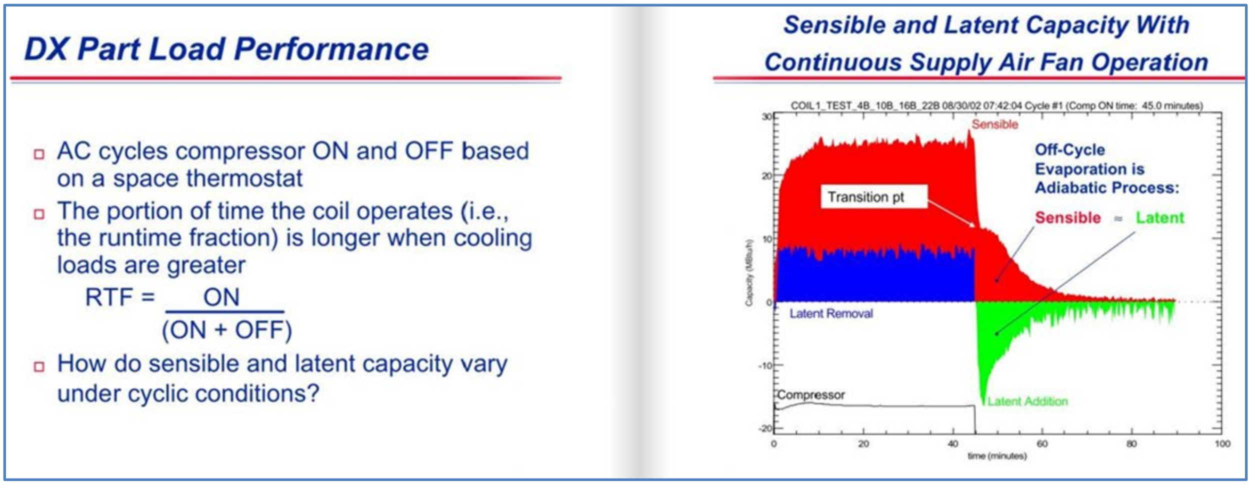
Image used courtesy of Emerson Climate Systems (2021).

Figure 5-10. Liquid desiccant dehumidification process.

5.3.4. Plant System Selections – Direct Expansion vs. Chilled-Water Systems

In comparing direct expansion to chilled-water cooling systems, it is necessary to understand the history or tradition of how the systems have operated in the past. For most designs, the load on the cooling system will be in the 60% to 70% of design range most of the time the system is operating. As it relates to HHC, the latent load of the system is fairly constant while the space sensible loads will vary based on use and other factors.

Direct expansion (DX) systems have typically been provided for smaller systems where a single AHU is served by a single outdoor condensing unit and the refrigerant flows through the coil in the AHU, boiling at low pressure and absorbing heat from the air passing over the coil. For times when the cooling load is not 100% of the design, the cooling cycles on and off to not overcool the space served. In systems requiring continuous dehumidification, this operation reverses some of the dehumidification process whenever the cooling cycles off (see Figure 5-11). If the load on the cooling coil is constant and nearly equal to the equipment's design capacity, the system can run continuously handling the latent load. However, this is rarely the case. It is far more often observed that the load is 60% to 70% of the design capacity of the equipment (or less) and refrigeration will overcool the airstream and then cycle off.



Source: D. H. Henderson (2005).

Figure 5-11. Part-load dehumidification with cycling compressor and continuous supply fan operation.

In recent decades, partial load operation has been improved upon in larger DX systems and these improvements are now trickling down to smaller system sizes (see Figure 5-12). New technology has improved systems by means of

- **Multiple compressors:** older technology where two smaller compressors with one or the other or both operating. In a one-third, two-third set up, the smallest compressor handles the smallest loads, the larger handles the moderate loads, and they both operate simultaneously to handle the maximum loads. No piece of equipment is more efficient than the one that is not running. For loads that are around 60% to 70% of design most of the time, this system is ideal. However, it is not usually available for systems smaller than 7 tons (84 kBtu) of capacity.
- **Hot-gas bypass:** older technology where a small amount of hot refrigerant coming out of the compressor is directed back to the suction side of the compressor reducing the cooling capacity of the system – available down to the 5-ton (60 kBtu) capacity range but saving very little power.
- **Digital scroll compressors:** newer technology compressors as small as 1 ton (12 kBtu/hr) capacity capable of being derated by means of the scroll plate's position and compressor speed to reduce the refrigeration capacity and showing some reduction in power consumption.
- **Variable speed compressors:** newer technology in smaller systems showing better energy savings at lower speeds with sizes down to 1 ton (12 kBtu/hr).
- **Hot-gas reheat:** provides compensation for overcooling similarly to hot-gas bypass but the hot refrigerant is fed to a reheat coil downstream of the cooling coil. If a DX system is provided for a DOAS, hot-gas reheat uses recovered heat and is energy efficient by its nature.

For most DX system designs, a combination of multiple compressors with digital scroll or variable speed operation and hot-gas reheat is required to provide adequate latent and sensible cooling control in HHCs.

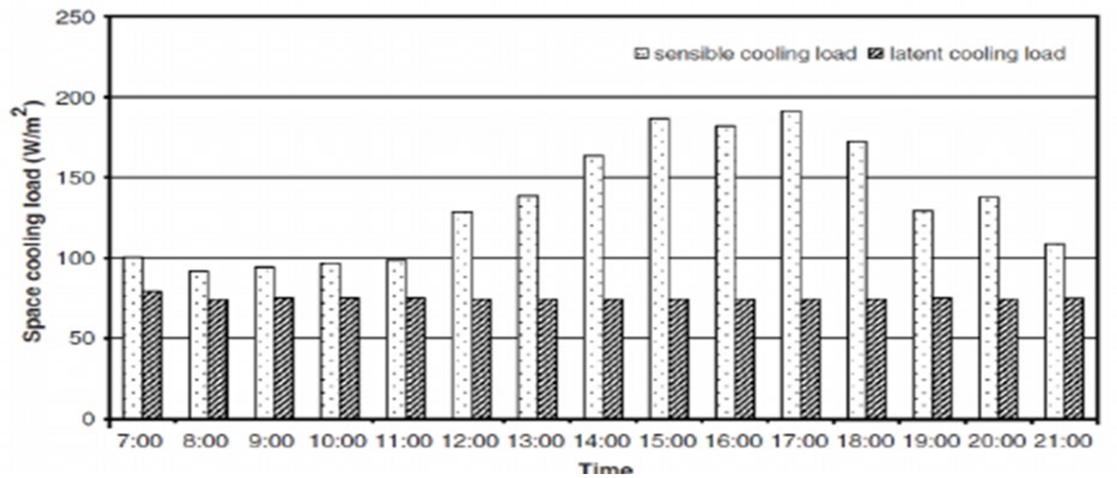


Figure 5-12. Sensible and latent load variation over time of day.

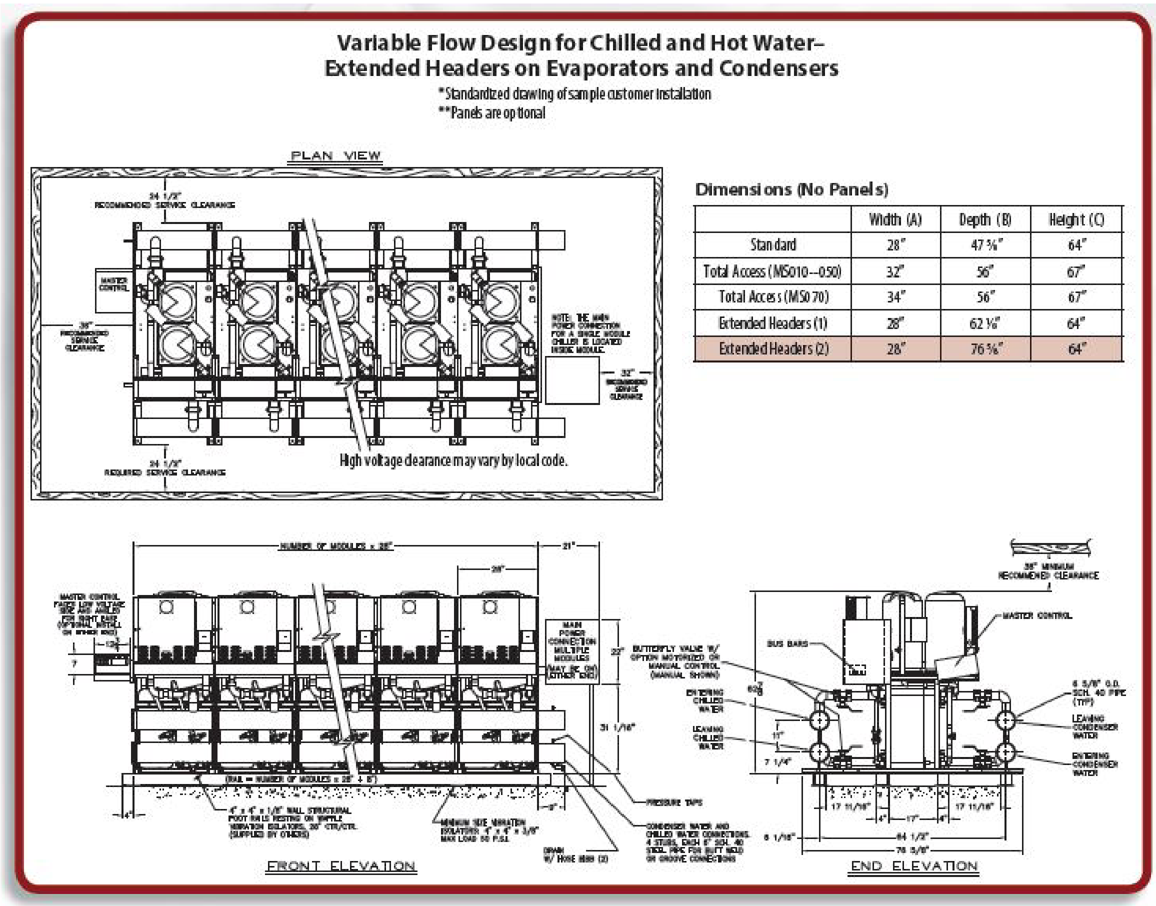
Chilled-water systems have an added heat exchanger in the cooling process. The cold side refrigerant is passed through a plate-type heat exchanger or a shell-and-tube heat exchanger cooling water in the opposite chamber of the heat exchanger. The water then circulates through a water coil in the AHU(s) cooling and dehumidifying the air. Because water has a fairly high specific heat relative to most other fluids, it functions well as a very stable cooling medium. Chillers with multiple compressors can cycle the compressors less frequently than DX systems to cool the water in part-load conditions, provided that the mass of CHW is large enough to avoid unstable control situations and cooling. Buffer tanks are often provided in chilled-water systems to stabilize the system control.

Using chilled-water coils in air-handling systems (DOAS or traditional), the water control valve on the cooling coil can be modulated to set the precise leaving air temperature. If the coil is performing latent cooling, this leaving air temperature will be the dewpoint temperature of the air supplied to the spaces/zones. Caution should be used when reducing the chilled-water flow through the cooling coil. When water flow is reduced to approximately 50%, laminar flow could develop thereby greatly reducing the latent capability of the cooling coil.

In many cases, HHC buildings will still require heating during the winters, albeit a minimal amount and will nearly always require reheating of refrigerated air in the DOAS. In buildings with high domestic water usage, heat from the cooling system may be used, not only for heating hot water to the building but also for heating the domestic hot water. Barracks and other buildings with large shower quantities and kitchens with large dishwashing hot water demands can all make use of this technology.

With or without a large domestic hot water load, if enough heat is required, a set of modular chiller/boiler systems can be provided to use site recovered energy. The controls on these systems can route both heating and cooling water from the hot or cold side of the chiller units to where it is needed or to the heat sink/source for the system when not needed. Detailed control sequences determine the best use of heat from each module and direct the cold water and hot water accordingly.

Designs such as MultiStack™ (Figures 5-13 and 5-14) use their internal control sequences and virtual movable endcap (VME) piping scheme to perform as efficiently as possible based on building load demands and available source/sink conditions. Figures 5-13 and 5-14 clearly show that any load, either CHW or hot water, that is called for by the building loads is routed from the "stack" to the building (to the left) for reuse. Whatever is not needed is routed to the right to the sink/source for storage, or is released into the sink source medium.



	Width (A)	Depth (B)	Height (C)
Standard	28"	47 5/8"	64"
Total Access (MS010--050)	32"	56"	67"
Total Access (MS0 70)	34"	56"	67"
Extended Headers (1)	28"	62 1/8"	64"
Extended Headers (2)	28"	76 5/8"	64"

Figure 5-13. MultiStack™ Chiller Boiler System. Note that chilled-water supply/return headers (from the evaporators or cold side) are set up for connection at both ends of the "stacks." Similarly heating hot water supply and return headers (from the condensers or hot side) are set up for connection at both ends of the "stacks." Isolation valves are in each of the four headers in between each of the individual chiller boiler modules creating the possibility of an end cap at any point in the stack.

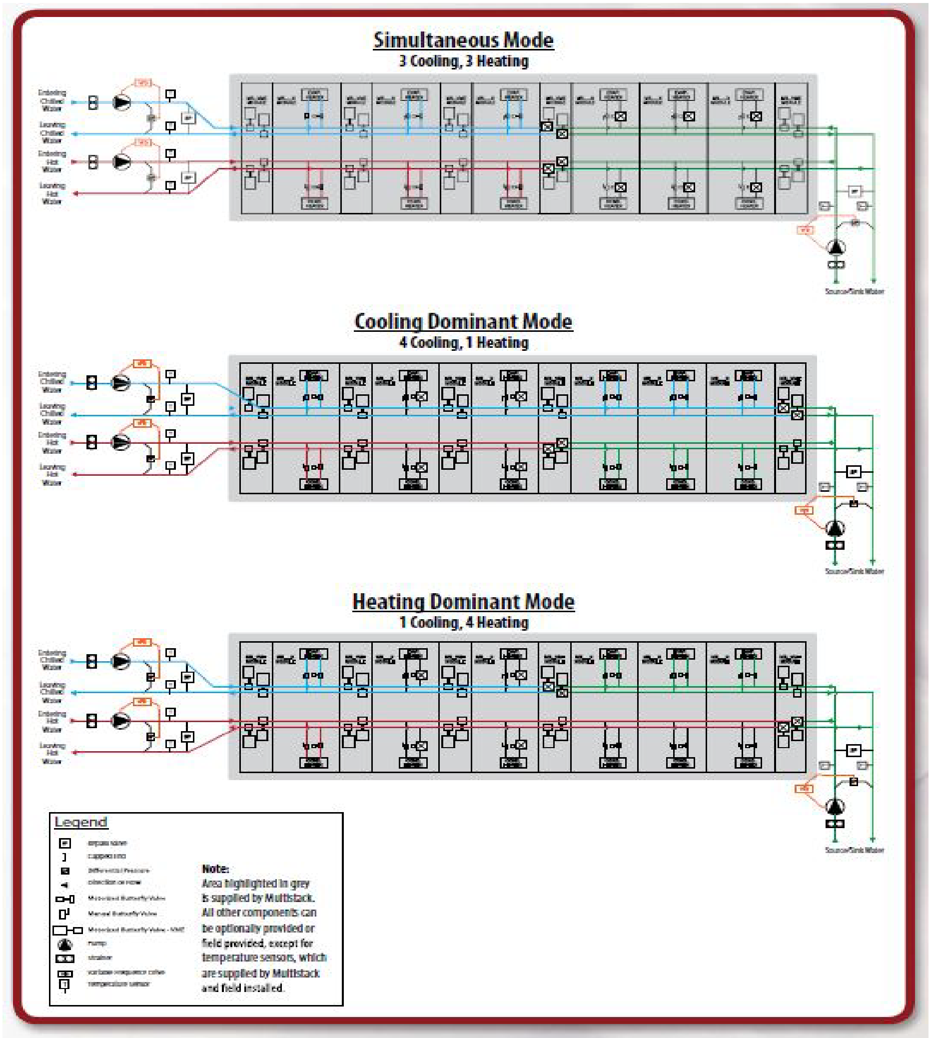


Figure 5-14. MultiStack Virtual Movable End Cap System: This system lends itself to ground-sink/ source operation if the real estate is available for the wells or other heat exchange fields. Large bodies of water would also be suited for use as sinks/sources if environmental regulations local to the proposed use will allow.

Again, these systems require knowledgeable, well trained maintenance personnel who can operate the systems as designed without taking shortcuts.

5.3.5. Central Systems

Traditional or conventional air-handling units and systems are described in Appendix C, section C.1, “Forced-Air Systems.” They generally have the following items in common:

- The draw in return air from the spaces/zones they serve,
- They mix the return air with outside air,
- They filter the mixed air,
- The heat, cool, and dehumidify the mixed air, and
- They supply the air back to the space at a temperature and humidity that will counteract the cooling, humidification, dehumidification, and heating loads seen in the space.

For our discussions, traditional systems will be those which treat both the space/zone airflow and the outside airflow in the same unit with the same cooling and heating coils. A traditional system may consist of one AHU in a large central equipment room or several smaller units in equipment rooms dispersed throughout the building. In HHC, using traditional systems means that all AHUs must deal with high humidity from the outside air, filtration of that outside air, and (in corrosive environments) dealing with the salt/sea air and its detrimental effects on the interior of the equipment.

DOAS, which are described in depth in Appendix C, section C.2, “Dedicated Outside Air System (DOAS),” are central air-handling systems that

- Draw in 100% outside air,
- Filter it,
- Heat, cool, and dehumidify it, and
- Supply it to the spaces/zones directly or through outside air connections on traditional air-handling units (not allowed in many DOD designs).

As discussed in section 5.3.3, in most cases in HHC, it becomes advantageous to separate the outside air load on the building from the space/zone cooling requirements. The typical means of accomplishing this is with one or more DOAS units located strategically throughout the building. Given their design to deal with high humidity loads, corrosive environments, and energy recovery from exhaust airstream, in all but the smallest of conditioned spaces, DOAS should be chosen to pressurize the building with conditioned outside air having a low dewpoint temperature and relieves the zone/space cooling systems of the majority of the latent cooling loads.

5.3.6. Zone System Selections

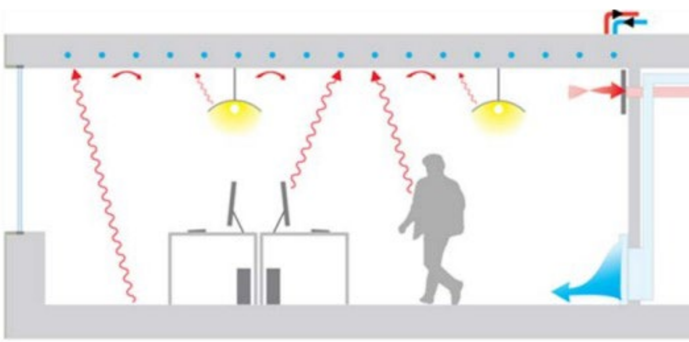
Zone/space cooling and heating using traditional central systems have been discussed at length. While certain building arrangements, sizes, and/or constraints may dictate their use for all outside air and space-conditioning, we will now discuss zone conditioning options where a DOAS supplies the pressurization air with a reduced dewpoint temperature suitable for the proper operation of the zone/space-level systems.

Forced-air systems such as those of section 5.3.5 can still be used with DOAS units. Specialized dual-duct terminal units may control both the space/zone cooling requirements via one of the primary air connections and space outside air for ventilation and pressurization via the other connections (see Figure 5-15). The control dampers in each connection will regulate the cooling air for temperature control and the ventilation air from the DOAS based on occupancy or other measurable factors.

Other systems such as space/zone-level fan-coil units, packaged heat pumps, unit ventilators, and induction units can also be used locally to handle space sensible cooling and heating.

Figure 5-15. A dual-duct VAV terminal unit can be used for control of both cooling air and air from the DOAS.

Radiant cooling of space/zones (Figure 5-16) is being considered to counteract the space/zone internal loads and the conduction/convection of heat from outside into the space/zone. Radiant cooling/heating systems work by radiantly transferring heat between objects with differing temperatures. In cooling mode, the cool radiant system absorbs energy from occupants and other warm objects in the space.



a.

c.

b.

Figure 5-16. Ceiling-mounted radiant cooling system.

Source: A- Schematic Fred Bauman, P.E., New Findings on Radiant System Comfort and Energy Performance, https://cbe.berkeley.edu/wp-content/uploads/2019/10/Bauman-2019-radiant-symposium.pdf - B - Radiant Cooling through ceiling embedded pipes. http://www.oorja.in/oorja/what-is-radiant-cooling/types-of-radiant-cooling-systems/; C - capillary, radiant cooling system: installation on the pre-finished surface as a two-side cooling mat detail with water feeding (or water return) along the edges.

Radiant ceiling systems are suspended or embedded into the ceiling and provide thermal energy exchange between the room and people present in the space and the heated or cooled surfaces. Again, the heat transfer depends on the temperature difference between the cooled or heated surface and the other surfaces in the space/zone for heat transfer. Radiant floor systems are installed in the floor but work similarly. Surfaces are cooled with a fluid having a temperature relatively close to the room air temperature.

While the ASHRAE Standard 55 (2017) thermal comfort recommendation allows radiant cooling ceiling/panel surface temperature to be 25 °F (14 °C) cooler than the floor surface temperature, the minimum surface temperature of the ceilings/panel cannot be lower than the dewpoint temperature of surrounding air, which is typically is above 60 °F (16 °C). A lower dewpoint temperature value can be maintained with a DOAS and building pressurization if there are minimal sources of humidity and latent heating in the space/zone. Howev er, if the ceiling/panel surface temperature is colder than the dewpoint temperature of the air in the space/zone, condensation will form on the cold ceiling damaging the finishes and anything in the room below.

Radiant floor systems should not result in a surface temperature colder than 66 °F (19 °C) and provide approximately 12 to 14 Btu/h/ft2 (42.1 to 44.1 W/m^2) of cooling with a space temperature of 75 °F (24 °C). In a typical barracks room, 20 Btu/hr/ft2 (63 W/m^2) is required. In a more commercial space, this value increases to 30 Btu/hr/ft2 (94.5 W/m^2).

Studies have shown that occupants perceive thermal comfort differently with radiant cooling/heating systems as compared to conventional all-air cooling/heating systems. According to ASHRAE, with radiant systems, occupants perceive comfort at thermostat settings approximately 2-3 °F (3.6 to 5.4 °C) higher (in the=cooling season) or lower (in the heating season) than with all-air systems. This translates directly into energy savings and the radiant surfaces perform better with the higher temperature differences.

Also, the radiant cooling/heating system can effectively take advantage of warmer CHW (55 °F to 58 °F [13 °C to 14 °C]) and cooler hot water (95 °F to 110 °F [35 °C to 43 °C]). With these systems, it is possible to use return CHW from the DOAS as supply water for the radiant cooling system. This cascaded use of CHW raises the temperature of the CHW returned to the chiller. This increased ΔT increase the capacity and efficiency of the chiller. Radiant cooling/heating systems have numerous other potential advantages over all-air systems, including

- Zoning radiant cooling/heating systems provide improved occupant comfort.
- They require less above-ceiling space because hot-water/chilled-water piping takes less space than HVAC ducts. This can be especially helpful when renovating buildings that have minimal space between the existing ceiling and the floor/roof above.
- They generate no noise and reduce the circulation of dirt and dust.
- They reduce operation and maintenance requirements due to system properties such as no air filters in occupied spaces and controls that only require a simple space thermostat and valve.
- They transport energy by water instead of air. Circulation pumps require less auxiliary energy than do fans. According to Lawrence Berkeley National Laboratory, approximately 13% of the peak sensible cooling load for a typical office building is attributable to the fan energy required to distribute air throughout the building. A radiant cooling/heating system eliminates the fan energy required for sensible cooling/heating and replaces it with the energy required by a more efficient chilled-water/hot-water pump that consumes about 5% of the energy required by a fan system. Fan energy is still required for the DOAS air distribution.
- They increase the potential use of renewable energy sources due to the use of water temperature close to room temperature.
- They eliminate cooling/heating energy losses from all-air systems due to duct leakage from all-air systems.

These are all good things, but in a hot and humid climate such as that of the northern Gulf of Mexico, failure of the DOAS means that the building can no longer be cooled without the possibility of making it rain in the space. Failure of the DOAS results in the indoor dewpoint temperature coming up to match the outdoor dewpoint temperature fairly quickly. As soon as the indoor dewpoint exceeds the temperature of the radiant surfaces, they will begin to condense moisture. If radiant cooling systems are desired in ASHRAE Climatic Zones 0A, 1A, 2A, and 3A, then a complete redundancy of the DOAS should be considered for the entire building. If part of the building is a critical space using radiant cooling and it must operate during a power failure, the entire building's DOAS units must be on critical power.

Concerns about the use of radiant cooling systems in HHC due to potential condensation are real and should not be dismissed. These concerns should be discussed with building occupants and maintenance personnel before deciding to use them. Additional discussions are included in Appendix C, section C.2, "Dedicated Outside Air System (DOAS)."

The ASHRAE *Design Guide for Dedicated Outdoor Air Systems (DOAS)* (ASHRAE 2017c, in revision) spends significant time addressing the importance of demand control ventilation for DOAS system selection, which influences not only the system itself, but also the control of exhaust air and the selection of recirculation units. Ventilation represents a very large part of the total building load. Limiting ventilation when it is not required can offer a major savings opportunity. Determining the ventilation requirement requires knowing whether the building is unoccupied, partially occupied, or fully occupied. Sensor and time of day controls can help with this. To ensure adequate ventilation as required by ANSI/ASHRAE Standard 62.1- 2016, installing a system of dampers and individual space airflow measurement devices is necessary.

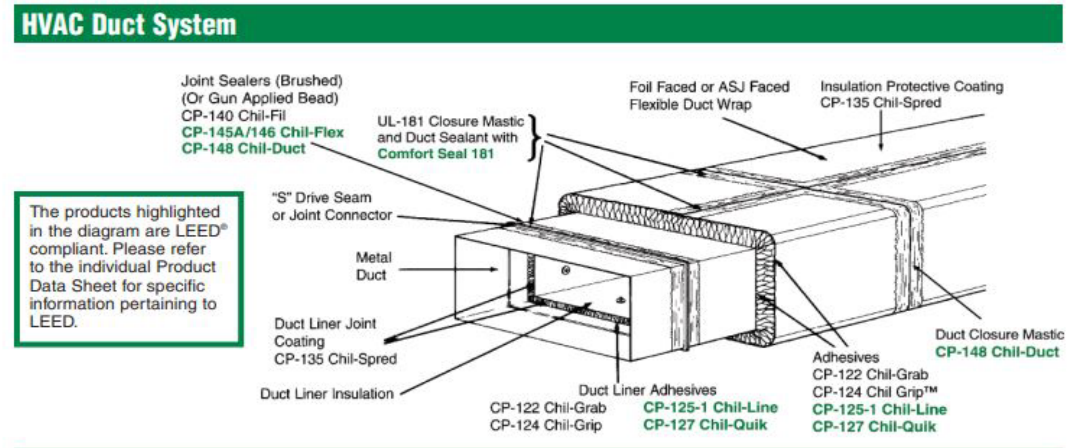
5.3.7. Other HVAC System Considerations

Seal Ductwork

Specify Sheet Metal and Air-Conditioning Contractors' National Association, Inc. (SMACNA) Seal Class A and a Pressure Class that is higher than the anticipated pressure inside the duct. Verify with commissioning that the Duct Air Leakage Tests (DALT) have been performed. Air leaking from ducts above sealings can create cold spots on ceiling tiles or other surfaces that will cause condensation and create opportunities for mold and mildew growth and may create problems for the installation of insulation (see Figure 5-17).

Insulate all piping and ductwork in such a manner as to prevent condensation on the piping and ductwork and on the insulation outer surface. The insulation thickness required by ASHRAE 90.1 (2019c) is required to save energy, not to prevent condensation. Increase thickness as necessary.

For cold piping, increase the piping insulation thickness such that the outer surface temperature of the insulation is higher than the dewpoint temperature of the air in the space. Do not use glass fiber insulation on cold piping. Use cellular glass or flexible elastomeric materials that have an extremely low permeability and apply a vapor barrier jacket on top of these materials.



Courtesy Specialty brands, Inc. Aurora, IL.

Figure 5-17. Ductwork sealing and insulation for prevention of condensation.

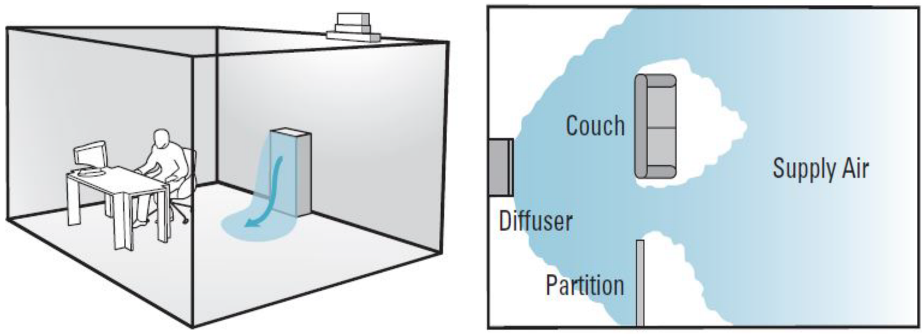
Cold Ductwork

For cold ductwork, increase the insulation thickness as necessary to prevent sweating. Specify duct wrap insulation as semi-rigid or blanket type with a foil vapor barrier all-service jacket. Consider the use of internally lined ductwork with adequate insulation thickness. In areas where dust accumulation is possible, double walled ductwork can be used to allow for cleaning of the interior of the ductwork. Butt ends and other seams of insulation together to avoid thermal bridges in the insulation. Lap jacket over edge, apply tape and mastic. Where edges of fiber insulation cannot be avoided (such as at damper quadrants, damper shafts, sensors, etc.), paint exposed edge with mastic sealant and apply tape or other impermeable membrane to edge so as not to allow humid air to penetrate into the fibrous core of the insulation where it may condense on the cold duct surface and then waterlog the insulation (Figure 5-18).

Figure 5-18. Condensation on ceilings and diffusers.

Air distribution must be considered in the context of mixing vs. displacement systems and sources of humidity within the spaces served. In supplying air to the conditioned spaces/zones, traditional ceiling air diffusers that create jets attached to ceilings can cause issues in HHC. Certain spaces, such as auditoriums, conference rooms, theaters, waiting areas, dining rooms, and gymnasiums can see high humidity loads generated within, not just coming from outdoors. When large quantities of people gather, a significant amount of latent load will be generated by the occupants.

In spaces/zones where the humidity generated within the space/zone increases the space dewpoint temperature more than the DOAS has been designed to offset, condensation can become a problem as VAV air supply reduces the airflow causing the jets from the ceiling diffusers to detach from the ceiling. Warmer air can come into contact with the previously cooled ceiling resulting in condensate forming on the ceiling and the edge of the diffuser (Figure 5-19). Over time, mold and mildew will grow in these locations. If the room dewpoint temperature cannot be maintained lower than the supply-air temperature coming from the ceiling diffusers, other means of air distribution must be considered.



Source: Price Displacement Ventilation Engineering Guide

Figure 5-19. Airflows from displacement ventilation diffusers in cooling.

Displacement ventilation is one such means. Displacement cooling airflow is accomplished by supplying air (at no more than 10 °F [18 C] cooler than the space) from near floor level with return/exhaust air intakes located in the ceiling. Diffusers consist of perforated face geometric shapes such as cylinders and cylinder segments and rectilinear forms (Figure 5-20). Given the limit on temperature difference, the flow of conditioned air will be significantly larger. While mixing systems with ceiling diffusers typically supply 55 °F (13 °C) air at approximately 400 cfm to 500 cfm (189 L/s to 236 L/s) per ton of cooling, displacement ventilation can require over 1000 cfm (472 L/s) of 65 °F (18 °C) supply per ton of cooling. According to Price's Displacement Ventilation Design Manual, the maximum velocity of airflow out of the diffusers should be no more than 40 ft/minute (12 m/minute). A 400 ft^2 (37 m^2) office requiring 1 ton of cooling (12000 Btu [4 kWh] per hour) will need 25 ft^2 (0.19 m^2) of diffuser surface. A typical ceiling diffuser in a mixing system would only require 4 ft^2 to 8 ft^2 (0.37 m^2 to 1 m^2) of diffuser on the ceiling. With displacement diffuser outlets located at the floor, the need for significant floor space must be considered. In addition, some find it quite uncomfortable to have cold air at floor level.

For some projects, there may be a synergy that can be obtained using radiant floor systems with displacement ventilation supplying only the air from a DOAS unit. This reduced volume of air would result in smaller diffusers and ductwork and reduce recirculation of airborne germs, viruses, pathogens, etc.

Source: Price Displacement Ventilation Engineering Guide.

Figure 5-20. Displacement ventilation diffusers in use.

Displacement ventilation can provide a solution, but a designer should choose carefully based on the occupancy, floor space, airflows required, and required space conditions. Cooling airflow requirements in hot and humid climates tend to be high and may make displacement ventilation impractical.

5.4. Controls and Modes of Operation in Normal (Blue Sky) & Off-Emergency (Black Sky) Conditions

The HVAC controls should continually monitor the occupancy of the building, the total of all exhaust airflows, and the actual outside airflow, and to adjust the DOAS airflow to always meet the minimum building pressurization (Equation B) and the minimum ventilation for IAQ (Equation A) when it becomes the greater airflow requirement. If scheduling shuts down certain exhaust fans, the airflow for pressurization may also be reduced. However, the net conditioned airflow into a building should never be reduced to less than that required for pressurization (Q_{Press}) in a hot and humid climate when the outside conditions include a dewpoint temperature greater than 55 °F (13 °C).

5.4.1. Normal (Blue Sky) Operation

Conventional systems in HHC should not cycle the cooling/dehumidification systems off unless the supply and exhaust fans are also cycled off and the associated dampers closed. Except in the case of extremely small systems, use chilled-water cooling for better control of part-load conditions if possible, or set the discharge dewpoint temperature of the supply air to lower than required so that as the refrigeration system cycles to unload, the drift will not exceed the required dewpoint temperature. Dryer air is better in HHC.

DOASs outside airflow rates generally are dictated by

- IAQ needs (based on ASHRAE Std. 62.1 [2019b])
- Makeup air (for example, for bathroom and kitchen exhausts, when needed)
- Building pressurization to prevent infiltration which allows for reduction of heating/cooling and moisture loads.

As a rule, a DOAS operates at an airflow rate that is fairly constant and only varies based on the requirements in the list above. Refer to Equations 5-4 and 5-5 in section 5.2.2.

Regarding DOAS unit sensors and controls, the DOAS should have the following control points (sensors and output controls) at a minimum

- Outside airflow measuring station (prefer thermal dispersion type) somewhere in the outside airstream, downstream of the air filtration,
- Outside air motorized, two-position damper,
- Outside air damper position feedback sensor (end switch or potentiometer),
- Outside air entering temperature sensor, downstream of the air filtration,
- Outside air entering RH sensor, downstream of the air filtration,
- Analog control output to the cooling coil control valve or analog/stepped operation of the refrigeration system,
- Cooling coil leaving air temperature sensor,
- Supply air leaving air temperature sensor, and
- Supply-air RH sensor.

If the unit includes an energy recovery exhaust system, the following control points:

- Exhaust air entering (from building-side) temperature sensor, downstream of the air filtration,
- Exhaust air motorized, two-position damper,
- Exhaust air damper position feedback sensor (end switch or potentiometer),
- Outside air entering RH sensor, downstream of the air filtration,
- Energy wheel motor run/stop,
- Energy wheel exhaust leaving air temperature sensor, if applicable, and
- Pump, valve, and energy transfer sensors and controls based on actual system chosen.

If the building is in a climate that can have freezing temperatures, the following control points will be required if applicable:

- Chilled-water cooling coil freeze stat,
- Preheating coil control, and
- Cooling coil entering air temperature sensor.

Zone/space system controls must include not only the inputs and sensors to monitor the space or zone temperature and the occupants' desired setpoints, but also the humidity sensing capability to establish the actual dewpoint temperature in each space/zone. These dewpoint temperature readings will be used to set the dewpoint temperature of the supply air coming from the DOAS or the cooling coil in the main AHU in more traditional systems. The control system should poll every space/zone to determine the highest dewpoint temperature and, after validation ("Is the sensor functioning correctly?") set the supply-air dewpoint temperature to counteract that of the out-of-tolerance humid space or zone. If all the space/zone dewpoint temperatures are well below the required humidity requirements, the system may reset the supply-air dewpoint temperature higher to conserve energy.

5.4.2. Emergency (Black Sky) Operation

For emergency (black sky) operations, consider three different types of facilities and three different types of emergency (black sky) situations.

The three types of facilities are

- Fully mission-critical
- Facilities of non-mission-critical type but having spaces/zones within that are mission-critical
- Fully non-mission-critical spaces.

Leased spaces will typically fall under the "fully non-mission-critical" spaces and because the buildings are owned by others, emergency (black sky) operation will be the building Owner's responsibility. However, the lease should specify the requirements and responsibilities that the Owner must fulfill to maintain the property in question. It is recommended that the applicable requirements for one of the three types above be written into the Lease Agreement between the Government and the Owner/Lessor.

The three types of emergency (black sky) operation to be considered are

- Short-term power failure less than 8 hours
- Long-term power failure more than 8 hours due to hurricanes and natural disasters
- Long-term vacancies or low occupancy.

Long-term vacancies or low occupancies encompass conditions where the normal building occupants are absent from the building, and the building sits mostly vacant but must be protected from the ambient conditions, elements, and weather. One variant of this is when a facility is newly constructed or renovated and then handed over to the Government for beneficial occupancy, but the building occupants may not move in for several months. In either of these cases, the building operation should be handled in accordance with the "long-term vacancies or low occupancy" requirements.

Table 5-2 lists a selection of operating modes based on situations that may be encountered for any building. Table 5-3 lists the operating modes in detail.

Table 5-2. Emergency (black sky) operating modes for various building types and situations.

Event\Building	Fully Mission-Critical Buildings	Partial Mission-Critical Spaces in Buildings with Large Percentage of Non-Critical Spaces	Fully Non-Mission-Critical
Short-term Power Fail	A	D	F
Long-term Power Fail	A & B	D	E
Long-term Vacancies	C	C	C

Table 5-3. Description of actual operating modes for use with Tbl. 5-2.

Emergency (black sky) Operating Mode	Description
A	The entire building is backed up on Critical Power (generator). HVAC operates as if the building has power.
B	Provide HVAC load shedding wherever possible. Reduce exhaust air volumes where spaces are unoccupied, or facilities are not being used.
C	All unrequired exhaust systems and all systems serving equipment that is turned off can be shut down. DOAS remains operating at reduced airflows, minimum flow required to maintain building pressurization, and dewpoint temperature below that of any exposed cold surfaces in the building.
D	A critical portion of building HVAC and **all DOAS** (for the whole building) remain in operation. Exhaust systems and DOAS in non-critical areas reduce or shut off flow to load shed and preserve fuel reserve. Critical space air balance must be designed such that critical spaces are at positive pressure relative to no critical spaces.
E	Provide temporary (roll-up) generator connection ports outside the building and manual transfer switch. Segregate power systems in the building between loads that need to run to protect the building and provide some occupant comfort and those that are not required. During an outage, a temporary generator is leased and connected to building ports. The generator supplies power to transfer switch to power systems that need to operate during the long-term outage.
F	All systems shut down. All outside air and exhaust air dampers are spring-return, normally closed and close to reduce infiltration.

5.5. Energy-Efficient Design in HHC

While energy use and savings by HVAC systems is important, in HHC, many of the energy efficiency strategies of other climates are not feasible. In considering the systems to use, include serious consideration of the cost of replacing the building because of

- Structural failures caused by corrosion of load-bearing members (see section 4.7)
- HVAC system failures caused by environmental factors such as proximity to the ocean or saltwater
- Gutting and refurbishing the building due to sick-building syndrome and mold/mildew growth
- Other problems caused by run-away humidity within the building envelope.

All the energy saved during the life of an HVAC system will not offset the cost of building repair or replacement.

That said, there are technologies available to maximize efficiency and reduce total energy use of hot-and-humid-climate HVAC systems. Where the project is large enough, economies of scale will allow for TES, energy recovery, and higher-efficiency equipment. Life-cycle cost evaluation must always determine system selection (subject to mission requirements).

5.5.1. Thermal Energy Storage

TES is discussed at length in Chapter 6, however, some storage systems that immediately come to mind are as follows

- Chilled-water storage tanks allow for the cooling of chilled-water medium during the off-peak (time of day) hours of the local power utility company followed by the use of the stored CHW in lieu of chiller operation during the peak utility rate. This load shifting assists the utility company by shedding peak demand and avoiding the construction of additional power plants, and it saves the Government or other user money. One drawback is the requirement that the storage tank be insulated to maintain the stored water temperature. In some cases, the stored water can be made available for fire suppression sprinklers systems where building water supplies are not reliable.
- Ground-source water wells or geothermal exchange wells can serve as storage for heating and cooling with water-source heat pump systems. Where the ground is of a high clay or rock content, the well field may perform as a giant thermal storage sink/source, being charged with heat in the summer and discharged in the winter. However, the quantity of heat discharged in the summer can usually be two to three times what is used in the winter and an auxiliary means of heat rejection should be provided in HHC or unwanted heating can occur rendering the well field unusable for heat rejection. In designing a system such as this, the well field should only be sized for the required heating load and the above-ground heat rejection system be sized for the differential between the cooling heat rejection and the heating absorption. Advantages include the fact that much of the heat rejection equipment is buried and not subject to storm damage or airborne saltwater corrosion. Required auxiliary heat rejection (cooling towers and the like) will be smaller than those required for non-ground-source systems. Also, in HHC, boilers and other primary heat sources are never required for systems like these. However, the geographic space requirements of these systems can be prohibitive, on the order of 160,000 ft^3 (4480 m^3) and 400 ft^2 (37.2 m^2) of surface/site area for each ton of refrigeration.
- Bodies of water such as the ocean or large lakes may be usable as heat sinks and sources, but existing environmental regulations and regulations associated with endangered wildlife species that frequent the geographic area of the project may be prohibitive. In addition, saltwater related corrosion may render such system life-cycle cost prohibitive.

5.5.2. Thermal Energy Sinks and Sources

With any HVAC system, a (heat) sink must be provided for rejection of heat from the cooling system and the associated compressor energy. If heat pumps are being used to produce winter heating, a source must be available for the system to draw heat from. As discussed above, the quantity of heat discharged in the summer can usually be two to three times what is used in the winter. As such, if thermal storage is not the objective, there are several options for rejection and absorption of heat for HVAC systems in HHC.

The atmosphere is the first and most readily available option and has been since the advent of refrigeration. However, in HHC, the possibility of wind damage and corrosion of air-sink/source heat exchange equipment can reduce the resiliency of these systems.

The ocean or other large bodies of water can also be a sink/source, but as discussed above, environmental regulations may be prohibitive.

Waste heat is often discussed in terms of capture and reuse. However, in HHC, there is almost never a shortage of heat. Unless there is a process demand for heat associated with the project, most of the heat must be rejected to a heat sink such as the atmosphere, body of water, or the ground.

Ground-source wells should be considered where the scale of the project is sufficiently large, and the geotechnical characteristics of the area lend themselves to efficient operation of the system. Sandy soils that run the full depth of the wells and have water tables that are within 5 ft to 10 ft (1.5 m to 3 m) of the surface can act as efficient sink/sources for water-source heating and cooling of buildings. These conditions will rarely result in energy storage but can result in water-source systems that may require little or no above-ground auxiliary heat rejection equipment.

5.6. General Considerations

5.6.1. Refrigerants

As with projects in all climates, select refrigerants with zero ozone depletion factors and as efficient as are available (high specific heats and high heats of vaporization). Global Warming Potential (GWP) refrigerants should be considered if their use is suitable in terms of overall efficiency, flammability, and building code developments.

5.6.2. Space and Site Availability

The designer must always consider the real estate required for the systems chosen including indoor and outdoor spaces, above-ground and below-ground equipment, and other factors in the LCCA used to select the system.

Providing an indoor chiller will protect the chiller from the corrosive environment, but the cost of the extra building square footage to be maintained and conditioned must be included in the LCCA. A 40 ton (48 kBtu/hr), water-cooled chiller may require 300 ft^2 to 500 ft^2 (27.9 m^2 to 46.5 m^2) extra floor space inside the building (including the condenser-water pumps). At \$400/ft^2 (\$4301/m^2) that could be as much as \$200,000 for the space alone.

Sinks and sources must always be selected similarly. Heat rejection and TES may occupy a good deal of above-ground and below-ground real estate. A 200-ton (3600 kBtu) demand required to operate from a chilled-water storage tank for 12 hours before being recharged by chiller operation will require approximately 300,000 gal (1,135,500 L) of insulated, chilled-water storage (assuming a 14 °F (25.2 °C) chilled-water ΔT through the building loads). This tank would be 70 ft (2.13 m) in diameter and 10 ft (0.30 m) tall.

A 200 ton (2400 kBtu) well field will occupy 80,000 ft^2 (7440 m^2) of site area. This area can be paved for parking but must never be under a building or structure or aircraft parking apron.

A standard, crossflow cooling tower for a 200-ton (2400 kBtu) chiller would only occupy about 800 ft^2 (74.4 m^2).

The LCCA should always consider the additional space requirements in the choice of which system to select for the final design.

5.6.3. Synergies

As discussed in section 5.5, the use of waste heat from the condenser side of cooling systems is of principle importance. Wherever this heat can be put to use, it will prevent the use of new energy. Nevertheless, LCCA should (as always) be used to determine that more energy is not spent constructing an energy recovery system than will be saved over the life of the system. Economies of scale usually result in more use of recovered energy. Small systems (less than 5 tons (60 kBtu) cooling) are rarely modified to capture waste condenser heat. Appendix C, section C.3, "Condenser-Water Energy Recovery," includes some select ideas for harvesting waste heat.

Use of waste heat for reheat is the first focal point of energy recovery synergy. A building employing a DOAS should always use either condenser-water or hot-gas reheat to heat the supply air from its dewpoint (leaving the cooling coil) to the neutral temperature that is supplied to the spaces/zones. If the DOAS is large enough and the building exhaust airflow high enough, an air-to-air heat exchanger may allow exhaust air to reheat the conditioned outside air.

Use of waste heat for domestic water for showers and dishwashing should always be included in LCCA in buildings where commercial kitchen/dish washing is performed and in buildings where more than four bathing shower stalls are located. Where water-source systems are employed, water-source heat pump domestic water heaters can be provided. In some instances, a water-to-water, domestic, heat pump, water heater may draw heat from a chilled-water return line and return it to the CHW system, thereby providing free cooling.

Small, air-cooled, DX systems (5 tons [60 kBtu] cooling and less) have been fitted with de-superheat exchangers between the hot-gas line on the compressor of a small unit and a domestic water circulating line to provide some domestic hot water production and slightly improved performance of the refrigerating system. However, these systems should only be supplied in climates that do not require freeze protection.

Where DOD buildings require fire suppression water storage, consider using the fire water tank as a chilled-water or other TES tank as one option in LCCA. Locations with varying time-of-day electric rates or time-of-day demand charges may make this usage more attractive.

5.6.4. Anti-Synergies

In HHC, there will be costs associated with operating the building HVAC to protect the building itself from life-shortening damage. While buildings in cool/dry climates may be able to shut down their cooling systems much of the year, HHC buildings must always maintain the building pressurization and dewpoint temperature control inside the building.

Building pressurization will increase energy use but will save the energy required to replace or substantially repair the building should it become damaged by corrosion, or biological contamination (mold and mildew).

While discussed only in passing, many HHC mitigation strategies require more sophisticated maintenance and operation. Better trained and more talented/more motivated maintenance personnel are required to perform the work, and better supervision is required to ensure that shortcuts are not taken to make something "work" for now but that results in a long-term detriment to the building. The maintenance force must all be trained to know why systems work the way they do and be able to protect the modes of operation designed for the systems.

5.7. Summary

In HHC, the HVAC system must always pressurize the building with conditioned outside air that has a sufficiently low dewpoint temperature to offset any exhaust airflows, resist infiltration due to wind speeds up to 12 knots (22.2 kph) prevent surfaces within the space from sweating, and offset most internal latent (water vapor) loads.

5.7.1. Pressurize the Building

It is recommended that the following requirements be added to UFC 3-410-01 (NAVFAC 2021b):

> *For buildings in ASHRAE CZs 1A, 2A, and 3A, provide conditioned outside air to the building at a rate sufficient to pressurize the building to approximately 0.1 inches water gage (24.9 Pascals) based on the allowable leakage rate for the building air barrier or as required to meet ASHRAE 62.1 ventilation rate requirements, whichever is larger. Refer to Equations 5-1 and 5-2 for an outside airflow rate to the building.*
>
> *If the outside air requirement of ASHRAE 62.1 (2019b, Equation A) is higher than that required for pressurization (Equation B), provide relief air, preferably through the Dedicated Outside Air System (DOAS) exhaust air path so that the building is not over-pressurized.*
>
> *The conditioned outside airstream must always be supplied to the building.*

5.7.2. Control and Keep the Indoor Dewpoint Temperature Low

In lieu of controlling space RH, control the dewpoint temperature of the air supplied to the spaces/zones in the building. It is recommended that the following requirements be added to UFC 3-410-01 (NAVFAC 2021b):

> *For buildings in ASHRAE CZs 1A, 2A, and 3A, provide separate cooling and dehumidification of outside air streams greater than 750 ft^3/minute (21 m^3/minute) such that the dewpoint temperature of the air supplied to the building spaces/zones is the lower value of*
>
> - *55 °F (12 °C),*
> - *5 °F (4 °C) lower than the expected coldest surfaces that will be exposed to the space/zone air, or*

- *10 °F (18 °C) lower than the radiational zone cooling surfaces if installed, and*
- *As required to offset anticipated space latent loads and maintain the space dewpoint temperatures at the applicable requirement of the three preceding temperatures.*

For buildings with zone cooling provided by radiant floors or ceilings, provide DOAS for conditioning the outside airstream and controlling the building dewpoint temperature. Where radiant cooling is the space cooling method of choice, provide complete redundancy of DOAS units (2xN redundancy where N is the number of DOAS units required) serving the radiant cooled spaces/zones.

5.7.3. Design and Specify Outdoor Equipment Located in Sea Coast Environments for Resilience

The process if system selection and equipment specification for use in projects located within 2 miles (3.2 km) of large bodies of saltwater should include the increased replacement frequency of outdoor equipment in life-cycle cost analyses, and should specify that equipment with surfaces that are exposed to outdoor air have seacoast coatings and pass salt spray tests for 3,000-hour life or greater.

5.7.4. Conclusion

HHC pose serious design challenges for HVAC systems. However, with proper design, resilient equipment specification, communication of operational requirements, system operation in accordance with the design requirements, and maintenance that always restores the systems to as-designed condition, building HVAC systems can provide a level of protection to the interior of the building that envelope design alone may not provide.

CHAPTER 6. DISTRICT COOLING SYSTEMS

District thermal energy systems are used to supply heating, and cooling to campuses to building clusters, campuses, or even entire communities. Major driving forces for district thermal energy systems are

- Economy of scale
- Use of renewable energy sources that would not be easily assessable at building levels
- Focused, dedicated and professional system operation
- Maximum energy efficiency
- Simple, effective, and minimum footprint of end-user thermal interfaces
- Robust and reliable thermal supply systems
- Resilient infrastructure in case of disruptions
- Minimization of losses related to corrosion, e.g., with the elimination of the use of individual building condensers
- Smart integration of the energy sectors
- Ability to momentarily provide load shedding capabilities to prevent the power grid from collapsing in case of power demand exceeding the power generation supply
- Efficient use of waste energy from different sources.

While this chapter focuses primarily on district cooling systems, district heating systems can be used in HHC to supply heat for air reheat, domestic water heating, and, in some climate zones, for building heating using heat generated by boilers, combined heat and power (CHP) plants, and from renewable energy sources or waste heat, e.g., from chillers.

6.1. System Design and Operation

The first consideration when planning district cooling systems is the mapping of cool sources, cooling demands, location of critical consumers, and critical limitations to the distribution pipeline layout. Critical limitations can be railroads or highways that the pipeline is crossing. With that information, it is possible to plan the location of the cooling plants considering the urban spatial plan and local conditions and the role of the plants (base and peak load) as well as the layout of the distribution pipeline. To maximize the supply security to critical buildings, it is possible to both locate peak/backup chiller plants at their premises and apply dual supply lines, coming from different parts of the distribution network. For exceptionally temperature-sensitive buildings, a thermal storage tank can be located next to the peak/backup chiller plant to maintain a stable supply until the chiller is warmed up and in operation. For other buildings, supply security is maximized by distributing the cooling plants around the system and by applying loop connections in the network. In the layout, the most optimal supply temperature, which can meet most of the demand, typically comfort cooling designed according to the local building regulation, must be defined. Cooling demand at lower temperatures can be connected via a local heat pump that boosts the temperature down to the required temperature, e.g., for freezers. Cooling demand at temperatures larger than the return water in the cooling grid can be connected by a three-pipe connection, thereby increasing the return temperature in the grid.

6.2. Cooling Supply Flexibility

District cooling systems can provide superior flexibility compared to building-level solutions. The most important aspects of the demand flexibility are

- The district cooling system clusters all consumer demands and the installed capacity can be based on measured actual consumption. Whereas building-level solutions are normally oversized in the design stage due to compensate for demand uncertainties, district cooling will be able to consider the actual demand.
- The district cooling installation at the building is, in general, flexible and can be extended at a low cost.

Other important parameters of flexibility provided by district cooling are

- A change in buildings' cooling demand can normally be absorbed by the existing system's cooling capacity, and at peak-load periods, by using backup chillers.
- Fuel disruptions can be split into short- and long-term disruptions. The impact of short-term fuel disruptions is minimized by using thermal storage systems. The impact of long-term fuel disruptions is minimized by operating diversified cooling plants, consisting of both electric and heat-driven chillers and any local free cooling opportunities.
- Heat-driven chillers can be combined with a multi-fuel capable boiler.
- During heat waves, district cooling systems generally have the flexibility to go beyond design conditions by using spare capacity from backup cooling plants, by pre-charging thermal storage systems, and by changing distribution operation parameters like supply temperature and flow velocities.
- During emergency (black sky) response measures, capacity limitations could be implemented for non-critical buildings.

In many energy systems, the most important flexibility is the ability to reduce the "cooling peak" in the power system, compared to individual uncontrolled electrical chillers. The peak reduction can be a combination of chilled-water storages, ground-source cooling, or any ambient cooling source and absorption chillers, depending on the local conditions.

6.3. Resilience Enhancing Operation

As with all systems, it is critical to ensure that the system is well maintained. For infrastructure systems with long lifetimes, as district cooling systems, it is important to implement appropriate operation and maintenance procedures from the time the system is commissioned.

The experience from district heating systems has shown that such trivial things as documenting the exact location, types, and ages of pipes along the distribution lines are sometimes neglected. This negligence can have serious implications in the event of disruptions decades into the operation, as it can delay the identification of failure points and materials needed for repair:

- *Continuous system surveillance.* Various measures can ensure system stability and early fault detection. The priority is to prevent faults, the second priority is to detect faults early, and the third priority is to schedule the emergency operation and maintenance at times that accommodate minimum supply interruption. Measures for fault prevention include
  - Ensure high water quality to prevent internal corrosion.

- Use pre-insulated steel pipes with welded muffs and bonded system without expansion joints.
- Use leak detection in the pre-insulated steel pipes.
- Ensure outside and inside draining and ventilation of underground construction.
- Ensure pressure and temperature levels are within parameters.
- Inspect periodically and exchange critical components before they fail.
- Monitor for unwanted behavior, such as pressure and temperature oscillations.

- Measures for early detection include
  - Leakage detection wires in pipe insulation
  - Periodic visual inspections of accessible equipment
  - Continuous parameter analysis on available data
  - Test operationality of critical components periodically, such as shutoff valve and backup units.

Many faults occur gradually; with surveillance systems in place, it is possible to detect and locate failing pipes or components before they collapse. A Supervisory Control And Data Acquisition (SCADA) system monitors vital parameters and offers remote operation of components, and allows the system operator to react more quickly to unforeseen disruptions. Scheduling preventive and non-critical repairs at periods of low cooling demand minimizes the impact on consumers.

The system should be designed with the redundancy of critical components. An example of this is the N+1 design for distribution pumps and heat exchangers. This approach makes it possible to take one of the distribution pumps or heat exchangers offline for maintenance without impacting system operation.

6.4. Cooling Generation and Supply

District cooling systems generally operate with multiple cooling generation plants and units to cope with potential disturbances. As cooling demand generally can have both large daily and seasonal variations the cooling generation systems are designed to adapt to large demand variations. For this reason, the cooling plants are typically built with multiple cooling generation units. To avoid site-specific disruptions, the generation units can be distributed around the distribution system to minimize the likelihood of total supply failures in case of disruptions. If a single generation plant fails, the supply is maintained by operating reserve and peak-load chillers or by using portable emergency chillers.

An important parameter to maximize the security of the supply is the location of the cooling generation plants, both base- and peak-load plants. Large baseload plants may have restrictions on locations, due to power demand, noise from operating mechanical chillers, and limitations for fuel deliveries and air pollution in case of heat-driven cooling generation. The location of peak and reserve chillers, which have limited operating hours annually, are generally more relaxed and should be determined to maximize overall supply security or alternatively, to maintain energy supply near-critical building complexes.

Thermal storage systems can be used to increase short-term supply security and reduce the impact of daily peaks. In areas with large seasonal access to renewable energy, large thermal storage systems can be used to store cooling between seasons. Although thermal storage systems are commonly found next to thermal plants, they can be located strategically along the distribution grid or at critical consumers to increase supply security.

Because district cooling is a basic infrastructure that supplies a large number of buildings, it is generally recommended that district cooling utilities own and operate their emergency power generators to ensure operationality in case of power grid failure. The emergency power generators should have the capacity to maintain the defined critical cooling plant operation and the district cooling distribution pumps.

The most important positive impact of district cooling on the energy systems in large cities is probably the ability to down-regulate the electricity consumption or even avoid it in case of large electricity prices and load shedding in the event of disruptions in the power grid. The main benefits of district cooling are

- District cooling in cities reduces the electricity demand from uncontrolled small chillers.
- The electricity consumption to the central cooling plants can be managed using existing SCADA systems, providing the means to disrupt the operation at any time. Centrally located chilled-water storages can be designed and operated to offer load shedding service to the power system without impacting the cooling supply.
- The electricity consumption for cooling and city heat island effects are reduced in general due to diversification of the production with larger efficiency and use of ambient cooling, e.g., groundwater or deep lake water cooling.
- The diversification of production includes absorption heat pumps fueled with deep geothermal energy, super-heated water from boilers, or gas turbine-driven compressors.

6.4.1. Heat Pumps/Chillers

The most common technology used in district cooling systems is heat pumps. A heat pump uses a closed refrigerant loop to draw heat from a heat source, e.g., district cooling systems, and deliver it to a heat sink, which cools the refrigerant down. The efficiency of the heat pump is directly related to the required cooling of the heat source and the efficiency of the heat sink to remove the heat.

Heat pumps are the common name for a variety of technologies, such as

- Compression heat pumps/chillers, using electricity for driving the process.
- Compression heat pumps/chillers, using a combustion engine to drive the process.
- Absorption heat pumps/chillers, using high temperature heat to drive the process.
- Adsorption heat pumps/chillers, using low-temperature heat to drive the process.

District cooling systems can enable unique opportunities in regard to the heat sink, as they can take advantage of local conditions, such as access to rivers, sea, or heating systems, to get rid of the waste heat in an energy-efficient way. The optimal heat sink would be to use the waste heat for heating purposes, such as in district heating systems, as that would enable to use of both sides, hot and cold side, of the heat pump, resulting in double thermal efficiency per driving energy unit compared to only cooling.

6.4.2. Free Cooling

In the case where the location is next to the ocean, lake, rivers, or has cold groundwater streams these can be used as a free cooling source, enabling a very high efficiency of the cooling generation. There is no number of district cooling systems that take advantage of free cooling in operation, such as the district cooling system in Stockholm, Sweden; Copenhagen and Aalborg, Denmark; Bora Bora, French Polynesia, Toronto, Canada; and many other places.

Depending on the temperature level the free cooling can be used directly or as a pre-cooling before the chiller, which will significantly reduce the chiller work required. Alternatively, the free cooling can be used as an efficient heat sink for the hot side of the chiller, removing the need for cooling towers and associated the costs of their operation and potential water usage.

With free cooling, the electrical, water, and sewage demands from cooling operation are significantly reduced, up to 90% compared to conventional cooling operation. The drastic reduction of electrical demands makes these systems significantly less sensitive to future electric cost hikes (Figure 6-1). Additionally, the system will drastically reduce the electric peak demands from cooling operations.

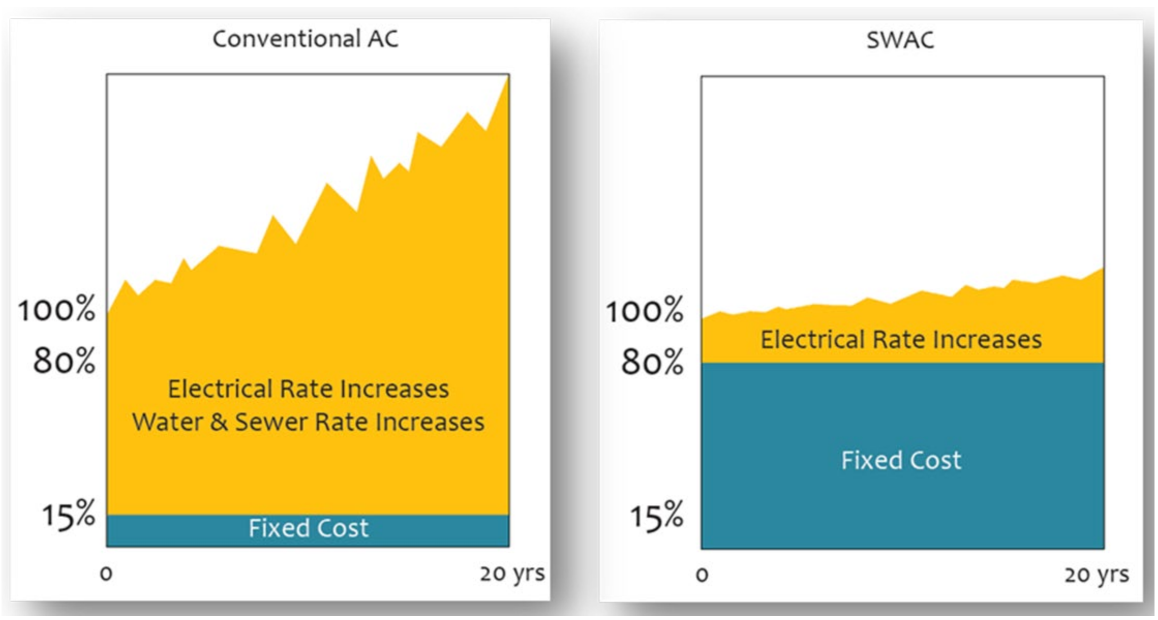


Figure 6-1. Example of cost development that can be expected for conventional (left) and deep-water cooling systems (right).

6.4.3. Deep-Water Cooling

Deep Water Source Cooling (DWSC) is a simple and effective system that uses the cold water from the deep ocean or a lake as a cool source for the district cooling system. These systems are particularly attractive in tropical regions where a large, dense cooling load is located near a lake or ocean, with a short distance to cold (~40-43 °F/4-6 °C) deep water (steep bathymetry). Figure 6-2 illustrates the principles of deep-water cooling systems.

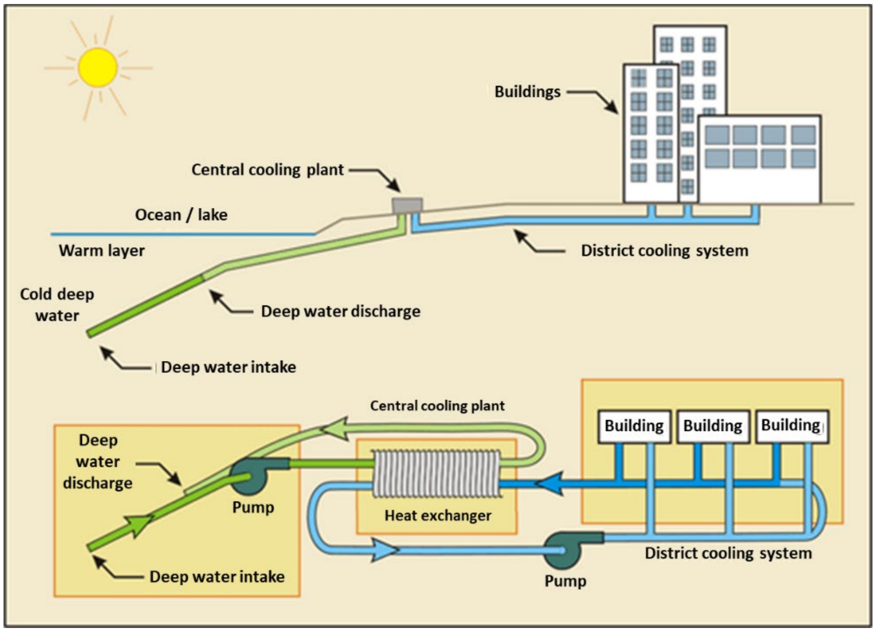


Figure 6-2. A principal schematic of a deep-water district cooling system.

In the case of seawater cooling, seawater is brought to the cooling station through a deep-water polyethylene pipeline. These pipelines reach out several kilometers offshore and have a nominal intake depth of 800 m to 1,000 m (2624 ft to 3280 ft). The seawater is then returned to the ocean via a second outfall pipe. The district cooling return water is cooled by the deep cold seawater via a heat exchanger. To prevent corrosion the seawater heat exchangers are from titanium. Due to the purity of the deep seawater fouling is generally not an issue.

6.4.4. Shallow Water Cooling

In case the distances to sufficiently cold water might be prohibitive, or the ocean depth is not available, there are alternative solutions available to take advantage of the local resources. In such cases, there are other options for taking advantage of the local water source to reduce the energy costs associated with air-conditioning, such as lake or seawater cooled chillers (hybrid seawater air-conditioning [SWAC]).

If a site with high air-conditioning costs has no access to cold or deep seawater, then the nearshore, relatively warm sea, or lake water can also be used to significantly boost chiller efficiency and consequently reduce energy consumption. This is done by replacing an air-cooled or evaporative cooling tower cooled condenser with seawater cooling. The amount of energy saved will depend on the change in condensing temperature. Locations with access to cooler mid-depth waters at around (~50-55 °F [~10-13 °C]), would provide drastic improvements in Coefficient Of Performance (COP) of modern chillers compared to traditionally cooled chillers. Even shallow warm waters at temperatures (as high as ~80 °F, [~27 °C]) can still provide significant energy savings.

Shallow surface seawater will typically be much cooler than the air, especially during the hottest time of year. Thus, an air-cooled condenser can be replaced by sea or lake water cooling and obtain 25% or more energy savings. If the chiller uses an evaporative cooling tower for condenser cooling, usually shallow seawater can both improve chiller performance and can eliminate the noise, water demand, and sewage fees associated with the evaporative cooling tower. Figure 6-3 shows a schematic of a conventional chiller with its condenser cooled with shallow surface seawater.

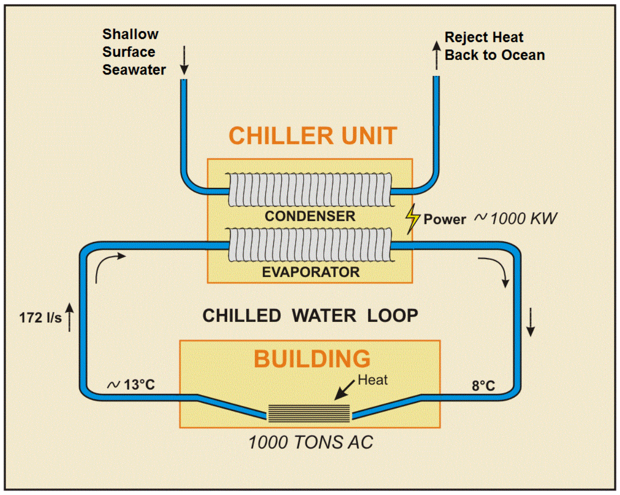


Figure 6-3. Schematic of a shallow water-cooled chiller unit.

Figure 6-4 shows a typical vertical temperature profile of the ocean in tropical regions. The applicability of water-source cooling approaches is indicated, with full SWAC typically needing less than 43 °F (6 °C), and hybrid SWAC less anything above 43 °F (6 °C).

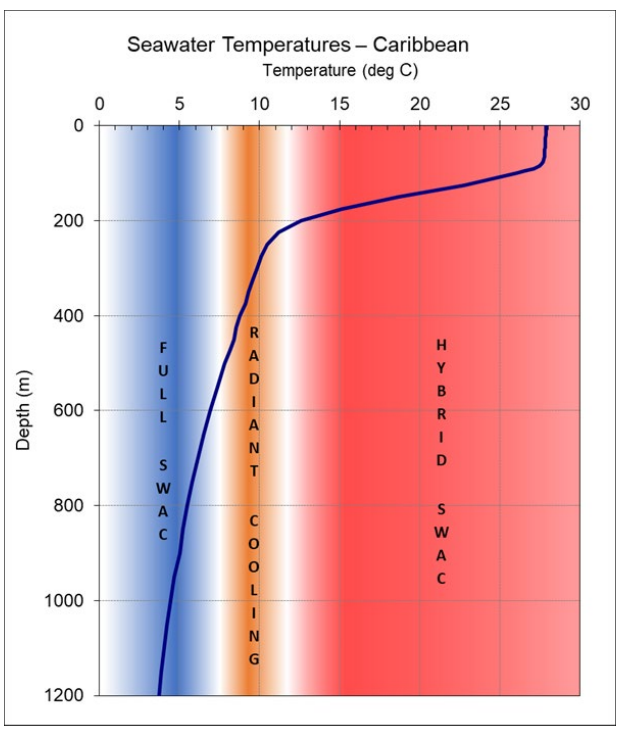


Figure 6-4. Vertical temperature ocean profiles for tropical regions.

6.4.5. Combined Cooling, Heat, and Electricity

The district energy systems allow the use of waste heat from thermal power plants, which would otherwise be wasted to the ambient environment. Thermal power plants typically have power efficiency of 30% to 50%, depending on the type of fuels used, meaning 50% to 70% of the input energy is lost to the surroundings. By combining thermal power generation with modern district cooling systems, it is possible to use the waste heat from the power generation to operate adsorption chillers and significantly increase fuel efficiency. The waste heat from the adsorption chiller can be used for heating purposes via district heating systems. The side effect of extracting heat from power plants is that the power output will drop as heat is extracted. The relation between power generation and heat extraction can be shown using iron diagrams (Figure 6-5):

- While going from point a) to b), more heat is being extracted (at max fuel load), which impacts the power output from the plant. The impact comes from the fact that to get a high amount of heat, it is necessary to extract the steam at higher temperature levels, which reduces the power generation potential.
- While going from point b) to c) the boiler load is reduced (less fuel is fed to the boiler) at the same time as maximum heat output is maintained. The line d) to c) further represents the minimum load the boiler can be operated at.
- The slope of the line a) to b) indicates the trade-off between power and heat, which is independent of the boiler load.

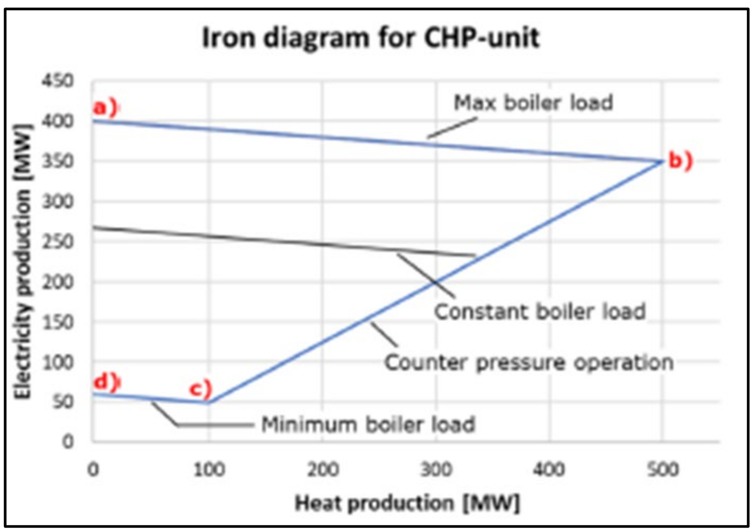
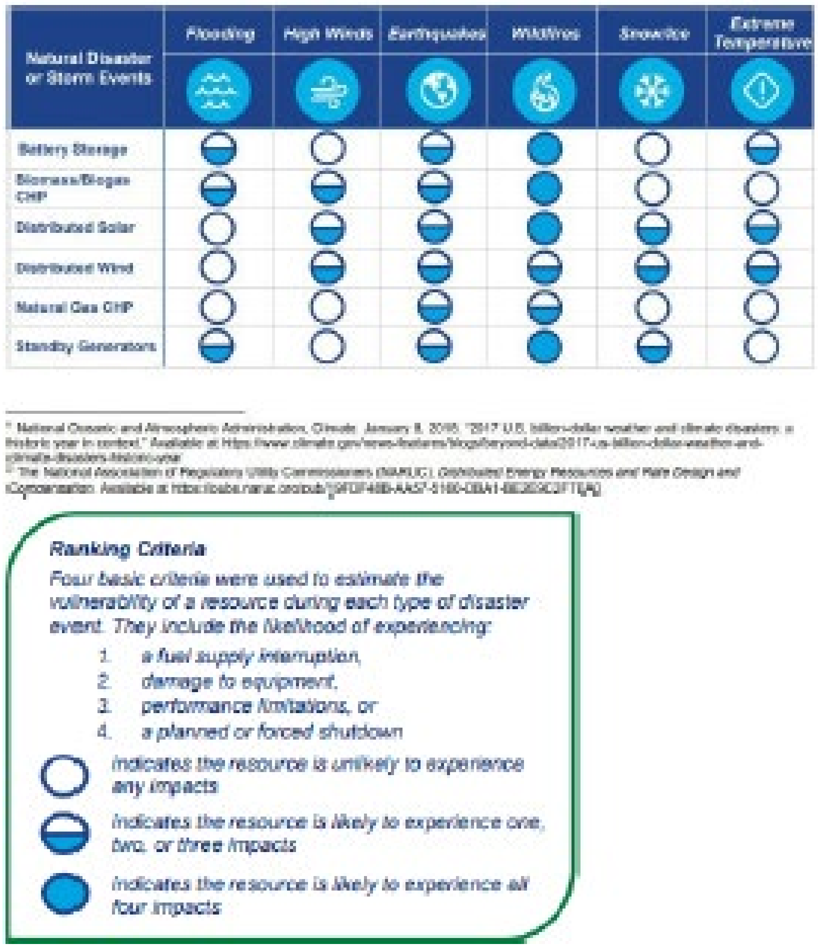


Figure 6-5. Iron Diagram for modeling of an extraction condensing unit. The vertical axis indicates the power output and the horizontal axis the heat output.

6.4.6. Combined Cooling, Heat, and Power (CCHP) Resilient Design

Though district energy systems aggregate thermal loads of multiple customers, they cannot always provide electricity to the same customers because of utility franchise laws. District energy systems are not always integrated with CCHP systems; however, combining district energy with a CCHP system can be a unique opportunity to provide both thermal energy and electrical power, thereby serving multiple energy needs at once.

CCHP can effectively contribute to state and local planning efforts to build resiliency for both critical infrastructure and other facilities (Figure 6-6). CCHP systems allow facilities to remain functional in the event of a disaster, and for non-critical loads to resume functionality as quickly as possible.



Source: USDOE (2018).

Figure 6-6. Matrix of DER vulnerability to weather events.

A CCHP plant, in which a local plant generates electricity, district heating, and district cooling in an efficient combination, improves the resiliency in case the power grid is unreliable.

In considering how to incorporate CCHP applications, it is recommended to review the U.S. Department of Homeland Security's National Infrastructure and Protection Plan (NIPP) (DHS 2018), which provides emergency planners with a variety of assessment tools. In 2009, the New York State Energy Research and Development Authority (NYSERDA) conducted an assessment with the assistance of the NIPP and found that the most appropriate focus and prioritization of CCHP should be at hospitals and water treatment/sanitary facilities, followed by nursing homes, prisons, and places of refuge (Energetics Inc. 2009).

In its funding solicitation, NYSERDA specified a preference for CCHP systems that can run during grid outages to provide electric power to the site's priority loads for all facilities, and not just critical facilities (NYSERDA 2019).

6.4.7. Emergency Generation and Mobile Chillers

In case of disruption causing a long-duration failure of either a cooling plant or pipeline, utilities can prepare by either having a standby, or they can rent portable emergency chillers. Emergency chillers can be housed in containers or built on trailers (Figure 6-7) or can consist of smaller chillers that can be installed at buildings or strategic points in the network for use in case of emergency. Mobile chillers consist of compressors, condensers, evaporators, fans, control equipment (continuously adjustable), all safety devices and pumps. Depending on the power connection availability, they may be accompanied by mobile power generators. Similarly, to the way emergency power generators are provided, connections for mobile chiller plants can easily be provided in the mechanical areas of critical facilities to allow the use of CHW from the mobile chiller plants to back up utility cool sources or building site chillers(s). This strategy would require a small additional capital investment of limited piping and valves but would require an additional level of effort to operate in a contingency (finding/storing available chillers, connecting them to the system, etc.). Using mobile chillers may require running several connections to an external wall, e.g., chilled-water supply line; fuel line (natural gas or oil) in case the mobile chiller is accompanied by mobile generator without its own fuel tank; makeup water line, chilled-water return line, power (panel box) for external hook up, blowdown or drain line, etc.

Source: Portable Air

Figure 6-7. Mobile 1.8 MW Chiller.

6.5. Thermal Energy Storage

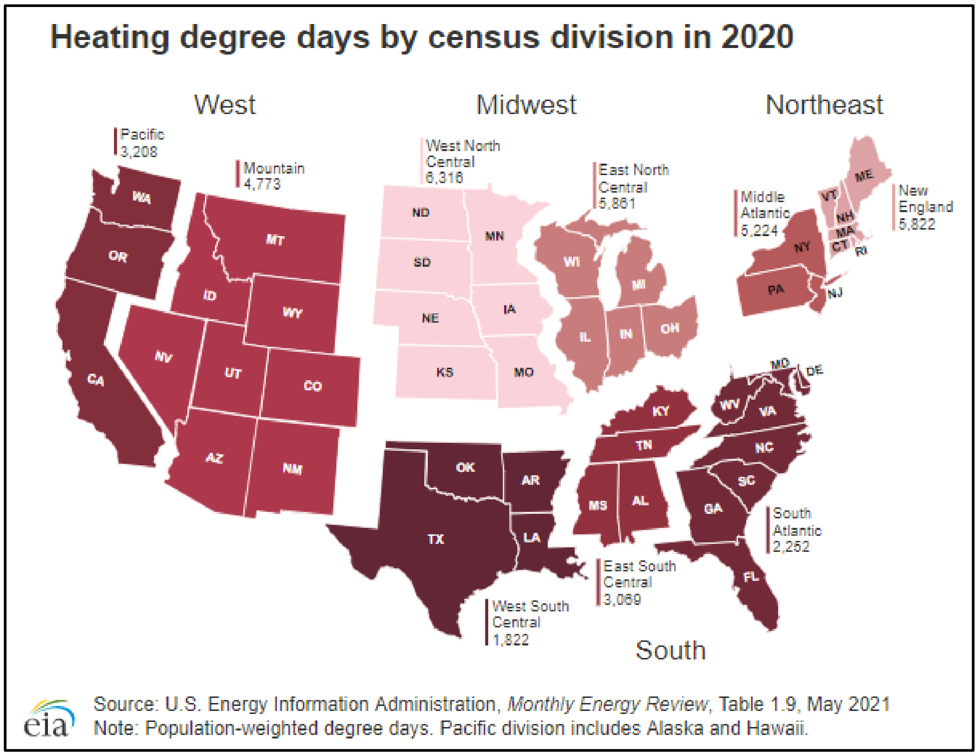
TES allows for the storage of heating or cooling energy for use later in air-conditioning or process needs. TES can be designed to charge, store, and discharge energy daily, weekly, or seasonally, providing a unique decoupling opportunity between the heat/cool generation and the heat/cool demand. Examples of daily cycling of TES include hot water storage in the domestic hot water (DHW) system; chilled-water storage designed for load shifting to reduce the peak demand and the size of cooling equipment; and emergency supply units to critical or load sensitive heat/cool users. TES can further enable short- to medium-term load shedding of production units without interrupting the heat/cool supply to the consumers and can provide balancing services to the power sector. Seasonal TES are typically used to store heat during the months with high solar radiation to be used for heating needs during the colder months. In a combined district heating and cooling system, seasonal TES (STES) coupled with a heat pump can further serve as chilled-water storage at the end of the heating season. TES can be designed to be used in heating or cooling system configurations with several days' capacity based on the user load profile. It can be charged using waste heat, e.g., generated by CHP plants or by cooling equipment. All the above is directly related to realizing a resilient thermal supply system as well as increasing the power system resilience.

The medium used in TES can be hot water, CHW, or another chilled fluid, ice, or another phase change material.

TES provides a uniquely cost and energy-efficient storage of energy and reduces the capacity requirements of district energy systems via peak shaving operation. In the context of the future renewable energy-based system, which will be dependent on power generation from intermittent energy sources, TES in combination with district energy systems will enable a high level of flexibility of large amounts of capacity, to the benefit of the whole energy system.

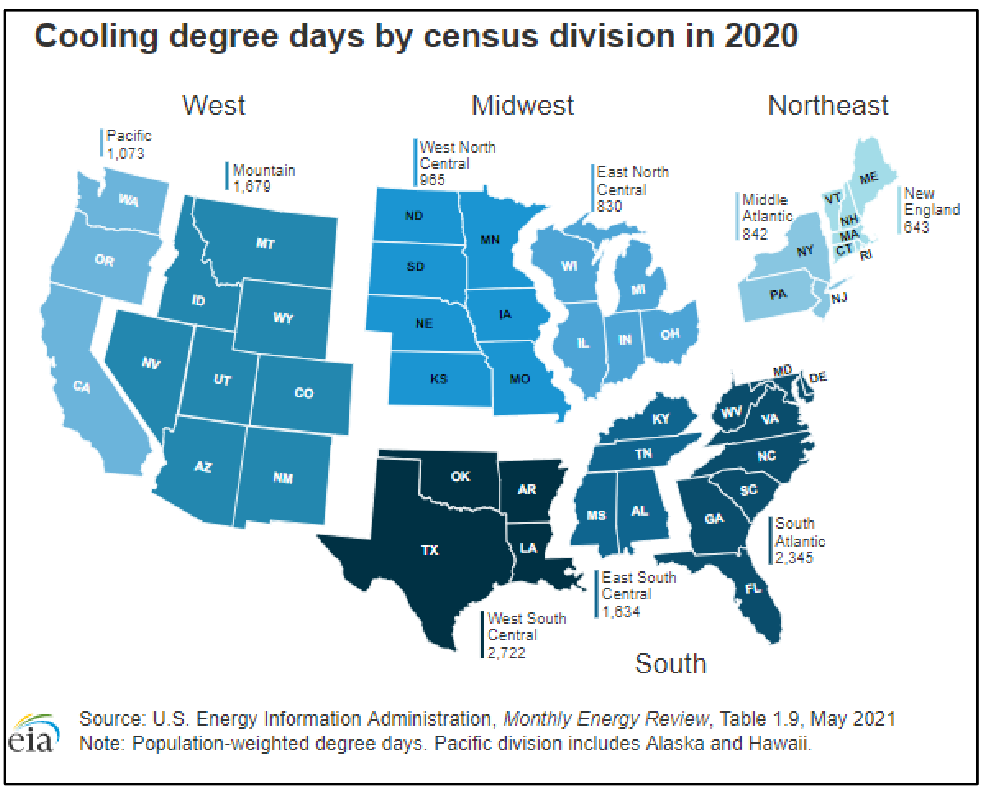
The concept of seasonal storage of thermal energy can be quite interesting as it would give a very high energy efficiency of thermal generation via heat pumps. If the annual heating demand is similar to or higher than the cooling demand, it would be more cost-effective to design the STES as heat storage. For most of Europe and the United States, this is the case and is confirmed by comparing the number of heating and cooling degree days for the United States in Figures 6-8 and 6-9, which show that in most cases the heating demand is dominating the annual thermal demand. Under these conditions the STES is charged with the waste heat from cooling generation during the cooling season, at the heating season, the STES is discharged, by direct discharging while the temperatures are sufficiently high and later on via heat pumps, which at the end of the heating season will deliver the STES at temperatures that would be directly useful at the start of the cooling season. This operating circle would then be repeated in the following year. For hot and humid climates, the amount of heat extracted from cooling and dehumidification processes far exceeds the amount of heating needed during the winter season. This is always a deterrent to using TES unless there is a process need for the waste heat.

Even though a STES is available, it may not be suitable for short-term cold storage, which generally serves a different purpose, e.g., reducing daily peaks, enabling short-term load shedding in case of high strain on the electricity system, and providing backup cold supply in case of unexpected disruptions. The short-term cold storage could further be located at critical locations in the network.



Source: EIA

Figure 6-8. A number of heating degree days in the United States.



Source: EIA

Figure 6-9. A number of cooling degree days in the United States.

6.5.1. Types of Thermal Energy Storage

TESs come in various forms with various properties. In general, they can be split into manmade and natural TESs, where the former are specific constructions specifically built for the purpose and usually with higher temperature tolerances and the latter takes advantage of local natural formations.

Cold TES can be operated with the cooling medium at one phase (liquid) or with two phases (liquid and ice). In comparison to liquid phase operation, ice slurry or ice can increase the volumetric storage capacity, up to factor 4.5, due to the phase change of the storage medium, compared to having only the liquid phase. The drawback of ice slurry or ice storage is the longer load and unload times compared to liquid water storage, additionally due to the lower temperature levels on which they operate, the cooling generation efficiency is reduced. Charging ice storage can lead to up to 50% less cooling generation efficiency compared to charging cold-water storage. Due to the drawbacks, ice slurry or ice storage is mainly applied in areas where electricity is plentiful and inexpensive.

In district cooling, the single-phase, liquid, based TES is the far most applied, as they are more cost efficient in construction and operations compared to dual-phase TES. Furthermore, space issues are less restrictive at the district level than in single building cooling systems.

Figure 6-10 shows some commonly used TES configurations, including

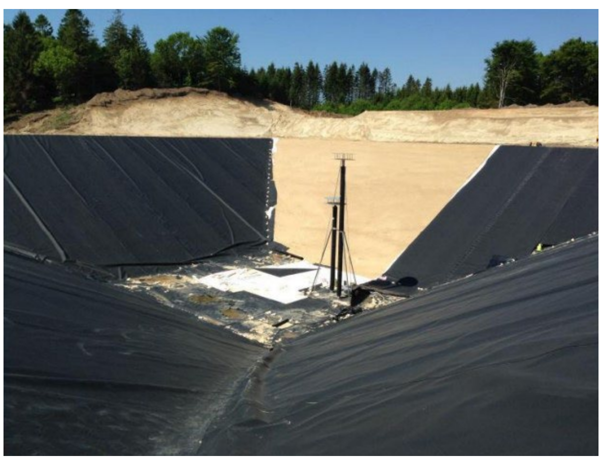
- Steel, concrete, or plastic Tank Thermal Energy Storage (TTES)
- Pit Thermal Energy Storage (PTES)
- Aquafer Thermal Energy Storage (ATES)
- Borehole Thermal Energy Storage (BTES).

70,000 plus 15,000 m³ hot water TTES at Fynsværket in Odense Denmark (Ramboll)

2,000 m³ chilled-water TTES, Taarnby Forsyning, Denmark (Ramboll)

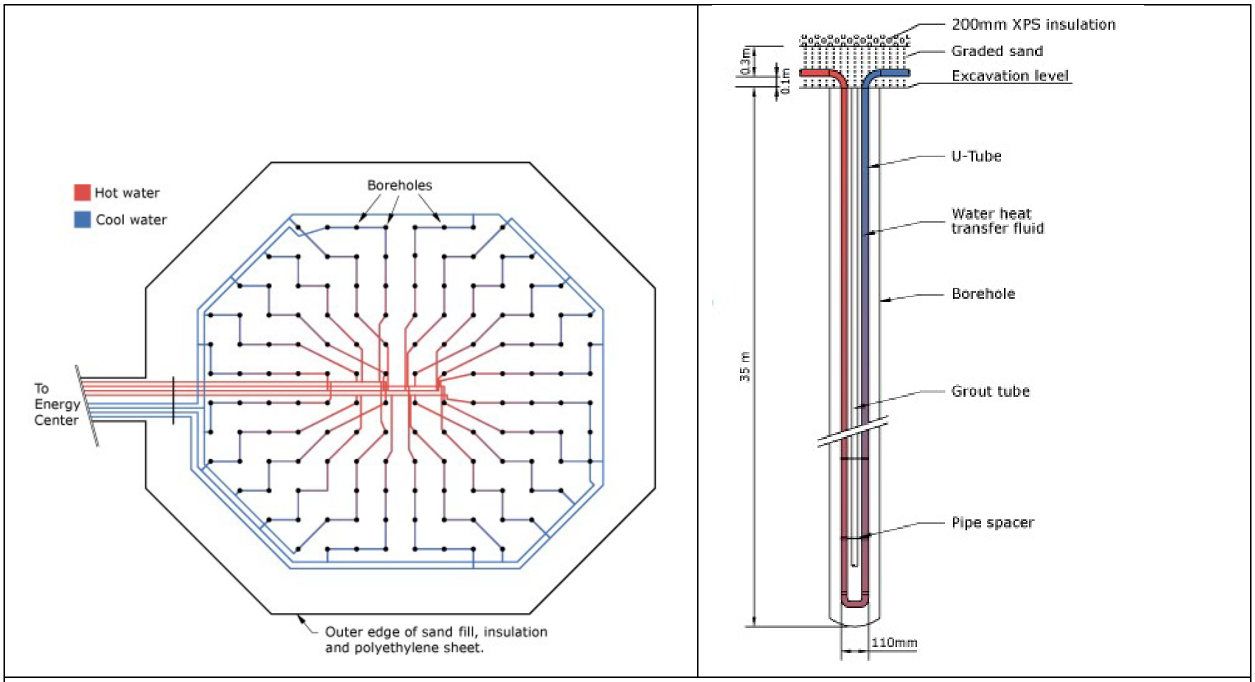
3,000 m³ chilled-water PTES in Frederiksberg Forsyning, Carlsberg City, Denmark (Ramboll)

2 x 24,000 m3 pressurized hot water TTES in Copenhagen Denmark, up to 257.0 °F (125 °C) sectioned from network by 10 Bar (Ramboll)

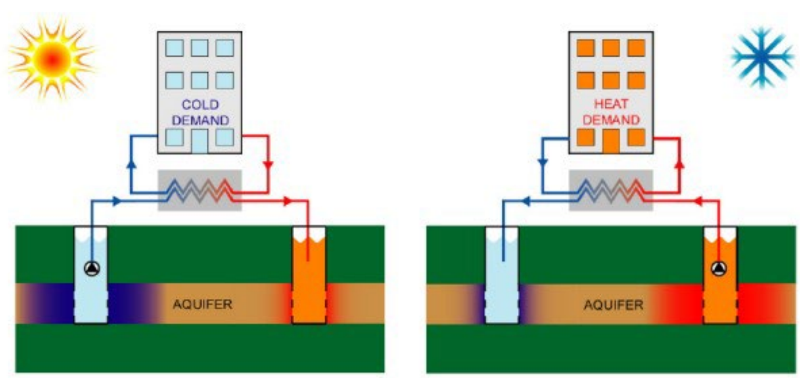


60 000 m³ “SUNSTORE 3” hot water PTES in Dronninglund 2013. (SHC Task 45)

Figure 6-10. Various types of thermal energy storage (TES).



Borehole Thermal Energy Storage (BTES) installed at Drake Landing Solar Community. 144 – 150 mm (6 in.) dia x 35 m (115 ft) deep boreholes spaced 2.25 m (7 ft) of center used for storing heat collected in summer for use later in winter (Drake Landing Solar Community (dlsc.ca).



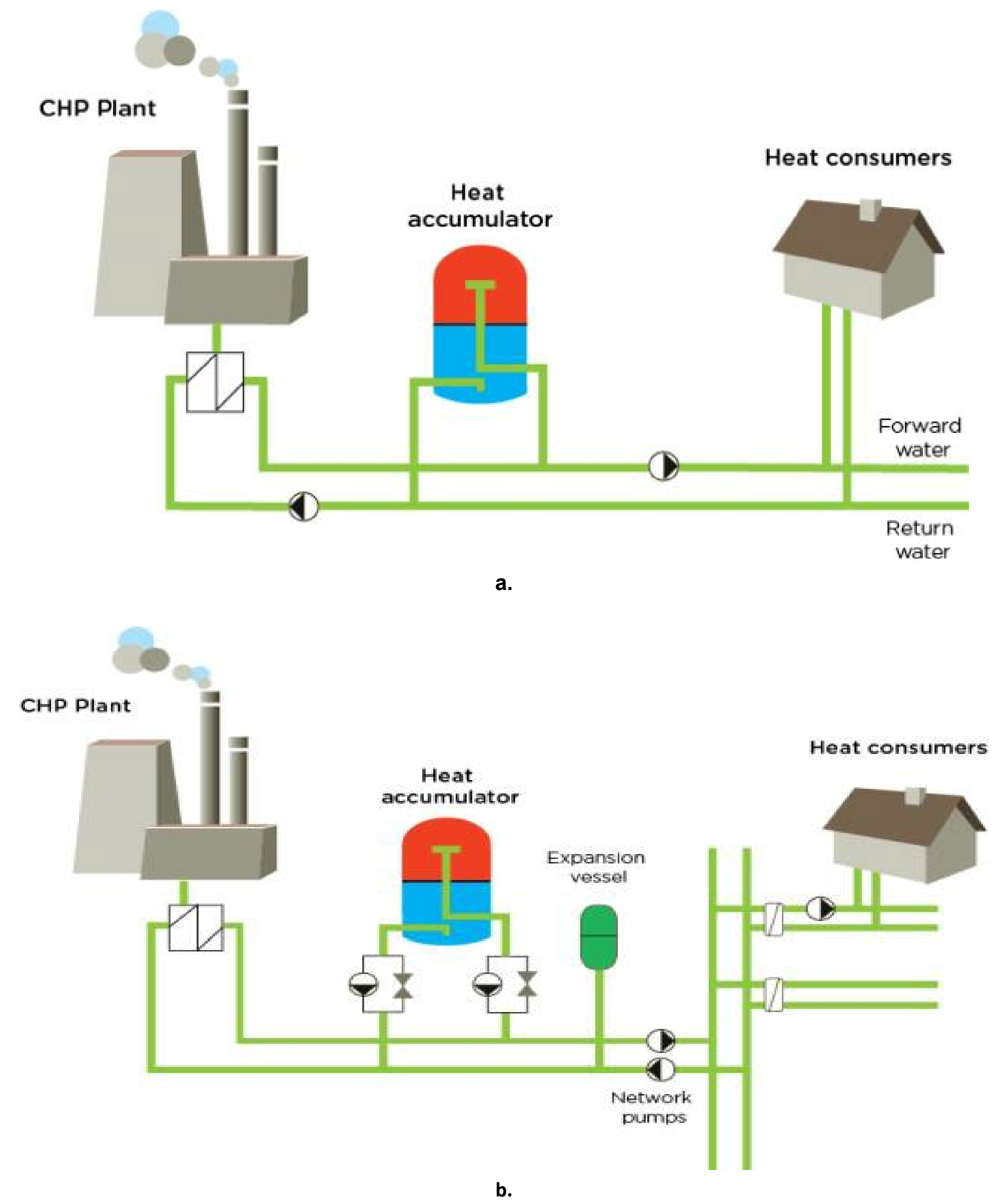
Open-loop ATES system scheme with the seasonable reversible operation. In summer, aquifer water is extracted from the cold well (left)and injected into the warm well (right). Free cooling (through a heat exchanger) or additional Ground Water Heat Pump (GWHP) (cooling mode) is used for cooling. During the winter period, the operation is reversed using GWHP for heating (Drijvert et al. 2001)

Figure 6-10. (Continued).

The most common TES are hot- and chilled-water tanks. An atmospheric steel tank is commonly used in district heating and district cooling systems. The water level in the tank maintains the pressure in the network. The largest steel tanks are up to 752,688 ft^3 (70,000 m^3), and the smallest prefabricated tanks are 2150 ft^3 (200 m^3). Pressurized tanks are designed to hold water with a temperature up to 74 °F (165 °C), compared to max 35 °F (95 °C), for atmospheric tanks. High temperature pressurized tanks typically have smaller sizes with smaller diameters due to very expensive steel construction. When the water temperature is below 52 °F (125 °C), the additional cost for a larger steel tank is modest.

Thermal Energy Storage Connection Principles

Thermal energy storage can be either direct or indirectly connected (Figure 6-11). The connection principle primarily depends on the TES type and usage. The benefit of a direct-connected TES is the high charge and discharge capacity capability. In the indirect connected TES, the charge and discharge capacities are determined by the capacity of the heat exchanger or pressure sections between the TES and the district energy system.



Source: Ramboll A/S.

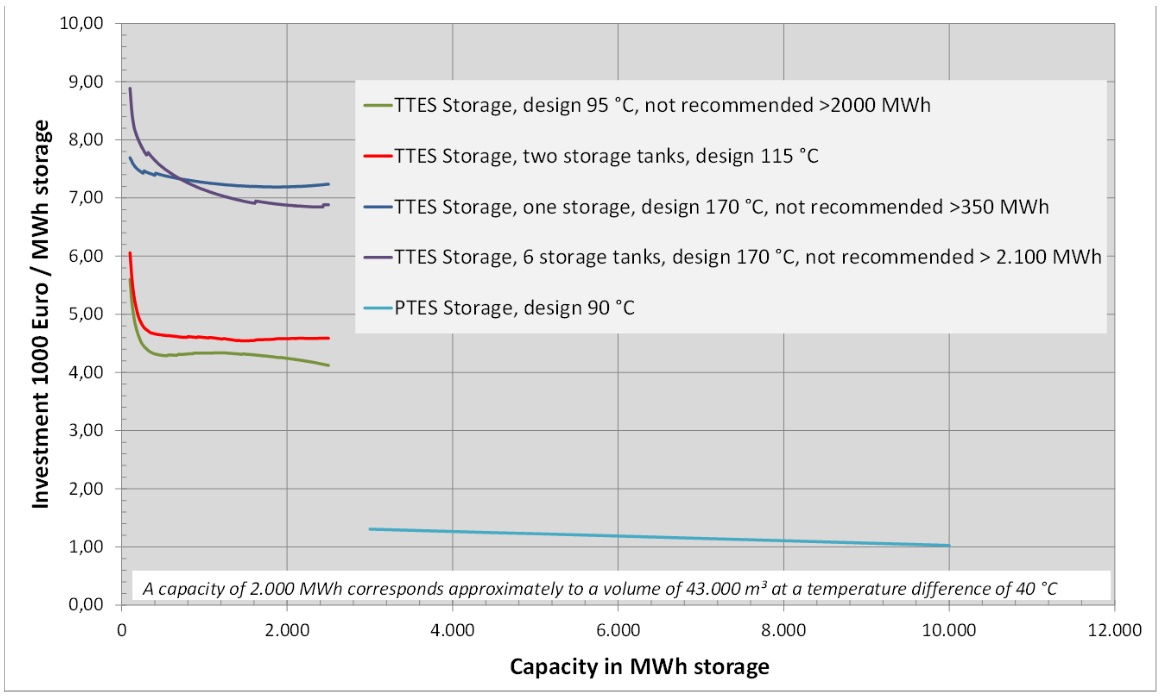
Figure 6-11. Diagrams of TTES integration into district heating system: a. atmospheric tank with direct connection to the network; b. TTES indirect connection to the network.

Operation in a Corrosive Environment

In coastal areas located in HHC, the exposure of parts of HVAC systems to corrosive salt-laden environments is the biggest concern. Due to this problem, air-cooling equipment is not recommended. Use of the water-cooled chillers allows for chiller waste heat recovery, which can be used for air reheating, DHW heating, and other needs, and these heating loads can be decoupled from the chiller operation using TES. Depending on specific heating and cooling needs, all or a part of the generated heat can be used. In the latter situation, the size of the air-cooled equipment can be significantly reduced by using TES for heat. For more information, see Chapter 5.

Economics of Thermal Energy Storage

The main influential parameters on the investment cost of TES are the types, design temperature, and storage capacity (Figure 6-12). Once a certain size of each TES type has been reached the cost of additional capacity becomes relatively stable.



Source: Ramboll A/S

Figure 6-12. Investment costs of heat storage tanks (TTES) and storage pits (PTES) including costs of design, construction, and materials.

The technology for hot water storage tanks and heat storage pits can be used for cooling, even with lower losses. The pressurized heat storage tank for temperatures from 257 °F to 329 °F (125 °C to 165 °C) can be used to store hot water for absorption heat pumps for cooling. Table 6-1 provides examples of technical and economic characteristics of hot and cold-water tanks and hot water storage pits.

Table 6-1. Examples of technical and economic characteristics of TES.

	Volume m3	Supply oC	Return oC	Diff oC	Content MWh	Load cycle hour	Capacity MW	Function
Hot water pit	100000	85	45	40	4560	8	570	Daily
Hot water pit	100000	85	45	40	4560	720	6	Seasonnal
Hot water tank	70000	95	45	50	3990	8	499	Daily
Super heat tank	48000	120	50	70	3830	8	479	Daily
Cold tank	3000	10	15	5	17	8	2,1	Daily
Cold tank	2000	10	15	5	11	8	1,4	Daily

Source: Ramboll

The summary information in Table 6-2 may be used to compare characteristics of different types of TES.

Table 6-2. Comparison of main parameters between different types of TES.

Thermal store type	Capacity, kWh/m³	Efficiency, %	Storage duration	Cost, $/kWh	Reference
Hot water	60-80	50	Day-year	Building-level pressure less: 67 DH: 5-7 Pressurized 5-7	Annex 73
Hot water	60-80	99	Day	DH	Ramboll 2021
Pit storage	40-50	70	Year	1-1.4	Ramboll 2021
Pit storage	40-50	90-95	Months	1-1.4	Ramboll 2021
Chilled water	10-20	70-90	Hour-week	28-57	ASHRAE 2019a
Aquafer heat storage	5-10	50-90	Months	NA	Mangold et al. 2016
Borehole heat storage	5-30	50-90	Months	4-35 (ground storage volume)	Mangold et al. 2016 SHC Task 45
Phase change materials	50-150	75-90	Hour-week	NA	Mangold et al. 2016
Ice storage	100	80-90	Hour-week	40-57	ASHRAE 2019a
Thermo-chemical heat storage	120-150	75-100	Hour-day	NA	Mangold et al. 2016

It is important to consider the characteristics of the TES and how it is operated when considering the heat and cold losses from thermal storage tanks:

- The losses depend on the insulation and the annual average temperature difference between the stored water and the ambient temperature.
- The losses in percentage of the stored energy depend significantly on the size of the tank, as the energy is proportional with the volume and the losses are proportional with the surface area (this is why large tanks in DH are more efficient than building-level tanks).
- The efficiency defined as the ratio between unloaded energy and loaded energy depends on the annual energy loss and not least on the number of load cycles (this is why seasonal storage pits have lower efficiency than day-day storage tanks).
- The storage energy volume of the pit storage includes the surrounding soil up to 1-2 meters, as the soil insulates. (That is why there is no insulation between the soil and the water.)
- The load and unload capacity of a directly connected tank depends on the difference between the maximal flow of the network pump and the production pump, and only efficient diffusers set the limit for the charge and discharge capacity.

Application of Thermal Energy Storage

The common current applications for TES include situations with cyclical loads; time-dependent electric energy costs (Time-of-Use Rate); excessive short duration process, power, cooling energy generation or heat energy generation; utility rebates, or other economic incentives for load-shifting equipment (Rouleau et al. 2015). Other situations where the application of TES is beneficial may include:

- The maximum heating or cooling load of a facility is significantly higher than the average load. This load profile is true for most nonindustrial as well as many industrial applications.
- An existing cooling system is undergoing expansion.
- Cooling is needed for an application in a remote region or country, where refrigeration equipment is extremely expensive.
- Where CHP systems would benefit from improved thermal and electric load-balance.
- When intermittent renewables are being considered. TES can be used to reduce the impact of the intermittency of e.g., wind and solar.
- When large cooling systems have occasional small loads that would otherwise require the use of small “pony” chillers.
- For Combustion Turbine Inlet Cooling to maximize power generation during hot weather (ASHRAE 2022).
- To couple chilled-water thermal storage with a firewater tank to use its volume that would otherwise sit idle.
- Molten Salt is also used for higher temperature thermal storage, particularly for point-focus solar thermal power generation applications.

TES permits the heating or cooling plant to be reduced in size because previously stored capacity can be used to meet peak loads. For a given cycle length, the energy generation plant can be sized for the average load. For example, office building cooling loads often peak at a level two or more times higher than the daily 24-hour average load and most commercial and educational facilities also have load profiles favorable to cool TES (Glazer 2019).

BY using TES, military barracks boiler plants can be sized for the average DHW use, rather than for a peak use during the shower time; CHP can be sized based on the annual average heat load, rather than the baseload.

TES operating strategies may be classified as either full storage or partial storage. Partial storage systems can be sized for load-leveling or demand-limiting operation. These terms refer to the amount of on-peak heating or cooling load that is shifted to off-peak. For more details about load strategies, refer to Glazer (2019).

6.5.2. Economic Considerations

Currently, the decision on using TES is based primarily on the LCCA performed for normal (blue sky) system operation. The main cost of adding TES into the cooling system is the cost of storage and additional interface equipment. This cost can be partially offset by savings resulting from a downsized cooling plant. For a plant designed for normal (blue sky) operations, the additional first cost must be paid back through operating cost savings.

Some applications where cool TES can result in decreased equipment costs include

- New construction, where the chiller plant with thermal energy storage can be sized for merely the average load on a peak day (plus any necessary spare capacity), versus a non-TES chiller plant that must be sized for the instantaneous peak load on a peak day (plus any necessary spare capacity).
- Expansion of an existing plant, where the combined cost of the storage tank and auxiliaries being added is less than an additionally installed chiller and potential future operating savings.
- Applications where the peak load is much higher than the average load.
- Applications in areas where chillers must be imported, which makes them very expensive.

In addition to the cost-effectiveness of TES in normal situations, significant benefits for both heating and cooling TES systems can be realized through their application in emergencies, especially in the case of mission-critical facilities, and in areas with corrosive (marine and coastal) environments.

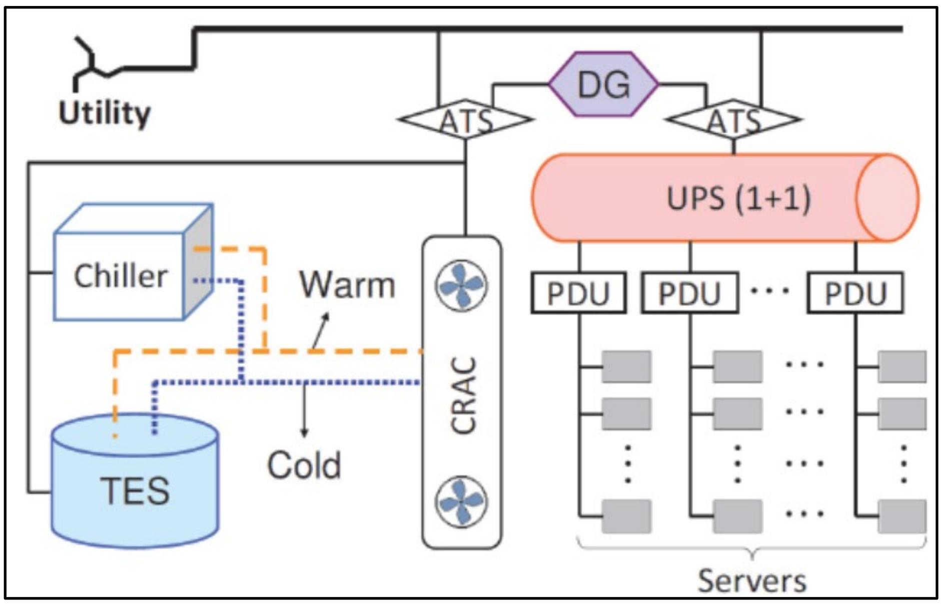
6.5.3. Emergency Operation

ASHRAE Design Guide for Cool Thermal Storage (Glazer 2019) provides an example of an important TES application for emergency cooling of mission-critical facilities, such as financial and data centers, that include computer servers in highly dense configuration and UPSs handle the electrical interruptions. These uninterruptible power supplies are essentially batteries that keep computers running when power is lost, or when the voltage is suddenly reduced, at least until an emergency generator can be started. While the cooling system can be operated using batteries, a more effective option may be to use a cool TES system. Even with the use of UPS for computers and emergency generators, there is typically a lag in time (15 to 30 minutes or more) to restart all the chillers following a power interruption; cool TES is often the chosen technology to provide cooling during this period while chiller operation is restored. Other mission-critical facilities that might also benefit from emergency cool TES include hospitals, clean rooms, control rooms in utility power plants, emergency command and control centers, emergency shelters, research laboratories, and museums. These applications, as well as others, have facilities that must maintain a strict range of temperature or humidity conditions even during power interruptions.

The need for emergency cooling is extremely critical. When a complete power failure or a significant voltage drop occurs, water chillers and pumps circulating the CHW will stop. It takes several minutes to restart a water chiller and those minutes are enough to cause communication or data loss. Even systems that use backup generators will take 10 seconds to a few minutes to start up and again provide enough power for the cooling system. While pumps and fans can be restarted immediately using generator power, large chillers, including large centrifugal chillers, will take at least 2 to 3 minutes each to get fully back online after a complete power failure; multiple large chillers must often be restarted sequentially. Some smaller chillers and some variable-speed-drive chillers can resume operation more quickly. While a data center could use UPS to power not only the servers but also the fans, pumps, and chillers, this would be very expensive. The fact is that electric water chillers are often the single largest load for a backup electrical power system. Also, the starting current for motors used in water chillers can be three times as high as normal (blue sky) operating conditions, which means the backup electrical system sizing may need to be able to supply that level of power. Some designs that might consider using internal combustion engine generation for backup power cannot obtain the required permits to do so because of local air quality concerns or rules. TES can be used to bridge the time it takes to start the backup generators or as an extra form of redundancy. Further, by installing TES for emergency cooling during power outtakes the saved fuel, that would otherwise be needed to operate emergency generators, can be used to extend the allowable time for repair of power supply from the grid.

For data centers, even a brief interruption of cooling can be dangerous to the equipment. The temperature in the server cabinets can get high enough to damage the equipment within minutes if no cooling is provided. The lack of cooling can result in permanent data loss and the costs of replacing expensive hardware. It is therefore critical to maintain continuous cooling of the equipment. Because data centers are operated using batteries during power outages, cooling must also be provided when no utility power is being supplied.

Figure 6-13 shows a system diagram of a data center with TES used in parallel to the chiller to provide redundancy for a chilled-water supply.



Reprinted with permission from Exploiting TES to Reduce Data Center Capital and Operating Expenses, 2014 IEEE 20th International Symposium (Zheng et al. 2013).

Figure 6-13. A schematic of a data center applying TES for redundancy and emergency cooling.

The following design criteria shall be considered for integration of cool TES system designed for emergency cooling:

- Cooling loads and duration.
- Recovery time—the allowed time between sequential emergency (black sky) events.
- Coolant temperature during charging.
- Coolant temperature during normal (blue sky) operation.
- Appropriate code designation for the facility (e.g., flood zone).
- Charging or storage inventory maintenance schedule
- TES tanks can provide the necessary cooling in the event of the loss of the main chiller.

- System parameters have a minor effect on how energy discharges from the TES tanks.
- Increasing the chiller setpoint temperature from original system settings will require additional chilled-water flow to cool the thermal load.
- Decreasing the chiller setpoint temperature from original system settings will reduce the amount of flow needed to cool the thermal load.
- Systems struggle to maintain the room air at a stable temperature when the chiller setpoint temperature is increased from original settings.
- TES tanks in a parallel configuration with no alternative cooling source can recharge faster than tanks in a series configuration.
- Raising the temperature difference across the cooling coils will increase the amount of time it takes to recharge the TES tanks.
- The amount of time ragged cooling (partial cooling occurring at greater than desired temperatures) lasts depends on the application of emergency cooling and the temperature difference across the cooling coil.
- TES tanks with alternative cooling sources will recharge faster than tanks that rely on the main chiller to recharge.

6.6. Distribution Network

The purpose of the distribution network is to connect the cool consumers to the heat suppliers. Apart from a few infrequently used shutoff valves, it is a static infrastructure consisting of insulated pipes with no moving parts. With thoughtful design and careful installation, the pipeline can be in operation for decades with minimal interference.

Where possible it is recommended to place the distribution network in an underground infrastructure, which would avoid many potential above-ground specific disruptions, including natural causes (storms, floods, severe cold/heat, fires, falling trees, etc.) and human causes such as vehicle collisions.

To ensure a long-lasting and robust pipeline, it is important to adhere to the pipeline design and installation guidelines from the pipe manufacturers. This minimizes weak points, which can lead to premature pipeline failure.

6.6.1. Meshed Network Layout and Pump Strategy

The impact of pipeline disruptions can be reduced by the design of the distribution layout. A meshed or looped layout is preferred over branched layouts. In a meshed layout, there can be multiple supply paths from the cool source to the individual branches. An example of a close to fully meshed layout would be the road network in a city center, where one can take multiple paths between points A and B. Due to practicalities, district energy systems are generally designed with loops in the main distribution pipeline (Figure 6-14).

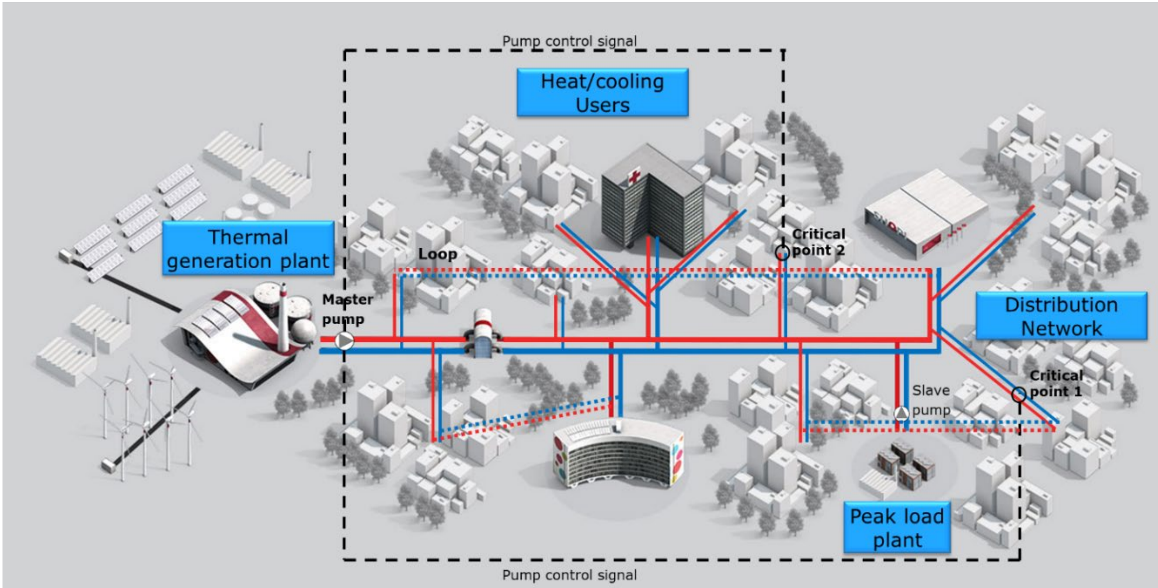


Figure 6-14. Example of multi-thermal source and meshed network layout structure of a district energy system. The dotted lines represent the transformation from a branch to a meshed system type. The black lines represent pump control signals.

If a pipeline failure occurs within a loop, the failure can be isolated using nearby shutoff valves and cooling delivered through alternative flow paths on both sides of the failure. Buildings within the faulty section, isolated from the cooling supply by shutoff valves, or in case of a failure, at a branch, would need to be addressed with an emergency portable chiller or building-level solutions. Figure 6-14 further shows that, by locating the peak chiller plants at locations different from the baseload plant, a cooling supply can be guaranteed even in case of total failure of the baseload plant site. Locating the peak-load plant out in the distribution network further reduces system operating pressure demands and consequently the strain on the pipeline.

An important way to limit the system strain is to minimize the required pump head. In general, the pumps feeding the system should be operated to guarantee the minimum differential pressure to operate the building substations at the critical points in the network. During periods where peak-load plants are in operation, the pressure level of the system can be minimized by decentralizing the peak-load chillers. When two or more plants are feeding the distribution network, the pumps are operated in a master and slave setting, where the operation is to ensure predefined differential pressure at specified points in the network. Further head reduction methods can include the use of booster pumps to overcome site-specific situations, e.g., in front of an elevated section of the network or at other strategic locations in the network to reduce the pressure level early in the system.

6.6.2. Strategic Location of Shutoff Valves

Despite careful planning and maintenance, failure can occur, and the impact of the failure should be contained to a reasonable level. Pipeline shutoff valves enable containing the impact of unexpected pipeline failures to a small section of the network as feasible. Due to the vast variations of distribution systems, there are no specific guidelines on where or how frequently shutoff valves are installed; instead, they are installed strategically for each network. Shutoff valves can be installed to increase the ability to isolate critical consumer groups or vulnerable sections of the pipeline, or to respond to some other case-specific need. Using shutoff valves distribution networks can be split up into multiple independent islands; each island can then be operated independently. When considering the shutoff valve strategy, it is important to consider that typically pipeline failures occur gradually and are usually detected well before total failures occur. Figure 6-15 shows ball and butterfly valves; both types can be controlled either manually or electronically.

Source: Danfoss A/S.

Figure 6-15. Example of valves: ball valves in various sizes (left), shutoff valves installed in a pipeline (right).

6.6.3. Fault Detection and Preventive Maintenance

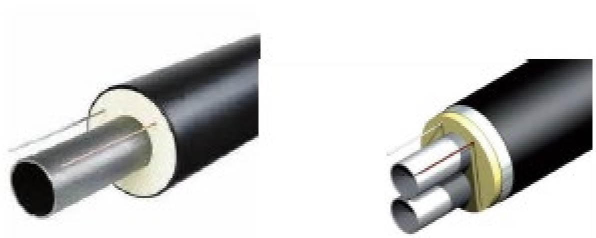
One of the common challenges with district cooling systems is corrosion. Corrosion is in general a complex process with a lot of influencing variables that make corrosion prevention a difficult task. While corrosion is generally not a problem in well-maintained hot water systems, the low system temperatures of district cooling can cause favorable conditions for corrosion, both from inside and from outside. Inside the pipeline the challenge associated with low temperatures are

- Reduced effectiveness of corrosion prevention methods commonly applied in hot water systems, such as oxygen scavenger additives. Due to the low-temperature levels, the additives have a very slow reaction rate and become ineffective to eliminate free oxygen.
- Unlike hot water systems, district cooling systems do not have built-in prevention for microbe growth, which can provide favorable conditions for corrosion formation.
- Outside the pipeline, the main challenge is that due to the low system temperatures any water that penetrates the pipe insulation stays there and facilitates exterior pipe corrosion. While corrosion is a common challenge for district cooling systems, the impact, once it has penetrated the pipeline, is the same as with any other leakages and can therefore be detected the same way as other faults the lead to leakages.

For the district cooling infrastructure, the typical faults are pipeline or in-line component leakages and uncontrolled bypasses. For detecting leakages, it is important to consider the fault detection method at the design of the network, as some cannot be retrofitted. The optimal pipeline leakage detection is to apply leakage detection wires installed into the pipeline insulation. If pipeline leakage detection wires are not installed, detecting and finding leakages can become a challenging and time-consuming task. For in-line components periodic condition check in manholes should be applied. Uncontrolled bypasses in the network can be identified by comparing flow measurements at the cooling plants (inputs), with flow measurements from the consumers (outputs). An unexpected mismatch between the measured inputs and outputs suggests there is an unintended bypass somewhere in the distribution network. Unintended bypasses can be a result of faulty bypass valves or simply forgotten bypasses from the time the network was installed. If inspection of bypass valves does not identify the location of the bypasses, the uncontrolled bypasses can be found by applying portable flow meters at manholes in the system or other places where the pipeline is accessible.

With early detecting of faults, before the point of collapse, maintenance can be scheduled and the impact of disruptions in the cool supply can be minimized. Although unexpected failures can occur, early warning signs, such as unexplained and increasing usage of makeup water typically indicate developing faults.

In new systems, leakage detection wires are installed in the insulation of the pre-insulated pipes (Figure 6-16). Pipe leakage or external water infusion will cause a short circuit between the wires so the leakage detection system will locate the potential leak and inform the utility.



Source: Lostor A/S.

Figure 6-16. Leakage detection wires in pre-insulated single and twin pipe.

In old systems without leakage detection wires, the leakage can be located by comparing supply and return flow volumes at branches and as well as in existing pipeline chambers. If there is a difference in the flow volume in the supply and return pipes the actual location of the leakage can be located and pinpointed using acoustic measurements, via a probe that is inserted into the pipeline.

In modern, well-maintained district energy systems, the lifetime of the pipe network is typically many decades; control components with moving parts can be expected to have a lifetime of 15 to 20 years. Reliability testing and scheduled replacement of pipes and components can minimize the impact of disruptions. Scheduled replacement should be balanced against the economic optimal replacement. Vital components that are difficult to replace during operation could be replaced on a schedule; non-critical components can remain as long as they are functional, or they can be replaced at a time when the maintenance does not interfere with system operation.

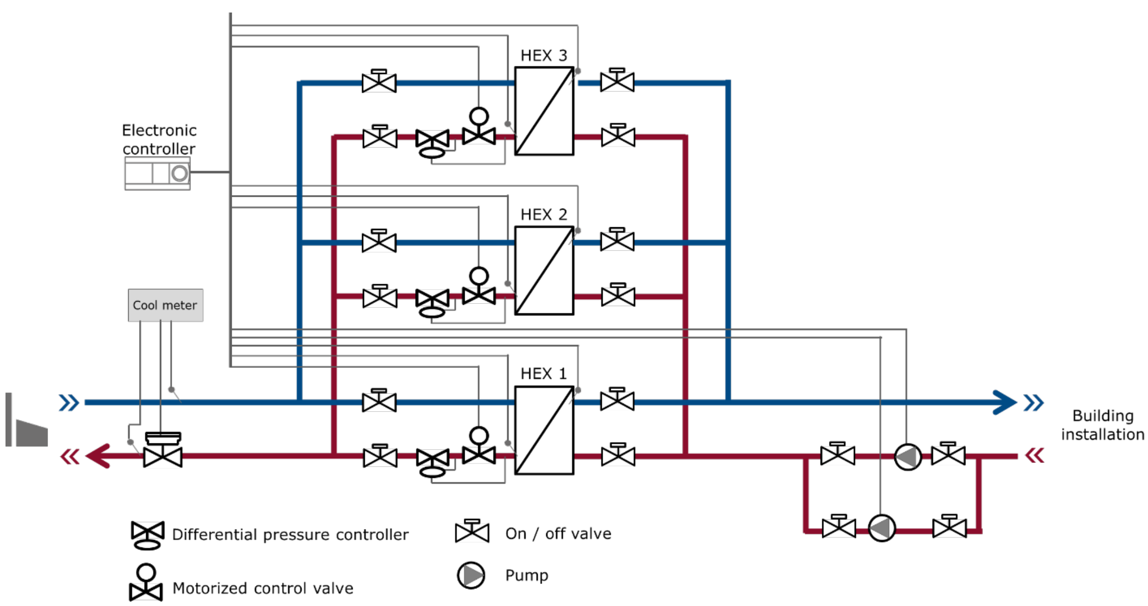
6.6.4. District Cooling Interface Units

As building owners connect to district cooling systems, the onsite cooling generation equipment footprint is drastically reduced, which allows the building owners to free up the space that would be used for the chillers as well as the external air-handling units. Furthermore, the district cooling interface units are relatively noiseless, which is a significant difference compared to the noise and vibrations from the chiller operation and the external air-handling units. The building owners will also avoid potential refrigerant emissions from the chillers.

In district cooling, indirect cooling interface units are generally applied. Indirect cooling interface units apply heat exchangers to separate the district cooling system and the building cooling system. This setup provides a clear separation of the two systems and marks the boundary of the district cooling system and is the general point of transfer of responsibilities from the district cooling operator to the building cooling system operator.

For small capacity connections, one heat exchanger cooling interface unit is used, but as the capacity increases, the number of heat exchanger units is increased, which provides increased supply security in case of component failures. For critical buildings, it is further common to have a redundant heat exchanger unit to allow full operation during maintenance of another part of the cooling interface station.

An indirectly connected interface has one or more heat exchangers that hydraulically separate the district cooling system from the building cooling installation (Figure 6-17).



Source: Danfoss A/S.

Figure 6-17. Schematic of three heat exchanger cooling interface units.

The benefits of indirect district cooling interface units are

- Impurities originating either in the district cooling or the building cooling installation will be isolated to that respective system.
- The heat exchanger will act as a pressure breaker if pressure surges occur in the district cooling system and effectively protect the building cooling installation.
- The system is highly flexible in accommodating district cooling pressure levels.
- The system reduces the impact of leakage in the building cooling installation, i.e., leakage is limited to the building cooling installation volume.

The disadvantages of indirect cooling interface compared to direct cooling interface units, without heat exchangers, are

- It is more expensive than a direct connection.
- There will always be a small temperature drop across the heat exchanger, which will reduce the efficiency of the product and increase the hydraulic load.

When connecting large cooling consumers to existing district cooling systems, for example, campuses that have had their cooling grid and indirect end-user cooling interface units, a direct connection of the campus grid can be considered. To satisfy the needs of consumers that have more critical temperature needs, it is important to reduce the number of heat exchangers from production to end-users.

In the cooling interface unit, the low dT syndrome is typically caused by a building supply setpoint being specified below the district cooling supply temperature, which causes the control valves to be continuously fully open, which in turn leads to excess flow levels through the heat exchanger, and consequently, low heating of the supply flow.

6.6.5. Building Cooling System

For a successful and energy-efficient district cooling system, it is important to put a focus on the correct and optimized operation of the building cooling system. A common challenge with district cooling systems is a low system temperature difference, commonly known as low dT syndrome. The low dT syndrome is generally a result of wrong setpoints of the building cooling interface unit or bad building cooling system operation. For detailed recommendations on the design and operation of the building cooling system see Chapter 5. In addition, de-coupler bridges at user buildings can be provided and set up to reduce central plant waterflow to the building when the returning temperature is low. Control measures such as these must be implemented to allow for a properly functioning District Cooling loop.

6.7. Case Studies

6.7.1. Case Study 1 – Taarnby District Cooling, Copenhagen

Taarnby Forsyning in the municipality of Taarnby in Copenhagen has established a district cooling system that demonstrates the symbiosis between district cooling, district heating, electricity, wastewater, and groundwater via Aquifer TES (ATES) for smart integration of intermittent renewable energy sources like wind and solar. In Taarnby district cooling, a large-scale electric heat pump is used to supply cold to the district cooling system and heat to the district heating system at the same time, thereby maximizing the energy efficiency and cost-effectiveness of the heat pump plant. Outside the cooling season, the heat pump plant uses the wastewater system as a heat source, which further improves the dispersion of the wastewater in the sea. During the coldest period, the waste heat from the wastewater is supplemented by extracting heat from the groundwater in the ATES. The cooled ATES is then used to supply the baseload cooling during the subsequent cooling season, hence regenerating the ATES for the next winter season. Additionally, the system applies a cold-water storage tank that can be used to cover peak cooling demands and to optimize production with respect to electricity prices or CO_2 emissions. Figure 6-18 shows the duration curve with the different load units. The heat production (mainly from wastewater) is optimized with respect to the production price of heat in the Greater Copenhagen District heating system, which includes mainly large CHP plants and large heat storage tanks. This smart integrated district cooling and heating system has a COP of 5.6. Further information can be found in "Smart Integration of Energy and Wastewater" (Margaryan and Dyrekland 2019) and in "*Taarnby's Smart Solution: Electric-Driven Combined Heating and Cooling plus Wastewater*" (Margaryan et al. 2021).

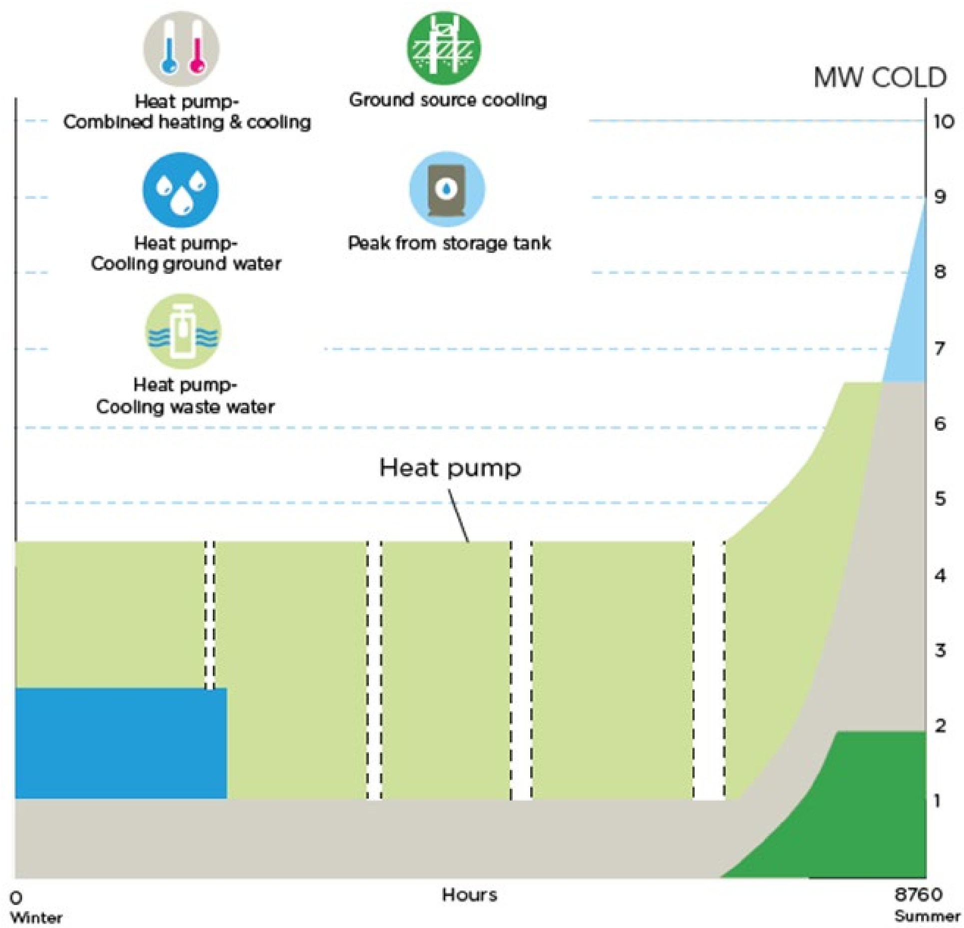


Figure 6-18. Schematic duration curve for the generation of cold energy in Taarnby District Cooling.

6.7.2. Case Study 2 – Bora Bora SWAC

The InterContinental Bora Bora & Thalasso Spa successfully implemented Sea Water Air-Conditioning in 2004 –reducing electrical demand for air-conditioning by more than 40%. The key element of the system is a down-the-slope polyethylene pipe that extends 3.8 miles (2.3 km) offshore to 2953-ft (900-m) depth. Seawater is recovered at a temperature of around 41 °F (5 °C). This seawater is passed through titanium heat exchangers where the seawater circuit accepts heat from the land side AC circuit. The warmed seawater is returned to the ocean at around 656 ft (200 m) deep, well below the productive photic zone.

6.7.3. Case Study 3 – Toronto Lake Source Cooling

The City of Toronto Lake Source Cooling system uses the highly dense cold water found at the bottom of Lake Ontario as the heart of its cooling solution. Water drawn from Lake Ontario for the city's potable water supply is pumped from a deeper region of the lake, allowing its cooler and more stable temperature to be used for air-conditioning before being added to the municipal water supply. The system employs three intake pipelines, each 3 miles (5 km) in length, laid on the bed of Lake Ontario. This $100 million system commissioned in 2003, took over 2½ years to complete, but now supplies an extensive list of downtown Toronto businesses and buildings with an alternative to conventional air cooling, with a capacity greater than 900 MBtu (75,000 tons) of cooling.

6.7.4. Case Study 4 – Bahrain District Cooling

Seawater cooled chiller system in Bahrain is a large district cooling system that uses surface seawater in Bahrain, where the temperature is >80 °F (>27 °C). Even though the seawater temperature is high, this system still provides large electricity cost savings over traditional cooling towers or other approaches. Locations with access to cooler mid-depth waters at around ~50 °F to 55 °F (~10 °C to 13 °C), would benefit more drastically from the higher COP of modern chillers, thus providing substantial savings.

6.8. Conclusions

District cooling systems have been in operation since 1960 and have established a long track record for being robust and reliable infrastructure. District cooling builds on the success of district heating, which has many thousands of systems in operation in multiple countries around the world.

The district cooling infrastructure is designed and built to withstand disruptions by using multiple cool sources that are often distributed around the geographical area of the system and meshed pipeline layouts. In the event of catastrophic failures, portable emergency chillers can be used to supply parts of the system or directly to critical buildings.

The key elements to realizing a resilient district cooling system are

- Design the distribution system layout with a meshed structure (loops).
- Design, install, and operate the pipeline and other components according to recommendations from the manufacturers.

- Apply two or more distributed cool sources at strategic locations in the distribution network.
- Use local energy sources to minimize the impact of fuel shortages, e.g., combining electric-driven heat pumps and absorption heat pumps driven by a variety of fuels.
- Apply thermal storage to
  - Reduce the impact of disturbances in the energy supply.
  - Reduce the impact of sudden plant failures or power outages.
  - Smooth the daily demand and avoid peak generation capacity.
  - Decouple the thermal production and the thermal demand.
  - Provide exceptional reassurance to critical consumers.
- Apply leakage detection methods to find pipeline failures before they become critical.
- Perform periodic visual and operational inspections of components.
- Apply preventive maintenance philosophies and schedule maintenance at times with minimum consumer impact.

The increased focus on renewable energy, along with the maximum use of primary energy sources will drive the development of district energy systems characterized by even more reliable and resilient operations than its predecessors. District energy utilities can facilitate this development by setting, and actively working toward, goals of having lower operating temperatures for heating and larger temperatures for cooling. To realize these goals, both the utilities and their customers must work together to realize energy-efficient heating and cooling systems. Once realized, low-temperature heat supply systems and the high temperature cold supply systems allow significantly more cost-efficient exploitation of local renewable and waste heat and cold sources.

Combined heating, cooling, and electricity enable maximum fuel efficiency, which reduces the amount of fuel that must be regularly delivered or stored in response to security restrictions or natural delivery barriers.

CHAPTER 7. EVALUATION OF MAXIMUM TIME TO REPAIR

7.1. Introduction

Chapter 3 of this Guide discussed the importance of thermal energy systems resilience for buildings located in HHC and its metrics. One of the most important parameters related to thermal system resilience is the **maximum time to repair (MaxTTR)**. MaxTTR can be defined in terms of how long the process can be maintained or how long the building remains habitable or protected from mold damage during the extended loss of energy supply from extreme weather events. Studies by Oberg et al. (2021) and Liesen et al. (2021) conducted for cold climate, have defined major factors affecting the time when the internal temperature reaches the threshold of building habitability or sustainability that include

- Difference between inside and outside air (OA) temperature,
- Building envelope leakage rate,
- Building envelope insulation properties, including insulation levels of its components, and thermal bridging,
- Thermal mass of building structures, and
- Internal thermal load (people and appliances/equipment connected to electric power).

Research results presented in this chapter provide some guidance to installation managers on how to protect their mission and equipment, and how to maintain safety for personnel in case of emergency like a power failure that takes out climate control in buildings. Results of analysis conducted using building modeling and presented in this chapter help to define "habitability" for the personnel, protection for the equipment from damage, and finally the sustainability of the facility itself. The analysis was done to evaluate the effect of the climate of the building location, standards used for building design, building envelope airtightness, and the construction type, i.e., mass, frame, etc., on the MaxMTTR.

As discussed in Chapter 2, habitability and sustainability thresholds depend not only on indoor DBT, but also on the moisture content and are described in terms of WBGT (see Chapter 2 for details). The habitability threshold was established to be less than WBGT = 85 °F (29 °C), and process-related threshold for equipment – below dry bulb (DB) temperature = 89 °F (32 °C). It was assumed that the MTTR would be calculated based on the time when the simulated WBGT or DB in the space reaches the habitability, sustainability, or process-related threshold.

This chapter presents the results of two separate studies. The first study conducted by the Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) was to analyze the impact of energy efficiency, infiltration, and the mass of the building on the building thermal energy resilience. This included energy efficiency of buildings built to three different building codes (ASHRAE Standard 90 pre-1980, ASHRAE Standard 90.1-2013 and ASHRAE Standard 90.1-2019) and having different functional space types. Buildings in this study were located in four climate zones (DOE climate zones 0A, 1A, 2A and 3A) characterized by HHC, where building standards prescribe basic envelope construction having mass walls, steel-frame walls, or metal walls. Building standards have been selected to address the energy efficiency of most existing buildings (built before 1980), the minimum current (2022) requirement to energy efficiency to the U.S. Federal Buildings (ASHRAE Std 90.1-2013), and the proposed requirements that will be needed for high efficiency buildings that are considering to be Net Zero Ready (ASHRAE Std 90.1-2019).

This study used standardized zone space types (i.e., restaurant/dining facility, retail, 24-hour Operation Center, office space, and residential/apartments) that are not necessarily representative of any one specific building category. The second study was performed by RWDI Consulting Engineers for a building with multiple spaces in and located only in CZ 0A (extremely hot and humid). The parameters and strategies investigated were for three building codes described above and with a focus on the following individual technologies: shading types with exterior overhangs and fins, exterior shutters/blackout blinds, window film reducing SHGC, operable windows for natural ventilation, operable/openable skylights, and white/cool roofs.

7.2. Input Used for the Analysis of Indoor Air Thresholds

7.2.1. Habitability – How Long Can Mission Be Sustained by Personnel

The habitability criteria used for the study is defined with the WBGT. The 85 °F (29 °C) WBGT is shown on the Psychrometric chart (Figure 7-1) and is well outside of the ASHRAE comfort requirements.

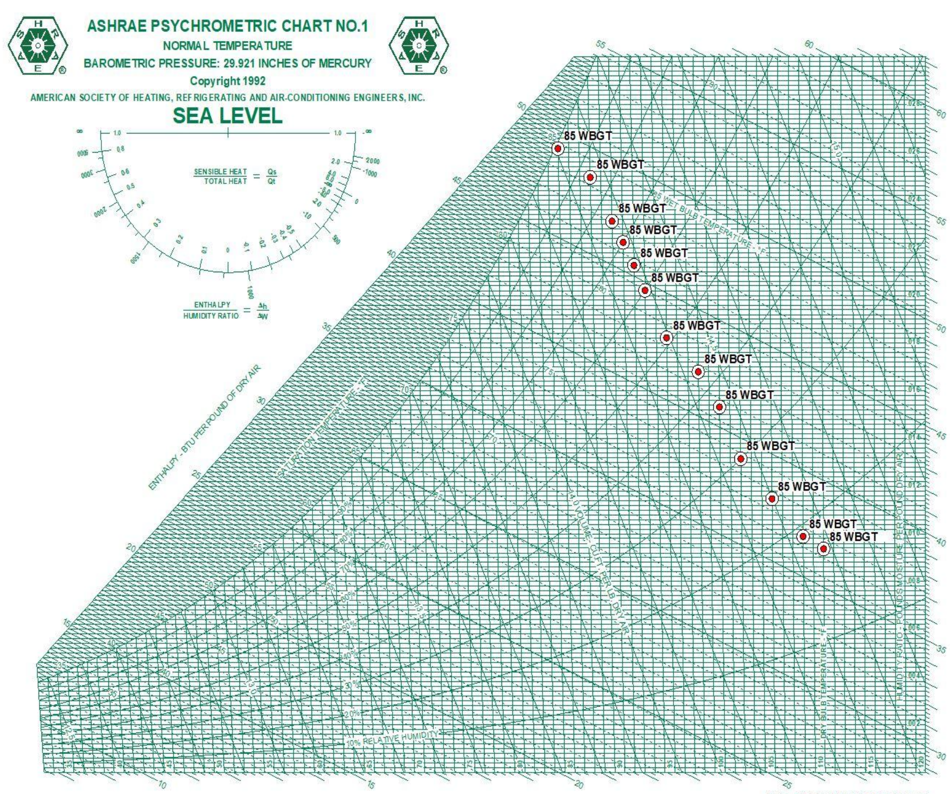


Figure 7-1. Plot of 85 °F (29.4 °C) wet bulb global temperature (WBGT) on psychrometric chart.

In hot areas, some U.S. military installations display a flag to indicate the heat category based on the WBGT. (See Table 7-1)

Table 7-1. The military guidelines for water intake and physical activity level for acclimated and unacclimated individuals in different uniforms based on the heat category.

Category	WBGT (°F)	WBGT (°C)	Flag color
1	≤ 78–81.9	≤ 25.6–27.7	White
2	82–84.9	27.8–29.4	Green
3	85–87.9	29.5–31.0	Yellow
4	88–89.9	31.1–32.1	Red
5	≥ 90	≥ 32.2	Black

Source: Army Technical Bulletin Medical 507 and Air Force Pamphlet 48-152(I) 7 March 2003

For this analysis the threshold of WBGT of 85 °F (29.4 °C) was selected since personnel working inside air-conditioning are not as acclimated to working in the heat and humidity as outdoor workers. When this threshold was met, that hour after cooling failure was recorded as the MTTR for habitability.

7.2.2. Process Requirements – Equipment

Based on allowable parameters in an emergency a different threshold is being used for equipment where operation above that threshold can damage the equipment. This threshold was selected as 89 °F (31.7 °C) DB and, as in the habitability case, when this threshold is first reached, that hour was recorded as the MTTR for process equipment.

7.2.3. Sustainability of the Building Structure

For sustainability in hot-humid climates, we wish to avoid mold growth on indoor building surfaces. Mold growth may be local and transient, such as following a spill, or in a room with occasional wet use such as a laundry. The purpose here is to investigate mold growth on indoor building surfaces in hot-humid climates associated with normal construction and use, as a function of operation or of space-conditioning.

Air-conditioning and building pressurization during operation should maintain conditions to sufficiently dry indoors so that mold does not grow on surfaces. Normal (blue sky) operating conditions with AC should be considered mold-safe with higher permeance wall and roof coverings used in the building. A condition permitting mold growth under normal (blue sky) operation is the use of low-permeance vinyl wall covering; this product is **not** recommended in hot-humid climates.

In hot-humid climates, indoor conditions in unconditioned spaces should tend toward the average temperature and the average RH of outdoors. This average is generally considered mold-safe, that is, the average RH stays well below 80%. An average RH of 50% to 60% is typical for coastal regions. As an exception, mold may grow on interior surfaces of unconditioned buildings following water damage, from flooding, roof leaks or wetting following fires.

If a building in a hot-humid climate is partially conditioned such that AC is used to lower the DBT but not remove indoor humidity, mold growth will be likely. It is advised to do partial conditioning using dehumidification, not dry bulb chilling.

A building may transition from an unconditioned space to a conditioned space. If so, this process takes place in a matter of a few hours, and such a short period of time does not permit significant mold growth. If space-conditioning of a building is interrupted or suspended, typically the indoor temperature will rise to the outdoor temperature more quickly than the indoor RH and will acclimatize to the average outdoor RH. This process typically does not grow mold and is considered mold safe. Again, the exception is mold may grow on interior buildings' surfaces during the failure time following water damage, from flooding, roof leaks, or wetting following fires.

In conclusion, if the buildings come to equilibrium with the outdoor environment, there should not be a problem unless additional moisture is introduced; therefore, no MTTR was established for this requirement.

7.3. Parametric Study

7.3.1. Weather Data

This study used EnergyPlus, a DOE building energy modeling program, using the weather data for the following locations representing climates zones 0a, 1a, 2a and 3a. EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model energy consumption for heating, cooling, ventilation, lighting, and plug and process loads. The hourly analysis goes through all the heat transfer modes (conduction, convection, and radiation) where the capacitance of the building structure is automatically considered. Table 7-2 lists representative locations for selected climate zones.

The weather files were downloaded from the EnergyPlus website and were formatted to be used with the program. These files are the latest TMY3 format prescribed by ASHRAE and used by the simulation program.

What is interesting about CZs 0A through 3A is that the summer high temperatures and humidity intensity do not differ very much. A big difference between the climate zones from Puerto Rico to Atlanta is the duration of the HHC. The failures were scheduled to start on July 14 with restoration on July 25 for each of the weather files.

Table 7-2. Representative locations for selected climate zones.

Climate zone	Location	EnergyPlus Weather files (November 2021)
0A	San Juan, Puerto Rico	PRI_San.Juan.Intl.AP.785260_TMY3.epw
1A	Miami, FL	USA_FL_MIAMI INTL AP_TMY3.epw
2A	Jacksonville, FL	USA_FL_Jacksonville.Intl.AP.722060_TMY3.epw
3A	Atlanta, GA	USA_GA_ATLANTA HARTSFIELD INTL AP_TMY3.epw

7.3.2. Loads

The load levels for selected spaces listed in Table 7-3 are default levels from the Design Builder program for those space types.

Table 7-3. Selected building zones and internal loads used in the study.

Model Type	Approximate Conditioned ft² (m²)	People/ft² (People/m²)	Lighting W/ft² (W/m²)	Total Loads W/ft² (W/m²) Computer, Equip, Kitchen, Misc.
Restaurant/DFAC	2000 (186)	0.0186 (0.0017)	1.1 (0.34)	4.75 (1.45)
Retail/Supply	8000 (744)	0.01 (0.0009)	1.5 (0.46)	1.48 (0.45)
24 Hour Ops Ctr.	9600 (893)	0.0099 (0.0009)	1.2 (0.37)	5 (1.5)
South Office Block	3050 (284)	0.01 (0.0009)	1.1 (0.34)	2 (0.6096)
SW Corner Office	360 (33.5)	0.01 (0.0009)	1.1 (0.34)	2 (0.6)
South Apts./Res	7400 (688)	0.001 (0.0001)	0.9 (0.27)	1.2 (0.4)

7.3.3. Building Zones

The 17 zones shown in Figure 1-1 (p 1) were modeled as shown in Figure 7-2: north facing retail, and south facing retail stores (2), east facing restaurant, and west facing restaurants (2), north, south, east, west facing offices (4), NW, NE, SW, and SE facing offices (4), 24-hour operations center as an interior space (1), north, south, east, west facing living spaces (apartments or barracks) (4).

All 17 zones were simulated, and six representative spaces were selected for the tables in this chapter, since they are either the limiting constraint locations or the ones that were most informative. All people, loads and lighting are modified by their appropriate schedules for the category and model type. The six representative zones are denoted in Figure 7-2 with an asterisk (*).

Parameters used in the study included

Building mass: (1) high mass building (CMU and poured concrete slabs) and (2) light or steel-frame Buildings, and (3) light metal panel building.

Thermal envelope characteristics: ranging from (1) pre-1980 code construction (ASHRAE Standard 90-1980), (2) current minimum energy efficiency requirements (lower efficiency) (ASHRAE Standard 90.1 -2013), and (3) state-of-the-art energy-efficient building characteristics (high efficiency) (ASHRAE Standard 90.1-2019). Tables 7-4 to 7-6 list specific characteristics for these three building categories.

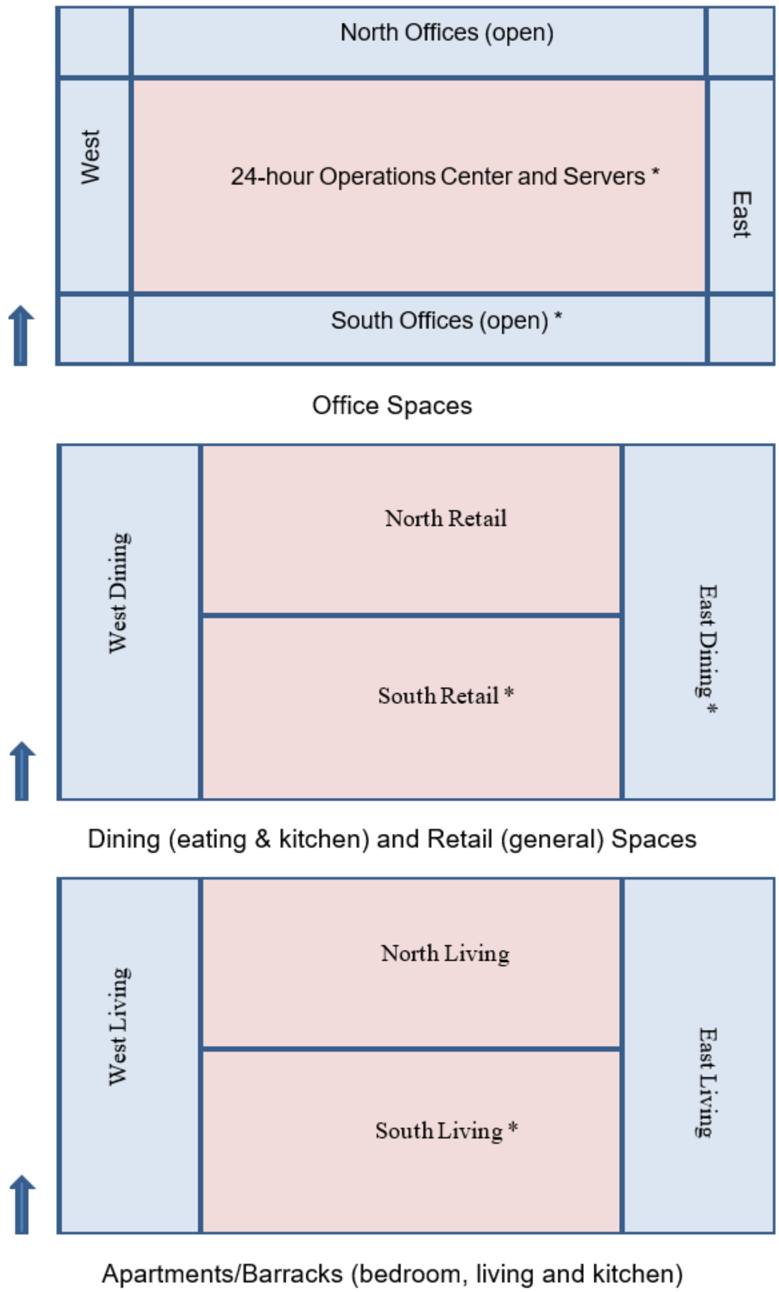


Figure 7-2. Representative building zones; representative spaces are marked with an asterisk.

Table 7-4. Building envelope characteristics representing ASHRAE Standard 90-1980.

Standard Pre-1980	0A	1A	2A	3A
Insulation Above Deck	R-9.22 ci	R-9.22 ci	R-9.22 ci	R-9.22 ci
Mass wall	U 0.58 / NR	U 0.58 / NR	R 3.498 ci	R 3.594 ci
Steel-Frame Wall	R-7	R-7	R-7	R-7
Metal Building Roof	R-13	R-13	R-13	R-13
Metal Building Wall	R-10	R-10	R-10	R-10
Window	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22	SHGC 0.54 / U 1.22
CFM75/ft^2(m^3/h/m^2 at 50 Pa)	1.2 (1.4)	1.2 (1.4)	1.2 (1.4)	1.2 (1.4)

Table 7-5. Building envelope characteristics representing ASHRAE Standard 90.1-2013

Standard 2013	0A	1A	2A	3A
Insulation Above Deck	U 0.048 / R-20ci	U 0.048g / R-20ci	U 0.039 / R-25ci	U 0.039 / R-25ci
Mass wall	U 0.58 / NR	U 0.58 / NR	U 0.151 / R 5.7 ci	U 0.123 / R-7.6 ci
Steel-Frame Wall	U 0.124 / R-13	U 0.124 / R-13	U 0.084 / R-13 +R3.8 ci	U 0.077 / R-13 +R-5.0 ci
Metal Building Roof	U 0.041/ R-10 + R-19	U 0.041/ R-10 + R-19	U 0.041/ R-10 + R-19	U 0.041/ R-10 + R-19
Metal Building Wall	U 0.094/ R-9.8 ci	U 0.094/ R-9.8 ci	U 0.094/ R-9.8 ci	U 0.094/ R-9.8 ci
Window	SHGC 0.25 / U 1.1	SHGC 0.25 / U 1.1	SHGC 0.25 / U 1.1	SHGC 0.25 / U 1.1
CFM75/ft2($m^3/h/m^2$ at 50 Pa)	0.25 (3.5)	0.25 (3.5)	0.25 (3.5)	0.25 (3.5)

Table 7-6. Building envelope characteristics representing ASHRAE Standard 90.1-2019.

Standard 2019	0A	1A	2A	3A
Insulation Above Deck	U 0.039 / R-25ci	U 0.048 / R-20ci	U 0.039 / R-25ci	U 0.039 / R-25ci
Mass wall	U 0.58 / NR	U 0.58 / NR	U 0.151 / R 5.7 ci	U 0.123 / R-7.6 ci
Steel-Frame Wall	U 0.124 / R-13	U 0.124 / R-13	U 0.084 / R-13 +R3.8 ci	U 0.077 / R-13 +R-5.0 ci
Metal Building Roof	U 0.041/ R-10 + R-19	U 0.041/ R-10 + R-19	U 0.041/ R-10 + R-19	U 0.041/ R-10 + R-19
Metal Building Wall	U 0.094/ R-9.8 ci	U 0.094/ R-9.8 ci	U 0.094/ R-9.8 ci	U 0.094/ R-9.8 ci
Window	SHGC 0.22 / U 0.50	SHGC 0.23 / U 0.50	SHGC 0.25 / U 0.45	SHGC 0.25 / U 0.42
CFM75/ft2($m^3/h/m^2$ at 50 Pa)	0.15 (2.13)	0.15 (2.13)	0.15 (2.13)	0.15 (2.13)

Interestingly, a general inference that can be drawn from the data in Tables 7-4 to 7-6 is that, for any Standard pertaining to CZs (climate zones) 0A to 3A, as you go further north the standards must optimize between the cooling requirements and the heating requirements. Therefore, some of the requirements may not affect the outcome for a cooling failure but will perform better in a heating failure.

There is significant improvement from pre-1980 to 2013. But in CZs 0 to 3 going from 2013 to 2019 there is less change than for the more northern climate zones. The improvements in 2019 are around the window specifications and the Army's proposed airtightness requirement.

The airtightness requirements for pre-1980 are taken from typical results from NIST studies; the 2013 study was taken Army/USACE airtightness, and airtightness for 2019 is a proposed requirement from ERDC studies as the new criteria. The air infiltration rate was determined using information from NIST regarding buildings built before 1980. For the building built to ASHRAE Standard 90.1-2013, USACE requirement of 0.25 cfm/ft^2 at 75Pa (4 $m^3/h/m^2$ at 50 Pa) has been adopted and for the buildings built to ASHRAE Standard 90.1-2019, requirements to airtightness have been increased to proposed 0.15 cfm/ft^{2}at 75Pa (2 $m^3/h/m^2$ at 50 Pa). The CFM75/ft^2 measure was used in the calculation for each model and entered as an air change per hour.

7.3.4. Results

The results of the parametric study were generated using the following process. The model was generated with a cooling failure happening on July 14 with restoration on July 25. The results verified that the cooling failure occurred and that the simulation responded correctly. The results were then exported for post processing. The graphs in Figure 7-3 show the process with the output for one case, 1A Miami mass building for ASHRAE Standard 90.1-2019.

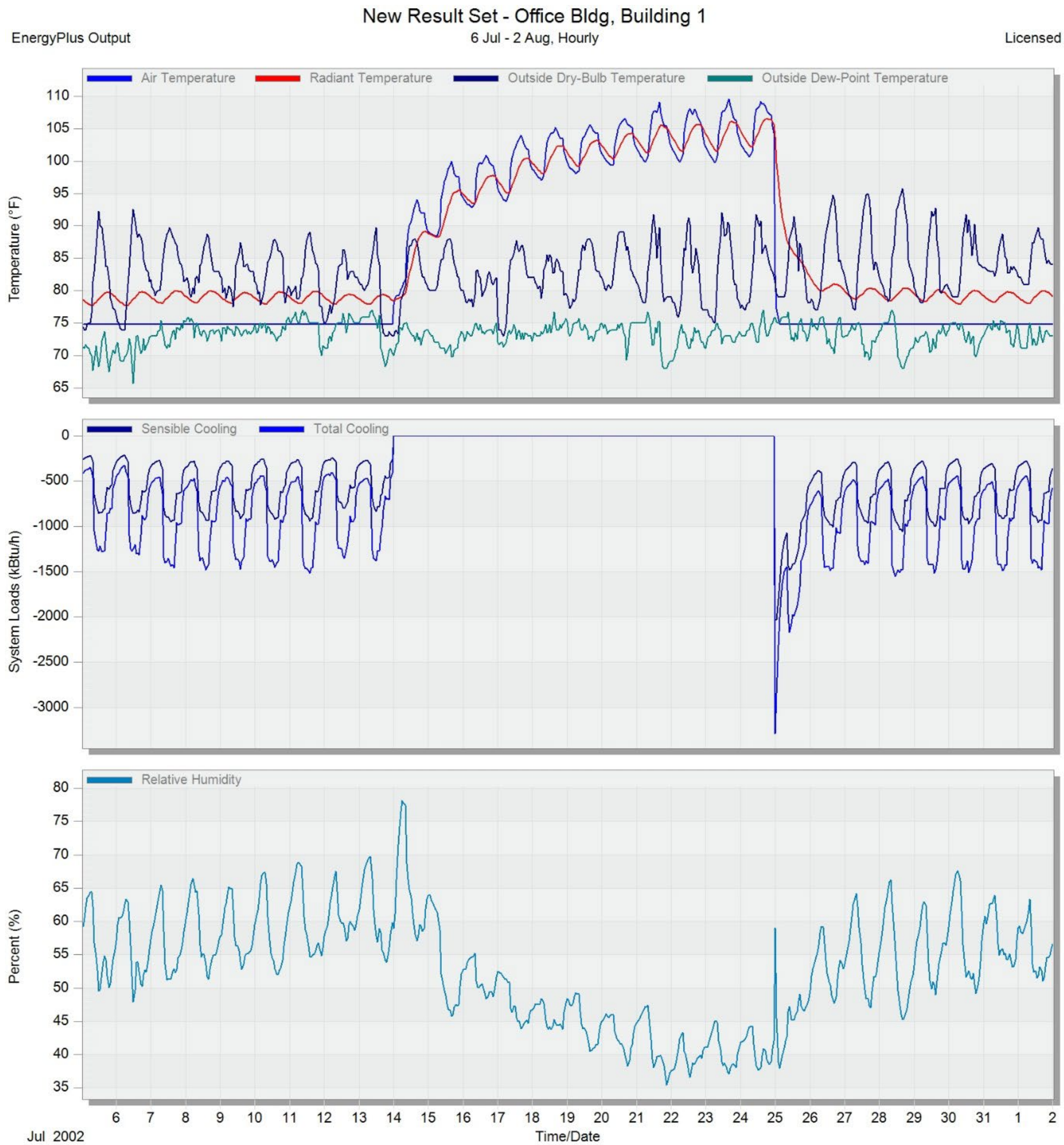


Figure 7-3. Sample results for 1A Miami mass building for ASHRAE Standard 90.1-2019.

The results were exported and processed, and the WBGT was calculated for each hour. Then, after the cooling failure, the hour to habitability limit was determined. Table 7-7 lists the hourly data for each of the six representative spaces, and the habitability threshold determined from this data for each case.

Table 7-7. Wet bulb global temperatures hourly for a typical space.

Cooling Load [W]	Hours from Failure [hrs]	Restaurant: Zone WBGT [F]	Retail:Zone WBGT [F]	24 Hour Ops Center:Zone WBGT [F]	South Office:Zone WBGT [F]	SW Corner Office:Zone WBGT [F]	South Residence: Zone WBGT [F]
71679.7812		67.3884964	68.9140625	62.399128	70.848587	69.7947159	68.031273
71483.6172		67.0621109	69.1614685	62.3655968	70.9730606	69.9230728	68.894646
0	1	68.9701996	70.0790787	71.3225098	72.2368851	71.9738693	70.182549
0	2	69.9841156	70.6886368	75.4835663	72.9531479	72.9528046	70.930649
0	3	71.3003998	71.626709	78.7523422	73.8671494	74.0297852	72.054596
0	4	72.3692169	72.4384995	80.3721313	74.3280945	74.5313721	73.035027
0	5	73.1541519	73.1084747	81.3143311	75.0874329	75.2316666	73.790405
0	6	74.1247177	74.084549	82.4074478	76.4044418	76.4038773	74.781067
0	7	74.8656693	74.8240891	82.872818	76.6101227	76.553833	75.534515
0	8	77.6277847	75.1280441	83.1497192	77.6521759	77.5410767	75.863709
0	9	78.5060806	75.3925781	83.4494171	78.9146805	78.6820908	76.14241
0	10	80.7945251	79.2441254	86.3606415	81.1156769	80.7433548	79.45311
0	11	81.8239136	81.4569702	87.4320602	82.1050339	81.6607895	80.855026
0	12	82.4597549	82.5025406	88.0953674	82.7398224	82.2640457	81.770454
0	13	84.7834854	82.4266968	88.4840546	82.4453354	81.9893036	82.386574
0	14	85.5174179	82.5217209	88.8057022	82.4453735	82.0183945	82.988091
0	15	84.1398392	83.3347702	89.1338501	83.3964539	82.9996567	83.423393
0	16	82.8397446	83.6544189	89.4069443	83.8720627	83.5604172	83.834114
0	17	82.6207047	84.0039368	89.7873535	84.3706055	84.071167	84.306549
0	18	82.5661087	83.6769409	88.4119415	83.299202	83.2496872	84.696976
0	19	83.7669525	81.3060913	88.0518417	81.9638901	82.0466537	85.042641
0	20	85.4260712	80.2842255	87.8744736	80.4192505	80.4850845	85.217606
0	21	85.7122421	79.7399521	87.7534332	79.5712814	79.7896423	85.377602
0	22	86.4962463	79.4091187	88.0782471	79.7068481	80.03759	85.766876
0	23	85.2555847	79.3640289	88.2857132	79.8364334	80.2122879	83.795776
0	24	82.777565	79.3307648	88.3845367	79.833046	80.2353897	82.809715
0	25	81.5801773	79.2839127	87.9300766	79.7837372	80.1735382	82.297554
0	26	80.3362045	78.9127502	87.2796021	78.8144455	79.2266922	81.604416
0	27	79.4391708	78.3610077	86.5433807	77.8435822	78.262146	80.98262
0	28	78.919136	78.1550369	86.406044	77.8151398	78.1467667	80.674385
0	29	78.7845001	78.261879	86.781311	78.4695206	78.7008667	80.665924
0	30	78.9674835	78.6906281	87.4337921	79.3655396	79.4507446	80.944382
0	31	78.9684677	78.8867645	87.5299225	79.3679886	79.3607559	81.009872
0	32	80.9670639	79.0055618	87.6373596	80.3740311	80.2695923	81.064438
0	33	81.7707138	79.1465225	87.7889786	81.8587494	81.6409454	81.137817
0	34	83.6703873	82.3104858	90.2786407	84.2870865	83.8017426	84.109612
0	35	84.4946518	84.3135681	91.1243362	85.2699738	84.6694489	85.334427
0	36	85.0695038	85.534935	91.6239777	85.9694519	85.2788544	86.272545
0	37	86.9825974	85.3105698	91.7980194	85.5177765	84.8468246	86.622109
0	38	87.4521408	85.3215408	91.984581	85.4756775	84.8283691	86.951141
0	39	86.2759628	85.9376221	92.213028	86.3207855	85.6879349	87.273079
0	40	85.0959473	86.1608429	92.3698654	86.693222	86.1305313	87.566856

This process was done for both the 85 °F (29 °C) WBGT and the 89 °F (32 °C) DBT; these results were then listed for all the scenarios in Tables 7-8 through 7-10. The results were summarized in the tables for these 36 scenarios with the 17 spaces for 612 simulations to assimilate all the results summarized for the 216 data points below.

Equipment Process Criteria 89 °F (32 °C) DB was selected as an example addressing requirements for servers, telecommunications, pharmaceutical, hospital, etc. (See Chapter 7).

Tables 7-8 through 7-10 show results of analysis representing time from the power failure till the DBT inside the space reaches 89 °F (32 °C) (Process Threshold).

Table 7-8. MaxTTR based on process requirements for the building built to the ASHRAE Standard 90-1980.

	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
Standard Efficiency Pre-1980	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**
Restaurant	11	13	11	12	10	12	10	11	10	11	10	11
Retail	14	15	12	13	12	12	11	12	11	12	11	12
24 Hour Ops	10	10	10	10	10	10	10	10	9	10	10	10
South Office	14	15	12	12	11	11	11	11	11	11	11	11
SW Corner Office	12	15	11	12	11	11	11	11	11	11	11	11
Residence/Barrack	12	13	12	12	11	11	11	11	11	11	11	11

Table 7-9. MaxTTR based on process requirements for the building built to the ASHRAE Standard 90.1-2013.

	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
Standard Efficiency 2013	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**
Restaurant	11	13	11	12	10	12	11	11	10	11	10	11
Retail	15	15	12	14	11	12	11	12	11	11	11	11
24 Hour Ops	8	9	9	9	4	6	8	4	4	6	8	4
South Office	12	14	12	12	10	11	11	11	10	10	10	11
SW Corner Office	12	15	12	13	11	11	11	11	11	11	11	11
Residence/Barrack	12	13	12	12	10	11	11	11	10	11	11	11

Table 7-10. MaxTTR based on process requirements for the building built to ASHRAE Standard 90.1-2019.

	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
Standard Efficiency 2019	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**
Restaurant	11	13	11	12	10	12	10	11	10	11	10	10
Retail	15	15	12	14	11	12	11	11	11	11	11	11
24 Hour Ops	7	8	9	9	4	6	4	3	4	5	5	5
South Office	12	14	12	12	10	11	10	11	10	10	10	10
SW Corner Office	12	15	12	13	11	11	11	11	10	11	11	11
Residence/Barrack	12	12	12	12	10	11	11	11	10	11	10	10

Based on results presented in Tables 7-8 through 7-10, the MaxTTR based on the process-related requirements to indoor air thermal conditions varies between 10 and 15 hours in HHC. As expected, in spaces with high internal loads, MTTR is shorter. It is also shorter in highly efficient buildings (e.g., built according to the ASHRAE Standard 90.1 dated 2013 and after), than in older existing buildings), since the heat generated by the process gets trapped inside the building.

Tables 7-11 through 7-13 show results of analysis representing time from the power failure till the WBGT inside the space reaches the habitability threshold of to 85 °F (29 °C)

Table 7-11. MaxTTR based on habitability threshold for the building built to the ASHRAE Standard 90-1980.

	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
Standard Efficiency Pre-1980	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**
Restaurant	13	37	61	37	12	13	13	13	11	13	13	13
Retail	36	113	112	110	14	41	49	39	14	39	40	38
24 Hour Ops	10	11	11	13	10	10	10	11	10	10	10	11
South Office	16	112	112	110	12	14	14	14	11	14	12	13
SW Corner Office	16	88	88	63	12	14	14	14	12	13	12	13
Residence/Barrack	16	89	88	62	11	12	12	13	11	12	12	13

Table 7-12. MaxTTR based on habitability threshold for the building built to the ASHRAE Standard 90.1-2013.

	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
Standard Efficiency 2013	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**	**0A**	**1A**	**2A**	**3A**
Restaurant	13	20	20	21	12	13	13	13	11	13	13	13
Retail	16	36	40	39	12	15	15	15	12	15	15	15

Standard Efficiency 2013	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
	0A	1A	2A	3A	0A	1A	2A	3A	0A	1A	2A	3A
24 Hour Ops	10	10	10	12	10	10	10	11	9	10	10	10
South Office	15	36	39	38	11	12	12	13	11	11	11	12
SW Corner Office	15	39	39	39	12	13	13	14	11	12	12	13
Residence/Barrack	14	36	36	37	11	12	12	12	11	12	12	12

Table 7-13. MaxTTR based on habitability threshold for the building built to ASHRAE Standard 90.1-2019.

Standard Efficiency 2019	Mass				Light Frame				Metal Panel / Metal Bldg.			
	Climate zone											
	0A	1A	2A	3A	0A	1A	2A	3A	0A	1A	2A	3A
Restaurant	13	20	20	20	11	13	13	13	11	13	13	13
Retail	15	36	39	38	12	15	15	15	12	14	14	14
24 Hour Ops	10	10	10	11	8	10	10	10	7	10	10	10
South Office	15	35	39	37	11	12	12	12	11	11	11	11
SW Corner Office	15	36	39	38	11	12	12	13	11	12	12	12
Residence/Barrack	15	19	19	37	11	12	12	12	11	12	11	11

All these cases were simulated for July weather conditions for a 30-day duration. The failure mechanism was assigned for Monday at midnight with internal loads in mission-critical areas remaining the same and all other loads following their normal (blue sky) schedules. During normal (blue sky) operation, models replicated the equipment schedules. The assumption is that there is enough standby generator capacity to run lights and equipment, and not enough capacity to operate Cooling for HVAC. This will provide the most conservative estimate where load shedding can extend the time before the temperature and WBGT thresholds are reached.

For the mass building structures described by the data in in Tables 7-11 through 7-13 for each Standard CZ 1A to 3A were included in Appendix D as Tables D-1 to D-9. In the results section above where the process was explained in a light mass structure, when the threshold was crossed, it typically maintained and continued to become hotter and more humid. In the mass construction there were times when the threshold was crossed but only slightly, possibly at the end of the day, and then would cool back off. For the mass structures, the MTTR criteria was selected when the building would consistently be beyond the temperature threshold, or cases where it was above for 2 to 3 hours for a more significant and consistent MTTR selection. These values are what is recorded in the tables above across climate zones. The light frame and metal building types of constructions were more consistent in their MTTR results and did not need additional interpretation and smoothing.

The data presented in Tables 7-11 through 7-13 show that MTTR based on the habitability threshold can be significantly higher than one based on the process requirements, and that it is longer in less efficient buildings. In some functional spaces, it can reach several days. MTTR based on habitability threshold is longer in mass buildings than in light frame or metal frame buildings.

7.4. Supporting Study of Education Center Building

7.4.1. Introduction

To complement the parametric analysis described in the previous section, additional analysis was completed using real-world design scenarios that focused on reviewing potential mitigation measures and building properties that have a significant effect on resilience. This analysis was completed using a whole-building energy model of a representative Education Center building located in an extremely hot and humid climate represented by CZ 0A. The project's 32,000 ft ($2{,}976\ m^2$) of gross floor area consists mainly of offices, classrooms, and multipurpose use space types. The variety of spaces allow us to explore the impact of occupancy density and cooling load diversities and to strategize the ability to maintain building functionality in the event of a power outage.

Key questions that will be considered through simulation include: Is it a good idea to gather people in larger spaces or spread them into smaller spaces? What is the impact of orientation? What impact does age of construction have on survivability? Can we suggest certain orientations for certain types of space use? What additional passive strategies can improve passive survivability?

7.4.2. Parameters and Passive Strategies Tested

The study considers the same three vintages of buildings previously presented in this chapter, as well as considering several passive design measures. These include

- Three versions of the envelope (2019, 2013, and pre-1980)
- Local shading types: exterior overhangs and fins
- Exterior shutters/blackout blinds
- Window film reducing SHGC
- Operable windows for natural ventilation
- Operable/openable Skylights, and
- White/cool roofs.

Under this study, a power failure was simulated with only enough back up power available to meet equipment, and lighting requirements, but not AC compressors. Thus, the space temperatures will float and come to equilibrium. Weather data was a typical meteorological year (TMY3) as represented by a representative city in CZ 0A.

The period of the year in which the power outage is to occur was selected based on the highest period of latent loads. The day and the following 2 weeks are selected based on highest humidity levels around the hurricane season of the studied climate in a typical year. (These weeks also correspond with the highest latent loads.) The failure mechanism was assigned for Monday at night, 12:00 am, with internal loads remaining the same over the simulated outage.

7.4.3. Model Inputs and Assumptions

Figures 7-4 and 7-6 show a visual representation of the key building massing, orientation, and geometry assumptions that influence energy consumption, and that were used to generate the energy performance results.

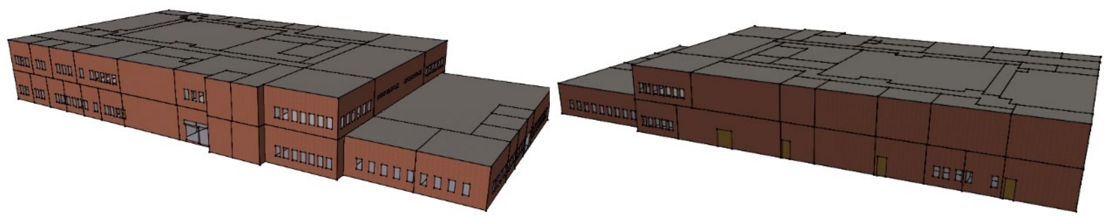


Figure 7-4. Renderings of Education Center model.

The following selected program areas (also see Figure 7-5) were chosen to represent a variety of orientations, occupant densities, and sensible and latent loads:

- Classroom/Lecture/Training: large area with high occupancy density (~1000 ft [~93 m^2])
  East and southeast (corner) orientations and no exterior surface condition
  Occupancy: 15.38 ft (1.4 m^2)/person, lighting: 1.24 W/ft^2 (0.38 W/m^2),
  plug loads: 1 W/ft^2 (0.3 W/m^2)
- Library: Large area with lower occupancy density (~2800 ft [~260 m^2])
  Northeast orientation, corner
  Occupancy: 100 ft (9.3 m^2)/person, lighting: 1.71 W/ft^2 (0.5 W/m^2),
  plug loads: 1.5 W/ft^2 (0.46 W/m^2)
- Office: Small area with minimal occupancy density (<150 ft [<14 m^2])
  South orientation
  Occupancy: 200 ft (18.6 m^2)/person, lighting: 1.11 W/ft^2 (0.3 W/m^2),
  plug loads: 1 W/ft^2 (0.3 W/m^2)
- Corridor: No exterior surface
  Occupancy: 0 ft^2/person, lighting: 0.66 W/ft^2 (0.2 W/m^2)ft,
  plug loads: 0.2 W/ft^2 (0.06 W/m^2)
- Telecom/Storage: North orientation
  Occupancy: 200 ft (18.6 m^2) /person, lighting: 1.11 W/ft^2 (0.34 W/m^2),
  plug loads: 1 W/ft^2 (0.3 W/m^2)
- Computer Lab: West orientation
  Occupancy: 200 ft (18.6)/person, lighting: 0.98 W/ft^2 (0.3 W/m^2),
  plug loads: 1.5 W/ft^2 (0.46 W/m^2)

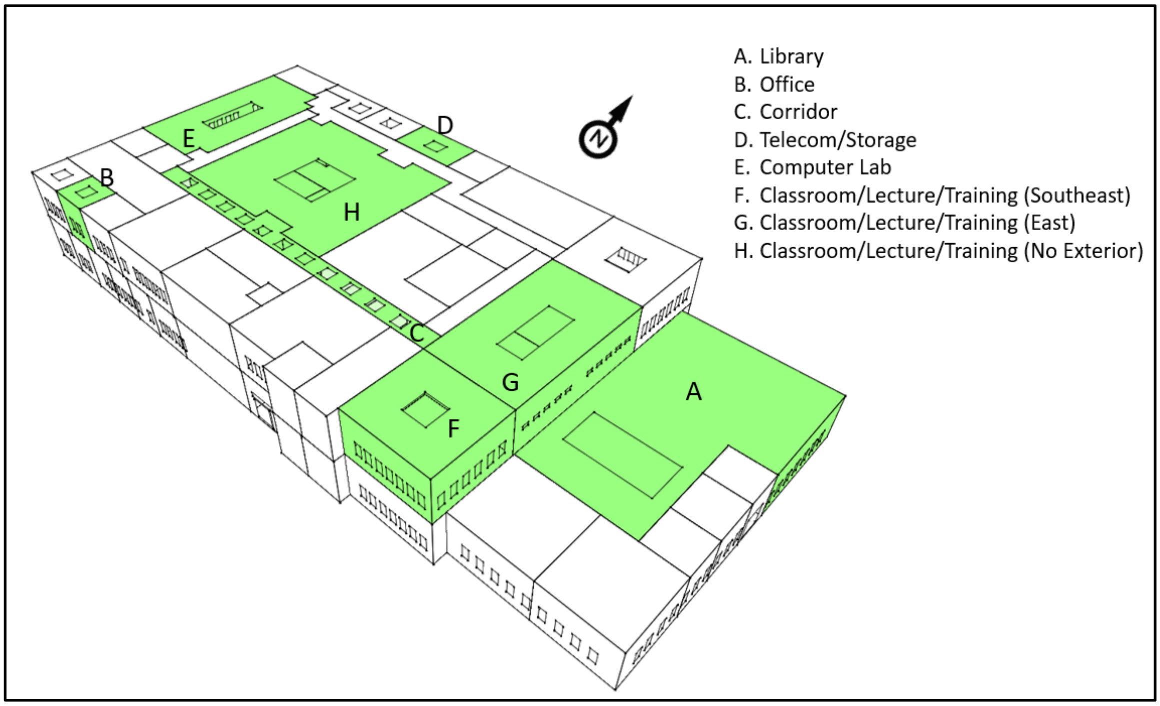


Figure 7-5. Rendering of Education Center with study spaces highlighted.

7.4.4. Study Parameters

Multiple assembly types were selected to represent a varying building stock. New construction is represented by ASHRAE 90.1-2019 envelope requirements, with older buildings represented by 2013, and pre-1980 envelope standards. Table 7-14 lists details for each a mass and steel-frame construction considered for a CZ 0A subset.

Table 7-14. Building envelope characteristics used in the study.

Climate Zone (CZ): 0A	ASHRAE Standard 90-1980	ASHRAE Standard 90.1-2013	ASHRAE Standard 90.1-2019
Insulation Above Deck	R-9.22 ci	U 0.048 / R-20ci	U 0.039 / R-25ci
Mass wall	U 0.58 / NR	U 0.58 / NR	U 0.58 / NR
Steel-Frame Wall	R-7	U 0.124 / R-13	U 0.124 / R-13
Window	SHGC 0.54 / U 1.22	SHGC 0.25 / U 1.1	SHGC 0.22 / U 0.50
Infiltration (75 cfm/ft^2 [381 LPS/m^2])	1.2	0.25	0.15

7.4.5. Passive Design Strategies

In addition to different energy efficiency standards and building mass, the following passive design strategies were studied:

- Local shading types: Typical Window dimension is 1 ft, 9 in. W x 3 ft, 9 in. H. 1 ft; 9 in. projected overhangs and fins are assigned (no offset).
- Exterior shutters/blackout blinds: Shutters are assumed to be operating full time after the power outage started. The shutters block out heat/radiation gains but have no insulation properties.
- Window film reducing SHGC: a common window film selected with high reflectance (0.32) and low transmittance (0.08) properties and applied to the inner pane.
- Openings for ventilation: Single sided windows, top hung, 60% openable area. Windows are open when the indoor temperature is higher than outside and more than 68 °F (20 °C).
- Operable/openable Skylights: Operable skylights are tested to understand the impact of cross ventilation. Glazing is fully shaded with louvers (not letting any heat gain/radiation in).
- White/cool roofs: White rubber tiles, which have high reflectance and high emittance properties, are added on top of the outside layer. White color is assigned for 100% reflectance.

7.4.6. Results

Results of a Power Outage at the Highest Latent Week

Tables 7-15 and 7-16 list the results for simulations representing a power outage that occurs during the period with the highest latent loads in the weather file. As in the above parametric study, the habitability threshold was established to be less than WBGT = 85 °F (29 °C), and process threshold for equipment below 89 °F (32 °C) DB. It was considered that the threshold is reached when the simulated WBGT in the space reaches the threshold. The details are discussed in Chapter 2. The results compare the hours to achieve the habitability thresholds in various spaces in the model for the three construction design cases (ASHRAE 90 pre-1980, ASHRAE 90.1-2013, ASHRAE 90.1-2019) and (mass and steel-frame) wall types. Table 7-16 lists the number of hours until the comfort threshold is exceeded, and “#N/A” indicates acceptable conditions are maintained for the remainder of the analysis period.

Table 7-15. Results for simulations representing a power outage that occurs during the period with the highest latent loads in the weather file (mass wall).

	Hours to 85 °F (29 °C) WBGT					
Area	**Pre-1980_Mass Wall**		**2013_Mass Wall**		**2019_Mass Wall**	
Library (East-North Corner)	#N/A	63	39	17	38	15
Office (South)	#N/A	#N/A	#N/A	67	92	67
Classroom (South-East Corner)	67	66	20	19	19	19
Classroom (No Exterior Wall)	69	66	19	19	19	19
Classroom (East Classroom)	67	66	19	19	19	19
Computer Lab (West)	#N/A	66	68	66	67	66
Corridor (No exterior Wall)	#N/A	#N/A	70	68	70	45
Telecom (North)	#N/A	#N/A	#N/A	91	#N/A	68

Table 7-16. Results for simulations representing a power outage that occurs during the period with the highest latent loads in the weather file (steel-frame wall).

Area	Hours to 85 °F (29 °C) WBGT					
	Pre-1980_Steel Frame Wall		2013_Steel Frame Wall		2019_Steel Frame Wall	
Library (east-north corner)	#N/A	63	39	15	36	14
Office (south)	#N/A	#N/A	#N/A	68	69	67
Classroom (south-east corner)	67	66	20	19	18	19
Classroom (no exterior wall)	69	66	19	19	18	19
Classroom (east classroom)	67	66	19	19	18	19
Computer Lab (west)	#N/A	66	70	66	67	66
Corridor (no exterior wall)	#N/A	#N/A	70	68	68	45
Telecom (north)	#N/A	#N/A	#N/A	92	237	69

The results show that the most significant difference in hours to reach threshold temperatures in the modeled spaces is a result of space type, and hence occupancy levels, lighting, and plug load gains. The higher occupancy rates of the classrooms and libraries reach the temperature thresholds faster than the lower occupancy spaces (office, corridors, etc.) that in some instances do not exceed the thresholds at all. Figures 7-6 and 7-7 show the DB temperature differences for low and high occupancy spaces.

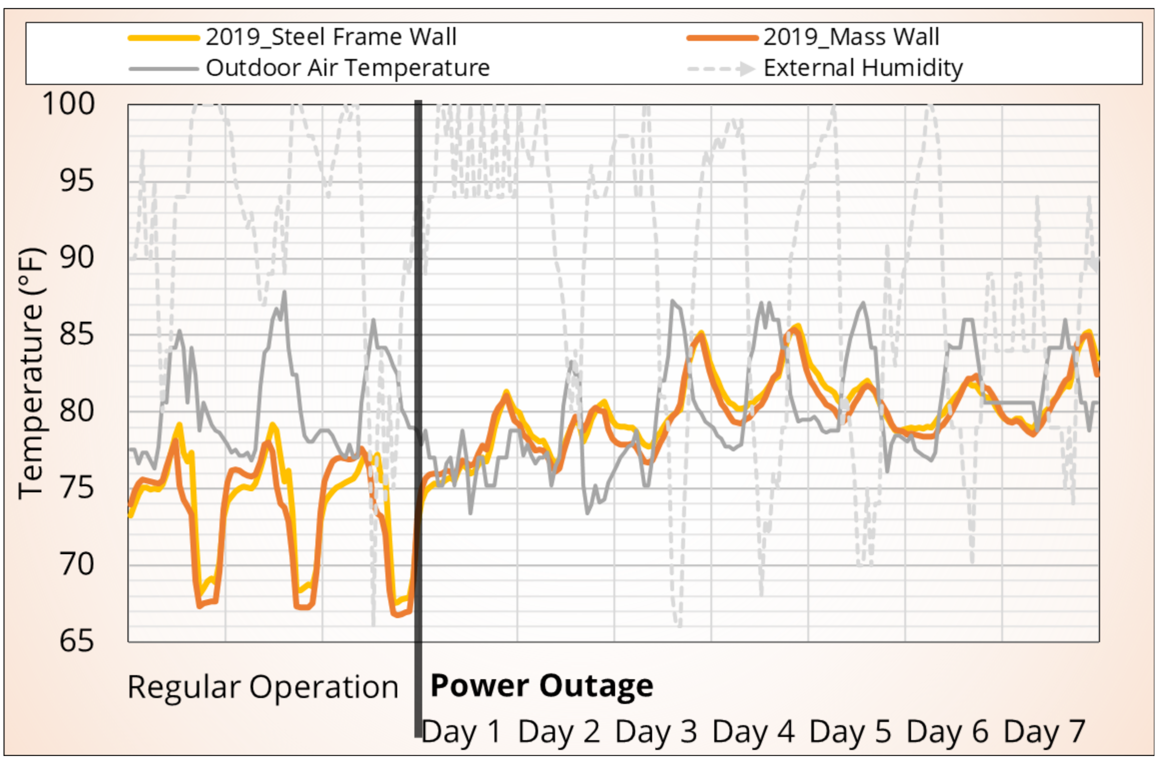


Figure 7-6. Office (Exterior, South) - Daily fluctuations are less due to low occupancy.

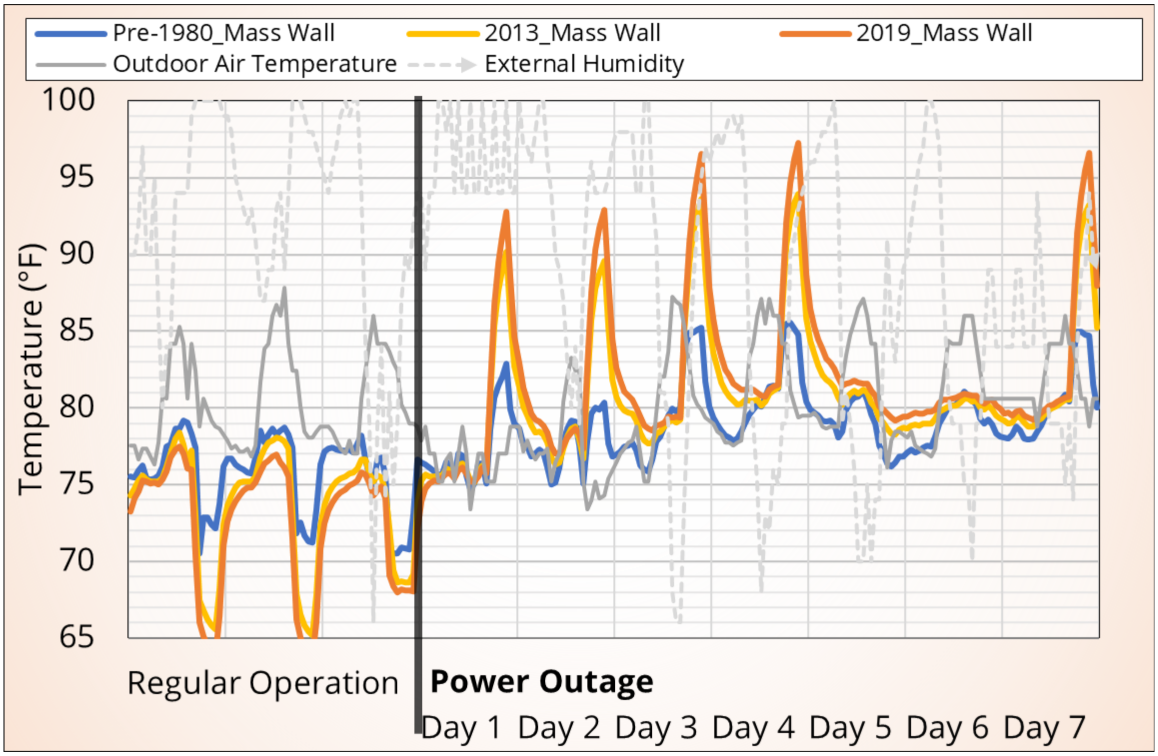


Figure 7-7. Classroom (No exterior) - High heat gain due to occupancy, no exterior surface for heat removal, high R- value/insulation at roof.

The variations in hours to exceedance across similar space types with different orientations is minor, showing a higher correlation with internal gains.

The pre-1980 code construction model shows a longer period of time before reaching threshold temperatures (both DBT and WBGT) compared to the models representing the current minimum energy efficiency requirements (lower efficiency) (ASHRAE Standard 90.1 -2013), and state-of-the-art energy-efficient building characteristics (high efficiency) (ASHRAE Standard 90.1-2019). This delay is due primarily to the higher infiltration rates in the pre-1980 construction as cool internal air is permitted to “leak” out of the space (see Appendix D, Figures D-1 and D-2).

The length of time to meet threshold temperatures is largely the same for the mass and steel-frame wall construction types (Figure D-3).

The next set of results (Table 7-17) show the same metrics for a series of models testing passive design measures on the steel-frame case meant to improve passive survivability in the spaces. These measures include shading devices, window films, and window openings, as previously described.

Table 7-17. Length of time to meet threshold temperatures for a series of models testing passive design measures on the steel-frame case.

	2019_Steel Frame Wall		2019_Steel Frame Wall_Overhangs and Fins		2019_Steel Frame Wall_Shutters		2019_Steel Frame Wall_Window Film		2019_Steel Frame Wall_White Roof		2019_Steel Frame Wall_Window Openings		2019_Steel Frame Wall_Window Openings_Skylights	
	Hours To 85 F WBGT	Hours To 89 F DBT	Hours To 85 F WBGT	Hours To 89 F DBT	Hours To 85 F WBGT	Hours To 89 F DBT	Hours To 85 F WBGT	Hours To 89 F DBT	Hours To 85 F WBGT	Hours To 89 F DBT	Hours To 85 F WBGT	Hours To 89 F DBT	Hours To 85 F WBGT	Hours To 89 F DBT
Library (East-North Corner)	36	14	37	14	38	14	37	14	37	14	#N/A	63	#N/A	#N/A
Office (South)	69	67	70	68	93	68	70	67	93	68	#N/A	#N/A	#N/A	#N/A
Classroom (South-East Corner)	18	19	19	19	19	19	19	19	19	19	#N/A	#N/A	#N/A	#N/A
Classroom (No Exterior Wall)	18	19	19	19	19	19	19	19	19	19	19	19	#N/A	#N/A
Classroom (East Classroom)	18	19	19	19	19	19	19	19	19	19	21	20	#N/A	#N/A
Computer Lab (West)	67	66	69	67	69	67	68	66	69	67	#N/A	235	#N/A	#N/A
Corridor (No exterior Wall)	68	45	69	45	69	45	69	45	70	45	69	68	#N/A	#N/A
Telecom (North)	237	69	238	69	238	69	238	69	238	70	#N/A	69	#N/A	#N/A

The results show that

- The impact on hours of habitability by adding overhangs and fins for solar shading is not significant with only a 1-hour delay for habitability.
- Shutters and a white roof are more effective on south facing offices.
- Skylights maximize the time by providing cross ventilation in all zones, or stratification driven ventilation for interior zones without vertical window exposure.

Results of a Power Outage at the Highest Sensible Temperature Week

The same simulations were repeated for the highest sensible temperature week in the weather file. Table 7-18 shows the results. In Table 7-18, these are the same simulations repeated for the highest sensible temperature week.

Table 7-18. Time to threshold for passive design measure simulations (high sensible week).

	Hours to 85 °F (29 °C) WBGT							
Area	**2019_Mass Wall**		**2019_Steel Frame Wall**		**2019_Steel Frame Wall Window Openings**		**2019_Steel Frame Wall Window Openings Skylights**	
Library (East-North Corner)	64	15	64	11	#N/A	84	#N/A	#N/A
Office (South)	238	17	#N/A	14	#N/A	#N/A	#N/A	#N/A
Classroom (South-East Corner)	67	1	67	1	#N/A	68	#N/A	#N/A
Classroom (No Exterior Wall)	67	1	67	1	67	1	#N/A	#N/A
Classroom (East Classroom)	67	1	67	1	67	1	#N/A	#N/A
Computer Lab (West)	163	16	#N/A	14	#N/A	235	#N/A	#N/A
Corridor (No exterior Wall)	165	1	165	1	165	1	#N/A	#N/A
Telecom (North)	#N/A	17	#N/A	67	#N/A	68	#N/A	#N/A

The results show that habitability rates during the "high sensible" week are higher than those presented previously for the "high latent" week, for all the zones and cases. There are no significant impacts observed from solar shading projections (fins and overhangs), window film and white roofs. The inclusion of full-cover shutters is shown to reduce the temperatures by 1 °F to 2 °F (1.8 °C to 3.6 °C) in south, west, and east orientations, but full-cover shutters had no considerable impact on the north orientation. As with the latent case, the most significant temperature reductions and increased habitability rates are seen with the inclusion of natural ventilation. The most significant temperature reductions are seen in spaces with crossflow ventilation potential, via either two facades with openings or a single façade combined with an operable skylight.

7.4.7. Conclusions

To be resilient, a community/campus/military installation must be prepared to serve its energy demands during disruption scenarios. To plan, develop, and evaluate resilient designs, the planner must stay informed of the dynamic demand of each asset or building during a disruption scenario and must scale energy supplies up or down to meet the demand for each critical function. The characteristics of the critical energy load can vary significantly between functions. For example, a communications function may require a large but steady supply of power to meet its equipment and conditioning needs. A shelter, on the other hand, may have little to no critical power demand, but may have a large but variable cooling demand to protect occupants from environmental conditions.

This study showed that a few things can be done in a disruption scenario. One construction consideration is the amount of building capacitance that is exposed to the indoor environment. This capacitance can help ride through some of the initial hours of a failure more effectively than without. Overall, many of the more stringent building parameters provided in the modern codes do not significantly impact the MTTR in a full cooling failure. This study tried to provide time to repair while maintaining the full mission load of lights and equipment. This will give a worst-case scenario response for MTTR and will provide a large factor to extend the time to repair and/or extend the fuel for electric generation through load shedding. With load shedding, these times can be extended significantly. However, not every mission can be reduced so this must be evaluated on a case-by-case basis.

As explained in Chapter 5, while the exfiltration leaks conditioned room air to the outside and should be minimized, infiltration of hot and humid OA into a conditioned space should be avoided. In normal (blue sky) operation, infiltration of "warm," moist OA increases the dewpoint temperature (DPT) of the space. While "hot," moist OA causes both an increase in moisture and temperature in the space, it can also cause condensation on cold surfaces and create moist areas in porous building materials creating areas in the envelope that can grow mold and other biologicals. Therefore, the improved building airtightness helps control the overall amount of outside makeup air that enters the building to keep problems from occurring while improving the overall energy usage, thereby accomplishing the building mission more efficiently. Chapter 5 discusses the importance of limiting air infiltration not just for energy savings, but also to prevent building damage caused by uncontrolled air infiltration.

Similarly, when exploring the impacts on habitability from passive design measures in a real-world case study, it was seen that envelope design, solar shading, and white roofs play only a minor role in improving habitability. This is true, particularly, of the spaces with high internal gains because of high occupancy. It is therefore advised, as much as possible, to distribute occupancy across spaces during periods of power outage in these climate zones.

The application of operable windows, with the resulting natural ventilation and passive cooling, was the most effective way to reduce internal temperatures when a power outage occurs. From a first glance this finding appears to conflict with the infiltration guidance in previous chapters but should only be used in a survivability situation and not in normal (blue sky) operations.

Most modern construction cases exceeded habitable levels (85 °F [29.4 °C] WBGT or 89 °F [31.7 °C] DBT) within the first 24 hours of a power outage. If outages exceed this period resulting in unhabitable conditions, a trade-off must be considered between the thermal benefits of opening windows for natural ventilation and the potential humidity and moisture risks of a “leaky envelope.” For power outage scenarios, when indoor temperatures increase beyond typical setpoint temperatures, it may be acceptable to allow outdoor air to enter the building for the purpose of cooling. Warmer surfaces will limit the condensation risks of introduced humidity. Once power is restored, a drying period would be required to dehumidify the space to normal (blue sky) operating levels. Depending on the duration of the power outage, this practice may or may not be deemed acceptable. Recommendations are to use operable fenestration (windows that open) for survivability and for resilience to maintain temperature and humidity control in the facilities, although not necessarily in normal (blue sky) operations.

Building efficiency measures may not impact the time to repair as much as anticipated but may impact the performance and comfort of the building during normal (blue sky) operations, which is most of the time during the building’s existence. Some of the tables do not show many changes between the building standards; there are things that can be done to improve resilience like load shedding planning, but building standards are optimized for normal (blue sky) operations, which hopefully is close to 100% of the time.

Based on the presented data, it may be concluded that, in spaces with mission-critical processes, highly efficient building envelope alone cannot support indoor air thermal conditions required by the process(es) performed in the building for a significant period of time. In spaces not constrained by process requirements, habitability can be maintained for a longer time. Therefore, to increase MTTR in buildings located in a hot and humid climate when power from the grid is lost, other measures can be applied, e.g., chilled-water or ice storage (described in Chapter 4 and Appendix D, which can typically extend the performance of cooling and humidity control systems by 8 to 10 hours without load shedding, and 2 to 3 days with load shedding. These systems typically require only emergency power for pumps and fans.

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ACRONYMS

Abbreviation	Term
ABAA	Air Barrier Association of America
ABS	Air Barrier System
ACI	American Concrete Institute
AEG	Academy Energy Group
AFCESA	Air Force Civil Engineer Support Agency
AHU	Air-Handling Unit
AMPP	Advanced Materials and Processing Program
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
ATES	Aquafer Thermal Energy Storage
ATS	Automatic Transfer Switch
AWVB	Air/Water/Vapor Barrier
BGWP	Base of Groundwater Protection
BSRIA	Building Services Research and Information Association
BTES	Borehole Thermal Energy Storage
CCHP	Combined Cooling, Heat, and Power
CFM	Cubic Feet per Minute
CHP	Combined Heat And Power
CHW	Chilled Water
CMU	Concrete Masonry Unit
CONUS	Continental United States
COP	Coefficient of Performance
CP	Cathodic Protection
CZ	Climate Zone
DALT	Duct Air Leakage Tests
DB	Dry Bulb
DBT	Dry Bulb Temperature
DCV	Demand Control Ventilation
DER	Deep Energy Retrofit
DH	District Heating
DHW	Domestic Hot Water
DOAS	Dedicated Outside Air System
DOD	Department of Defense
DOE	Department of Energy
DP	Dewpoint
DPT	Dewpoint Temperature
DS	Downstream
DWSC	Deep Water Source Cooling

Abbreviation	Term
DX	Direct Expansion
EBC	Energy in Buildings and Communities
ECB	Engineering and Construction Bulletin
EIFS	Exterior-Insulated Finish System
EMMO	Enhanced Mixed Metal Oxide
EOP	Electro-Osmotic Pulse
EPDM	Ethylene Propylene Diene M-Class
ERDC	U.S. Army Engineer Research and Development Center
ERH	Equilibrium Relative Humidity
ESC	Environmental Severity Classifications
ESTCP	Environmental Security Technology Certification Program
FEMA	Federal Emergency Management Agency
FSM	Flight Safety Manager
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWHP	Ground Water Heat Pump
HHC	Hot and Humid Climates
HPCA	High Performance Computer Architecture
HSD	High Strength Deformed
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	Indoor Air Quality
IRMA	Inverted Roof Membrane Assembly
IT	Information Technology
LCCA	Life-Cycle Cost Analysis
LGC	Low-Grade Concrete
MaxTTR	Maximum Time to Repair
MC	Marine Coastal
MTTR	Mean Time To Repair
NASA	National Aeronautics and Space Administration
NAVFAC	Naval Facilities Engineering Command
NDL	No Dollar Limit
NEBS	Network Equipment-Building System
NIPP	National Infrastructure and Protection Plan
NIST	National Institute of Standards and Technology
NYSERDA	New York State Energy Research and Development Authority
O&M	Operations And Maintenance
OA	Outside Air
OPEC	Organization of Petroleum Exporting Countries
OSA	Outdoor Supply Air
OSB	Oriented Strand Board

Abbreviation	Term
PIE	Professional Investigative Engineers
POH	USACE Honolulu District
PP	Pluvial Precipitation
PPE	Personal Protective Equipment
PTES	Pit Thermal Energy Storage
PVB	Polyvinyl Butyl
RCC	Reinforced Cement Concrete
RH	Relative Humidity
RU	Rural-Urban
SAM	USACE Mobile District
SCADA	Supervisory Control And Data Acquisition
SG	SentryGlas®
SHGC	Solar Heat Gain Coefficient
SPF	Spray Polyurethane Foam
STES	Seasonal TES (Thermal Energy Storage)
SWAC	Seawater Air-Conditioning
TD	Temperature Drop
TES	Thermal Energy Storage
TMT	Toxics Management Team
TOW	Time of Wetness
TTES	Tank Thermal Energy Storages
UFC	Unified Facilities Criteria
UFGS	United Facilities Guide Specifications
UPS	Uninterruptable Power Supply
USACE	U.S. Army Corps of Engineers
UV	Ultraviolet
VAV	Variable Air Volume
VHF	Very High Frequency
VLT	Visible Light Transmission
VME	Virtual Movable Endcap
VOC	Volatile Organic Compound
WBGT	Wet Bulb Global Temperature
WRB	Water-Resistive Barrier
XPS	Extruded Polystyrene

Appendix A. Building Construction Types

Table A-1. Commonly used building construction types and building characteristics in HHC.

Location	Climate Zone	ESC	Assembly Max (U-value)	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
Data from USACE Mobile District							
Gulf coast	0A, 1A, 2A	C4, C5			Steel-Frame Structure	Faster to construct. Able to resist blast and high wind forces with reinforced cladding.	Lacks mass of concrete. Will corrode over time if not protected or encapsulated.
	0A, 1A, 2A	C4, C5			Concrete Frame Structure	Able to resist blast and high wind forces. Will not corrode. Low maintenance.	Slower to construct. Labor intensive and more costly than steel-framed and metal buildings.
	0A, 1A, 2A	C4, C5			Metal Building	Faster to construct. Cost-effective. Provides longer spans.	Not as resistant to blast and high wind forces. Will corrode over time if not regularly maintained.
Climate Zone	Zone 0 (A,B)	Roof					
			U-0.039	R-25 c.i.	Insulation above deck		
			U-0.041	R-10 + R-19 FC	Metal Building		
		Walls					
			U-0.580	NR	Mass		
			U-0.094	R-0 + R-9.8 c.i.	Metal Building		
			U-0.124	R-13	Steel-framed		
Climate Zone	Zone 1 (A, B)	Roof					
			U-0.048	R-20 c.i.	Insulation above deck		

Location	Climate Zone	ESC	Assembly Max (U-value)	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
			U-0.041	R-10 + R-19 FC	Metal Building		
		Walls					
			U-0.580	NR	Mass		
			U-0.094	R-0 + R-9.8 c.i.	Metal Building		
			U-0.124	R-13	Steel-framed		
Climate Zone	Zone 2 (A, B)	Roof					
			U-0.039	R-25 c.i.	Insulation above deck		
			U-0.041	R-10 + R-19 FC	Metal Building		
		Walls					
			U-0.151	R-5.7 c.i.	Mass		
			U-0.094	R-0 + R-9.8 c.i.	Metal Building		
			U-0.084	R-13 + R-3.8 c.i.	Steel-framed		
Central America	1A	C4, C5	U-0.048	R-20 c.i.	Concrete or Metal Deck, Insulation entirely above deck. Standing Seam Metal Roof, Structural Standing Seam Metal Roof, and Metal Insulated Sandwich Panel Roof.	Able to resist corrosion, blast, and high wind forces. Most commonly used systems, materials are locally procurable. Able to resist corrosion, high wind forces, and ponding water. 20 – 25-year "no dollar limit" (NDL) warranty available.	Labor intensive and more time-consuming. 28-day cure time for concrete.

Location	Climate Zone	ESC	Assembly Max (U-value)	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
	1A	C4, C5	U-0.041	R-10 + R-19 FC	Metal building. Insulation entirely above deck. Standing Seam Metal Roof, Structural Standing Seam Metal Roof, and Metal Insulated Sandwich Panel Roof.	Faster to construct. Provides longer open spans. Able to resist corrosion, blast, and high wind forces. High roofing reliability. Conforms to Installation design aesthetics requirements. Long serviceable life cycle.	Steel prep and heavy-duty coating applications are labor intensive and expensive. Will corrode over time if not maintained. Higher first cost. Underlayment is required so the roof can perform as an air barrier. Long lead times.
South America	2A	C5	U-0.027	R-38	Concrete Roof Deck, Attic & other	Prefer to have corridors and circulation louvered to the exterior with no doors when possible.	Labor intensive and more time-consuming. 28-day cure time for concrete.
					Standing Seam Metal Roof, Structural Standing Seam Metal Roof, and Metal Insulated Sandwich Panel Roof.	Better access to materials for isolated locations. Relatively easy to install. No specialty equipment is required. Cost Efficient.	Lower puncture resistance. Cannot be installed during inclement weather.
Kwajalein, Guam, Saipan, Micronesia (FSM), AmericanSamoa	0A	C4, C5	U-0.580	NA	Concrete or CMU walls	Better access to materials for isolated locations.Able to resist corrosion, blast, and high wind forces. Insulation is notrequired.	Labor intensiveand therefore less affordable and more time-consuming. Needs to be maintained every5 to 10 years.

Location	Climate Zone	ESC	Assembly Max (U-value)	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
Hawaii	1A	C4, C5	U-0.580	NR	Concrete or CMU walls (mass)	Better access to materials for isolated locations.Able to resist corrosion, blast, and high wind forces.	Labor intensiveand therefore less affordable and more time-consuming. Needs to be maintained every 5 to 10 years.
	1A	C4, C5	U-0.094	R-0 + R-9.8 c.i.	Metal Building	Faster to construct. Provides longer spans. Able to resist blast and high wind forces. Insulation is not required.	Shipping is expensive. Long lead times. Steel prep and heavy-duty coating are labor intensive and expensive. Will corrode overtime if not regularly maintained.
	1A	C4, C5	U-0.124	R-13	Steel-Framed	Faster to construct. Ableto resist blast and high wind forces with reinforced cladding.	Cost-effective. Faster to construct. Will corrode over time if not wellprotected.
Okinawa	2A	C5	U-0.151	R-5.7 c.i.	Concrete or CMU walls (mass)	Able to resist corrosion, blast,and high wind forces.	Labor intensiveand more time-consuming. Needs to be maintained every to 10 years.

Location	Climate Zone	ESC	Assembly Max (U-value)	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
					Crystalline Cementitious Base of Groundwater Protection (BGWP) (recommend conc. admixture)	Easier to install around unusual conditions. Specialty equipment is not required to install. Can be installed wet. Can be installed on the positive or negative side or concrete additive.	Labor intensive to cure, need to keep wet for 72 hours. Use as a concrete additive is expensive. Crystalline structure cannot bridge through wall cracks greater than 1/8 in. wide. Material warranty only.
Japan (Southern Regions) 1A	2A 3A	C4, C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	Materials are easier to transport. Relatively simple to install. Specialty equipment is not required to install. Lower material cost.	Not as effective against hydrostatic pressure. Warranty 5 – 10 years. A limited number of local certified Installers.
					Crystalline Cementitious BGWP (recommend conc. admixture)	Easier to install around unusual conditions. Specialty equipment is not required to install. Can be installed wet. Can be installed on the positive or negative side or concrete additive.	Labor intensive to cure, need to keep wet for 72 hours. Use as a concrete additive is expensive. Crystalline structure cannot bridge through wall cracks greater than 1/8 in. wide. Material warranty only.

Location	Climate Zone	ESC	Assembly Max (U-value)	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
South Korea (Southern Regions)	3A	C3, C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	Materials easier to transport. Relatively simple to install. Specialty equipment is not required to install. Lower material cost.	Not as effective against hydrostatic pressure. Warranty 5 – 10 years.
					Hot Fluid-Applied, Rubberized Asphalt BGWP Reinforced	Durable, seamless, easy to detail, and bonds directly to the substrate. A long performance history of successful applications. Cost-effective. Long warranty 20 to 25 years.	Specialty equipment (kettle) is required to install. Strong fumes.

Notes:

1. Wood-framed construction is not recommended because it is susceptible to termite damage, wood rot, and mold.

2. Assumptions for air barrier components were based on ANSI/ASHRAE/IES Standard 90.1-2019, section 5.4.3.1.3, "Testing, Acceptable Materials, and Assemblies":

b. Materials that have air permeance not exceeding 0.004 cfm/ft^2 (0.02 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2178.

c. Assemblies of materials and components (sealants, tapes, etc.) that have an average air leakage not to exceed 0.04 cfm/ft^2 (0.2 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2357, ASTM E1677, ASTM E1680, or ASTM E283.

3. The following exterior wall types were designed to meet the requirement for testing per UFC 3-101-01 (NAVFAC 2021a), Change 1, 5 January 2021, 3-6.3 Inspections and Testing:

"For Army and Navy projects, the building air leakage rate must not exceed 0.25 cfm/ft^2 (1.25 LPS/m^2) when tested."

"The building air leakage rate for Air Force projects must not exceed 0.4 cfm/ft^2 (2.00 LPS/m^2)."

Table A-2. Below-grade occupied space commonly used archetypes (building construction types) for HHC.

Location	Climate Zone	ESC	Assembly Max	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
Data provided by USACE Pacific Ocean Division							
Kwajalein, Guam, Saipan, Micronesia (FSM), American Samoa	0A	C4, C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	Materials are easier to transport. Relatively simple to install. Specialty equipment is not required to install. Lower material cost.	Not as effective against hydrostatic pressure. Warranty 5 to 10 years. A limited number of local certified Installers.
					Crystalline Cementitious BGWP (recommend conc. admixture)	Easier to mold/flash around unusual conditions. Specialty equipment is not required for installation. Can be installed wet. Can be installed on the positive or negative side or concrete additive.	Labor intensive to cure, need to keep wet for 72 hours. Use as a concrete additive is expensive. Crystalline structure cannot bridge through wall cracks greater than 1/8 in. wide. Material warranty only.
Hawaii	1A	C4, C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	See Location (1)	See Location (1)
					Cold Fluid-Applied BGWP	BGWP materials are easier to install especially around unusual conditions.	BGWP requires thicker protection materials. Higher material cost. Warranty 10 to 20 years. Specialty equipment is required to install. Limited number of local certified Installers.
					Crystalline Cementitious BGWP (recommend conc. admixture)	Easier to install around unusual conditions. Specialty equipment is not required to install. Can be installed wet. Can be installed on the positive or negative side or concrete additive.	Labor intensive to cure, need to keep wet for 72 hours. Use as a concrete additive is expensive. Crystalline structure cannot bridge through wall cracks greater than 1/8 in. wide. Material warranty only.
					Hot Fluid-Applied, Rubberized Asphalt BGWP Reinforced	Durable, seamless, easy to detail, and bonds directly to the substrate. A long performance history of successful applications. Cost-	Specialty equipment (kettle) is required to install. A limited number of local certified Installers. Strong fumes.

Location	Climate Zone	ESC	Assembly Max	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
						effective. Long warranty 20 to 25 years.	
Okinawa	2A	C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	Materials are easier to transport. Relatively simple to install. Specialty equipment is not required to install. Lower material cost.	Not as effective against hydrostatic pressure. Warranty 5 to 10 years. A limited number of local certified Installers.
					Crystalline Cementitious BGWP (recommend conc. admixture)	Easier to install around unusual conditions. Specialty equipment is not required to install. Can be installed wet. Can be installed on the positive or negative side or concrete additive.	Labor intensive to cure, need to keep wet for 72 hours. Use as a concrete additive is expensive. Crystalline structure cannot bridge through wall cracks greater than 1/8 in. wide. Material warranty only.
Japan (Southern Regions)	1A 2A 3A	C4, C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	Materials are easier to transport. Relatively simple to install. Specialty equipment is not required to install. Lower material cost.	Not as effective against hydrostatic pressure. Warranty 5 to 10 years. A limited number of local certified Installers.
					Crystalline Cementitious BGWP (recommend conc. admixture)	Easier to install around unusual conditions. Specialty equipment is not required to install. Can be installed wet. Can be installed on the positive or negative side or concrete additive.	Labor intensive to cure, need to keep wet for 72 hours. Use as a concrete additive is expensive. Crystalline structure cannot bridge through wall cracks greater than 1/8 in. wide. Material warranty only.
South Korea (Southern Regions)	3A	C3, C5	C-1.140	NR	Sheet applied (recommend 2 layers of Bituthene) BGWP	Materials are easier to transport. Relatively simple to install. Specialty equipment is not required to install. Lower material cost.	Not as effective against hydrostatic pressure. Warranty 5 to 10 years.
					Hot Fluid-Applied, Rubberized Asphalt BGWP Reinforced	Durable, seamless, easy to detail, and bonds directly to the substrate. The long performance history of successful applications. Cost-effective. Long warranty 20 to 25 years.	Specialty equipment (kettle) is required to install. Strong fumes.

Location	Climate Zone	ESC	Assembly Max	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons

Notes:

1. In general, wood-framed construction is not recommended in HHC because it is susceptible to termite damage, wood rot, and mold. Metal stud framing if properly protected against corrosion can be used.
2. "Bentonite" waterproofing materials shall not be used due to exposure to saltwater and tidal fluctuation forces.
3. Per UFC 3-101-01 (NAVFAC 2021a), Change 1, 5 January 2021, 2-5.1 SECTION 1805 - DAMPPROOFING AND WATERPROOFING, supplement to IBC 2018, "If required to address hydrostatic pressure or as recommended by the geotechnical report, provide drainage planes combined with waterproofing material and a footing drain on below-grade walls."
4. Assumptions for air barrier components were based on ANSI/ASHRAE/IES Standard 90.1-2019, section 5.4.3.1.3, "Testing, Acceptable Materials, and Assemblies":

   b. Materials that have air permeance not exceeding 0.004 cfm/ft^2 (0.02 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2178.

   c. Assemblies of materials and components (sealants, tapes, etc.) that have an average air leakage not to exceed 0.04 cfm/ft^2 (0.2 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2357, ASTM E1677, ASTM E1680, or ASTM E283.
5. The following exterior wall types were designed to meet the requirement for testing per UFC 3-101-01 (NAVFAC 2021a), Change 1, 5 January 2021, 3-6.3 Inspections and Testing:

   "For Army and Navy projects, the building air leakage rate must not exceed 0.25 cfm/ft^2 (1.25 LPS/m^2) when tested."

   "The building air leakage rate for Air Force projects must not exceed 0.4 cfm/ft^2 (2.00 LPS/m^2)."

Wall Construction: Preferred Cast-in-place reinforced concrete or CMU.

IBC 2018, section 1402.6 Flood Resistance, for buildings in flood hazard areas as established in section 1612.3, exterior walls extending below the elevation required by section 1612 shall be constructed with flood-damage resistant materials.

Pros: Better access to materials for isolated locations. Will not facilitate rot or mold growth. Able to resist hydrostatic pressure from tidal fluctuations, flooding, and seismic events. Most below-grade waterproofing systems require Cast-in-place reinforced concrete or CMU substrate.

Cons: Labor intensive, more time-consuming, and long cure times. Susceptible to cracking or spalling if not protected or maintained.

Table A-3. Roofs commonly used archetypes (building construction types) for HHC.

Location	Climate Zone	ESC	Assembly Max	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
Data provided by USACE Pacific Ocean Division							
Kwajalein, Guam, Saipan, Micronesia (FSM), American Samoa	0A	C4, C5	U-0.027	R-38	Concrete Roof Deck, Attic & other	Able to resist corrosion, blast, and high wind forces. Preference to have insulation on the underside of the structural deck.	Labor intensive and more time-consuming. 28-day cure time for concrete.
					Fluid-Applied Silicone Roof Coating System	Greater access to materials for isolated locations. Relatively easy to install. No special equipment is required. Can withstand ponding water. Cost Efficient.	Lower puncture resistance. Should not be installed during inclement weather.
Hawaii	1A	C4, C5	U-0.048	R-20 c.i.	Concrete or Metal Deck, Insulation entirely above deck. Single Ply PVC or ethylene propylene diene M-class (EPDM) (i.e., rubber) Roofing System for Low-Slope Roofing System	Able to resist corrosion, blast, and high wind forces. A commonly used system, most materials are stocked on the island. Able to resist corrosion, high wind forces, and ponding water. 20 – 25-year NDL warranty available.	Labor intensive and more time-consuming. 28-day cure time for concrete. Roof and insulation adhesive attachments are easier but more expensive. Difficult to treat unusual conditions. The roof system must be fully adhered to w/ batten system. Lower puncture resistance. Reinforced EPDM only comes in the color "black."
	1A	C4, C5	U-0.041	R-10 + R-19 FC	Metal building. Insulation entirely above deck. Standing Seam Alum Roofing System	Faster to construct. Provides longer open spans. Able to resist corrosion, blast, and high wind forces. High roofing reliability. Conforms to Installation design aesthetics requirements. Long serviceable life cycle.	Steel prep and heavy-duty coating applications are labor intensive and expensive. Will corrode over time if not maintained. Higher first cost. Underlayment is required so the roof can perform as an air barrier. Long lead times.
Okinawa	2A	C5	U-0.027	R-38	Concrete Roof Deck, Attic & other	Prefer to have insulation on the underside of the structural deck. Able to resist corrosion, blast, and high wind forces.	Labor intensive and more time-consuming. 28-day cure time for concrete.

Location	Climate Zone	ESC	Assembly Max	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons
					Fluid-Applied Silicone Roof Coating System	Better access to materials for isolated locations. Relatively easy to install. No special equipment is required. Can withstand ponding water. Cost Efficient.	Lower puncture resistance. Cannot be installed during inclement weather.
Japan (Southern Coastal Regions)	1A 2A 3A	C4, C5	U-0.048 U-0.039 U-0.039	R-20 c.i. R-25 c.i. R-25 c.i.	Concrete Roof Deck, Attic & other	Able to resist corrosion, blast, and high wind forces. Preference to have insulation on top of the sloped structural deck.	Labor intensive and more time-consuming. 28-day cure time for concrete.
	1A 2A 3A	C4, C5	U-0.041	R-10 + R-19 FC	Metal building	Faster to construct. Provides longer spans. Able to resist blast and high wind forces.	Steel prep and heavy-duty coating applications are labor intensive and expensive. Will corrode over time if not maintained.
					Hydrokinetic Standing Seam Metal Roofing w/ Ice/water guard membrane underlayment (preferred for either roof substrate at 16% slope)	Able to resist corrosion, deflect explosive devices, and withstand high wind forces. High roofing reliability. Conforms to Installation design aesthetics requirements. Long serviceable life cycle.	Higher first cost. Underlayment is required so the roof can perform as an air barrier.
South Korea (Southern Coastal Regions)	3A	C3, C5	U-0.027	R-38	Concrete Roof Deck, Attic & other	Cost-effective and able to resist corrosion, blast, and high wind forces.	Labor intensive and more time-consuming. 28-day cure time for concrete.
	3A	C3, C5	U-0.041	R-10 + R-19 FC	Metal building	Faster to construct. Provides longer spans. Able to resist blast and high wind forces.	Steel prep and heavy-duty coating are labor intensive and expensive. Will corrode over time if not protected.
					Standing Seam Metal Roofing w/ Ice/water guard membrane underlayment (preferred for either roof substrate)	Able to resist corrosion, blast, and high wind forces. High roofing reliability. Conforms to Installation design aesthetics requirements. Long serviceable life cycle.	Higher first cost. Underlayment is required so the roof can perform as an air barrier.

Location	Climate Zone	ESC	Assembly Max	Insulation Min. R-Value	Recommended Architype (Building Construction Type)	Pros	Cons

Notes:

1. In general, wood-framed construction is not recommended because it is susceptible to termite damage, wood rot, and mold.
2. Per UFGS specifications and some Installation Design Guides, the roof system must have a 20 year NDL warranty available.
3. Assumptions for air barrier components were based on ANSI/ASHRAE/IES 90.1-2019, section 5.4.3.1.3, "Testing, Acceptable Materials, and Assemblies":

   b. Materials that have air permeance not exceeding 0.004 cfm/ft^2 (0.0203 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2178.

   c. Assemblies of materials and components (sealants, tapes, etc.) that have an average air leakage not to exceed 0.04 cfm/ft^2 (0.2032 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2357, ASTM E1677, ASTM E1680, or ASTM E283.
4. The following roofing systems were designed to meet the requirement for testing per UFC 3-101-01 (NAVFAC 2021a), Change 1, 5 January 2021, 3-6.3 Inspections and Testing:

   "For Army and Navy projects, the building air leakage rate must not exceed 0.25 cfm/ft^2 (1.25 LPS/m^2) when tested."

   "The building air leakage rate for Air Force projects must not exceed 0.4 cfm/ft^2 (2.00 L/sm^2)."
5. Per ANSI/ASHRAE/IES Standard 90.1-2019, section 5.5.3.1.1 "Roof Solar Reflectance and Thermal Emittance Roofs in CZs 0 through 3" shall have one of the following:
   a. A minimum 3-year-aged solar reflectance of 0.55 and a minimum 3-year-aged thermal emittance of 0.75 when tested in accordance with CRRC S100.
   b. A minimum Solar Reflectance Index of 64 when determined in accordance with the Solar Reflectance Index method in ASTM E1980 using a convection coefficient of 2.1 Btu/h·ft^2·°F, based on 3-year-aged solar reflectance and 3-year-aged thermal emittance tested in accordance with CRRC S100.
   c. Increased roof insulation levels found in Table 5.5.3.1.1.

Table A-4. Exterior fenestration for HHC.

Location	Climate Zone	ESC	Assembly Max. U	Assembly Max. SHGC	Recommended Architype (Building Construction Type)	Pros	Cons
Data provided by Pacific Ocean Division							
Kwajalein, Guam, Saipan, Micronesia (FSM), American Samoa	0A	C4, C5	U-0.50 *(Fixed)* U-0.62 *(Operable)* U-0.83 *(Entrance Door)*	0.22 *(Fixed)* 0.20 *(Operable)* 0.20 *(Entrance Door)*	IGU; High-quality UV, stabilized vinyl, marine-grade aluminum, aluminum with Kynar finish, or stainless steel windows w/SG (SentryGlas) laminated glazing and storm shutters	Able to resist small & large missile impacts. Able to resist corrosion, blast, and high/hurricane wind forces. Mitigate solar heat gain.	High first cost, long lead times, limitations on window size, must be installed from outside.
Hawaii	1A	C4,	U-0.50	0.23	IGU; High-quality	Able to resist small & large	High first cost,

Location	Climate Zone	ESC	Assembly Max. U	Assembly Max. SHGC	Recommended Architype (Building Construction Type)	Pros	Cons
		C5	*(Fixed)* U-0.62 *(Operable)* U-0.83 *(Entrance Door)*	*(Fixed)* 0.21 *(Operable)* 0.21 *(Entrance Door)*	UV, stabilized vinyl, marine-grade aluminum, aluminum with Kynar finish, or stainless steel windows w/ SG laminated glazing	missile impacts. Able to resist corrosion, blast, and high/hurricane wind forces. Mitigate solar heat gain.	long lead times, limitations on window size, must be installed from outside.
Okinawa	2A	C5	U-0.45 *(Fixed)* U-0.60 *(Operable)* U-0.77 *(Entrance Door)*	0.25 *(Fixed)* 0.23 *(Operable)* 0.23 *(Entrance Door)*	IGU; High-quality UV, stabilized vinyl, marine-grade aluminum, aluminum with Kynar finish, or stainless steel windows w/ SG laminated glazing and storm shutters	Able to resist small & large missile impacts. Able to resist corrosion, blast, and high/hurricane/typhoon wind forces. Mitigate solar heat gain.	High first cost, long lead times, limitations on window size, must be installed from outside.
Japan (Southern Regions)	1A 2A 3A	C4, C5	U-0.50 U-0.45 U-0.42 *(Fixed)* U-0.62 U-0.60 U-0.54 *(Operable)* U-0.83 U-0.77 U-0.68 *(Entrance Door)*	0.23 0.25 0.25 *(Fixed)* 0.21 0.23 0.23 *(Operable)* 0.21 0.23 0.23 *(Entrance Door)*	Same as location (2) except SG and heat-strengthened glass may not be required	Same as location (2), specifying local manufacturers required, provides daylighting	High first cost, limitations on window size, must be installed from outside.
South Korea (Southern Regions)	3A	C3, C5	U-0.42 *(Fixed)* U-0.54 *(Operable)* U-0.68 *(Entrance Door)*	0.23 *(Fixed)* 0.23 *(Operable)* 0.23 *(Entrance Door)*	Same as location (2) except SG and heat-strengthened glass may not be required	Same as location (2), provides daylighting	High first cost, limitations on window size, must be installed from outside.

Location	Climate Zone	ESC	Assembly Max. U	Assembly Max. SHGC	Recommended Architype (Building Construction Type)	Pros	Cons

Notes:

1. Per IBC 2018, section 1709.5.1 Exterior windows and doors, and UFGS section 08 51 13, areas that experience hurricanes/typhoons the windows and glazing must meet the following requirements:
    a. Air infiltration must not exceed the amount established by AAMA/WDMA/CSA 101/I.S.2/A440 for each window type.
    b. Water penetration must not exceed the amount established by AAMA/WDMA/CSA 101/I.S.2/A440 for each window type.
    c. Thermal Performance for Southern Climate as shown in ANSI/ASHRAE/IES Standard 90.1-2019, Table 5-5.
2. Total Vertical Fenestration Area shall not be greater than 0% to 40% of Wall per ANSI/ASHRAE/IES Standard 90.1-2019, section 5.5.4.2 “Fenestration Area.”
3. Incorporation of aluminum or stainless-steel sheet metal head flashing and sill pan flashing with end dams is required by UFC 3-101-01 (NAVFAC 2021a), section 1404.4.3 - Sill Pan Flashing.
4. UFC 1-200-01 (NAVFAC 2019), DOD Building Code cited IBC 2018 Ch 2, defines wind-borne debris regions and their requirements. Sentry Glazing (0.090 SG, See Figure 2) is used as the interlayer to meet the large missile impact requirement. Blast Mitigation as required by UFC 4-010-01 (NAVFAC 2021b), section 3-11.1 Glazing.
    a. Large Missile Test: For glazing located within (9.1 m) 30 ft of grade.
    b. Small Missile Test: For glazing located more than (9.1 m) 30 ft above grade.
5. Per USACE Japan District Design Guide, Jan 2018, Version 2.0, section 8.5.4 FENESTRATION, “For exterior windows, it is recommended to use the window sizes that are indicated in the PDC TR 12-08 to the maximum extent possible.”
6. Assumptions for air barrier components were based on ANSI/ASHRAE/IES Standard 90.1-2019, section 5.4.3.1.3 “Testing, Acceptable Materials, and Assemblies”:

    b. Materials that have air permeance not exceeding 0.004 cfm/ft^2 (.02 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2178.

    c. Assemblies of materials and components (sealants, tapes, etc.) that have an average air leakage not to exceed 0.04 cfm/ft^2 (0.2032 LPS/m^2) under a pressure differential of 0.3 in. of water (1.57 psf) when tested in accordance with ASTM E2357, ASTM E1677, ASTM E1680, or ASTM E283.
7. The following window types were designed to be incorporated into wall types that meet requirements for testing per UFC 3-101-01 (NAVFAC 2021a), Change 1, 5 January 2021, 3-6.3 Inspections and Testing:

    “For Army and Navy projects, the building air leakage rate must not exceed 0.25 cfm/ft^2 (1.25 LPS/m^2) when tested.”

    “The building air leakage rate for Air Force projects must not exceed 0.4 cfm/ft^2 (2.00 LPS/m^2).”

General Recommended Window Type for Hot and Humid Climates: Rain Screen, insulated, wet glazed, compression seal (Awning or Casement) windows. Specify operable windows to facilitate natural ventilation when possible. Glazing should include an inner pane of laminated heat-strengthened glazing with tinting and/or low-emissivity coating and an outer pane of tempered glass. Incorporate exterior shading devices, i.e., horizontal sunscreens, and vertical fins with interior window treatments.

Table A-5. Air barrier testing results for buildings located in HHC.

Test Date	Location	Bldg. Type	Bldg. Area	Floors	Air Barrier Enclosure Size ft² (m²)	Test Result	% Better Than Requirements	Enclosure Consultant	Design Review	Construction Observation
Data sources: Zhivov (2014) and PIE Consulting and Engineering										
10/20/20	Oahu, HI	Behavioral Health/Dental Clinic Addition	73,000	3	101,900 (9,477)	0.075	70%			
05/04/10	Fort Polk, LA	Barracks	34,365	3	52,476 (4,880)	0.10	60%	yes	Yes	Yes
06/30/10	Fort Polk, LA	Barracks	34,365	3	52,476 (4,880)	0.10	60%	yes	Yes	Yes
06/29/10	Fort Polk, LA	Barracks	34,365	3	52,476 (4,880)	0.13	48%	yes	Yes	Yes
06/31/10	Fort Polk, LA	Barracks	34,365	3	52,476 (4,880)	0.13	48%	yes	Yes	Yes
12/21/10	Fort Benning, GA	Weapons Repair Shop	22868	1	64,326 (5,982)	0.14	44%	Yes	No	Yes
12/21/11	Fort Stewart, GA	Soldier Family Care Clinic		1	102,051 (9,491)	0.14	45%	No	No	No
06/18/09	Corpus Christi, TX	CHSF	96,600	1	227,867 (21,192)	0.15	40%	No	No	No
02/11/11	Fort Benning, GA	Instruction Building	110,653	2	168,674 (15,687)	0.15	40%	Yes	No	Yes
09/16/10	Fort Polk, LA	Barracks	45,820	3	70,715 (6,576)	0.15	40%	Yes	Yes	Yes
04/12/11	Fort Benning, GA	Warehouse	7,106	1	17,377 (1,616)	0.16	36%	No	No	No
05/25/11	Fort Stewart, GA	Barracks	26,650	3	39,514 (3,675)	0.16	35%	Yes	Yes	Yes
04/26/11	Fort Polk, LA	Barracks	19,383	3	25,227 (2,346)	0.17	32%	Yes	Yes	Yes
03/29/11	Fort Stewart, GA	Barracks	26,650	3	39,514 (3,675)	0.17	32%	Yes	Yes	Yes
04/27/11	Fort Stewart, GA	Barracks	26,650	3	39,514 (3,675)	0.17	32%	Yes	Yes	Yes
03/29/11	Fort Stewart, GA	Barracks	26,650	3	39,514 (3,675)	0.17	32%	Yes	Yes	Yes
08/25/11	Fort Stewart, GA	Barracks	26,650	3	39,514 (3,675)	0.17	32%	Yes	Yes	Yes
08/25/11	Fort Benning, GA	Training Complex	22,399	1	56,999 (5,300.9071)	0.18	29%	No	No	No
06/22/11	Fort Benning, GA	Barracks		3	124,724 (11,599)	0.18	29%	No	No	No
7/10/12	Fort Polk, LA	Barracks	45,852	3	70,515 (6,558)	0.14	53%	Yes	Yes	Yes
6/6/12	Fort Bliss, TX	Health & Dental Clinic	39,024	1	102,949 (9,574)	0.08	68%	No	No	No
6/27/12	Fort Bliss, TX	TEMF	7,011	1	19,240 (1,789)	0.19	24	No	No	No
9/17/12	Fort Polk, LA	Barracks	34,605	3	51,372 (4,778)	0.15	50%	Yes	Yes	Yes
11/12/12	Fort Polk, LA	Barracks	45,852	3	70,515 (6,558)	0.17	43%	Yes	Yes	Yes
11/13/12	Fort Polk, LA	Barracks	34,511	3	51,372 (4,778)	0.17	43%	Yes	Yes	Yes
11/14/12	Fort Polk, LA	Barracks	34,511	3	51,372(4,778)	0.15	50%	Yes	Yes	Yes
11/15/12	Fort Polk, LA	Barracks	34,511	3	51,372 (4,778)	0.15	50%	Yes	Yes	Yes
11/30/12	Yuma, AZ*	Courthouse	61,760	2	108,980 (10,135)	0.15	63%	Yes	Yes	Yes
2/13/13	Fort Bliss, TX	Aquatics Center	51,385	1	122,575 (11,399)	0.13	48%	No	No	No
3/29/13	Fort Hood, TX	Small Office	2,118	1	7,688 (715)	0.15	40%	No	No	No
5/11/13	Southlake, TX*	Medical Center	254,532	3	231,500 (21,530)	0.11	N/A	No	No	No

Test Date	Location	Bldg. Type	Bldg. Area	Floors	Air Barrier Enclosure Size ft² (m²)	Test Result	% Better Than Requirements	Enclosure Consultant	Design Review	Construction Observation
7/16/13	Fort Benning, GA	Central Issue Facility	15,302	1	47,221 (4,392)	0.10	60%	Yes	Yes	Yes
12/03/13	Vandenberg AFB, CA	Education Center	38,960	2	72,356 (6,729)	0.10	62%	Yes	No	Yes
3/14/14	Fort Campbell, KY	Maintenance Hangar	25,401	2	70,540 (6,560)	0.12	53%	Yes	Yes	Yes
4/11/15	Fort Hood, TX	Clinic Building	337,842	7	405,308 (37,694)	0.13	49%	Yes	Yes	Yes
4/11/15	Fort Benning, GA	Army Lodge	457,180	4	513,984 (47,801)	0.12	53%	Yes	Yes	Yes
10/26/16	Fort Campbell, KY	Elementary School	89,965	3	259,215 (24,107)	0.09	64%	Yes	Yes	Yes
11/14/16	Fort Sam Houston	COF		2	28,270 (2,629)	0.13	49%	No	No	No
11/30/16	Kwajalein Atoll, Marshall Islands	Repair Building		1	25,341 (2,357)	0.09	64%	Yes	Yes	No
4/8/17	Cannon AFB, NM	Medical/Dental Facility				0.08	70%	No	No	No
10/30/18	Beale AFB, CA	Mission Control Center			135,419 (12,594)	0.14	44%	Yes	Yes	Yes
1/17/19	Honolulu, HI*	Traffic Management Center		3	80,340 (7,472)	0.06	76%	No	No	No
9/4/19	Fort Bliss, TX	Administration Building			137,759 (12,812)	0.15	40%	Yes	Yes	Yes
12/19/19	Luke AFB, AZ	Communicatio n Facility		2	53,269 (4,954)	0.13	49%	No	No	No
2/8/20	Guantanamo Bay, Cuba	School		2	199,800 (18,581)	0.16	36%	No	No	No
10/22/20	Fort Shafter, HI	Command Facility		5	152,138 (14,149)	0.12	58%	Yes	Yes	No

Appendix B. Application Procedures for Surface-Applied Corrosion Inhibitor and Sacrificial Cathodic Corrosion Protection Coating Technologies

Source: Stephenson et al. (2009)

B.1. Building 306, Ring Girder Side 1 (Surtreat) Surface Preparation

Scaffolding (Figure B-1) was brought in and constructed to facilitate work in Building 306 Naha Military Port.

Figure B-1. Scaffolding in Building 306 Naha Military Port.

Existing coatings were checked for lead before they were removed. Red coloring on the detection swab would have indicated the presence of lead. The indicator turned yellow, however, meaning that no lead was present. Coatings were removed using a grinder with a dust-collection system (Figure B-2). Failed existing repairs and new delaminated areas were demolished (Figure B-3).

Figure B-2. Coatings removed using a grinder with a dust-collection system.

Figure B-3. Failed existing repairs; new delaminated areas were demolished.

Figure B-4. Concrete repair.

Figure B-5. Exposed rebar in repair areas cleaned by using wire wheel.

After the demolition and cleaning (Figures B-4 and B-5), the rust converter direct contact corrosion inhibitor was applied directly to the exposed rebar in the demolished delamination areas.

Figure B-6. Organic vapor phase corrosion inhibitor applied to all demolished delamination areas.

Organic vapor phase corrosion inhibitor was applied (Figure B-6) to all demolished delamination areas, followed as necessary by water spray to help penetration and additional water cleaning when the prescribed rate was achieved. A hand pump was used to facilitate application.

Inorganic migratory corrosion inhibitor was applied following the application of the organic vapor phase corrosion inhibitor and was also applied to all demolished delamination areas followed as necessary by water spray to help penetration and additional water cleaning when the prescribed rate was achieved.

Additional thorough cleaning of repair areas was necessary following the organic vapor phase corrosion inhibitor and the inorganic migratory corrosion inhibitor application and before placement of the concrete repairs (Figures B-7 to B-11). Additional preparations were made with regard to extra time and equipment for this task.

Figure B-7. Electrical connections to the rebar were made to facilitate future testing.

Figure B-8. Concrete was mixed from local masonry with polymer added for improved strength and durability.

Figure B-9. Concrete repairs were made following corrosion inhibitor system application to the demolished delamination areas.

Figure B-10. Concrete repairs were placed and finished in accordance with generally accepted construction practices in all locations on the ring girder side 1 (Surtreat system).

Figure B-10. Cont'd.

Figure B-11. An example of concrete repairs to ring girder side 1.

B.2. Corrosion Inhibitor System Application to Ring Girder Side 1

Following placement of the repairs, new concrete was allowed to harden and cure sufficiently as to allow the forms to be removed. Following the removal of the form and visual inspection of the newly placed patches for quality, corrosion inhibitor system application continued. System application was performed by a combination of hand pump chemical sprayer and brush:

- Organic vapor phase corrosion inhibitor was applied to the entire surface of the girder, including the repaired areas. Multiple applications were made followed by intermittent water spray to inhibit surface drying and facilitate penetration. It was necessary to clean the surface thoroughly with water before continuing with inorganic migratory corrosion inhibitor application.
- Inorganic migratory corrosion inhibitor followed the organic vapor phase corrosion inhibitor and was also applied to the entire surface of the girder ("old" and "new"). Multiple applications were made followed by intermittent water spray to inhibit surface drying and facilitate penetration. It was necessary to clean the surface thoroughly with water before continuing with application of the reactive silicone surface protection agent.
- Reactive silicone surface protection agent followed the application of the migratory and vapor phase corrosion inhibitors and was uniformly sprayed on all treated surfaces.

Surtreat system application was concluded by visually verifying that water would bead on all treated surfaces, as intended.

B.2.1. Organic Vapor Phase Corrosion Inhibitor and Inorganic Migratory Corrosion

Inhibitor was applied in sequence to all newly placed and remaining concrete surfaces on Side 1 of the Ring Girder (Figure B-12). Reactive silicone surface protection agent was applied to all newly placed and remaining concrete surfaces on Side 2 of the Ring Girder (Figure B-13).

Figure B-12. Building 306, ring girder side 1 (NASA LGC).

Figure B-13. Building 306, ring girder side 2 (NASA LGC).

Based on the specifications provided by the coating supplier, the NASA LGC was applied to clean concrete by spraying. Following demolition of the delaminated areas (see section B.1), repair areas were cleaned and patched with concrete. The concrete mix was comprised of locally available masonry and contained a measure of polymer binder for better adhesion and strength.

As the delaminated areas were fairly large (some up to 5 ft to 6 ft (1.5 m to 1.8 m) long on the girder edge), squaring and forming according to generally accepted construction practices was necessary.

During the repairs, wires were connected to the rebar to provide electrical connection between the embedded reinforcing steel and the galvanic coating to assure proper installation and performance of the LGC on Side 2 of the Ring Girder as shown in section B.2.

Following placement of the repairs new concrete was allowed to harden and cure sufficiently as to allow the forms to be removed. Following removal of the forms, a visual inspection of the patches was performed to ensure that quality repairs had been made.

Before applying the coating, three titanium mesh strips were affixed to the surface of the girder with screws. The strips were run lengthwise and connected to the wires previously connected to the embedded rebar, as described above (Figures B-14 and B-15).

B.2.2. Installation of the Titanium Mesh Component of the LGC

Figure B-14. Appearance of the Ring Girder Side 2 before application of the LGC.

Figure B-15. Appearance of the Ring Girder Side 2 immediately after application of the LGC.

An airless sprayer was used to apply the galvanic coating according to the manufacturer's specifications. Two coats were necessary. Additional touch-up was performed by brush. Paint was continuously agitated in the container by mechanical means while spraying to prevent the settling of the metal paint components, to ensure uniform distribution and prevent sprayer clogging (Figures B-16 and B-17).

Figure B-16. Finished appearance of the Ring Girder Side 2 following application of the LGC.

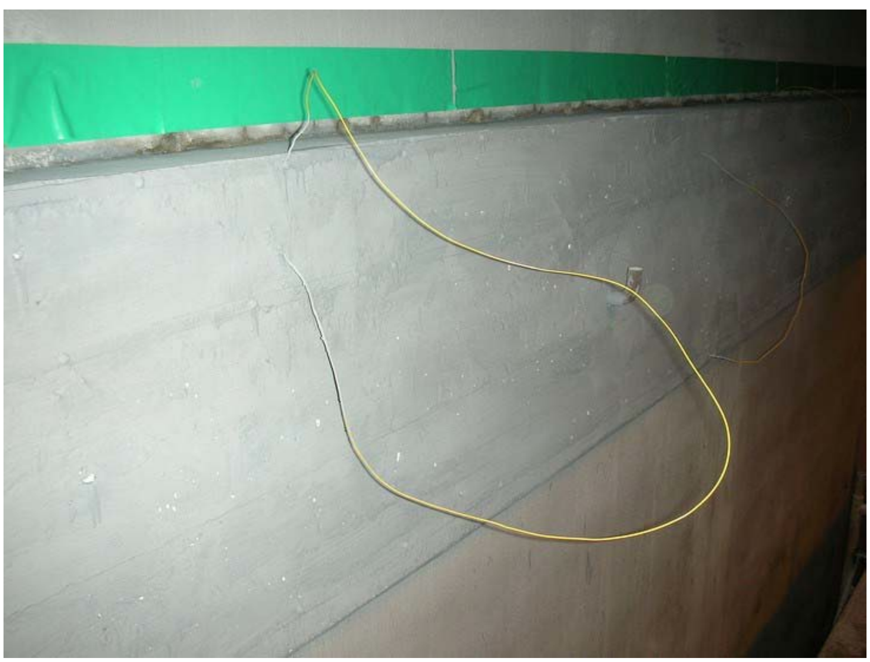


Figure B-17. The LGC application was finished when inspection showed that all concrete surfaces were uniformly covered.

Appendix C. Selected HVAC Technologies for Hot and Humid Climates

That criterion of avoiding an ERH of 80% (Reference and explanation) lasting 30 days or more is based on several long-term research efforts that are specific to real-world building systems and building materials in situ, as opposed to being based solely on laboratory studies in sealed chambers at perfect and static equilibrium with growth media engineered to be ideal for fungus and bacteria. Many comparisons between laboratory conditions and field conditions have been performed over the past 30 years in Northern Europe and North America, including those by Glass et al. (2015), Ueno (2015), Krus et al. (2010), Viitanen and Ojanen (2007), Sedlebauer (2001), Rowan et al. (1999). These referenced comparisons between models, laboratory results, and field results consistently show the threshold of concern varies according to the material and its exposure. For the robust materials inside exterior walls and the very long wetting-drying cycles endured by wood framing, plywood, or OSB inside exterior walls, the 30-day average 80% ERH upper limit is conservative (i.e., mold is very unlikely to grow even if that limit is not maintained and even when condensation occurs intermittently). However, these same comparison studies also show that for paper-based products indoors, such as the paper and cardboard faces of interior gypsum board, an ERH of 75% is still risky with respect to mold growth if accompanied by intermittently higher ERH or condensation, even if the time of being wet (time above an ERH of 75%) is less than a few hours.

Therefore, the logic for setting a threshold level than lower 80% surface ERH (0.80 aW) is the same as that for any “safety factor” used when the goal is to reduce risk in systems that have many unknowns. In short, the research shows conclusively that above 0.8 surface water activity (80% ERH) there is a risk of mold growth within 30 days. Therefore, using a threshold of concern known to be above normal levels, but also below the level of known risk is a water activity of 0.75.

Monitoring the dewpoint provides a more reliable risk indicator than monitoring the RH. Both air and surface temperatures throughout the complex spaces of any building vary widely above and below the thermostat set point temperature. So, using RH in the air as a metric of concern is highly misleading. Focusing on an RH limit leads to needless concern when the temperature of air is cool, as in the case of supply-air temperature during cooling operation. An RH focus also allows an unwarranted sense of safety when the air temperature is above normal such as in a building during summer vacation, when the indoor temperature may be quite high.

As another consideration, it is important to keep duct systems at less than saturated air conditions. It is recommended that the RH in any supply-air system duct not exceed 75% (except during start-up conditions). While sheet metal is not typically a robust growth medium for microorganisms, any surface that remains wet for long enough will become a growth medium.

C.1. Forced-Air Systems

Force-air systems can be single or multizone systems with constant or variable airflow in either case. In all cases, cooling and heating coils within the air-handling unit/furnace change the temperature and humidity of the air in some way. Fans within the AHU supply the motive force and pressure to distribute the air through ductwork to all areas served by the unit. There are many different airside topologies that can be applied in HHC depending on the application and space usage.

Single-zone air systems usually serve smaller areas than multizone and, while they can have cooling and heating heat exchangers within the single AHU, their capabilities for sophisticated control are limited. With such systems, a single AHU should serve only spaces with similar and simultaneous heating or cooling requirements. Such units can be constant or (mass, steel frame) systems, and, with the proper cooling plant technology, variable airflow will provide better humidity control. If constant volume systems are used, they should be sized to run as much as possible during peak outdoor humidity levels. Otherwise, their required OA intake will cause an unacceptable level of humidity in the spaces served when the space thermostat is satisfied (for space temperature). If the OA can be supplied by a separate system that continuously controls the dewpoint temperature of the OA supplied to the spaces served by the single-zone system, the space humidity will always be better controlled. Otherwise, single-zone systems should be avoided where they are expected to condition more than 15% OA (15% of the total supply air). Small units of this nature having chilled-water coils will be better at dealing with off-peak loads and dehumidification but may suffer due to available coil sizes and sufficient rows required for satisfactory dehumidification.

Multizone air systems can be either constant or VAV types with VAV systems being the most common commercial systems today. (Constant volume, multizone systems are rarely found in operation today other than in hospitals due to the complexity of the multiple zone dampers and duct connections at the AHUs and the low efficiency of the systems.) With VAV systems, a central AHU supplies cold air to individual zone terminal units usually consisting of a primary air damper, controller, and a small reheating coil. The terminal unit or VAV box will be controlled by a local thermostat. When the space requires cooling, the primary air damper is opened to full flow and the increased cold airflow from the AHU cools and ventilates the space. As the space temperature drops below the cooling set point, the primary air damper in the VAV box slowly closes or modulates to its minimum position to reduce cooling but to continue ventilation. If the space temperature continues to fall below the heating set point temperature, the reheat coil will be energized to warm the air supplied to the space, either to prevent overcooling or warm the space based on the room temperature. Note: the primary air from the AHU should be around 55 °F (13 °C) and approaching saturation (the dewpoint temperature will be 53 °F to 54 °F (11.7 °C to 12.2 °C) and the RH will be approaching 100%). The operation of the reheat coils at the terminal units will raise the DBT of the air supplied to the space while leaving the dewpoint temperature constant. This will lower the RH of the supply air. This operation can be forced by the system controls and used as a dehumidification mode for zones/rooms where there are latent loads (humidity sources) in spaces that need to be mitigated.

Centralized constant and variable-volume systems are the most common for large and medium sized office, healthcare, courtroom, lab, and other diversified “multizone” environments. Again, constant volume systems are less desirable in most applications due to high energy usage (except where required by code or for critical environments).

Centralized air systems offer advantages for dehumidification control based on simplifying the number of control surfaces required. Centralizing the air-handling requirements can result in fewer dedicated dehumidification systems and can offer the advantage of using exhaust energy recovery systems to reduce cooling and/or reheat energy required.

Additionally, by combining multiple zone types and uses, the diversity of VAV systems can result in more stable and continuous part-load operations, especially with well selected zone grouping. However, this can also be a source of excess OA due to the potential for zones with high occupant loads to push the whole VAV system to 100% OA during periods of low sensible cooling.

Separating the OA supply from the space cooling air supply can drastically improve this operation and reduce total OA ventilation requirements. Dual-duct VAV boxes are one method of accomplishing this. (One side of the terminal unit controls the cooling supply airflow based on space temperature while the other controls the OA supply based on occupancy or other parameters.)

Where the outside airflow is part of the total supply air from a single AHU, VAV zones with high OA requirements must be designed so that the minimum airflow is not less than 200% of the outside airflow required for the space/zone. This often results in VAV terminal units that have very little turn down and require reheating most of the time (in these specific zones). This is great for humidity control but bad for energy conservation. However, increased minimum airflow to one critical zone is still more efficient than having an entire VAV system that requires nearly 100% OA and the resulting cooling load increase.

There are several important design considerations for centralized constant and variable-volume systems in HHC.

1. As with all system designs in HHC, dehumidification control should be decoupled from space comfort control, wherever practical using DOAS units or preconditioning the OA stream to the main AHU. This may require separate dehumidification equipment to pretreat the outdoor air stream, which introduces most of the dehumidification capacity into buildings. Or it can be accomplished using specialized energy recovery designs in the air handlers. If space sources of humidity are expected such as cooking, light laundry, or wet cleaning, the DOAS supply-air dewpoint temperature should be lowered to account for the humidity being added to the space.
2. Care should be taken to ensure the building envelope is positively pressurized across all zones/ systems and operating modes (occupied/unoccupied/standby). This requires analysis of the exhaust and OA flow introduction throughout the building and under the different operating modes. These different flow requirements for various modes should be included on the design mechanical schedules for the ventilation equipment and in the sequences of operation for the HVAC controls.
3. Adequately designed and well thought out and implemented control sequences of operation are critical to the success of centralized air-handling systems. More discussion of controls and sequences of operation can be found in section 5.4.1.

C.2. Dedicated Outside Air System (DOAS)

A DOAS is a mechanical system that is specifically designed to deliver 100% filtered, dehumidified/humidified, cooled/heated OA to each individual space in the building via its own duct system.

As a rule, a DOAS operates at constant volume. For most applications, the DOAS is not capable of meeting all the thermal loads in the space by itself and requires a parallel system to accommodate any sensible and latent loads the DOAS cannot accommodate. The DOAS must not be confused with what is commonly called a 100% OA system, the flow rate of which is selected to meet the entire building sensible and latent loads, and which generally delivers only about 20% as much air to a space as a 100% OA system.

The thermodynamic state of the delivered air varies, but as a minimum it should condition the air to the desired space DPT, thus decoupling much of the latent load from the parallel system charged with the bulk of the space sensible load control.

Figure C-1 illustrates the concept of DOAS.

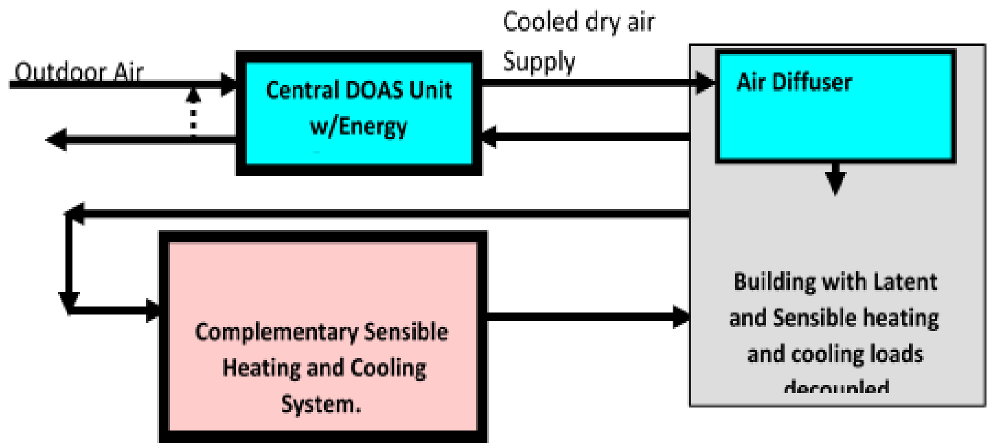


Figure C-1. Basic DOAS schematic with exhaust energy recovery.

There are concerns about the use of radiant cooling systems in HHC due to potential condensation on cold surfaces that prevented the widespread adoption of radiant cooling. This perceived limiting factor is accentuated in high humidity areas such as Southeast Asia. There is, however, significant evidence that proves these concerns are a thing of the past and that a well-designed radiant cooling system is effective in most climates (Robert Cubick 2016). Condensation occurs when the surface temperature of a cooling panel or slab is equal to or below the dewpoint.

The simulation results described by Zhen Tian and James Love (2009 and field tests conducted by Chang-Ho Jeong et al. 2018) indicate that the radiant slab cooling in hot-humid climates can be used when supply air is dehumidified to prevent condensation and the building envelope is very airtight to reduce infiltration rate through building envelope.

Simmonds et al. (2000) describe a successful implementation of a variable-volume displacement conditioning system in combination with a radiant cooled floor in concourses of the Bangkok International Airport (Thailand) (DOE c.z. 0a). The concourses and main terminals contain 1.6 million square feet of radiant cooling. With the supply water temperature of 53.6 °F (12 °C), and the return temperature 64.4 °F (18 °C), the floor surface temperature is maintained around 69.8 °F (21 °C) and with a dewpoint of 50.0 °F (10 °C), there is no condensation. Control strategies were established to optimize energy consumption and contain moisture levels within specified limits.

Another example of radiant cooling system is at the commercial building of Infosys IT company in Hyderabad, India (DOE c.z. 0a), having a total built-up area of about 258,240 ft^2 (24000 m^2). The building is split into two identical halves – one with a conventional highly efficient VAV air-conditioning system (surpassing ASHRAE Standard 90.1 baseline by about 30%) and the other with radiant cooling. About 85% of the total building area is an air-conditioned office area and the total occupancy of the building is about 2500. Both parts of the building have highly efficient building envelopes. The radiant cooling system controlling sensible heat has pipes embedded in the slab with the surface temperature being maintained at about 68 °F (20 °C). Cooling inside the office space is achieved when the cold slab absorbs the heat (radiation) generated by people, computers, lighting, and other equipment which are exposed to the slab. Fresh air is supplied by the DOAS to maintain a healthy indoor environment and to control the moisture inside the office space. The building construction has been completed and the building achieved full occupancy in February of 2011. The comparison results of monitoring of both sides of the building during the period between April 2011 and March 2012 allowed to conclude that

- Radiant cooling system is easier to build since it requires less equipment, and the overall cost of the system is slightly lower than the conventional air-conditioning system.
- Radiant cooling system occupies just one-third of the space compared to the conventional air-conditioning system.
- The efficiency of the radiant cooling system is about 33% better than a highly efficient conventional air-conditioning system.
- Radiant cooling system provides a better IAQ and thermal comfort compared to conventional air-conditioning.

C.3. Condenser-Water Energy Recovery

Condenser-water energy recovery can be used in certain chilled-water and heat pump applications where a hydronic condenser-water loop is available. Energy recovery coils can be placed in both the precool and reheat positions as shown in Figure C-2. Condenser-water heat recovery can be used for both centralized DOAS pretreatment solutions and distributed AHU energy recovery.

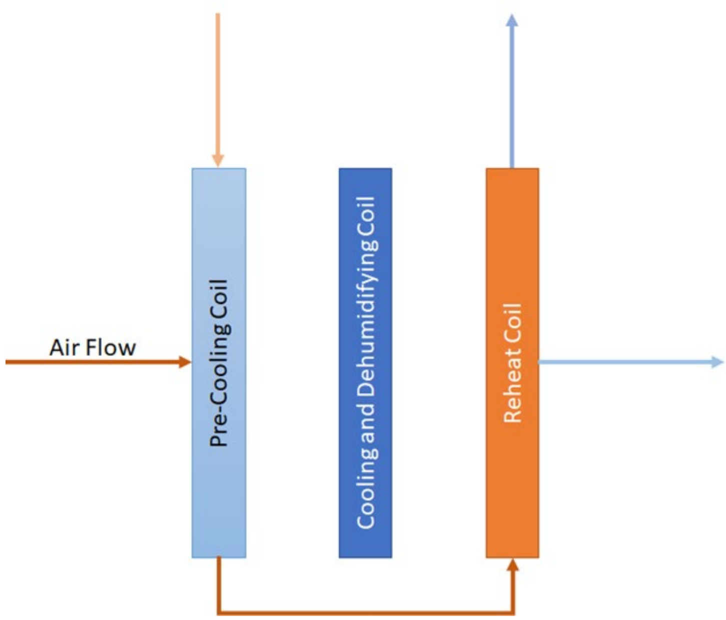


Figure C-2. Energy recovery coils placed in both precool and reheat positions.

There are two types of heat recovery chillers. Both can produce condenser-water from 105 °F to 115 °F (41 °C to 46 °C) rather than the normal 95 °F (35 °C). Figure C-3 shows the piping arrangement for a single condenser heat recovery. Typically, a heat exchanger is used to transfer the heat from the condenser loop into the hot water loop. This is done to avoid contamination from the open tower condenser loop entering the hot water loop. Using a heat exchanger introduces another approach into the system since the condenser water must be about 2 °F (3.6 °C) warmer than the hot water loop.

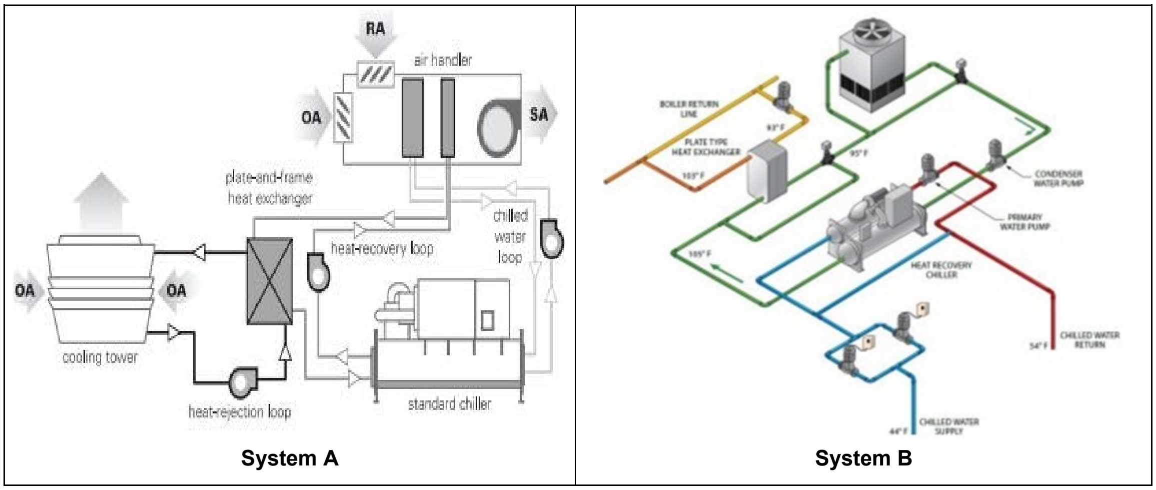


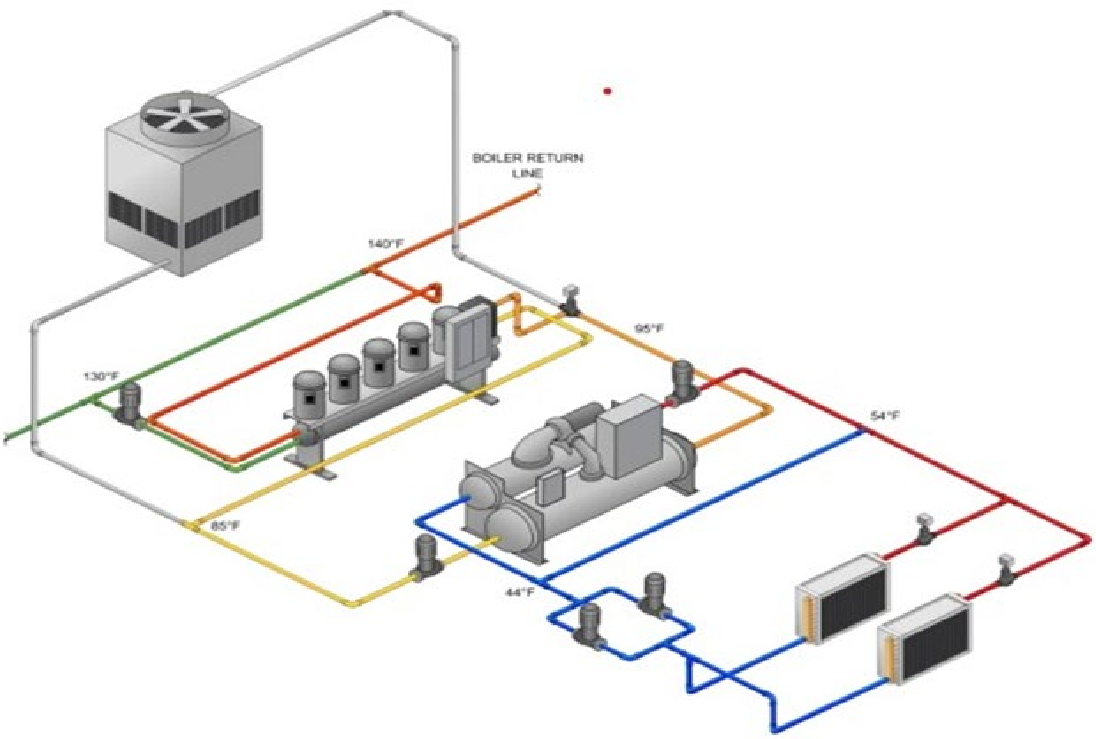
Photo courtesy of Daikin Applied.

Figure C-3. Single Condenser Heat Recovery: System A, Trane condenser-water heat recovery using a plate-and-frame heat exchanger; System B, Daikin water-cooled chiller with heat recovery used for air reheat and contributing to domestic water heating.

The second type has an additional condenser shell that allows the rejected heat to be rejected to a separate heat recovery water loop. Since the hot water loop is heated directly by the refrigerant, warmer water is possible for the same condensing pressure (compressor work) than with single condenser recovery (Figure C-3). The use of heat recovery will heat the water between 105 °F to 115 °F (41 °C to 46 °C). Hot water can be used for air reheat, DHW, and for charging TES for future use. Whereas single row heating coils in terminal heating units would have worked with a conventional design, now 3- or 4-row heating coils may be required. These coils will add to the capital cost of the project. Further, they will increase the fan static pressure drop every hour the fan system operates. DHW systems range from 120 °F (49 °C) for showers, baths, etc. to 140 °F (60 °C) for kitchens. These temperatures exceed the capabilities of a heat recovery chiller; however, a heat recovery chiller can be used for preheating. When heat recovery is used for DHW, local codes may require an isolating heat exchanger.

Functioning as a Heat Pump Water Heater, a Templifier™ is designed to economically turn waste heat into useful heat by providing hotter water than a typical chiller's condenser is capable of. It can produce hot water in the 140 °F to 160 °F (60 °C to 71 °C) range with a COP between 3 and 5. Templifiers can be used in any application where heat recovery chillers are considered. Figure C-4 shows a Templifier used in a chiller plant system. In this arrangement, the Templifier can produce 140 °F to 160 °F (60 °C to 71 °C) from the heat of rejection of the chiller.

Daikin Templifier



Piping schematic of Daikin Templifier™ application for air reheat
Photos used courtesy of Daikin Applied.

Figure C-4. Chiller heat recovery using Templifier.

When heat recovery is not required, the refrigerant condensing temperature and pressure can be lowered, and the heat rejected to the cooling tower at the typical condenser-water temperature range. This reduces the compressor work and increases the chiller efficiency.

Appendix D. Mass Building Cooling Failure Results

Table D-1. Miami mass building cooling failure-(2019 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		71608.8	67.36016	68.61228	62.28836	70.49924	69.45908	67.39178
214		71679.7	67.3885	68.91406	62.39913	70.84859	69.79472	68.03127
215		71483.6	67.06211	69.16147	62.3656	70.97306	69.92307	68.89465
216	1	0	68.9702	70.07908	71.32251	72.23689	71.97387	70.18255
217	2	0	69.98412	70.68864	75.48357	72.95315	72.9528	70.93065
218	3	0	71.3004	71.62671	78.75234	73.86715	74.02979	72.0546
219	4	0	72.36922	72.4385	80.37213	74.32809	74.53137	73.03503
220	5	0	73.15415	73.10847	81.31433	75.08743	75.23167	73.79041
221	6	0	74.12472	74.08455	82.40745	76.40444	76.40388	74.78107
222	7	0	74.86567	74.82409	82.87282	76.61012	76.55383	75.53452
223	8	0	77.62778	75.12804	83.14972	77.65218	77.54108	75.86371
224	9	0	78.50608	75.39258	83.44942	78.91468	78.68209	76.14241
225	10	0	80.79453	79.24413	86.36064	81.11568	80.74335	79.45311
226	11	0	81.82391	81.45697	87.43206	82.10503	81.66079	80.85503
227	12	0	82.45975	82.50254	88.09537	82.73982	82.26405	81.77045
228	13	0	84.78349	82.4267	88.48405	82.44534	81.9893	82.38657
229	14	0	85.51742	82.52172	88.8057	82.44537	82.01839	82.98809
230	15	0	84.13984	83.33477	89.13385	83.39645	82.99966	83.42339
231	16	0	82.83974	83.65442	89.40694	83.87206	83.56042	83.83411
232	17	0	82.6207	84.00394	89.78735	84.37061	84.07117	84.30655
233	18	0	82.56611	83.67694	88.41194	83.2992	83.24969	84.69698
234	19	0	83.76695	81.30609	88.05184	81.96389	82.04665	85.04264
235	20	0	85.42607	80.28423	87.87447	80.41925	80.48508	85.21761
236	21	0	85.71224	79.73995	87.75343	79.57128	79.78964	85.3776
237	22	0	86.49625	79.40912	88.07825	79.70685	80.03759	85.76688
238	23	0	85.25558	79.36403	88.28571	79.83643	80.21229	83.79578
239	24	0	82.77757	79.33076	88.38454	79.83305	80.23539	82.80972
240	25	0	81.58018	79.28391	87.93008	79.78374	80.17354	82.29755
241	26	0	80.3362	78.91275	87.2796	78.81445	79.22669	81.60442
242	27	0	79.43917	78.36101	86.54338	77.84358	78.26215	80.98262
243	28	0	78.91914	78.15504	86.40604	77.81514	78.14677	80.67439
244	29	0	78.7845	78.26188	86.78131	78.46952	78.70087	80.66592
245	30	0	78.96748	78.69063	87.43379	79.36554	79.45074	80.94438
246	31	0	78.96847	78.88676	87.52992	79.36799	79.36076	81.00987
247	32	0	80.96706	79.00556	87.63736	80.37403	80.26959	81.06444

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
248	33	0	81.77071	79.14652	87.78898	81.85875	81.64095	81.13782
249	34	0	83.67039	82.31049	90.27864	84.28709	83.80174	84.10961
250	35	0	84.49465	84.31357	91.12434	85.26997	84.66945	85.33443
251	36	0	85.0695	85.53494	91.62398	85.96945	85.27885	86.27254
252	37	0	86.9826	85.31057	91.79802	85.51778	84.84682	86.62211
253	38	0	87.45214	85.32154	91.98458	85.47568	84.82837	86.95114
254	39	0	86.27596	85.93762	92.21303	86.32079	85.68793	87.27308
255	40	0	85.09595	86.16084	92.36987	86.69322	86.13053	87.56686
256	41	0	84.79342	86.43696	92.6406	87.10558	86.54659	87.91357
257	42	0	84.699	86.12749	91.31069	85.87182	85.59035	88.16914
258	43	0	85.64844	84.36285	90.89986	84.4183	84.27727	88.3377
259	44	0	87.12412	83.34199	90.65057	82.64194	82.49507	88.40318
260	45	0	87.3187	82.55262	90.43672	81.74985	81.73411	88.44519
261	46	0	88.03376	82.10207	90.68013	81.80795	81.85627	88.70393
262	47	0	86.80083	81.98674	90.85674	81.9153	81.99505	86.36514
263	48	0	84.49054	81.8666	90.92809	81.89343	81.98157	85.14876
264	49	0	83.30798	81.80009	90.4352	81.80327	81.85954	84.89261
265	50	0	82.0704	81.37682	89.70036	80.82885	80.87939	84.29021
266	51	0	81.21113	80.78472	88.90224	79.8663	79.89716	83.64602
267	52	0	80.68945	80.55423	88.71478	79.78803	79.72933	83.28635
268	53	0	80.53926	80.64098	89.05886	80.39264	80.23405	83.22906
269	54	0	80.69222	81.00758	89.67539	81.20305	80.90989	83.43423
270	55	0	80.67046	81.14534	89.72957	81.15887	80.77625	83.43553
271	56	0	82.43572	81.24092	89.80134	82.06401	81.60748	83.44797
272	57	0	83.51417	81.40638	89.96912	83.51284	82.94337	83.50543
273	58	0	85.18681	84.15907	92.26616	85.99031	85.24647	86.2579
274	59	0	85.92813	86.06654	93.02068	86.99297	86.04769	87.47465
275	60	0	86.4669	87.32481	93.46767	87.70792	86.63025	88.39735
276	61	0	88.20792	87.13914	93.59022	87.19012	86.1513	88.69383
277	62	0	88.60215	87.11448	93.7235	87.08391	86.08025	88.9612
278	63	0	87.48155	87.64429	93.91032	87.91533	86.91586	89.23506
279	64	0	86.35289	87.81294	94.01422	88.23383	87.31513	89.46685
280	65	0	86.05619	88.02826	94.24035	88.57874	87.67687	89.75543
281	66	0	85.94243	87.71255	92.96533	87.25276	86.65656	89.95604
282	67	0	86.8991	85.77517	92.49799	85.43547	85.06945	90.09326
283	68	0	88.17939	84.60009	92.21564	83.73101	83.27399	90.11797
284	69	0	88.26987	84.21023	91.98246	83.05416	82.68574	90.07897
285	70	0	88.92985	83.80598	92.20136	83.13261	82.81481	90.29222

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
286	71	0	87.76596	83.68194	92.36011	83.22639	82.93781	87.97237
287	72	0	85.30689	83.56657	92.39321	83.17996	82.89532	86.87473
288	73	0	84.34013	83.47102	91.90882	83.07418	82.75822	86.51783
289	74	0	83.35369	83.06859	91.1428	82.08437	81.7548	85.93179
290	75	0	82.36139	82.5203	90.30569	81.14249	80.78736	85.21157
291	76	0	81.8531	82.29797	90.11105	81.04423	80.60175	84.83585
292	77	0	81.67453	82.36182	90.43456	81.61403	81.07722	84.73982
293	78	0	81.80328	82.6763	91.0321	82.37816	81.71738	84.89805
294	79	0	81.74947	82.77819	91.07015	82.31544	81.57003	84.86639
295	80	0	83.36174	82.85987	91.12628	83.18004	82.37167	84.85854
296	81	0	84.4308	83.00075	91.27536	84.52723	83.62218	84.8884
297	82	0	86.05099	85.37557	93.46835	86.9385	85.90824	87.53339
298	83	0	86.8753	87.51736	94.25795	88.15861	86.87664	88.9136
299	84	0	87.37408	88.68028	94.62585	88.81905	87.43885	89.74907
300	85	0	88.97703	88.39627	94.71383	88.20587	86.89335	89.97576

Table D-2. Miami mass building cooling failure-(2013 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		75228.2	67.58451	69.77763	62.71289	70.76999	69.8014	68.29821
214		75272.1	67.73086	70.16783	62.83785	71.12595	70.15347	69.24199
215		75060.6	67.78477	70.43539	62.79749	71.2379	70.27965	70.4091
216	1	0	69.8908	71.24703	71.77585	72.36837	72.17087	71.5883
217	2	0	70.99708	71.79498	75.8302	73.01411	73.05112	72.25542
218	3	0	72.41455	72.64587	78.84447	73.85516	74.01816	73.26144
219	4	0	73.45374	73.31567	80.16058	74.25253	74.43282	74.05727
220	5	0	74.22358	73.96098	80.9965	75.05516	75.17568	74.74196
221	6	0	75.24409	75.0191	82.07805	76.41894	76.39466	75.75615
222	7	0	75.81983	75.63243	82.42246	76.57613	76.50699	76.33289
223	8	0	78.25018	75.87003	82.68156	77.60947	77.48607	76.58249
224	9	0	78.92763	76.11811	82.98721	78.85068	78.61669	76.8367
225	10	0	80.99735	79.62817	85.92482	81.01787	80.64893	79.95098
226	11	0	81.88245	81.58147	86.98315	81.96317	81.5463	81.20274
227	12	0	82.40691	82.44131	87.61404	82.54549	82.11584	81.95102
228	13	0	84.62135	82.24586	87.96788	82.21809	81.8156	82.40789
229	14	0	85.29822	82.26447	88.26438	82.21611	81.85226	82.82323
230	15	0	83.8861	83.06079	88.58701	83.14842	82.82105	83.16919

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
231	16	0	82.54908	83.3564	88.83872	83.58953	83.37128	83.5051
232	17	0	82.27946	83.7254	89.23689	84.1041	83.8745	83.94119
233	18	0	82.19492	83.34613	87.79464	83.00753	83.06866	84.24889
234	19	0	83.39445	80.84283	87.36672	81.66315	81.81894	84.48038
235	20	0	85.04408	79.71658	87.12671	80.10248	80.19731	84.5385
236	21	0	85.30082	79.08903	86.96486	79.28389	79.52484	84.59065
237	22	0	86.07711	78.83023	87.32546	79.50803	79.83847	84.97994
238	23	0	84.65091	78.84672	87.54765	79.64912	80.01501	82.6433
239	24	0	81.99506	78.84103	87.63901	79.63165	80.01826	81.51569
240	25	0	80.7614	78.82011	87.11494	79.55085	79.91357	81.3202
241	26	0	79.36478	78.30354	86.28065	78.44456	78.81818	80.64788
242	27	0	78.3296	77.53507	85.41877	77.41743	77.79034	79.88922
243	28	0	77.89207	77.35542	85.29316	77.41273	77.69476	79.61025
244	29	0	77.97413	77.63293	85.75507	78.12648	78.31267	79.7648
245	30	0	78.43479	78.29142	86.49005	79.05695	79.10373	80.27003
246	31	0	78.52505	78.55191	86.54855	79.01797	78.97935	80.39394
247	32	0	80.52171	78.71221	86.66356	80.02322	79.90021	80.4926
248	33	0	81.61506	78.98151	86.89261	81.63838	81.38029	80.67231
249	34	0	83.39513	82.12451	89.4499	83.91812	83.43795	83.56511
250	35	0	84.15771	84.03316	90.30075	84.82462	84.2485	84.81104
251	36	0	84.64116	85.08804	90.77872	85.41461	84.76845	85.64275
252	37	0	86.5439	84.78079	90.9342	84.9328	84.31386	85.90187
253	38	0	87.01044	84.75965	91.11041	84.89625	84.31127	86.16039
254	39	0	85.78415	85.38178	91.33624	85.72424	85.16019	86.4314
255	40	0	84.53583	85.58824	91.47661	86.06417	85.59485	86.66815
256	41	0	84.20122	85.85639	91.74721	86.45431	85.9794	86.96138
257	42	0	84.0745	85.50108	90.36109	85.23554	85.06333	87.17413
258	43	0	85.10789	83.18201	89.84054	83.59374	83.5603	87.27283
259	44	0	86.57037	81.75635	89.53608	81.78401	81.69782	87.24514
260	45	0	86.69163	81.32231	89.29831	81.14429	81.15327	87.16683
261	46	0	87.40389	81.00409	89.57936	81.30645	81.36701	87.4422
262	47	0	86.05505	80.96709	89.7453	81.4069	81.49108	85.04651
263	48	0	83.50815	80.91604	89.7814	81.35899	81.44606	83.87674
264	49	0	82.22494	80.86366	89.2351	81.24899	81.30042	83.6437
265	50	0	80.85805	80.31712	88.33012	80.14912	80.18747	82.93091
266	51	0	79.85889	79.63747	87.40377	79.12912	79.14384	82.1401
267	52	0	79.3798	79.4474	87.24218	79.07288	78.99589	81.79832
268	53	0	79.439	79.69135	87.68347	79.73542	79.56448	81.89929

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
269	54	0	79.85415	80.27222	88.39413	80.58281	80.28465	82.33179
270	55	0	79.90997	80.45486	88.40642	80.49977	80.11901	82.38836
271	56	0	81.74959	80.59163	88.48285	81.42027	80.97015	82.44827
272	57	0	82.84761	80.81604	88.67295	82.8479	82.30893	82.57339
273	58	0	84.56395	83.57864	91.09662	85.28036	84.5372	85.31934
274	59	0	85.30469	85.50267	91.8886	86.2373	85.33853	86.56065
275	60	0	85.78152	86.60465	92.32468	86.84549	85.84966	87.37905
276	61	0	87.55556	86.32121	92.43439	86.31184	85.35381	87.59547
277	62	0	87.96269	86.26497	92.56265	86.21732	85.30511	87.79678
278	63	0	86.77954	86.80908	92.75114	87.03133	86.13345	88.02366
279	64	0	85.56985	86.96867	92.84326	87.33056	86.53389	88.20366
280	65	0	85.2317	87.19073	93.07362	87.66455	86.88272	88.44479
281	66	0	85.07905	86.8129	91.70662	86.33697	85.89336	88.59874
282	67	0	85.96274	84.97556	91.21918	84.75458	84.45168	88.66172
283	68	0	87.31483	83.82889	90.86668	83.05177	82.67133	88.56039
284	69	0	87.45007	82.90259	90.5688	82.24551	81.9356	88.44688
285	70	0	88.12885	82.4715	90.82204	82.37795	82.11687	88.68628
286	71	0	86.81874	82.41456	90.96665	82.45873	82.21994	86.29517
287	72	0	84.34906	82.34265	90.9728	82.38858	82.15123	85.14913
288	73	0	83.0649	82.28229	90.41572	82.2589	81.98605	84.88866
289	74	0	81.7516	81.75211	89.46891	81.15362	80.86184	84.14998
290	75	0	80.7543	81.09149	88.51657	80.14356	79.82141	83.35238
291	76	0	80.26729	80.87965	88.33535	80.06238	79.65276	82.98753
292	77	0	80.30758	81.09621	88.76212	80.69351	80.1963	83.05995
293	78	0	80.69279	81.63126	89.46063	81.49767	80.88411	83.45367
294	79	0	80.73412	81.78236	89.4599	81.39805	80.70664	83.47916
295	80	0	82.48519	81.90485	89.52213	82.28856	81.53374	83.52387
296	81	0	83.54671	82.10401	89.69601	83.62612	82.80076	83.62591
297	82	0	85.23251	84.57762	92.04578	86.00314	85.09072	86.28288
298	83	0	85.95641	86.40941	92.80288	87.01677	85.88538	87.49501
299	84	0	86.42528	87.55181	93.21683	87.65572	86.39056	88.30248
300	85	0	88.13239	87.28205	93.30633	87.08181	85.87768	88.49716

Table D-3. Miami mass building cooling failure-(pre-1980 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		95288.0	68.63754	71.90955	64.54411	71.58065	70.82887	70.9381
214		94898.8	69.21271	72.27139	64.73003	71.93472	71.19971	72.32363
215		94492.6	70.17992	72.34912	64.64689	71.94765	71.24305	73.27613
216	1	0	72.31205	72.52427	73.23802	72.66735	72.74766	73.46734
217	2	0	73.15838	72.81268	76.31792	73.14143	73.37311	73.67379
218	3	0	73.93655	73.37685	77.83134	73.77973	74.01391	74.14166
219	4	0	74.34377	73.7123	78.42356	74.03527	74.25877	74.40775
220	5	0	75.27184	74.73017	79.5154	75.23103	75.37897	75.3521
221	6	0	76.37876	76.04688	80.61997	76.46911	76.48096	76.50938
222	7	0	76.38891	76.15858	80.63011	76.44565	76.42054	76.54903
223	8	0	78.36352	76.46592	81.00565	77.53493	77.4752	76.86149
224	9	0	78.93703	76.85026	81.40215	78.67596	78.54113	77.24162
225	10	0	80.82478	79.78901	84.32269	80.66629	80.44114	80.00245
226	11	0	81.57953	81.27647	85.23821	81.44628	81.22704	80.97961
227	12	0	82.00331	81.87498	85.73698	81.89598	81.70439	81.50833
228	13	0	83.93575	81.43212	85.9149	81.49935	81.35918	81.69937
229	14	0	84.38675	81.46221	86.16133	81.61523	81.53785	81.97124
230	15	0	83.03959	82.19688	86.4726	82.44617	82.45285	82.31908
231	16	0	81.57654	82.34797	86.60699	82.7062	82.91173	82.53458
232	17	0	81.48076	82.65342	86.97198	83.11191	83.30283	82.91303
233	18	0	81.41626	82.09127	85.3765	81.97192	82.55373	83.03994
234	19	0	82.33994	79.80576	84.85201	80.80709	81.38536	82.97604
235	20	0	83.77254	78.54424	84.36515	79.20956	79.62318	82.64806
236	21	0	83.8968	77.85567	84.10439	78.63927	79.13584	82.43277
237	22	0	84.64565	78.18691	84.63692	79.14128	79.6756	82.94857
238	23	0	83.09641	78.2888	84.71566	79.16705	79.72427	80.91345
239	24	0	80.27049	78.22465	84.6485	79.05306	79.61671	80.1278
240	25	0	79.16695	78.12565	84.01949	78.91731	79.45841	79.82407
241	26	0	77.64583	76.92068	82.54392	77.44073	78.01766	78.5883
242	27	0	76.81342	76.12756	81.53444	76.61994	77.19621	77.743
243	28	0	76.43114	75.83368	81.11938	76.35976	76.88509	77.33807
244	29	0	77.04129	76.54971	81.99708	77.22263	77.64491	77.91969
245	30	0	77.71621	77.36443	82.91499	77.99752	78.28754	78.5909
246	31	0	77.87526	77.64593	83.12872	78.08768	78.28058	78.73309
247	32	0	79.67165	77.94218	83.39192	79.06868	79.19978	78.95278
248	33	0	80.62666	78.3708	83.75242	80.43041	80.47179	79.28665
249	34	0	82.3941	81.2439	86.48972	82.5858	82.46108	81.89782

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
250	35	0	83.10236	82.86171	87.30055	83.31925	83.17065	82.98708
251	36	0	83.4731	83.4837	87.68981	83.69435	83.55089	83.49232
252	37	0	85.24731	83.00604	87.76403	83.1894	83.08688	83.58047
253	38	0	85.6386	82.97601	87.91145	83.21566	83.16673	83.75849
254	39	0	84.32738	83.62162	88.13314	83.98322	84.00311	84.01697
255	40	0	82.85454	83.72255	88.18211	84.17438	84.38399	84.14511
256	41	0	82.67525	83.95383	88.45152	84.48125	84.67131	84.41479
257	42	0	82.57704	83.37574	86.84185	83.21664	83.82133	84.46612
258	43	0	83.48795	80.76801	86.18087	81.72282	82.33924	84.27728
259	44	0	84.77753	79.42217	85.65035	80.21231	80.64658	83.85269
260	45	0	84.79738	78.95898	85.31536	79.72101	80.20289	83.4792
261	46	0	85.49227	79.28121	85.77982	80.17904	80.68089	83.88888
262	47	0	83.96002	79.37576	85.81538	80.17538	80.68704	81.86015
263	48	0	81.11148	79.31398	85.69969	80.0293	80.53456	81.23422
264	49	0	80.0668	79.22595	85.00467	79.8631	80.33592	80.91457
265	50	0	78.60792	78.06734	83.34354	78.35912	78.85233	79.64302
266	51	0	77.74484	77.30249	82.24121	77.54201	78.02164	78.77502
267	52	0	77.33672	76.99929	81.81102	77.25262	77.67706	78.33182
268	53	0	77.91666	77.68154	82.62016	78.06931	78.39046	78.87309
269	54	0	78.87766	78.80008	84.06828	79.08511	79.25585	79.81879
270	55	0	78.76434	78.76177	83.99774	78.87474	78.97413	79.67352
271	56	0	80.34583	78.95681	84.19294	79.75816	79.80141	79.78951
272	57	0	81.26067	79.31516	84.53257	80.98063	80.9659	80.05688
273	58	0	83.04877	81.95539	87.26487	83.20037	83.06775	82.57435
274	59	0	83.74455	83.62112	88.05215	83.97982	83.75375	83.65684
275	60	0	84.11366	84.27621	88.42069	84.36446	84.12296	84.16694
276	61	0	85.82061	83.78771	88.46291	83.81879	83.62335	84.22462
277	62	0	86.18511	83.72945	88.58108	83.81218	83.67389	84.37036
278	63	0	84.8978	84.33863	88.7795	84.56898	84.4965	84.60462
279	64	0	83.5825	84.41078	88.80551	84.72992	84.83554	84.70007
280	65	0	83.34306	84.62018	89.05802	85.01877	85.12074	84.95576
281	66	0	83.11079	83.99834	87.41995	83.67364	84.21503	84.95576
282	67	0	83.91167	81.64156	86.76762	82.22943	82.78645	84.73609
283	68	0	85.16391	80.3362	86.17158	80.73398	81.08871	84.22021
284	69	0	85.2014	79.66882	85.80496	80.20704	80.59327	83.83139
285	70	0	85.8811	79.98348	86.25003	80.65175	81.05656	84.25111
286	71	0	84.36635	80.06729	86.26954	80.63778	81.05027	82.31426
287	72	0	81.50657	79.99169	86.13043	80.47652	80.88114	81.69337

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
288	73	0	80.52036	79.88917	85.3879	80.29581	80.66705	81.35423
289	74	0	79.06552	78.72974	83.65691	78.78791	79.17555	80.06835
290	75	0	78.20617	77.97146	82.62872	77.97049	78.3424	79.19746
291	76	0	77.7859	77.65365	82.20889	77.66547	77.98386	78.73851
292	77	0	78.34758	78.31139	82.97771	78.46217	78.68087	79.26165
293	78	0	79.22536	79.32742	84.29765	79.39222	79.47155	80.12534
294	79	0	79.07708	79.2494	84.27097	79.16622	79.1745	79.94476
295	80	0	80.64086	79.48272	84.51495	80.07781	80.0326	80.09772
296	81	0	81.51982	79.84229	84.872	81.26668	81.16861	80.37234
297	82	0	83.35829	82.35638	87.61572	83.42014	83.23051	82.85258
298	83	0	84.04951	84.01324	88.39725	84.26379	83.96471	83.92883
299	84	0	84.40968	84.67513	88.75314	84.65886	84.33829	84.43591
300	85	0	86.09363	84.18388	88.78688	84.09799	83.82922	84.48618
301	86	0	86.44596	84.11285	88.89578	84.07993	83.87289	84.62353
302	87	0	84.98399	84.76411	89.08604	84.90608	84.75385	84.85323
303	88	0	83.66063	84.76939	89.09216	84.99748	85.04684	84.92908
304	89	0	83.47205	84.94356	89.32835	85.25308	85.29408	85.16061
305	90	0	83.32635	84.31325	87.69775	83.87924	84.37556	85.15933
306	91	0	84.13186	81.96873	87.0286	82.42107	82.94036	84.91669
307	92	0	85.37262	80.7096	86.42161	80.97002	81.25861	84.38777
308	93	0	85.396	80.06151	86.04327	80.44953	80.76298	84.00883
309	94	0	86.0714	80.37592	86.47932	80.89107	81.22353	84.42913
310	95	0	84.55109	80.44366	86.48502	80.86533	81.20605	82.50344
311	96	0	81.67434	80.35607	86.33746	80.69635	81.02985	81.89323
312	97	0	80.73939	80.24959	85.57565	80.51381	80.81454	81.55511
313	98	0	79.2991	79.09885	83.84431	79.01225	79.32796	80.27522
314	99	0	78.43368	78.33418	82.84336	78.18833	78.48792	79.39686
315	100	0	78.01006	78.01032	82.43084	77.87941	78.12694	78.93437
316	101	0	78.56367	78.65551	83.18508	78.66621	78.81683	79.45041
317	102	0	79.43324	79.65501	84.42458	79.58606	79.60172	80.30697
318	103	0	79.27451	79.56278	84.4327	79.34989	79.2962	80.11595
319	104	0	80.80885	79.78696	84.68563	80.25219	80.14814	80.26289
320	105	0	81.65276	80.13447	85.04575	81.42313	81.27203	80.53034
321	106	0	83.506	82.57867	87.79919	83.55538	83.31813	82.99124
322	107	0	84.21111	84.23801	88.59049	84.43052	84.07793	84.08712
323	108	0	84.54976	84.78345	88.91525	84.79173	84.43739	84.52005
324	109	0	86.23677	84.37705	88.96243	84.24626	83.9353	84.62119
325	110	0	86.57594	84.30431	89.0596	84.21479	83.96675	84.74899

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
326	111	0	85.29643	84.89315	89.24354	84.97053	84.78427	84.9695
327	112	0	83.98006	84.94948	89.25484	85.12022	85.11565	85.05105
328	113	0	83.71699	85.12793	89.48866	85.38522	85.38467	85.28496
329	114	0	83.47231	84.47791	87.8471	83.98324	84.45584	85.26998
330	115	0	84.25999	82.1402	87.16852	82.55268	83.01732	85.01565
331	116	0	85.48772	80.91988	86.55675	81.10474	81.34707	84.4847
332	117	0	85.4958	80.27605	86.16595	80.57796	80.84727	84.10159
333	118	0	86.16718	80.58443	86.59426	81.0149	81.3038	84.517
334	119	0	84.64091	80.64694	86.59567	80.98605	81.28388	82.59795
335	120	0	81.75211	80.56009	86.44626	80.81754	81.10897	82.00214
336	121	0	80.85348	80.44649	85.66689	80.62912	80.88895	81.66019
337	122	0	79.29868	79.18159	83.78121	79.02978	79.31337	80.26405
338	123	0	78.49135	78.47511	82.90092	78.2685	78.5288	79.44528
339	124	0	78.14326	78.21774	82.5645	78.00413	78.21111	79.05096
340	125	0	78.67472	78.83788	83.28423	78.76862	78.88136	79.54531
341	126	0	79.53037	79.82011	84.49158	79.6792	79.65897	80.39004
342	127	0	79.3723	79.72646	84.50934	79.44432	79.35562	80.1999
343	128	0	80.86024	79.93797	84.7669	79.72208	79.58817	80.33173
344	129	0	81.62617	80.28262	85.13308	80.06946	79.89072	80.59517
345	130	0	83.56613	82.69701	87.88936	80.58563	80.39059	83.06108
346	131	0	84.26733	84.32388	88.65496	81.03474	80.84661	84.15061
347	132	0	84.62296	84.86495	88.96056	81.28355	81.10851	84.5796
348	133	0	86.30917	84.4482	88.99611	81.25568	81.0788	84.67027
349	134	0	86.64742	84.37257	89.0937	81.32506	81.18842	84.79651
350	135	0	85.36295	84.95805	89.2764	81.48164	81.45774	85.01311
351	136	0	84.03468	85.00914	89.28328	81.45747	81.61705	85.0885
352	137	0	83.75427	85.17641	89.51124	81.6099	81.79772	85.30885
353	138	0	83.47922	84.50294	87.85851	81.4561	81.90249	85.2642
354	139	0	84.22836	82.18344	87.17654	81.13599	81.62672	84.97771
355	140	0	85.62083	80.87434	86.51038	80.5218	80.91699	84.41048

Table D-4. Jacksonville mass building cooling failure-2019 WBGT data.

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		70935.7	67.49905	69.07413	62.31774	70.85827	70.07535	67.51124
214		71011.6	67.575	69.39334	62.42934	71.18491	70.37121	68.18955
215		70832.0	67.44859	69.64555	62.39568	71.28239	70.45113	69.12654

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
216	1	0	69.05337	70.40041	71.27617	72.29855	72.07228	70.29089
217	2	0	69.96951	70.92303	75.40535	72.92907	72.91775	70.98474
218	3	0	71.21424	71.75976	78.65644	73.7878	73.90434	72.06068
219	4	0	72.24932	72.49866	80.27258	74.24063	74.38952	73.0144
220	5	0	73.03548	73.13803	81.21466	75.01925	75.11999	73.76317
221	6	0	73.99442	74.06225	82.26228	76.30042	76.28979	74.71345
222	7	0	74.70124	74.72	82.68497	76.49291	76.44123	75.40266
223	8	0	77.47979	75.0544	83.00485	77.60677	77.51023	75.77303
224	9	0	78.8507	75.47839	83.41588	79.0882	78.89629	76.22169
225	10	0	81.0675	79.28336	86.30729	81.261	80.994	79.50438
226	11	0	82.13067	81.49728	87.3821	82.28826	82.01261	80.94704
227	12	0	82.7545	82.54766	88.0563	82.94692	82.65788	81.89214
228	13	0	85.07501	82.47469	88.45722	82.66515	82.41015	82.53016
229	14	0	85.82941	82.5645	88.79321	82.66087	82.44828	83.1477
230	15	0	84.46048	83.37107	89.13243	83.60777	83.49676	83.58957
231	16	0	83.10624	83.68711	89.41635	84.08144	84.11832	84.01189
232	17	0	82.6498	84.07802	89.82581	84.64425	84.82998	84.57301
233	18	0	82.6147	83.73412	88.45642	83.53445	83.89529	84.96082
234	19	0	83.83429	81.33427	88.10003	82.1321	82.39575	85.31991
235	20	0	85.53898	80.28397	87.93025	80.54197	80.78056	85.51701
236	21	0	85.87196	79.70986	87.81779	79.64926	79.97428	85.69713
237	22	0	86.67822	79.36202	88.14921	79.76883	80.16792	86.10679
238	23	0	85.36707	79.31174	88.38948	79.92337	80.36135	83.80125
239	24	0	82.85127	79.25756	88.52221	79.9423	80.41285	82.61735
240	25	0	81.63834	79.23215	88.04721	79.89355	80.3566	82.3957
241	26	0	80.68517	79.16548	87.89226	79.74122	80.17633	82.10047
242	27	0	80.19593	79.05176	87.67401	79.47096	79.84999	81.85542
243	28	0	79.79959	78.96889	87.55383	79.36724	79.68517	81.65379
244	29	0	79.48608	78.8815	87.43658	79.2309	79.48586	81.46385
245	30	0	79.20323	78.7838	87.28577	79.03796	79.2277	81.27464
246	31	0	79.02588	78.72622	87.21696	79.00013	79.12308	81.1307
247	32	0	81.18248	78.79974	87.30099	80.11819	80.16513	81.14337
248	33	0	82.18386	78.89374	87.34713	81.71035	81.61205	81.15345
249	34	0	83.73826	81.72698	89.52819	83.67615	83.44803	83.96765
250	35	0	84.34145	83.33023	90.12726	84.46326	84.20583	84.9914
251	36	0	84.91185	84.51393	90.71558	85.31805	85.01824	85.83472
252	37	0	86.8503	84.39523	90.99758	84.97385	84.70007	86.22756
253	38	0	87.58093	84.51849	91.31958	84.98226	84.74371	86.68773

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
254	39	0	86.48432	85.28245	91.6699	86.00117	85.84454	87.06526
255	40	0	85.46091	85.78893	92.08994	86.66119	86.65451	87.5066
256	41	0	85.03693	85.92027	92.24584	86.93248	86.99406	87.89746
257	42	0	84.70781	85.34785	90.71658	85.37597	85.57467	88.06638
258	43	0	85.77048	83.31628	90.37655	83.75273	83.96679	88.31183
259	44	0	87.46192	82.40012	90.35136	82.30232	82.51488	88.50368
260	45	0	87.75382	81.91569	90.33988	81.6885	81.95823	88.68867
261	46	0	88.27483	81.56071	90.54942	81.64575	81.92924	88.97968
262	47	0	87.15519	81.49834	90.76084	81.80383	82.11222	86.6599
263	48	0	85.01609	81.48681	90.98087	81.98957	82.31057	85.44383
264	49	0	83.8705	81.52223	90.58822	82.00732	82.29232	85.25114
265	50	0	82.91301	81.43652	90.27749	81.63511	81.87501	84.90744
266	51	0	82.35024	81.28075	89.99065	81.33531	81.52486	84.59794
267	52	0	82.04636	81.29401	90.0778	81.56776	81.68583	84.47234
268	53	0	81.92016	81.40582	90.21059	81.72147	81.75326	84.44621
269	54	0	81.7332	81.41177	90.05854	81.46292	81.42004	84.32089
270	55	0	81.58688	81.38404	89.94609	81.36014	81.25461	84.18562
271	56	0	83.14287	81.40353	89.88794	82.09084	81.92951	84.12053
272	57	0	84.64381	81.60374	90.17129	83.88566	83.65586	84.19907
273	58	0	86.52653	84.50218	92.68964	86.77211	86.43937	87.09595
274	59	0	87.03351	86.1748	93.27737	87.61254	87.13155	88.30788
275	60	0	87.17642	86.87575	93.44582	87.92439	87.39518	88.9752
276	61	0	88.87765	86.9436	93.73375	87.51326	87.04769	89.38882
277	62	0	88.86698	86.67715	93.65154	87.04345	86.68061	89.60181
278	63	0	87.9355	86.92995	93.73927	87.7596	87.43724	89.81292
279	64	0	86.99634	87.11517	93.87345	88.13841	87.8081	90.03692
280	65	0	86.64918	87.34462	94.06621	88.47762	88.14979	90.31112
281	66	0	86.68808	87.44955	93.11376	87.29781	87.13739	90.60484
282	67	0	87.80033	86.066	92.93546	85.84966	85.60279	90.89477
283	68	0	89.32678	85.36331	92.89613	84.63447	84.37003	91.04511
284	69	0	89.56114	84.90045	92.83508	84.06155	83.80303	91.16373
285	70	0	89.54582	84.40926	92.71329	83.59966	83.34914	91.22004
286	71	0	88.57921	84.28898	92.85313	83.73531	83.48553	88.88265
287	72	0	86.34795	84.26201	93.05675	83.97352	83.71314	87.81857
288	73	0	84.84229	83.81178	91.91766	82.88428	82.65038	87.0867
289	74	0	83.58935	83.13335	90.83303	81.72923	81.49314	86.2146
290	75	0	83.04169	82.87618	90.64235	81.66447	81.33946	85.79707
291	76	0	82.5835	82.66153	90.4553	81.52825	81.13556	85.43179

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
292	77	0	82.2002	82.46053	90.22762	81.26097	80.79657	85.09412
293	78	0	81.90504	82.32358	90.09274	81.12708	80.57863	84.82232
294	79	0	81.76538	82.29222	90.14072	81.24857	80.61651	84.65893
295	80	0	83.84815	82.53957	90.60564	82.79545	82.07185	84.7935
296	81	0	85.42818	82.91866	91.2064	84.80273	84.05594	85.04639
297	82	0	86.99533	85.3304	93.34307	87.23051	86.32303	87.74699
298	83	0	87.65037	87.0741	93.99843	88.20525	87.18283	88.93783
299	84	0	88.56413	88.7384	94.83483	89.32578	88.27244	90.07366
300	85	0	90.3777	88.87354	95.22868	89.06271	88.07973	90.57258

Table D-5. Jacksonville mass building cooling failure (2013 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		74507.9	67.72864	70.1872	62.74502	71.11071	70.40227	68.42799
214		74556.7	67.92474	70.58456	62.87085	71.44585	70.71964	69.41339
215		74363.1	68.18562	70.84909	62.8303	71.53242	70.80087	70.65678
216	1	0	69.96056	71.48209	71.72963	72.40856	72.23975	71.69445
217	2	0	70.94457	71.93336	75.75196	72.96931	72.98215	72.29449
218	3	0	72.26195	72.67616	78.74913	73.75774	73.85834	73.23581
219	4	0	73.2557	73.27854	80.06203	74.15139	74.26254	73.99704
220	5	0	74.03223	73.90601	80.89784	74.97517	75.03907	74.67728
221	6	0	75.04958	74.93475	81.93318	76.30245	76.26102	75.65699
222	7	0	75.62488	75.48236	82.24207	76.4549	76.37994	76.18246
223	8	0	78.05019	75.76183	82.54498	77.56419	77.45073	76.48139
224	9	0	79.15147	76.15871	82.95783	79.01834	78.8308	76.88475
225	10	0	81.19603	79.63757	85.87251	81.15011	80.89628	79.97134
226	11	0	82.15021	81.60375	86.93303	82.13658	81.89548	81.26525
227	12	0	82.66743	82.47417	87.57298	82.73982	82.48837	82.04415
228	13	0	84.89458	82.28539	87.93883	82.42474	82.21326	82.5247
229	14	0	85.59264	82.30054	88.24917	82.41785	82.25963	82.95749
230	15	0	84.18384	83.09181	88.58227	83.34713	83.32294	83.31238
231	16	0	82.78637	83.38249	88.84409	83.7793	83.91763	83.65678
232	17	0	82.31345	83.75843	89.2468	84.30907	84.60664	84.11979
233	18	0	82.26167	83.36863	87.82101	83.18396	83.65645	84.44366
234	19	0	83.45899	80.84402	87.40473	81.79436	82.08269	84.70667
235	20	0	85.15085	79.69481	87.1728	80.20034	80.44671	84.79317
236	21	0	85.44297	79.03862	87.01897	79.34101	79.67108	84.86575

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
237	22	0	86.23695	78.76611	87.3856	79.55075	79.92767	85.27589
238	23	0	84.82227	78.78463	87.6124	79.69246	80.0949	82.93732
239	24	0	82.1317	78.78511	87.70873	79.68285	80.10699	81.76939
240	25	0	80.83273	78.77374	87.18989	79.61287	80.01825	81.56342
241	26	0	79.86371	78.71957	86.98289	79.42809	79.79695	81.29688
242	27	0	79.35263	78.58726	86.7247	79.13579	79.4444	81.03942
243	28	0	78.97821	78.49809	86.59615	79.03005	79.27196	80.83949
244	29	0	78.70401	78.4013	86.46479	78.87989	79.05676	80.65163
245	30	0	78.45201	78.27961	86.29232	78.6729	78.78403	80.45052
246	31	0	78.35415	78.22717	86.22446	78.64351	78.69164	80.31745
247	32	0	80.59985	78.35378	86.33177	79.77434	79.76716	80.37685
248	33	0	81.69488	78.50028	86.38853	81.32217	81.17353	80.42116
249	34	0	83.27787	81.34311	88.63222	83.21222	82.9483	83.21619
250	35	0	83.86143	82.90103	89.2439	83.93205	83.6452	84.20582
251	36	0	84.40693	84.01958	89.85519	84.72076	84.40208	85.005
252	37	0	86.36251	83.8428	90.12778	84.35474	84.06725	85.35931
253	38	0	86.97762	83.96337	90.43843	84.44378	84.20296	85.73045
254	39	0	85.88966	84.73175	90.80288	85.41861	85.27148	86.11844
255	40	0	84.83236	85.23476	91.22282	86.04085	86.06628	86.55819
256	41	0	84.33412	85.3057	91.32659	86.22993	86.3137	86.87556
257	42	0	83.92698	84.63882	89.68103	84.62891	84.85063	86.94095
258	43	0	84.9287	82.76031	89.32652	83.21744	83.39646	87.11214
259	44	0	86.73422	81.71391	89.26457	81.74475	81.95326	87.23975
260	45	0	87.02834	80.97048	89.20351	81.09081	81.29497	87.3542
261	46	0	87.55742	80.60291	89.41255	81.08855	81.30605	87.64178
262	47	0	86.29311	80.58385	89.60837	81.2311	81.45951	85.25114
263	48	0	83.89822	80.62708	89.80215	81.39417	81.62527	84.13225
264	49	0	82.66933	80.68331	89.35293	81.38664	81.57643	83.97958
265	50	0	81.57363	80.57821	88.93302	80.97415	81.11384	83.62379
266	51	0	81.07057	80.38574	88.62685	80.63872	80.7224	83.28786
267	52	0	80.8692	80.46025	88.72905	80.87231	80.87824	83.21866
268	53	0	80.85548	80.63172	88.85806	81.00309	80.922	83.25
269	54	0	80.68773	80.60304	88.65169	80.70458	80.55022	83.0953
270	55	0	80.57816	80.5593	88.51951	80.6041	80.39354	82.94005
271	56	0	82.17796	80.58158	88.44975	81.33399	81.06947	82.88166
272	57	0	83.75284	80.87223	88.78246	83.10077	82.81222	83.05817
273	58	0	85.72926	83.80907	91.47153	85.95121	85.57308	85.98695
274	59	0	86.18561	85.48905	92.05628	86.69929	86.1784	87.18398

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
275	60	0	86.25166	86.06515	92.18439	86.90945	86.33946	87.73146
276	61	0	88.03745	86.04089	92.46856	86.48867	85.98373	88.08392
277	62	0	87.98064	85.66219	92.32615	85.95574	85.54845	88.16749
278	63	0	86.94337	85.9296	92.39251	86.64017	86.29677	88.30087
279	64	0	85.87947	86.10786	92.51142	86.97206	86.63564	88.466
280	65	0	85.46812	86.33137	92.69907	87.28939	86.95967	88.67497
281	66	0	85.50322	86.395	91.68071	86.15559	85.97322	88.9677
282	67	0	86.71226	84.73828	91.47304	84.78514	84.49989	89.24563
283	68	0	88.33939	83.90092	91.40911	83.61175	83.30843	89.33702
284	69	0	88.55618	83.3651	91.31118	83.06931	82.75271	89.3812
285	70	0	88.52325	82.88028	91.14552	82.62717	82.31691	89.36371
286	71	0	87.52038	82.84212	91.28252	82.77725	82.47202	87.24522
287	72	0	85.31066	82.9076	91.47623	83.00565	82.68931	86.24367
288	73	0	83.3904	82.32233	90.12973	81.77556	81.4733	85.22361
289	74	0	82.36865	81.81534	89.34081	80.95448	80.61256	84.51073
290	75	0	81.6088	81.47944	88.91849	80.64963	80.23663	83.96266
291	76	0	81.02277	81.20246	88.5994	80.37601	79.89062	83.51611
292	77	0	80.57747	80.96741	88.30795	80.06133	79.50349	83.13601
293	78	0	80.27889	80.82556	88.16085	79.92403	79.28521	82.85777
294	79	0	80.22283	80.84267	88.23804	80.05921	79.34209	82.7438
295	80	0	82.28751	81.20104	88.75197	81.5551	80.77592	83.00707
296	81	0	84.1217	81.77673	89.48218	83.69372	82.92439	83.45988
297	82	0	85.80764	84.33859	91.77004	86.08434	85.09121	86.21216
298	83	0	86.46696	86.0918	92.45573	86.96572	85.9077	87.39515
299	84	0	87.40704	87.6694	93.32559	88.04362	86.96921	88.52195
300	85	0	89.33539	87.72991	93.72063	87.79385	86.79175	89.005

Table D-6. Jacksonville mass building cooling failure-(pre-1980 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		95019.4	68.68195	71.96844	64.55477	71.64962	70.95134	70.96326
214		94640.3	69.26283	72.32326	64.74058	71.99093	71.29911	72.34982
215		94250.9	70.25323	72.3941	64.65689	71.99139	71.31889	73.302
216	1	0	72.31034	72.52772	73.2277	72.66372	72.74412	73.47129
217	2	0	73.13502	72.80097	76.30269	73.12772	73.35498	73.67204
218	3	0	73.9003	73.35669	77.81506	73.76135	73.98849	74.13564
219	4	0	74.30666	73.68958	78.4076	74.01838	74.23703	74.39922

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
220	5	0	75.24518	74.71144	79.49972	75.21986	75.36761	75.34139
221	6	0	76.36773	76.03691	80.60423	76.46466	76.4883	76.49546
222	7	0	76.41248	76.15199	80.61416	76.45515	76.44933	76.53458
223	8	0	78.43387	76.4684	80.99029	77.55612	77.53996	76.85384
224	9	0	79.05639	76.86884	81.38853	78.72017	78.67401	77.24046
225	10	0	80.98946	79.80019	84.31284	80.71761	80.6066	79.99993
226	11	0	81.77781	81.29134	85.23242	81.50298	81.41029	81.00368
227	12	0	82.12247	81.87816	85.73578	81.92504	81.7953	81.55483
228	13	0	84.04045	81.43193	85.91692	81.52129	81.42427	81.77519
229	14	0	84.52168	81.40372	86.16214	81.57903	81.54082	82.07021
230	15	0	83.09478	82.16516	86.47765	82.43245	82.60053	82.45512
231	16	0	81.76483	82.31942	86.62802	82.68037	83.06827	82.73823
232	17	0	81.51914	82.63952	87.00511	83.11479	83.72111	83.22635
233	18	0	81.43611	82.07079	85.42077	81.9715	82.78275	83.395
234	19	0	82.35857	79.78535	84.91017	80.81567	81.28274	83.36232
235	20	0	83.81176	78.52711	84.43589	79.22408	79.6552	83.04768
236	21	0	83.93246	77.83546	84.18912	78.66287	79.19715	82.81931
237	22	0	84.68855	78.17086	84.73217	79.1778	79.74422	83.31661
238	23	0	83.15663	78.28008	84.8195	79.21953	79.81672	81.22974
239	24	0	80.33376	78.22126	84.75714	79.11898	79.73418	80.47272
240	25	0	79.24885	78.13053	84.13065	78.99706	79.60224	80.158
241	26	0	78.56078	77.89605	83.75282	78.70625	79.28721	79.78558
242	27	0	78.2419	77.6193	83.46854	78.37981	78.91335	79.40641
243	28	0	78.09305	77.55696	83.38318	78.3104	78.79074	79.22691
244	29	0	77.89004	77.42284	83.20393	78.10193	78.53111	78.98441
245	30	0	77.63298	77.23195	82.98248	77.8636	78.24067	78.69133
246	31	0	77.64074	77.24991	82.97755	77.87179	78.19276	78.59847
247	32	0	79.78999	77.58169	83.24804	78.93004	79.16896	78.80139
248	33	0	80.77822	77.87662	83.37486	80.16293	80.35373	78.91147
249	34	0	82.21081	80.34032	85.645	81.73356	81.84537	81.17472
250	35	0	82.62417	81.52417	86.15994	82.18108	82.27425	81.92883
251	36	0	83.06992	82.34997	86.77989	82.80109	82.87488	82.64683
252	37	0	84.89478	82.01785	86.97543	82.40123	82.48991	82.94894
253	38	0	85.4145	82.15086	87.27974	82.57574	82.72504	83.3456
254	39	0	84.24844	82.95409	87.65104	83.497	83.80696	83.82494
255	40	0	83.25019	83.43302	88.07582	84.04626	84.59453	84.35076
256	41	0	82.61716	83.21112	87.92811	83.90826	84.53956	84.38535
257	42	0	82.00783	82.22806	85.9453	82.19115	82.98408	84.0266

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
258	43	0	83.10371	80.0705	85.57308	81.026	81.65507	83.95076
259	44	0	84.91759	79.17649	85.44853	80.01628	80.62318	83.84897
260	45	0	84.96532	78.66046	85.23898	79.598	80.21621	83.65001
261	46	0	85.45025	78.80811	85.50101	79.83958	80.47143	83.90003
262	47	0	83.93719	78.93388	85.55356	79.90971	80.5607	82.00597
263	48	0	81.24793	79.07078	85.60639	80.01185	80.66742	81.5803
264	49	0	80.45941	79.10548	84.96396	79.92135	80.54266	81.34109
265	50	0	79.57362	78.68314	84.2024	79.30628	79.89546	80.70898
266	51	0	79.20416	78.36742	83.8221	78.99106	79.54623	80.26429
267	52	0	79.42722	78.69414	84.06445	79.32103	79.81228	80.43127
268	53	0	79.49577	78.87014	84.21994	79.34217	79.75565	80.453
269	54	0	79.11826	78.57436	83.90711	78.92937	79.28597	80.0243
270	55	0	79.01913	78.50899	83.82338	78.86935	79.18	79.83263
271	56	0	80.28175	78.51166	83.73716	79.43368	79.71886	79.72871
272	57	0	81.48862	79.09477	84.33958	80.92765	81.18294	80.18201
273	58	0	83.95754	82.10958	87.60124	83.56258	83.73219	83.03265
274	59	0	84.07272	83.40284	87.98975	83.95262	84.00593	83.79023
275	60	0	83.79613	83.38381	87.85302	83.76279	83.79217	83.73479
276	61	0	85.71939	83.0731	88.10738	83.33608	83.41448	83.93192
277	62	0	85.40948	82.23258	87.61192	82.48502	82.64545	83.48966
278	63	0	83.95787	82.52703	87.57566	83.05267	83.31268	83.36091
279	64	0	82.56263	82.6991	87.63643	83.28424	83.68061	83.42243
280	65	0	82.20514	82.95142	87.83941	83.57668	84.01685	83.61632
281	66	0	82.53692	83.04295	86.76902	82.74239	83.30775	84.13504
282	67	0	83.96069	81.37832	86.61702	82.01127	82.27243	84.46373
283	68	0	85.8175	80.69733	86.50784	81.12202	81.36927	84.48165
284	69	0	85.85593	80.26808	86.26309	80.69801	80.95682	84.29786
285	70	0	85.68964	79.89618	85.94686	80.29306	80.56846	84.02321
286	71	0	84.56702	80.11535	86.24641	80.5933	80.86513	82.27881
287	72	0	82.19005	80.4183	86.56162	80.89778	81.14986	82.03868
288	73	0	79.86161	79.11016	84.31031	79.13855	79.45238	80.51241
289	74	0	78.76994	78.12252	82.82877	78.09174	78.42251	79.42593
290	75	0	78.2903	77.80469	82.38248	77.83843	78.1289	78.96336
291	76	0	77.97463	77.58237	82.09388	77.54292	77.78746	78.61333
292	77	0	77.6036	77.28238	81.71807	77.13739	77.33703	78.18842
293	78	0	77.44552	77.20986	81.67242	77.05175	77.18473	77.98926
294	79	0	77.6326	77.44002	81.96544	77.26892	77.33087	78.09351
295	80	0	80.21159	78.43824	83.33401	79.09806	79.05648	78.97682

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
296	81	0	81.87302	79.44395	84.53651	81.10847	81.0151	79.88403
297	82	0	83.57764	81.98945	87.08727	83.06754	82.80171	82.382
298	83	0	84.06932	83.39704	87.72845	83.64676	83.36731	83.25719
299	84	0	84.82527	84.35728	88.50953	84.44026	84.16608	84.10287
300	85	0	86.81226	84.32148	88.92432	84.28055	84.05222	84.62537
301	86	0	86.85156	84.09765	88.85171	84.05706	83.86916	84.7133
302	87	0	85.44691	84.51904	88.91396	84.66331	84.66508	84.8453
303	88	0	84.41441	84.83927	89.22411	85.09577	85.39932	85.202
304	89	0	83.90218	84.86018	89.28646	85.20586	85.68301	85.4351
305	90	0	83.9587	84.53062	87.89339	84.12823	84.79492	85.6621
306	91	0	84.88355	82.3563	87.3893	82.8376	83.6366	85.60844
307	92	0	86.49915	81.03353	87.0322	81.58867	81.99872	85.27699
308	93	0	86.48636	80.66012	86.77321	81.13931	81.56934	84.99358
309	94	0	86.12688	80.27236	86.36236	80.71336	81.17647	84.62245
310	95	0	84.66275	80.21451	86.3469	80.66708	81.14578	82.6454
311	96	0	81.90637	80.17379	86.31535	80.60747	81.08665	82.07915
312	97	0	81.00845	80.01077	85.57411	80.37511	80.82651	81.68758
313	98	0	80.64706	80.09485	85.49398	80.49552	80.90498	81.57063
314	99	0	80.63725	80.20422	85.5358	80.51648	80.88947	81.54797
315	100	0	80.27667	79.91224	85.11955	80.11601	80.45487	81.14404
316	101	0	80.00881	79.71481	84.88178	79.87717	80.17052	80.83363
317	102	0	79.92606	79.69237	84.83657	79.83625	80.0818	80.70074
318	103	0	79.83967	79.62518	84.67566	79.70966	79.92616	80.5322
319	104	0	81.26234	79.73845	84.73461	80.42153	80.60803	80.55515
320	105	0	82.4503	80.20861	85.32816	81.7932	81.9212	80.92281
321	106	0	84.44661	82.80219	88.12936	84.10272	84.19955	83.4743
322	107	0	84.96276	84.3274	88.75993	84.73113	84.73943	84.45842
323	108	0	84.96059	84.45277	88.70054	84.68967	84.73675	84.56923
324	109	0	87.13922	84.48552	89.30361	84.65434	84.75242	85.0867
325	110	0	87.25333	84.3262	89.31491	84.50999	84.69835	85.28161
326	111	0	85.78897	84.50203	89.23985	84.95506	85.28202	85.16718
327	112	0	84.89493	85.0972	89.83244	85.6436	86.00179	85.65603
328	113	0	84.69949	85.38913	90.10094	85.96236	86.31062	86.04198
329	114	0	84.36727	84.77218	88.40818	84.47345	85.03712	85.99718
330	115	0	85.25011	82.73116	87.85557	83.29033	83.63993	85.88519
331	116	0	87.04179	81.99641	87.67498	82.37981	82.6508	85.7921
332	117	0	87.11733	81.61453	87.48759	82.01724	82.29396	85.66393
333	118	0	87.25533	81.44621	87.43537	81.88554	82.16797	85.62902

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
334	119	0	85.22358	81.11891	86.89929	81.48001	81.81028	83.34077
335	120	0	82.8139	81.219	86.84886	81.60246	81.93835	82.95792
336	121	0	81.94945	81.2407	86.20393	81.47342	81.77219	82.69624
337	122	0	81.02732	80.47246	85.0736	80.51854	80.79482	81.79761
338	123	0	80.16206	79.72439	84.31743	79.72369	79.9649	80.91846
339	124	0	80.12503	79.77757	84.38855	79.84628	80.03147	80.83492
340	125	0	80.52939	80.28617	84.96732	80.34314	80.45006	81.19806
341	126	0	80.62778	80.45869	85.09571	80.40823	80.46626	81.24432
342	127	0	80.65141	80.46243	85.04901	80.35056	80.3678	81.13756
343	128	0	82.28078	80.64336	85.39417	80.53496	80.50922	81.22211
344	129	0	83.39824	81.16908	86.08389	81.17014	81.10868	81.6591
345	130	0	84.89289	82.97439	88.19746	81.02717	80.97115	83.59832
346	131	0	85.54839	84.48077	88.85122	81.1898	81.12701	84.51814
347	132	0	86.02625	85.07299	89.27538	81.60479	81.52267	85.00949
348	133	0	87.96497	84.83242	89.58375	81.86919	81.78889	85.37804
349	134	0	88.37928	85.01173	89.93984	82.20011	82.16139	85.8264
350	135	0	86.9285	85.59119	90.04398	82.25538	82.41795	86.04387
351	136	0	85.34098	85.44737	89.86608	81.97879	82.41592	85.97278

Table D-7. Atlanta mass building cooling failure (2019 WBGT data).

Elapse d Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		72422.1	65.66886	66.59852	61.2415	67.4116	66.75561	66.09106
214		71413.1	65.73003	66.72392	61.33061	67.65509	66.97397	66.44025
215		71384.2	65.48412	66.83209	61.29745	67.69476	66.98981	66.93279
216	1	0	67.65533	68.08324	70.67257	70.50421	70.41459	68.64755
217	2	0	68.6896	68.80401	74.5418	71.53008	71.59772	69.52475
218	3	0	69.88027	69.68925	77.4892	72.28639	72.58427	70.61501
219	4	0	70.82945	70.46708	78.84737	72.5581	72.89455	71.53498
220	5	0	71.31127	70.8818	79.20163	72.316	72.64845	72.03393
221	6	0	71.6568	71.20744	79.42993	72.29373	72.59922	72.41013
222	7	0	71.9872	71.54218	79.73622	72.52763	72.79024	72.76384
223	8	0	74.60447	71.75732	79.97901	73.79693	73.96521	72.98082
224	9	0	75.6977	72.08861	80.44116	75.63112	75.70746	73.29711
225	10	0	78.29227	76.38752	83.7172	78.33806	78.25871	77.07313
226	11	0	79.68224	79.06676	85.23937	79.82038	79.6497	78.64693
227	12	0	81.00781	80.90578	86.65063	81.25744	81.03615	79.9609

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
228	13	0	84.33877	81.55065	87.79143	81.75092	81.5323	81.08152
229	14	0	85.30225	82.01139	88.46207	82.16699	81.92978	81.9282
230	15	0	83.86771	82.99903	88.9251	83.18271	82.94225	82.60124
231	16	0	82.38052	83.28704	89.17886	83.5893	83.37045	83.08617
232	17	0	81.82925	83.52454	89.44402	83.96455	83.8386	83.68306
233	18	0	81.74731	83.11225	87.93845	82.82813	82.91151	84.07735
234	19	0	83.13557	80.88954	87.73309	81.81695	81.82603	84.47813
235	20	0	85.21484	79.82228	87.58018	80.40014	80.40187	84.71176
236	21	0	85.43508	79.01339	87.43141	79.46033	79.51426	84.89429
237	22	0	85.67464	78.41389	87.41486	78.92829	78.991	85.10442
238	23	0	84.12672	78.22492	87.43765	78.75474	78.91024	82.96092
239	24	0	81.43037	78.11212	87.43985	78.61568	78.84111	81.91772
240	25	0	80.18687	77.97265	86.8774	78.41812	78.7275	81.33862
241	26	0	79.04768	77.6011	86.37343	77.70744	78.08262	80.68784
242	27	0	78.29678	77.11954	85.70742	76.81545	77.19846	80.13258
243	28	0	77.71088	76.79565	85.32933	76.43354	76.7689	79.70707
244	29	0	77.21437	76.50042	85.03149	76.13853	76.43546	79.32268
245	30	0	76.85493	76.30019	84.88724	76.03473	76.27782	79.03729
246	31	0	76.66023	76.2305	84.91768	76.1581	76.34455	78.87608
247	32	0	78.43575	76.26215	84.97967	77.12543	77.2393	78.83826
248	33	0	79.61238	76.48083	85.31794	79.16522	79.12455	78.954
249	34	0	81.79042	79.86286	88.08916	82.13156	81.85768	82.11433
250	35	0	82.94254	82.32488	89.33005	83.55374	83.17047	83.59394
251	36	0	84.09206	84.02768	90.48083	84.8885	84.44324	84.73344
252	37	0	86.99628	84.6785	91.41345	85.26746	84.81802	85.67284
253	38	0	87.79724	85.08841	91.93193	85.5731	85.10693	86.35818
254	39	0	86.48255	85.90435	92.26687	86.51231	86.03855	86.88135
255	40	0	85.13055	86.11043	92.40611	86.82922	86.38351	87.23745
256	41	0	84.76205	86.25249	92.56366	87.06456	86.73125	87.60117
257	42	0	84.61569	85.91122	91.15443	85.83257	85.72236	87.90797
258	43	0	85.7604	84.026	90.8867	84.66389	84.51904	88.20607
259	44	0	87.47439	82.9575	90.65948	83.00288	82.85561	88.33447
260	45	0	87.60942	82.24683	90.47572	81.9745	81.88429	88.41277
261	46	0	87.6885	81.47073	90.34371	81.28284	81.29671	88.50536
262	47	0	86.17747	81.21674	90.31316	81.16782	81.22283	86.00663
263	48	0	83.74068	80.99301	90.2701	81.05816	81.14272	84.70633
264	49	0	82.52133	80.84989	89.6908	80.90411	81.01194	84.39292
265	50	0	81.42979	80.46059	89.12649	80.22821	80.36417	83.8497

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
266	51	0	80.68099	79.96015	88.41617	79.34541	79.47377	83.28413
267	52	0	80.11217	79.60958	88.00295	78.93694	79.01616	82.83067
268	53	0	79.62635	79.30008	87.67017	78.61796	78.6552	82.41204
269	54	0	79.26759	79.09085	87.49328	78.48112	78.4651	82.08904
270	55	0	79.05982	79.0044	87.49176	78.56494	78.49374	81.88553
271	56	0	80.55708	79.02216	87.52467	79.44187	79.31088	81.81357
272	57	0	81.96746	79.20579	87.84851	81.30978	81.08266	81.86381
273	58	0	83.9151	82.07748	90.42045	84.30862	83.96618	84.77882
274	59	0	85.01608	84.47145	91.58892	85.80699	85.24989	86.28036
275	60	0	86.11005	86.18253	92.67733	87.10905	86.46558	87.37516
276	61	0	88.76086	86.88834	93.55048	87.40932	86.76389	88.25124
277	62	0	89.4692	87.28217	94.01972	87.65862	86.99714	88.87833
278	63	0	88.25416	87.98721	94.30707	88.5563	87.88195	89.34054
279	64	0	86.97765	88.13168	94.40152	88.82605	88.17422	89.64433
280	65	0	86.61106	88.20976	94.51276	89.01084	88.47042	89.94822
281	66	0	86.46263	87.89379	93.17103	87.69382	87.40537	90.20412
282	67	0	87.56348	85.86647	92.8459	86.19499	85.93446	90.46269
283	68	0	89.01989	84.88856	92.5935	84.48301	84.17481	90.5228
284	69	0	89.09326	84.07545	92.30766	83.33278	83.10253	90.51465
285	70	0	89.09004	83.51331	92.21859	83.04935	82.84338	90.56377
286	71	0	87.69906	83.27934	92.17937	82.9423	82.7768	88.10158
287	72	0	85.42271	83.06766	92.11922	82.82767	82.68462	86.79354
288	73	0	84.22097	82.91838	91.54429	82.66944	82.54165	86.47475
289	74	0	83.17386	82.52647	90.95136	81.99963	81.88992	85.92798
290	75	0	82.45399	82.07773	90.21723	81.11515	80.99345	85.34733
291	76	0	81.88055	81.75977	89.78667	80.68984	80.52007	84.87202
292	77	0	81.38914	81.45763	89.43571	80.35518	80.14323	84.43122
293	78	0	81.02187	81.24601	89.24248	80.19844	79.93495	84.08538
294	79	0	80.80189	81.14934	89.22523	80.25889	79.94215	83.85759
295	80	0	82.33012	81.15855	89.25272	81.20125	80.81993	83.75986
296	81	0	83.45758	81.29112	89.52509	82.67973	82.24288	83.77571
297	82	0	85.3142	83.68175	91.96706	85.52541	85.01398	86.53857
298	83	0	86.53358	86.30022	93.22147	87.39535	86.63942	88.19639
299	84	0	87.5778	87.94736	94.2577	88.69014	87.84705	89.25622
300	85	0	90.00323	88.55198	95.05429	88.88289	88.04826	90.04174

Table D-8. Atlanta mass building cooling failure (2013 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		76771.6	65.78159	67.17834	61.4989	67.48331	66.83263	66.62836
214		75583.8	65.92085	67.35311	61.60466	67.76254	67.09535	67.18243
215		75581.0	65.89623	67.47768	61.56383	67.79311	67.11008	67.84232
216	1	0	68.47323	68.96861	71.11341	70.73822	70.68539	69.73772
217	2	0	69.58538	69.73592	74.81895	71.67632	71.76473	70.59063
218	3	0	70.53799	70.37189	77.03919	72.13411	72.41985	71.3844
219	4	0	71.48402	71.06349	78.34669	72.40264	72.73142	72.19989
220	5	0	71.88427	71.36958	78.67501	72.20356	72.52551	72.55662
221	6	0	72.10282	71.56614	78.86621	72.18842	72.47845	72.77141
222	7	0	72.34599	71.82082	79.15869	72.43492	72.68365	73.01291
223	8	0	74.67313	72.03123	79.40356	73.67379	73.84999	73.20426
224	9	0	75.83211	72.43942	79.90884	75.5453	75.62858	73.57561
225	10	0	78.36581	76.59301	83.253	78.24213	78.17422	77.28724
226	11	0	79.69962	79.13816	84.80245	79.71145	79.56442	78.85533
227	12	0	81.00423	80.88256	86.23202	81.14299	80.96938	80.16839
228	13	0	84.25831	81.46837	87.37215	81.63339	81.48007	81.26649
229	14	0	85.16021	81.87793	88.01347	82.03304	81.87299	82.03619
230	15	0	83.68875	82.81911	88.4493	83.01326	82.86985	82.61385
231	16	0	82.16465	83.06107	88.66909	83.36477	83.23734	82.99416
232	17	0	81.57	83.2512	88.90348	83.68134	83.67561	83.42732
233	18	0	81.4763	82.81383	87.36251	82.55064	82.77239	83.73798
234	19	0	82.8672	80.54966	87.13823	81.58479	81.69137	84.07832
235	20	0	84.95367	79.43221	86.93771	80.20119	80.28665	84.21372
236	21	0	85.10716	78.66798	86.768	79.37675	79.45618	84.27262
237	22	0	85.27945	78.17911	86.74944	78.89779	78.96774	84.41346
238	23	0	83.6759	77.88756	86.72786	78.62132	78.78909	82.18796
239	24	0	80.82547	77.7191	86.69008	78.42931	78.6653	81.07865
240	25	0	79.45805	77.52713	86.06963	78.20811	78.50604	80.47797
241	26	0	78.16052	77.01371	85.43169	77.38272	77.7225	79.77328
242	27	0	77.24011	76.35338	84.64617	76.42475	76.76563	79.09615
243	28	0	76.64332	75.96099	84.2439	76.03725	76.3234	78.62587
244	29	0	76.16324	75.62377	83.92706	75.71835	75.95604	78.21491
245	30	0	75.87504	75.44992	83.78128	75.60731	75.78881	77.955
246	31	0	75.79162	75.45226	83.82831	75.73758	75.86204	77.86051
247	32	0	77.65576	75.54576	83.89606	76.70094	76.75727	77.8857
248	33	0	78.99567	75.8966	84.29174	78.69557	78.64963	78.12431
249	34	0	81.30596	79.4638	87.20631	81.66241	81.37149	81.32293

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
250	35	0	82.4967	81.96913	88.50338	83.06509	82.67274	82.93739
251	36	0	83.68333	83.65517	89.69309	84.38717	83.94877	84.16214
252	37	0	86.60647	84.26844	90.64151	84.76005	84.33047	85.14391
253	38	0	87.38441	84.63603	91.14205	85.05445	84.61842	85.79791
254	39	0	86.01848	85.4291	91.4586	85.96183	85.53748	86.26551
255	40	0	84.59314	85.59436	91.56701	86.22856	85.82819	86.53732
256	41	0	84.17332	85.70553	91.70132	86.42842	86.16535	86.8059
257	42	0	83.99741	85.32561	90.23009	85.20387	85.18179	87.04769
258	43	0	85.16678	83.33056	89.93594	84.08485	83.98901	87.29034
259	44	0	86.91975	82.1507	89.65816	82.44582	82.34641	87.31532
260	45	0	87.02485	81.31924	89.43366	81.42732	81.34991	87.28175
261	46	0	87.06857	80.45293	89.27349	80.79208	80.78664	87.27361
262	47	0	85.43134	80.20095	89.21514	80.66187	80.69054	84.66425
263	48	0	82.76225	80.00516	89.13887	80.52604	80.57651	83.37037
264	49	0	81.53741	79.86075	88.55734	80.33666	80.39732	83.0788
265	50	0	80.25132	79.35054	87.77421	79.52652	79.59965	82.45945
266	51	0	79.36115	78.76421	86.96312	78.59248	78.65361	81.77329
267	52	0	78.73714	78.41017	86.51382	78.17239	78.17921	81.27312
268	53	0	78.23149	78.08706	86.16109	77.82536	77.7801	80.82311
269	54	0	77.92351	77.90826	85.98239	77.67928	77.57908	80.52243
270	55	0	77.81269	77.88924	85.99769	77.76716	77.61134	80.38076
271	56	0	79.41274	77.96764	86.03678	78.65598	78.43592	80.37358
272	57	0	80.97142	78.28584	86.42104	80.494	80.20849	80.56499
273	58	0	83.06622	81.27778	89.17506	83.46241	83.0936	83.55165
274	59	0	84.20871	83.78178	90.41312	84.93741	84.35795	85.16383
275	60	0	85.34985	85.48294	91.549	86.24211	85.58247	86.34747
276	61	0	88.0834	86.15376	92.44714	86.55425	85.90347	87.27332
277	62	0	88.77887	86.50414	92.89996	86.79598	86.13873	87.86953
278	63	0	87.48505	87.20799	93.17315	87.66991	87.01744	88.28439
279	64	0	86.11301	87.31686	93.23815	87.88927	87.25635	88.50336
280	65	0	85.69023	87.36752	93.32912	88.03719	87.54383	88.71519
281	66	0	85.51354	86.99993	91.90544	86.73038	86.50349	88.909
282	67	0	86.5918	85.14619	91.58982	85.48662	85.22807	89.10421
283	68	0	88.1618	83.97471	91.28461	83.74169	83.47955	89.07411
284	69	0	88.21039	83.12612	91.02734	82.825	82.55828	88.98934
285	70	0	88.20453	82.24229	90.83283	82.24548	82.0132	88.93006
286	71	0	86.74763	81.99184	90.7483	82.10234	81.89636	86.62808
287	72	0	84.11507	81.78027	90.6424	81.95076	81.76231	85.17633

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
288	73	0	82.87885	81.63217	90.05656	81.75414	81.57011	84.82034
289	74	0	81.67095	81.17748	89.23447	80.94728	80.76537	84.15073
290	75	0	80.78021	80.61259	88.39366	80.01176	79.81495	83.43655
291	76	0	80.14413	80.23698	87.92767	79.5742	79.32431	82.90328
292	77	0	79.62586	79.89965	87.55582	79.20958	78.90738	82.42483
293	78	0	79.30452	79.70327	87.36169	79.0435	78.68855	82.09785
294	79	0	79.17695	79.66235	87.36276	79.10737	78.69901	81.92905
295	80	0	80.56932	79.72763	87.38959	79.96056	79.49012	81.90519
296	81	0	82.0686	80.01521	87.76223	81.68333	81.16393	82.06689
297	82	0	84.1758	82.62721	90.42635	84.48804	83.92634	84.92651
298	83	0	85.42944	85.30321	91.74362	86.23225	85.44576	86.69334
299	84	0	86.5175	86.93384	92.81963	87.50121	86.64327	87.83073
300	85	0	89.05367	87.49095	93.6382	87.70345	86.8568	88.65578

Table D-9. Atlanta mass building cooling failure (pre-1980 WBGT data).

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
213		104539	66.24315	67.97111	62.53644	67.6624	66.98631	67.91566
214		102248	66.61152	68.29182	62.71826	68.01208	67.30638	68.7473
215		102339	66.96428	68.31199	62.62865	67.94987	67.25321	69.13389
216	1	0	71.25464	70.95824	72.8923	71.86068	72.09478	72.14996
217	2	0	72.23367	71.61247	75.57153	72.46172	72.85666	72.74107
218	3	0	72.88985	71.91571	76.92515	72.69485	73.3294	73.1921
219	4	0	72.97869	71.96003	77.0757	72.55212	73.17083	73.21736
220	5	0	72.66103	71.69338	76.89668	72.2346	72.83553	72.89618
221	6	0	72.57536	71.67661	76.96697	72.22584	72.78274	72.81278
222	7	0	72.77119	71.94364	77.28381	72.50956	73.01131	72.99801
223	8	0	74.6307	72.18088	77.52152	73.48473	73.90366	73.1683
224	9	0	76.0432	73.06174	78.35294	75.57329	75.86195	73.90848
225	10	0	78.57312	76.89199	81.79915	78.1785	78.39884	77.4442
226	11	0	79.88808	79.13194	83.34621	79.57455	79.747	79.06664
227	12	0	81.2389	80.71635	84.78346	81.00284	81.17944	80.52191
228	13	0	84.22929	81.25652	85.89137	81.54305	81.74387	81.68458
229	14	0	84.92225	81.59206	86.4305	81.92468	82.12532	82.32874
230	15	0	83.47639	82.41182	86.79228	82.79717	83.07357	82.78573
231	16	0	82.0155	82.47466	86.86458	82.96422	83.32271	82.96822
232	17	0	81.55824	82.53144	87.00401	83.13342	83.73532	83.18797

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
233	18	0	81.54108	82.08683	85.4878	82.14147	83.05407	83.43338
234	19	0	82.83338	80.0723	85.33256	81.44296	82.14187	83.7293
235	20	0	84.56808	79.00302	84.96655	80.14635	80.70039	83.5712
236	21	0	84.58428	78.2569	84.68115	79.35444	79.89182	83.34071
237	22	0	84.48	77.74509	84.48778	78.85831	79.54676	83.15078
238	23	0	82.67796	77.49257	84.3166	78.58101	79.36053	80.71397
239	24	0	79.64458	77.27544	84.13036	78.34109	79.16261	79.75226
240	25	0	78.42809	76.97709	83.35897	78.04405	78.90382	79.29557
241	26	0	77.10838	75.94867	82.009	76.87765	77.79234	78.25963
242	27	0	76.25958	75.16888	81.032	75.99561	76.89922	77.39256
243	28	0	75.49586	74.51762	80.27248	75.31503	76.17314	76.61027
244	29	0	75.02702	74.13904	79.83812	74.89483	75.69004	76.09444
245	30	0	74.85468	74.05976	79.76213	74.75463	75.47453	75.86407
246	31	0	74.95691	74.24149	79.97801	74.9008	75.53898	75.8918
247	32	0	76.42835	74.40365	80.13611	75.66429	76.23526	75.93073
248	33	0	77.76375	75.1188	80.94192	77.37662	77.80847	76.48407
249	34	0	80.4136	78.52789	84.28487	80.25976	80.56467	79.55968
250	35	0	81.70238	80.97332	85.71228	81.67741	81.86714	81.2749
251	36	0	82.99154	82.55707	87.02011	83.02964	83.19735	82.68552
252	37	0	85.81013	83.10309	88.00401	83.47397	83.64901	83.76847
253	38	0	86.43058	83.39606	88.43269	83.77216	83.93559	84.32706
254	39	0	85.02342	84.11617	88.69312	84.57543	84.80622	84.69403
255	40	0	83.57397	84.10931	88.66554	84.65487	84.96189	84.7751
256	41	0	83.04611	84.09672	88.70215	84.73315	85.28516	84.88328
257	42	0	82.99051	83.64522	87.16369	83.63425	84.5015	85.0502
258	43	0	84.19933	81.66745	86.93102	82.79012	83.45718	85.26177
259	44	0	85.77861	80.43821	86.48985	81.27357	81.81885	85.00117
260	45	0	85.72513	79.61223	86.1233	80.46646	81.08103	84.64617
261	46	0	85.55399	79.05427	85.83674	80.03608	80.72596	84.26733
262	47	0	83.76017	78.7799	85.60432	79.77927	80.5178	81.80544
263	48	0	80.70039	78.56313	85.35607	79.52282	80.28336	81.04195
264	49	0	79.48283	78.29823	84.37704	79.21542	80.00228	80.56109
265	50	0	78.21967	77.31813	82.74434	77.96262	78.78098	79.4492
266	51	0	77.10304	76.27529	81.47125	76.84686	77.65816	78.28235
267	52	0	76.62392	75.90215	81.08073	76.41741	77.16112	77.74702
268	53	0	76.2028	75.56937	80.67371	75.98695	76.66584	77.25709
269	54	0	75.99983	75.45671	80.53445	75.803	76.40607	76.98233
270	55	0	76.06913	75.6013	80.6872	75.91125	76.433	76.96606

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
271	56	0	77.40822	75.73402	80.80804	76.62582	77.08596	76.97089
272	57	0	78.5556	76.39125	81.73516	78.21696	78.56165	77.47263
273	58	0	81.243	79.46152	85.19052	80.92654	81.15073	80.39247
274	59	0	82.53071	81.87873	86.60848	82.45845	82.55526	82.0652
275	60	0	83.80136	83.48483	87.88656	83.81934	83.88548	83.46928
276	61	0	86.55325	84.05022	88.84084	84.24146	84.3131	84.53542
277	62	0	87.14207	84.32912	89.24009	84.51659	84.57593	85.0703
278	63	0	85.75542	85.00743	89.47142	85.3097	85.43259	85.40769
279	64	0	84.30513	84.96694	89.41216	85.35778	85.55669	85.45314
280	65	0	83.75294	84.91575	89.41602	85.3982	85.85064	85.5218
281	66	0	83.68407	84.46123	87.87494	84.24024	85.03388	85.663
282	67	0	84.8591	82.48925	87.61757	83.32278	83.93001	85.84575
283	68	0	86.36832	81.19788	87.14785	81.76134	82.25255	85.54562
284	69	0	86.28051	80.34399	86.74793	81.04066	81.57707	85.11645
285	70	0	86.08057	79.83075	86.43336	80.6393	81.23278	84.67149
286	71	0	84.28261	79.60464	86.16811	80.37001	81.00712	82.3596
287	72	0	81.21722	79.39679	85.89128	80.10182	80.75778	81.6175
288	73	0	80.10507	79.13727	84.83645	79.7854	80.46327	81.12189
289	74	0	78.96385	78.26134	83.32294	78.62111	79.316	80.09755
290	75	0	77.86802	77.23561	82.12767	77.49345	78.18214	78.93531
291	76	0	77.25825	76.74248	81.57916	76.96197	77.59037	78.28035
292	77	0	76.81338	76.38873	81.17484	76.52261	77.08604	77.77023
293	78	0	76.59714	76.2565	81.01257	76.32361	76.81418	77.48016
294	79	0	76.64916	76.37794	81.13409	76.41348	76.82534	77.44671
295	80	0	77.91602	76.48923	81.21418	77.10068	77.45664	77.43589
296	81	0	79.01485	77.11745	82.04159	78.65249	78.90373	77.91841
297	82	0	81.58949	79.98355	85.63408	81.28097	81.43785	80.77203
298	83	0	82.92594	82.33555	87.04078	82.82862	82.85575	82.40677
299	84	0	84.19913	83.96645	88.30651	84.19683	84.18512	83.81256
300	85	0	86.9227	84.5491	89.24911	84.61041	84.60354	84.87635
301	86	0	87.49712	84.82404	89.63606	84.87683	84.85747	85.403
302	87	0	86.12201	85.48633	89.85478	85.66932	85.71014	85.72932
303	88	0	84.66842	85.42893	89.78136	85.70181	85.82084	85.76004
304	89	0	84.10323	85.35448	89.77059	85.72499	86.10389	85.81172
305	90	0	84.02898	84.89613	88.22915	84.53989	85.27206	85.94238
306	91	0	85.19057	82.92068	87.9595	83.58108	84.13839	86.11322
307	92	0	86.67377	81.62721	87.47998	82.02454	82.44029	85.79333
308	93	0	86.58401	80.58862	86.98642	81.22073	81.69853	85.22435

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
309	94	0	86.34514	80.3073	86.71944	80.93839	81.45642	84.87288
310	95	0	84.535	80.08136	86.4409	80.67316	81.23292	82.61774
311	96	0	81.46198	79.87321	86.15202	80.40363	80.98155	81.89468
312	97	0	80.28898	79.59387	85.01611	80.06992	80.67227	81.35263
313	98	0	79.26924	78.73419	83.57909	78.91601	79.53134	80.36087
314	99	0	78.17818	77.70694	82.4038	77.78609	78.39481	79.19633
315	100	0	77.57608	77.20544	81.85599	77.24809	77.79799	78.53762
316	101	0	77.12642	76.84181	81.4446	76.80173	77.28799	78.02135
317	102	0	76.90251	76.6981	81.27248	76.59503	77.01037	77.72441
318	103	0	76.94643	76.80664	81.38101	76.6761	77.01492	77.68346
319	104	0	78.33373	76.91428	81.44918	77.42429	77.70586	77.66853
320	105	0	79.30215	77.52405	82.21899	78.90296	79.08951	78.1432
321	106	0	81.79578	80.27457	85.91359	81.46735	81.58275	80.9614
322	107	0	83.13192	82.57327	87.27184	83.0154	83.0018	82.577
323	108	0	84.40321	84.21774	88.52633	84.39074	84.33083	83.98111
324	109	0	87.11248	84.81337	89.46282	84.80089	84.74526	85.04538
325	110	0	87.67949	85.0894	89.84368	85.06489	84.99581	85.56884
326	111	0	86.31018	85.74496	90.05613	85.85603	85.84564	85.89034
327	112	0	84.85471	85.6766	89.97556	85.88107	85.9506	85.91402
328	113	0	84.28109	85.58968	89.95734	85.89587	86.22902	85.95739
329	114	0	84.20426	85.12852	88.41576	84.6954	85.38933	86.08299
330	115	0	85.36928	83.12103	88.13625	83.70066	84.22568	86.24952
331	116	0	86.82795	81.83622	87.65184	82.16469	82.53607	85.91777
332	117	0	86.72657	80.85339	87.14933	81.38916	81.81931	85.32593
333	118	0	86.47967	80.57478	86.87212	81.10602	81.57516	84.99429
334	119	0	84.6563	80.34859	86.58356	80.83878	81.34901	82.75188
335	120	0	81.61694	80.1374	86.28439	80.56639	81.09505	82.03689
336	121	0	80.46391	79.85594	85.10469	80.23043	80.78368	81.4943
337	122	0	79.45189	78.97226	83.75416	79.05736	79.61822	80.48775
338	123	0	78.5744	78.19169	82.78995	78.15272	78.70136	79.56455
339	124	0	77.80292	77.51782	82.04401	77.42417	77.92561	78.72949
340	125	0	77.29055	77.0892	81.58656	76.9477	77.38614	78.15224
341	126	0	77.064	76.94157	81.41698	76.74383	77.11267	77.85424
342	127	0	77.10452	77.04321	81.5176	76.81886	77.11265	77.80981
343	128	0	78.42969	77.12777	81.57843	76.85468	77.10302	77.76865
344	129	0	79.37095	77.67015	82.2324	77.47576	77.67442	78.18383
345	130	0	81.83206	80.39767	86.01342	78.42294	78.56232	81.00594
346	131	0	83.24949	82.65201	87.35978	79.45786	79.5381	82.63929

Elapsed Hours	Hours since Failure	Cooling Load	East Restaurant Zone WBGT (°F)	South Retail Zone WBGT (°F)	24 Hour Ops Center Zone WBGT (°F)	South Office Zone WBGT (°F)	SW Corner Office Zone WBGT (°F)	South Residence Zone WBGT (°F)
347	132	0	84.55547	84.32145	88.60413	80.74269	80.78905	84.05995
348	133	0	87.2885	84.93523	89.53567	81.78884	81.80457	85.14151
349	134	0	87.85242	85.22074	89.91652	82.22741	82.22223	85.67217
350	135	0	86.47807	85.87603	90.12916	82.46007	82.54288	85.99372
351	136	0	85.0051	85.79624	90.04469	82.25143	82.46265	86.00364
352	137	0	84.40907	85.69555	90.01915	82.11748	82.57474	86.02975
353	138	0	84.32302	85.22421	88.47262	82.12276	82.82552	86.13726
354	139	0	85.46638	83.22592	88.19003	82.16859	82.76983	86.28064
355	140	0	86.90901	81.94452	87.70403	81.67918	82.26183	85.94405
356	141	0	86.79254	80.9743	87.19996	81.18381	81.78423	85.32655
357	142	0	86.5396	80.69274	86.9205	80.94652	81.57543	85.02352
358	143	0	84.71855	80.4651	86.62812	80.70736	81.36479	82.78662
359	144	0	81.69617	80.25204	86.32475	80.4591	81.1205	82.05433
360	145	0	80.56901	79.9695	85.14653	80.14446	80.81616	81.50887
361	146	0	79.5562	79.08547	83.80112	78.98688	79.65578	80.50242

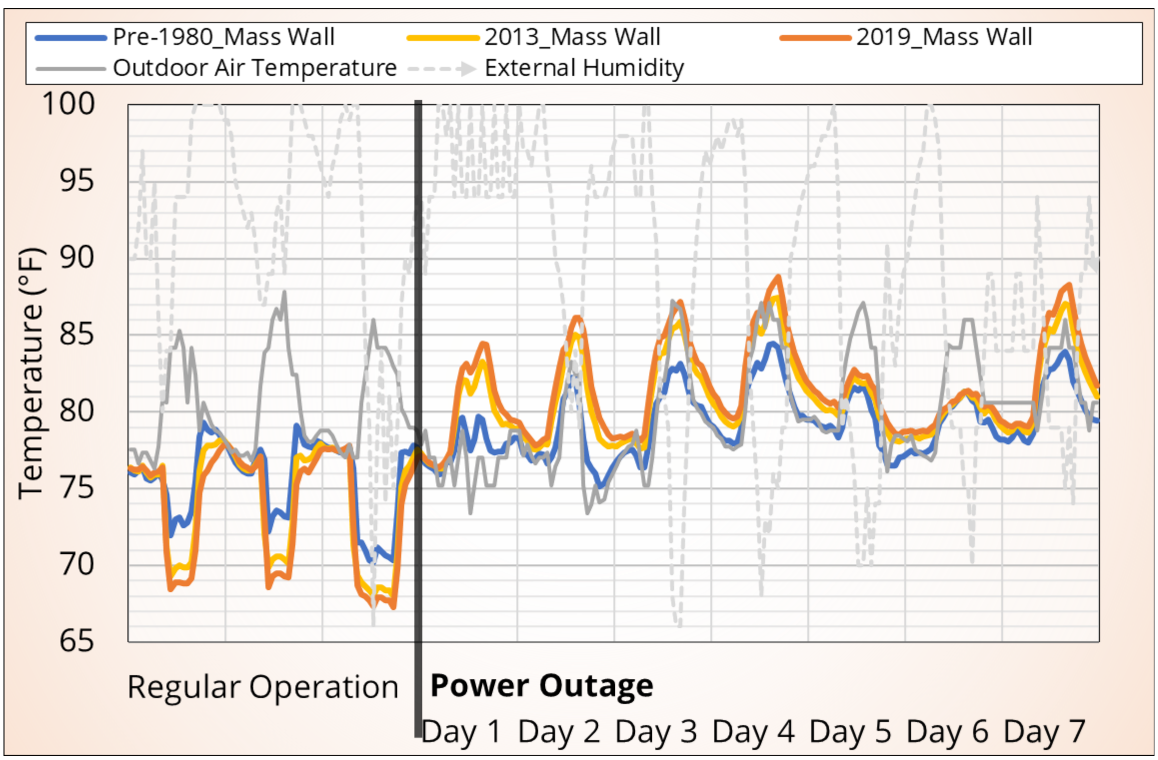


Figure D-1. Library (Northeast Corner) - Heat removal is higher at Pre-1980 Construction.

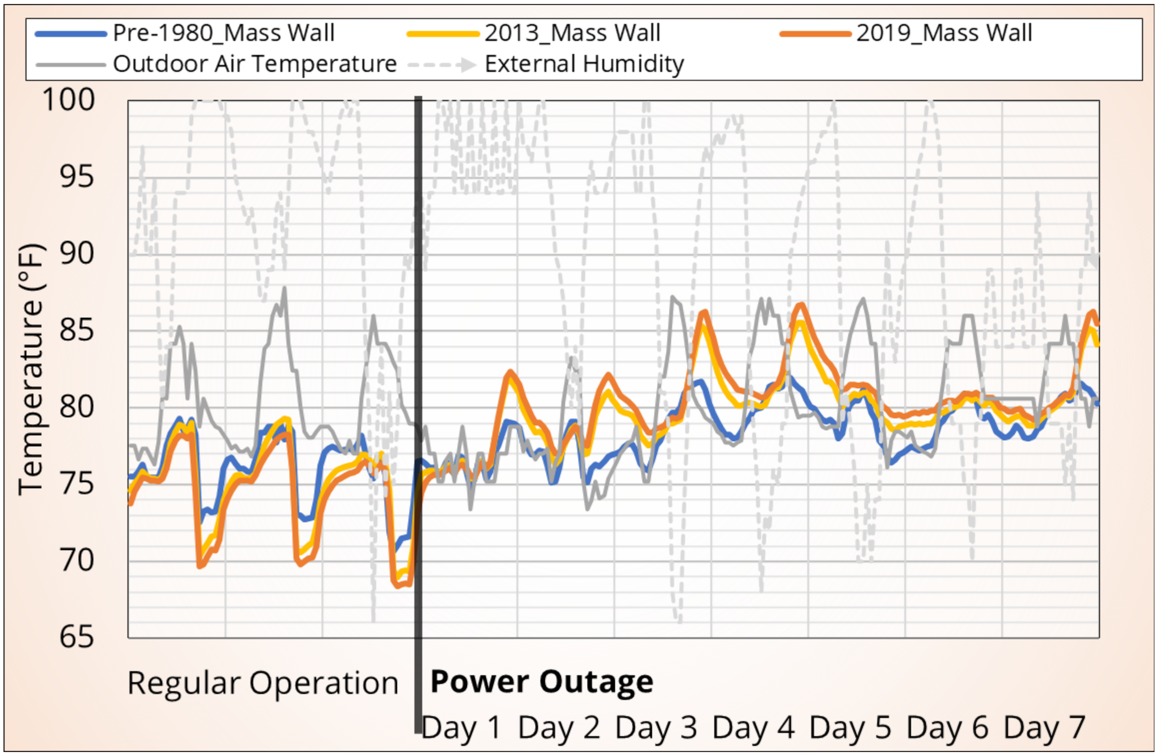


Figure D-2. Corridor (No exterior) - Heat removal is higher at Pre-1980 Construction.

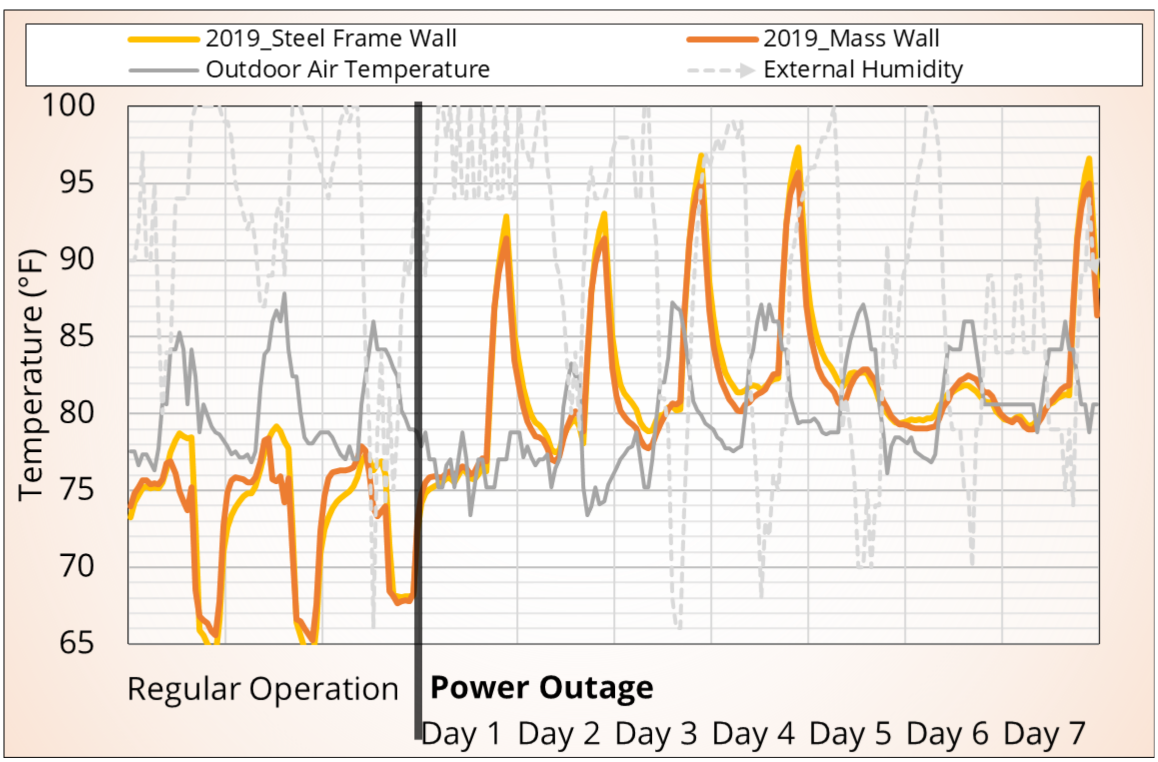


Figure D-3. Classroom (Exterior, East) - Due to high occupancy, the difference between steel and mass is not obvious.

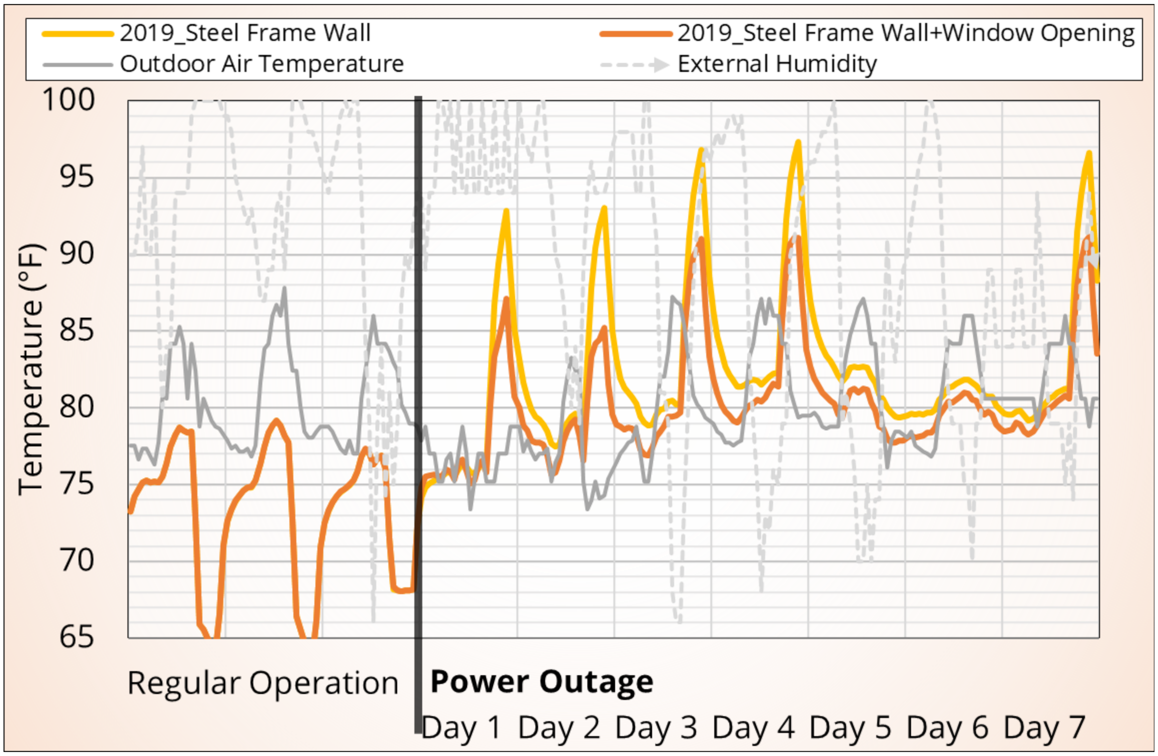


Figure D-4. Classroom (East facing, single sided windows) - Single sided window openings are less effective.

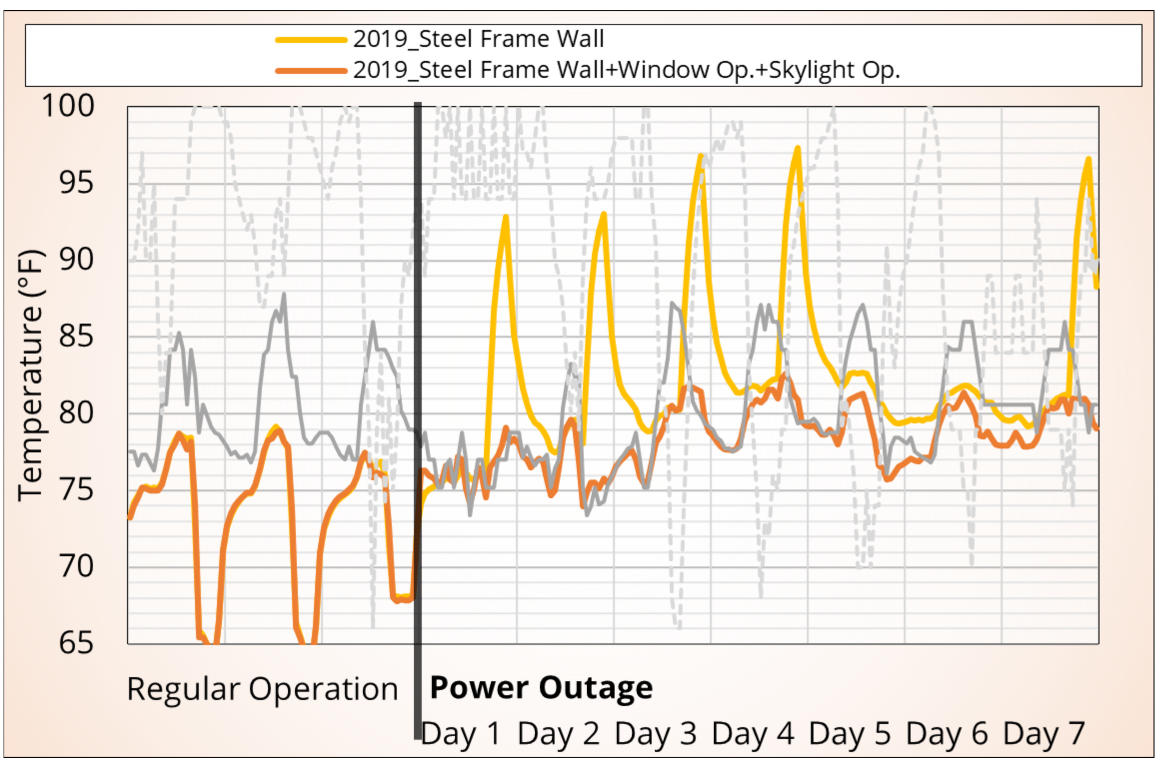


Figure D-5. Classroom (East facing, single sided windows + skylight openings) - Cross ventilation provided with skylight openings.

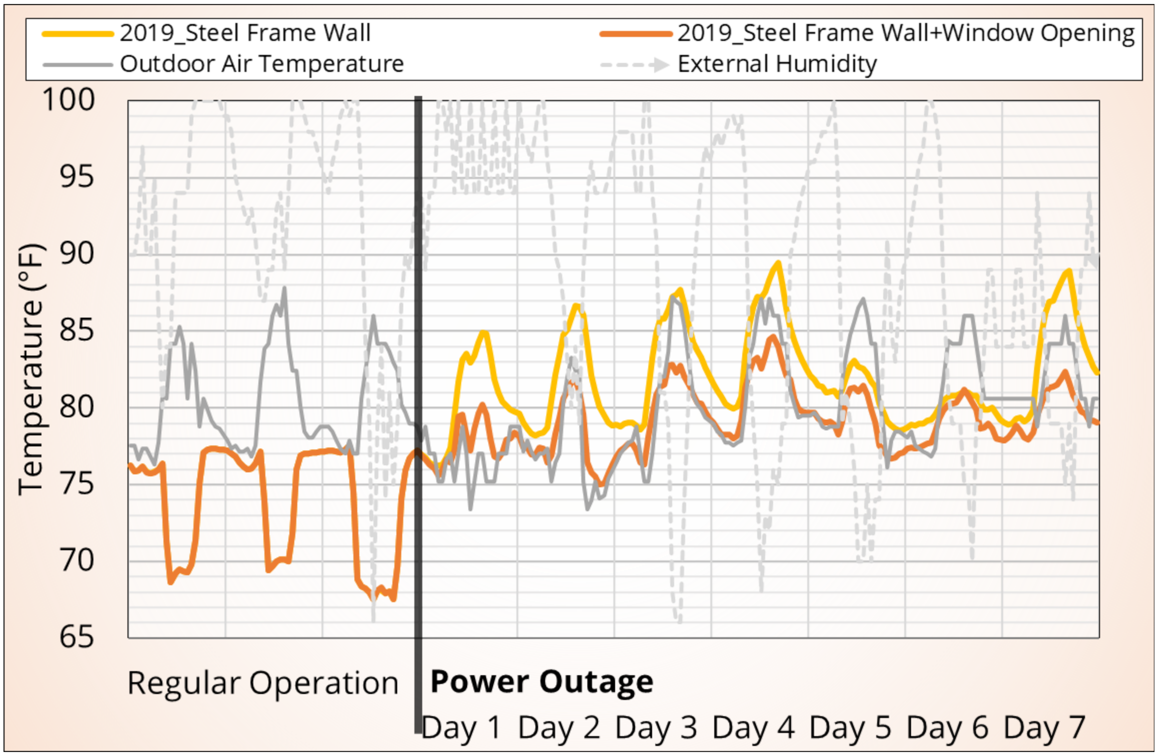


Figure D-6. Library (northeast facing, corner, double sided windows).

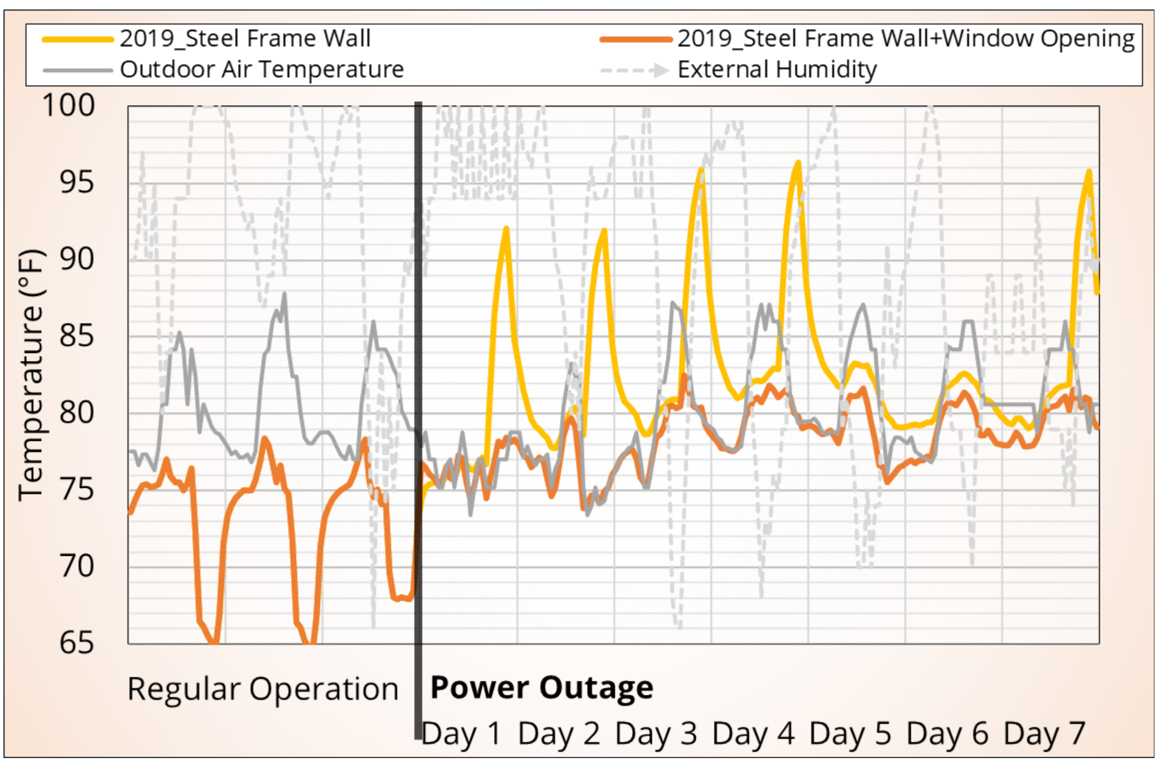


Figure D-7. Classroom (Southeast corner, double sided windows) - Benefit of window opening is higher because of high occupancy.

Hot and humid climates (HHC) present some of the most complex challenges for sustainable building design and operation to maintain high IAQ efficiently. Additionally, high temperatures and high humidity create extreme comfort issues and exacerbate the potential for condensation, mold, and mildew.

Buildings in humid climates, especially in coastal locations, are also subject to rust and the decay of materials much more quickly than in other environments. In extreme situations, e.g., at Kwajalein or Okinawa, concrete elements of the building envelope break down, and condenser units installed outside of the building envelope must be replaced within two to three years due to premature corrosion caused by salt-laden ambient air. Additionally, many coastal areas located in HHC are frequented by tropical storms and hurricanes with heavy winds, which can force water into the building and be damaging to the building envelope.

HHC provide unique challenges to HVAC, plumbing, and thermal energy system designers. Considering facility operation in the context of high OA temperatures and humidity, system reliability and building resiliency cannot be understated. This Guide describes best practice examples of robust and reliable systems emphasizing redundancy, durability, and functionality.

The target audience for this Guide is technical experts involved in building and energy systems design, renovation, operation, and maintenance; architectural and engineering professionals; and energy service companies. The content of this Guide may also be of interest to building owners, executive decision-makers, and energy managers of public, government, and military organizations.

The Guide was developed with partial support from the DOD Environmental Security Technology Certification Program, the Office of the Deputy Assistant Secretary of the Army (Energy and Sustainability), and the International Energy Agency Energy in Buildings and Communities Program Annex 73.

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