

GUIDE FOR
RESILIENT THERMAL ENERGY SYSTEMS DESIGN
IN COLD AND ARCTIC CLIMATES

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Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates

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Foreword

Thermal energy systems resilience is especially 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 earth's cold regions.

Thermal energy systems addressed by this Guide consist of both the demand and supply side. The demand side is comprised of active and passive systems including thermal demand by the process; heating, 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 for occupants include criteria to maintain thermal comfort and health, to support process needs, and to prevent mold, mildew, and other conditions that can damage building materials or furnishings.

In one of the first-of-its-kind attempts to address a deficiency in our ability to monitor and model thermal decay in cold environments, a thermal decay test (TDT) was envisioned, developed, and conducted by a team of Engineer Research and Development Center (ERDC) researchers with collaborators from the University of Alaska, Fort Wainwright, Fort Greely, and Alaska Thermal Imaging, LLC to better understand the level of reliability required for energy supply systems that can support environmental conditions required for the facility's mission, comfort of people, and sustainment of a building in arctic environments under predominant threat scenarios. The TDT included testing the reliability of the thermal systems in real time under actual extreme conditions (in extreme temperatures, down to -40 °F (-40 °C) and high winds up to 62 mph (100 kmph), summer and winter air leakage tests, and the build out of a model to better forecast future cases and vulnerable failure mechanisms. Based on field studies, a reliable building model has been developed to identify the maximum allowable time available to correct any problems with energy supply to mission critical facilities for different facility archetypes (building mass and insulation characteristics) and air leakage rates before the indoor air temperature reaches habitability or sustainability thresholds.

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 operation, but not to the level of their optimal comfort conditions. Beyond these threshold (habitable) levels, effective execution of a critical mission is not possible and mission operators have to be moved into a different location. 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 cold stress thresholds: in a heating mode, air temperature in spaces with mission critical operations should be maintained above 60.8 °F (16 °C) (ACGIH 2018).

Prescriptive guidelines for thermal insulation in the design of buildings in cold 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 the Arctic and Subarctic regions of the world are as influenced by the differing priorities of the governing bodies

that set these requirements as they are on actual physical demands and conditions. Usually, national requirements for building envelope characteristics, e.g., thermal insulation values of its components, building envelope air tightness, 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. This Guide summarizes best practice requirements to the building envelope characteristics for buildings located in cold and arctic climates of the United States, Canada, and Scandinavian countries and compares the effect of different levels of building envelope efficiency and mass on indoor air temperature decay when heat supply is interrupted.

Arctic climates provide unique challenges for designers of HVAC, plumbing, and thermal energy systems. The importance of considering the operation outside air temperatures, system reliability, and building resiliency cannot be understated. This Guide describes best practice examples of robust and reliable systems with the emphasis on their redundancy, durability, and functionality. It also discusses the most common heating system and ventilation system approaches used in arctic climate and emphasizes the importance of a maintenance program that allows building operators to successfully troubleshoot and maintain buildings in the arctic. Concepts are illustrated by several best practice examples, e.g., U.S. military bases in Alaska and Søndre Strømfjord and the international airport of Greenland that previously was used as a U.S. military base.

This Guide is designed for energy systems designers, architects, energy managers and building operators and is a valuable resource for those who are involved in building planning and operation in cold and arctic climates. This Guide, with its focus on resilience of thermal energy systems, is meant to complement the ASHRAE *Cold-Climate Buildings Design Guide, Second Edition* (ASHRAE 2021).

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CHAPTER 1. INTRODUCTION

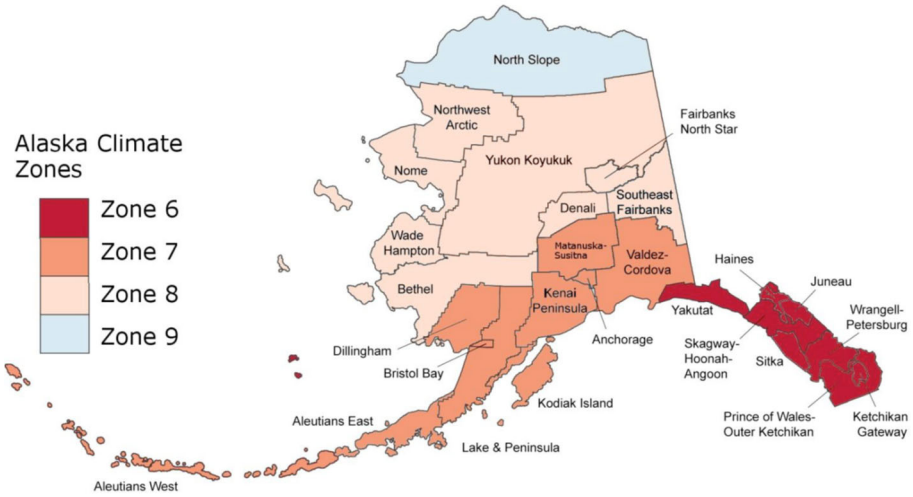
1.1 Traditional parameters of cold climate construction

The U.S. Department of Energy (DOE) classifies locations with more than 5,400 HDD (65 °F) [3,000 HDD (18 °C)] as "cold" (zone 6), and any area with more than 9,000 HDD (65 °F) [5,000 HDD (18 °C)] as "very cold" (zone 7). Places with more than 12,600 HDD (65 °F) [7,000 HDD18 (18 °C)] are considered "subarctic" (zone 8). The problem with using these climate zones to discuss "cold climates" is that the "cold" designation applies to both Des Moines, IA with 6,426 HDD (65 °F) [3,570 HDD (18 °C)]); and Utqiaġvik (Barrow), AK with 18,996 HDD (65 °F) [10,553 HDD (18 °C)]). The climate specific construction requirements for Utqiaġvik are significantly different from those of Des Moines. Codes for cold climates are often diluted by the "warmer" end of cold climate. This document focuses on the "colder" end of the cold climate spectrum, i.e., areas with greater than 8,000 HDD (65 °F) (4,500 HDD [18 °C]).

1.2 Alaska –A case study

Alaska is a land of extremes with high summer temperature spikes and extensive periods of cold temperatures and darkness during the winter. In cold climates the indoor environment can be a welcome relief for occupants. For many, there are more hours spent indoors than outdoors during the winter months. Creating a healthy indoor environment with comfortable, reliable, and sustainable spaces and resilient energy supply systems is a high priority and design decisions should consider the life cycle cost effectiveness of building and energy systems holistically, including current and future anticipated functions.

Alaska is the case study for cold climates; it encompasses all three DOE cold climate zones (Figure 1-1). Because Alaska is an arctic state, Alaskans add a fourth zone, Climate Zone 9 or "Arctic," which includes areas with greater than 16,800 HHD (65 °F) [9,300 HDD (18 °C)] (Alaska Housing Finance Corporation 2018a,b). Climate Zone 9 is a unique place; construction in the Arctic requires specialized design if it is going to remain functional in the long term.



Source: Alaska Housing Finance Corporation 2018a,b.

Figure 1-1. Alaska climate zones.

1.3 Weather considerations

Very cold temperatures drive building design in cold climates. For people to survive in the cold, buildings that are warm and comfortable are essential. A tight, warm building envelope goes a long way toward mitigating the effects of cold, harsh weather. Quality building envelopes are also imperative for resiliency; if there is a disruption in services (which can be quite common in the remote Arctic) the building envelope is the first defense against facility failure. Tight building envelopes create extra requirements for ventilation and may necessitate heat recovery. Ventilation with heat recovery capability is important in cold regions as it lowers heat loss and improves building efficiency. The use of operable windows or "natural ventilation," though code compliant, is not a viable solution during the winter months.

Mechanical systems need to be able to handle the effects of freezing temperatures: automatic defrost cycles in ventilators are necessary to prevent frost build up, the location of exterior exhaust hoods need to be carefully chosen to limit ice buildup on and above walkways, personnel doors, and vehicle entries, and intake and exhaust penetrations need to have adequate screen opening sizes and configurations to prevent frost and blowing snow from blocking them. Tight, heavily insulated buildings often have enough internal heat gain to require cooling in the warmer months. Well water cooling, ammonia absorption, and vapor-compression refrigeration are all options.

Extreme cold exterior temperatures create low relative humidity inside buildings. Ten percent relative humidity is not uncommon in commercial buildings that are not humidified. Low humidity (less than 25%) can create human health problems like increased spread of bacteria and viruses, respiratory infection, allergic rhinitis, and asthma (Sterling et al. 1985). Low humidity also creates excess static electricity, which is dangerous to sensitive electronics. Proper humidification is energy intensive, requires regular maintenance, and is difficult to achieve at low outdoor temperatures, but is often necessary. Humidification must be coupled with appropriate building envelope design including inspection and/or envelope commissioning during construction. Systems design should include controls that offset the indoor relative humidity setpoint based on outdoor air temperature (ASHRAE 2021). Many warm climate conventional wall and roof designs fail in cold climates due to the extreme vapor drive at low winter temperatures (Craven and Garber-Slaght 2012). Thermal bridges through walls and ceilings need to be avoided as higher indoor humidity can result in dew or frost occurring on surfaces where thermal bridging occurs. It is highly recommended that facilities or portions of facilities that are actively humidified have a detailed hygrothermal analysis completed by a design professional for all building envelope components. Building indoor positive air pressure should be kept to a minimum to avoid forcing warm humidified air into wall or ceiling cavities where condensation and frost buildup can occur. Where facilities have isolated rooms that are humidified, such as operating rooms or data centers, humidity migration to the surrounding spaces should be limited through the use of internal vapor barriers, sealed vestibules, or by using a box-within-box design layout. This will not only reduce the energy used in the humidification process but will also limit humidity exposure to the exterior envelope. Humidification in improperly designed and/or installed envelopes can lead to the generation of mold, which can have a significant negative impact on indoor air quality.

In addition to very cold temperatures, frozen and freezing precipitation are also building design drivers in subarctic and arctic regions. Local snow depth and potential snow drifting should determine the structural design of the roof. The amount of snow and prevailing winds along with wind speed can complicate the location of exterior penetrations. Ventilation hoods need to be specially designed for

use in environments with blowing snow. Snowflake crystals fracture when transported by winds and become small particles that can penetrate small openings in building envelopes and accumulate in ventilation hoods. Strong winds in far northern (tundra) areas of Alaska only enhance the need for strict air tightening requirements for buildings in the Arctic.

Extreme weather events in arctic locations can exacerbate failures. Rapid climatic warming in the Arctic is leading to more extreme weather events (U.S. Climate Resilience Toolkit 2017). Many locations in Alaska are currently receiving more precipitation, which calls the current snow load design code for building roofs into question. Other locations are much drier, which lead to more wildfires and the need to design and redesign buildings and sites to be resilient to fast and large wildfires (Federal Emergency Management Agency 2008). River and coastal locations are prone to flooding and erosion due to increased precipitation, loss of vegetative cover from wildfires, and loss of winter sea ice. Site selection and building planning should consider the flood potential of a specific location (Jones 2017).

1.4 Remote locations challenges

Many locations in Alaska are very remote, which creates unique challenges. The logistics of construction and maintenance in such remote locations is unique and can be daunting. For example, many remote locations in Alaska may have only one or two barge deliveries in the summer; the rest of the year, those locations are accessible only by airplane, snowmobile, or not at all. Even in locations normally accessible by road and airplane, extreme weather events (winter storms and avalanches) can make these locations inaccessible for several days at a time. In some areas, ice roads are constructed annually to move materials and equipment during the winter to some remote communities and industrial areas. Heavy construction equipment is not often available on site and must be shipped by barge. It can be difficult to find room and board for construction crews in smaller communities; for larger projects, this often creates a need to bring in construction camps. Transportation of replacement parts and equipment to remote locations can affect the original system design. For instance, it may be more desirable to use a cast iron sectional boiler or a series of smaller boilers rather than a large water-tube boiler. Technical maintenance expertise is generally not available at remote sites; such personnel must be flown in from urban areas to resolve issues. Straightforward uncomplicated designs allow local maintenance personnel to make repairs more easily.

Shipping costs make fuel to provide electricity and heat expensive at remote sites. For example, heating fuel in a remote village in Alaska can be 2-5 times higher than fuel in larger cities like Fairbanks or Anchorage. The use of static resiliency measures, such as a robust building envelope design, makes sense not only from the standpoint of mission operation, but also from simple economics; such designs significantly reduce long-term operational costs. Balancing energy efficiency with robustness in all building system designs makes remote facilities more resilient and reduces the need for costly fuel.

The remoteness of many locations in Alaska is a major factor for installation resilience. Designs must include redundancy in critical infrastructure to ensure minimal operating conditions under all equipment failure scenarios. This includes power, fuel, and heating systems, and in some situations water and sewer utilities. It can also be critical to maintain communication systems to allow for monitoring and diagnosis of remote systems. For example, Wi-Fi networks are now being leveraged with live video streaming services to allow remote technicians to walk local operators through emergency repairs.

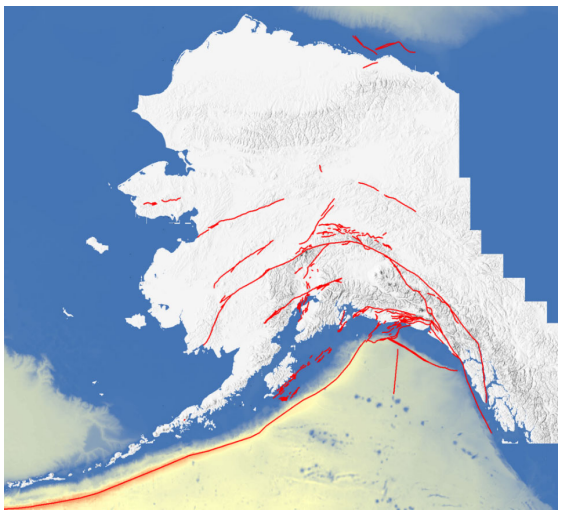
Utility infrastructure in remote communities can be prone to failure. Most communities have a single power plant and limited redundancy in their power distribution network. In addition to power outages, it is not uncommon for the utility power to experience high and low voltage conditions as well as loss of phase events. In addition to standby power generation, critical infrastructure and control systems should consider the use of devices such as over/under voltage protectors, phase loss monitors, and general power conditioning through the use of uninterruptible power supply (UPS) equipment.

It important to consider location logistics when specifying equipment for remote locations. It is best to use equipment with a track record in the area and equipment someone in the area already knows how to repair. Getting parts to keep equipment running can take months. Supply lines are long and not always functional. Equipment installed in remote locations should be as robust as possible.

Many materials do not work well in extreme cold; they become brittle and prone to failure (Jacobson 1965). Equipment that needs to function outdoors should be designed and tested to handle very low temperatures (-40 °F [-40 °C] and colder). Most manufacturers do not test their equipment and materials under extreme low temperatures so direct contact with the manufacturer is sometimes required to fully vet a product. It is preferred to shelter equipment in extreme temperature locations inside the building envelope or within temperature-controlled structures to not only ensure its operation but also to extend the life of the equipment and to facilitate maintenance.

1.5 Seismic considerations

The very foundation of Alaska is in constant movement. Most of central and southern Alaska is underlain with seismic faults (Figure 1-2). These faults have produced some of the largest earthquakes in the world in the past 100 years and the majority of U.S. earthquakes greater than magnitude 5 have occurred in Alaska (Alaska Earthquake Center 2020). Buildings designed for Alaska need to conform to strict structural codes and guidelines so that they can withstand most earthquakes (Municipality of Anchorage 2018).

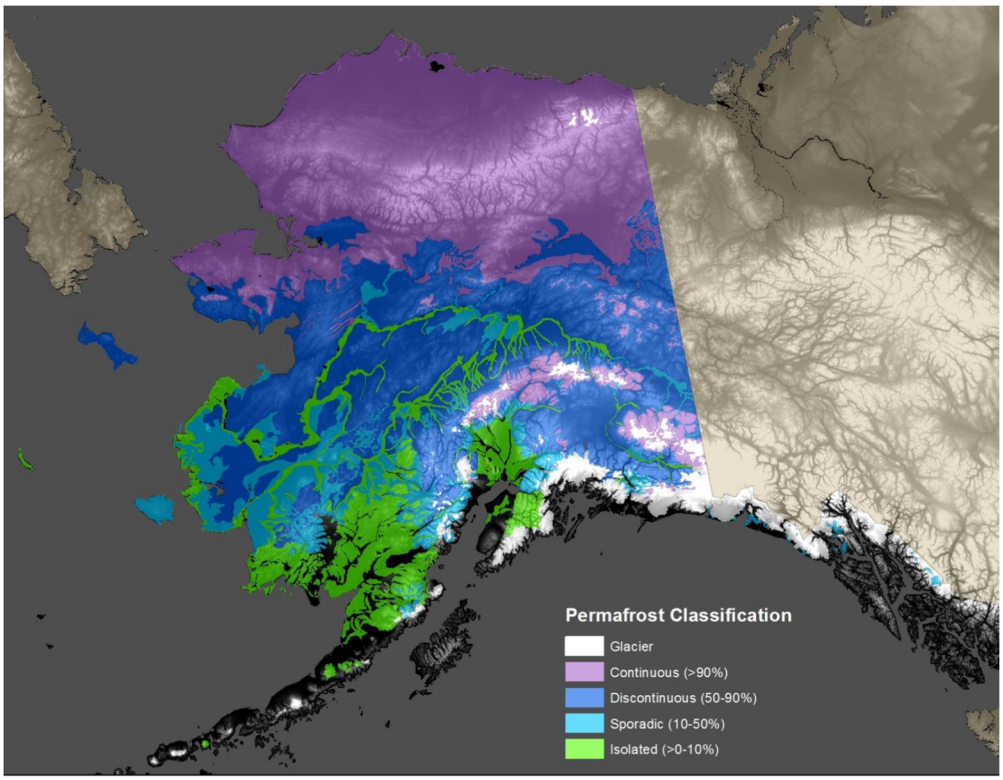


Credit: Adrian Bender, USGS, Alaska Science Center. Public domain. (https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/styles/full_width/public/thumbnails/image/Alaska_fault_model_10-11-2018_Adrian_Bender_1.png)

Figure 1-2. Fault lines in Alaska.

1.6 Permafrost considerations

Alaska has seasonally frozen and permafrost soils (where "frozen" is defined as colder than 31 °F [-1 °C]). Permafrost soils occur when soil or rock remains frozen for 2 or more years. Discontinuous permafrost is laterally discontinuous, meaning it includes numerous permafrost-free areas that decrease in size and number from south to north. North of the discontinuous zone, continuous permafrost is present almost everywhere below the land surface except under lakes and rivers that do not freeze to the bottom. In Alaska, there is a transition from seasonally frozen soils to discontinuous permafrost (subarctic) to continuous permafrost (arctic) from the southern coastal areas of Alaska to Alaska's north slope (see Figure 1-3). For both seasonally frozen and permafrost soils the surface layer that undergoes an annual freeze-thaw cycle is referred to as the active layer (Figure 1-4). In seasonal frost locations it is the depth of freeze and for permafrost locations it is the depth of thaw.



Source: C. Hiemstra, CRREL Modified from Brown and others, 1998 by the U.S. Arctic Research Commission Permafrost Task Force Report (2003)

Figure 1-3. Permafrost distribution in Alaska.

Geotechnical site exploration is required for successful foundation design. In most cases, this requires drilling and retrieval of core samples along with laboratory analysis of the cores. Soil type, dry density, and moisture content are the minimum data required for thermal analysis of the in-situ soils. It is advised to retain a geotechnical engineering firm familiar with frozen soil mechanics and permafrost. If frozen soils or ice are encountered below the active layer when drilling, then it can be concluded permafrost has been encountered. Soil temperature measurements along the depth of the hole or below the depth of zero annual amplitude are often conducted for further evidence to the occurrence of frozen soils during the coring process.



Source: T. Douglas (ERDC-CRREL)

Figure 1-4. The seasonally thawed "active layer" (dark brown surface soil) and underlying permafrost along a coastal bluff near Utqiaġvik, Alaska.

Frozen soils are often ice-rich. This means that when the frozen soil is thawed there is water in excess of the thawed void volume. Ice-rich soils will exhibit thaw settlement as they thaw: water drains away and the soil consolidates. This is one of the major challenges with respect to foundation design for buildings in subarctic and arctic locations with underlying ice-rich permafrost.

Two general types of foundations are used for permafrost sites: on-grade or above ground. On-grade foundations usually consist of a floor slab, a layer of non-frost susceptible (NFS) material, a layer of insulation covered by a protective membrane, followed by another layer of NFS material over the in-situ frozen soils. Below the insulation layer, a refrigeration system is usually installed to prevent the permafrost from thawing. Common refrigeration systems include

1. Vapor-compression mechanical refrigeration with a piping grid beneath the insulation, similar to ground source heat pump systems.
2. Air ducts installed beneath the insulation with fans that move outdoor air through the ducts whenever outdoor air temperature is colder than subgrade temperature. In this case, thawing below the insulation does occur during the summer months but the NFS pad below the insulation is thaw-stable and its thickness is sufficient, so the thaw front does not reach the underlying ice-rich permafrost soils.
3. Thermosyphon systems that passively remove heat from below the insulation whenever the air temperature is colder than the subgrade temperature. Thermosyphon system designs are similar to air ducts systems as summer thawing occurs below the insulation within the NFS pad. Thermosyphons

consist of a sealed pipe charged with a pure working fluid such as carbon dioxide or ammonia. The lower end of the pipe contains the liquid phase of the working fluid, the middle includes an evaporator section, and the upper end contains the vapor phase, condenser section. Heat from the ground causes some of the liquid to evaporate, which then travels as a vapor to the above-ground or upper section where it condenses due to the cooling effect of the colder ambient air. Cold condensate then returns to the evaporator section via gravity to complete the cycle.

The alternative to on-grade foundations with insulation and refrigeration are above-grade designs. Foundation support systems are typically either post and pad or piles. The design concept is that heat passing through the insulated floor of the building will be carried away by winter winds and will not warm the ground surface beneath the building, which could lead to thermal degradation of the permafrost. The footprint of the building shades the ground from solar radiation, which is a thermal plus. Care must be exercised to avoid snow accumulation beneath the building as the snow tends to insulate the ground from ambient temperatures. For the post and pad support systems, the foundation pads are typically concrete or treated timber with the posts constructed from treated timber or steel. In cases where there are potential thaw settlement issues the posts are designed to be adjustable to maintain a level foundation. In ice-rich permafrost, friction piles are usually deployed. These are generally steel pipe piles for buildings and are typically installed in predrilled oversized holes. Sand slurry is placed in the annular space between the pile and the hole. In warm permafrost, adequate time must be allowed for the slurry to "freeze back" before loading the pile.

If the active layer for a seasonally frozen or permafrost site is a frost susceptible soil, then it will likely frost heave over the course of a winter. Frost heave is the capillary movement of water to the freezing front and the formation of ice lenses (segregation ice). Since frost heave is never uniform, it results in differential movement and lifting forces on conventional and pile foundations. In seasonal frost locations, frost heaving damage can be minimized if an NFS soil is used beneath the foundation, good surface water management is practiced, and proper use of subgrade insulation is applied (HQUSACE 2004) so building heat prevents frost penetration below the foundation. Upward frost heave forces and potential lifting of a pile foundation can be mitigated by anchoring the pile, breaking the bond between the active layer and the pile, increasing the load on the pile, minimizing the surface area of the pile in the active layer zone, and ensuring proper use of NFS material.

1.7 Conclusions

Infrastructure design for cold climates requires special attention to extreme weather, but also to remote locations and frozen soils. In cold climates, for resilient infrastructure requires planning well beyond the typical resiliency planning for infrastructure in more moderate locations. Building envelopes are the first defense against harsh cold climates; they can be designed and built in a way to increase building resiliency. Mechanical systems must be designed with cold climates in mind; some equipment simply does not work in the cold and getting repairs in remote locations is not quick or easy. Resilient mechanical and energy systems for cold climates usually require backup equipment.