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Best Practices for HVAC, Plumbing, and Heat Supply in Arctic Climates

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ABSTRACT

Arctic climates provide unique challenges for designers of heating, ventilating, and air-conditioning (HVAC), plumbing, and thermal energy systems. The importance of considering outdoor air temperatures, system reliability, and building resiliency cannot be understated. This paper describes best practice examples of robust and reliable systems with the emphasis on their redundancy, durability, and functionality. The paper 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, the international airport of Greenland that previously was used as a U.S. military base).

The paper results from experts' discussions during the Thermal Energy Systems Resilience in Cold/Arctic Climates (ERDC 2020) consultation forum and research conducted under the International Energy Agency's Energy in Buildings and Communities (IEA EBC) Program Annex 73, the Environmental Security Technology Certification Program (ESTCP) Project "Technologies Integration to Achieve Resilient, Low-Energy Military Installations," and U.S. Army Program Project 633734T1500 under Military Engineering Technology Demonstration. The paper is complementary to the ASHRAE Cold-Climate Design Guide *(ASHRAE 2015) with a focus on resilience of thermal energy systems.*

INTRODUCTION

Alaska is a land of extremes, with high summer temperature spikes to extensive periods of cold temperatures and darkness during the winter. Building owners have typically been willing to increase first-cost investment on both reasonable energy reduction measures and reasonable comfort measures. In cold climates, the indoor environment can be a welcome relief for occupants, and for many, there are more hours spent indoors than outdoors during the winter months. Creating a good 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.

RESILIENCY IN COLD CLIMATES

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 an outage in the heating plant, either locally or from a centralized source. For the purposes of this paper, *resiliency* is defined as *the ability of a commercial building to withstand an interruption in the function of the heating system*. In other words, a building that has a fast rate of temperature degradation with the loss of heating system function has low resiliency. A building that has a slower rate of temperature degradation has high resiliency. There are certainly other factors that improve the ability of a building to withstand an outage of the primary heat source, such as redundant equipment and backup heat sources, among others.

In extremely cold climates, resiliency can play an integral role in protecting property during an outage. A drop in indoor temperature can pose a risk of freezing plumbing and wet sprinkler piping. Frozen pipes can burst and flood the build-

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ing's interior. Pipe breaks due to freeze conditions are common in Alaska in both commercial and residential contexts. Flooding in commercial buildings can cause enormous damage that can cost thousands of dollars to repair and cause the loss of workspace in an office building.

Therefore, it is necessary to look not only at the building HVAC installations, but also at the building envelope and the whole energy infrastructure. Large thermal capacity of concrete and brick walls, internal water pipes, critical system redundancy, a well-sealed and well-insulated building envelope without thermal bridging, and a centralized controlled hot-water heat supply can offer a more resilient low-carbon system than, for example, building-level steam boilers.

HEATING SYSTEMS IN ARTIC CLIMATES

Unlike comparatively warmer climates, heating with air is not typical in construction in cold climates. This is due to high heating loads. Heating with air in a commercial application should be used with caution. Air heat from above is not effective unless it reaches the floor, and it cannot reach the floor from above without significant velocity; additionally, the heating distribution fan is typically subject to the possibility of a single point failure for the forced air heating system. Since the density of warm air is less than that of cold air, chances are that without sufficient velocity it will remain at ceiling level, outside of the working area of the occupants of the space.

As noted, heating systems in arctic climates are considered critical infrastructure. It may take days or even weeks to get a failed heating system component fixed and operational. Resiliency in mechanical system design is first achieved through system redundancy. Examples of this include:

- Two or more boilers sized to be able to keep the facility above freezing under reduced operational conditions with one unit down for maintenance. Reduced operation may include temporarily turning off the ventilation system. This has traditionally resulted in two boilers sized at 66% of peak heating load or three boilers sized at 50% peak load.
- For critical pumps, such as main circulating pumps, two pumps are provided in a primary/backup configuration with independent starters/variable-frequency drives and power circuits.
- The use of multiple heat sources. This may be adding gas-fired rooftop units to a hydronic system, having fuel-fired space heaters, or having a solid fuel backup heat source.
- Multifan arrays where ventilation is a mission critical part of the facility.

In critical infrastructure, this may mean the use of N+1 levels of redundancy at all levels of the building systems including power generation and controls.

Working Fluid. Hydronic heating is the preferred method and typically uses a glycol/water solution as the heating system fluid. This provides freeze protection and allows the heating system fluid to be used in air-handling unit heating coils that heat incoming air that could be as low as –60°F (–51 °C). Glycol to water percentages are selected based on a conservative winter design temperature and either the glycol's associated freeze or burst protection volume percentage. Typical glycol mixture percentage in extreme temperature zones is 50%, with some building owners opting for up to 60% glycol heating system fluid. There is a thermal performance de-rate and significant viscosity increase when using glycol over water, which needs to be considered when designing hydronic systems. Ethylene glycol and propylene glycol are the most typical heating system mediums. Ethylene glycol performs better from a de-rate and pressure drop perspective as compared to propylene glycol. However, in some cases it may be preferred to use propylene glycol as it is not toxic to humans.

Chiller systems that are expected to be filled and/or operated year-round also utilize glycol. The preferred fluid for these systems is ethylene glycol due to the better viscosity performance at lower temperatures.

In addition to a performance de-rate, the wetted surfaces of equipment must be compatible with glycol to prevent premature failure of components. The most common issue is pump seals and gaskets. Pump seals and system gaskets compatible with the glycol mixture concentration should be selected. Glycol is also susceptible to degradation under high temperatures which can form acid molecules. It performs well in cast iron sectional boilers but can degrade in water-tube boilers.

Glycol must have regular maintenance to ensure a proper pH balance and the presence of corrosion inhibitors. Annual testing of the pH and glycol freeze protection is recommended. Fluid should be sent in or inhibitor and other chemical analysis as well on a regular basis. Improperly maintained glycol can become acidic and corrode pipes and gaskets as well as seize control valves.

When using glycol as a heating or cooling medium, it is recommended that the system not be connected to the domestic water system for makeup as is traditionally done with water-based systems. A stand-alone, automatic feed glycol makeup tank is recommended. History has shown that water makeup systems will slowly dilute the glycol over time, either through unseen system leaks or maintenance drain-down operations. This lower glycol percentage results in freezing and bursting of coils.

Perimeter Heat Using Finned Tube Radiators. The high thermal flux across the building envelope is best addressed at the bottom of the envelope with either finned tube radiation (FTR) cabinets or radiant panel heating. In areas of significant glass, such as architecturally appealing entry lobbies, this is typically handled with FTR cabinets. Heating with FTR cabinets is most economical when using high fluid temperatures of about 180°F (82°C) compared to floor radiant heating systems that typically should have a maximum fluid temperature of 120°F (49°C). This makes combining the two systems using a single distribution system difficult and expensive as it requires separate piping systems or a control valve and a pump at each radiant manifold. When using cast iron sectional boilers, the return water temperature should be considered during design. A temperature differential too high can result in cracked sections, rendering the boiler inoperable.

A benefit of using finned tube and radiant panel radiators is the ease of renovation. In applications where renovations are expected at relative frequency, it is recommended to use these approaches. Heating zones are easily modified and piping is accessible in the ceiling space or in the floor below. An additional benefit is the ability to do effective nighttime setbacks as the response to set point changes of finned tube radiators and cabinet unit heaters is relatively short.

Compared to radiant slab heating systems, which will be discussed in the following section, perimeter radiant heat using finned tube or radiant panels radiators will result in lower resiliency compared to the same building with a radiant slab heating system, due to the high thermal mass of the heated slab (Figure 1).

Radiant Slab Heating. In-floor radiant heating, also known as radiant slabs, can be used successfully to address building heating load, but the output is limited by the allowable surface temperature before it exceeds the rated temperature of the flooring assembly or acceptable floor temperature for given building function. For example, for sedentary work, such as many office spaces, a higher floor temperature can result in favorable fungal growth temperatures for those who are seated for long periods of time. Many flooring adhesive products have a maximum temperature rating between 85°F and 90°F (29°C and 32°C), also limiting the slab surface temperature.

A driver for many building owners opting for radiant heating systems is the quality of heat it provides. Radiant heating provides a fairly uniform heat, which is welcome during cold periods in Arctic climates. Since the heating is within the floor, assembly the furniture layout is not driven by the location of heating terminal units as is sometimes the case with FTR cabinets.

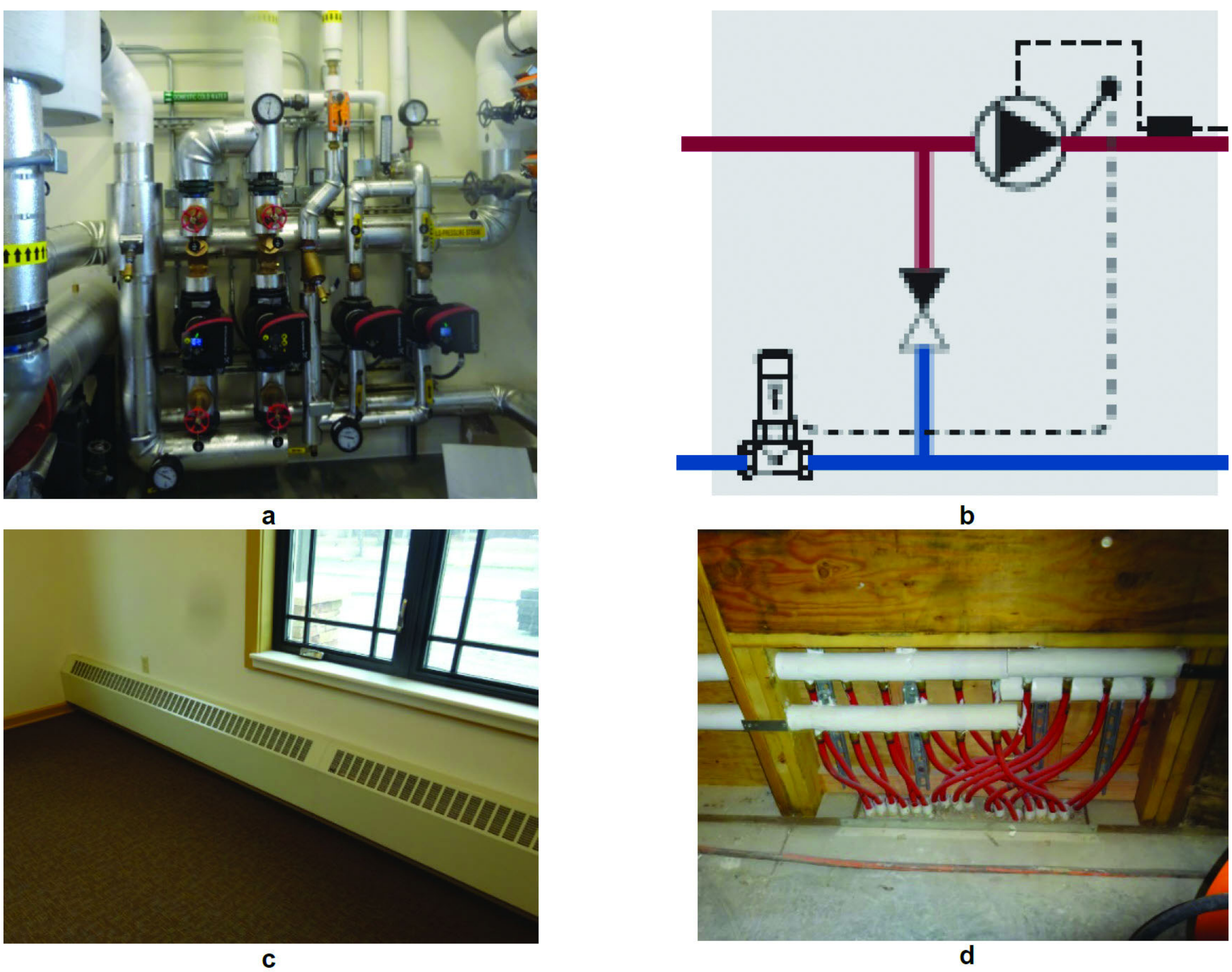

Figure 1 *Hydronic heating system: (a) system interface with district steam system (designed by Design Alaska), (b) mixing shunt, (c) finned tube radiator at a perimeter wall, and (d) radiant tubing manifold during construction.*

Building owners and system designers should consider the ability to renovate spaces when selecting radiant slab heat. When tubing is located within the slab, relocating interior walls can require careful coordination to avoid puncturing a tube when anchoring new walls into the slab. In some cases, tubing is located in a sand bed below the slab to allow for anchorage into the slab during initial construction and in the future with limited risk of damage to the radiant tubing. Locating the tubing in a topping slab would also be a consideration. In this case, the tubing would be repoured in a remodel. All radiant floor systems should use insulation under the slab (or under floorboards in staple-up applications) and at the slab perimeter to direct the heat upwards toward the occupant and improve heating efficiency. In garages and hangars, it is recommended to install a hydrocarbon resistant liner above the insulation to ensure that fuel and oil leaks do not erode rigid insulation.

Another complication of radiant heating is zoning. While heating zones can be customized to the current programming during building design, this can change dramatically over time. Additional zones results in additional cost for construction, therefore spaces with similar load are often zoned together with the controlling temperature sensor located in the highest priority space—a manager's office in an office space for example. A downfall to fewer and larger zones is that it is less adaptable to floor plan changes. A remedy to this challenge is to have many smaller zones in a grid pattern provided the project budget can sustain the added cost. Types of spaces that are typically renovated often, such as hospital patient treatment areas, should be considered with care. Significant cost may be added to all future renovations to accommodate the needs of programming changes.

Manifolds should be located at permanent features such as bearing walls or columns as these will be consistent in future renovations. Manifolds can also be located in interior walls near fairly permanent spaces such as mechanical rooms or bathroom groups as these walls are typically more consistent during the life of a building compared to typical space divider walls. With larger diameter tubing, the manifold itself can be done away with for smaller rooms. The radiant tubing can be run up to the ceiling space to avoid a wall accessible connection.

Resiliency of a building is improved when using radiant slab systems due to the fact that the high thermal mass of the slab itself is charged to a higher temperature. These buildings, compared to similar counterparts with FTR cabinets and radiant panels will perform better in a thermal degradation test in which the heating system is disabled. This can be of great benefit to building owners with unreliable heat plants and frequent outages, which is common in remote sites in Alaska.

In the same way that temperature loss is slowed with the use of radiant slabs, the ability for a space to maintain set point temperature is also reduced, as well as any pick up after nighttime setback. Radiant slabs are slow reacting, both to heat up and to cool down; therefore, design consideration should be given in areas that may experience rapid temperature loss such as garages and loading docks. In these areas, it is typical to provide a supplementary hydronic unit heater, which can pick up temperature quickly before the freezing of plumbing piping becomes a risk. Care must also be taken when locating plumbing within areas with garage doors or other large openings.

Centralized and Decentralized Heat Supply Systems

Historically, in the Fairbanks area of Alaska, the majority of commercial building owners who are not connected to district steam or heating water call for redundant boilers. Until recently these were almost exclusively fuel oil-fired, cast iron sectional boilers. Owners of large facilities stock spare parts for these boilers to reduce downtime, and this approach has worked well to prevent freeze up conditions due to equipment failure.

With the introduction of natural gas, this has stayed virtually the same except that natural gas boilers rely on the natural gas distribution system. In Fairbanks, natural gas arrives as liquid natural gas (LNG), is vaporized, and distributed through underground piping. To date, these systems have been comparable in reliability to oil-fired equipment except that the variety of gas-fired boilers is much greater.

Local schools and the hospital operate dual fuel boilers that switch between oil and gas depending on the cost and availability of gas. When the distribution system is heavily loaded, there is an arrangement with the utility whereby these users switch back to oil.

The two military bases in the area rely on district steam generated by coal-fired cogeneration power plants. These plants distribute steam through below-ground utilidors at medium pressure between 65 psi to 85 psi (448 kPa to 586 kPa) Once inside, the building the pressure is reduced to a 15 psi (103 kPa) low-pressure steam, where it is typically used in a shell and tube heat exchanger to produce high temperature glycol for distribution throughout the building to heating terminal units. The utilidors are also used to distribute domestic water and sometimes sanitary sewer.

Scandinavian experience with heat supply systems in cold climates shows that there are many advantages to using hot-water district heating compared to steam systems, in particular low temperature system with a maximal supply temperature of 212°F (100°C), for example:

- a simple system to be operated and maintained in remote areas,
- low risk and more resilient in case of break down,
- access to many efficient low carbon heat sources, not least free heat from local diesel generators,
- ability to store at low cost in thermal storage tanks,
- lower heat losses, and
- lower total costs

In some small communities in Greenland with microgrids, a significant part of the heat demand is produced by excess heat from diesel generators.

Distribution Networks and Resilience. Distribution network for building heating serving mission critical facilities can include redundant branches, creating loops sectioned by stop valves (Figure 2) that ensure heating energy backup (Gudmundsson 2020).

Emergency Heat Supply Solutions

The total reliance on a single power plant at Interior Alaska Military Installations has come under question; one alternative that should be considered is the purchase of trailer-mounted backup boilers.

One emergency backup option is a mobile boiler connection. This option is similar to the provision of emergency power generators; in this option, connections from mobile boiler plants could be easily provided to the mechanical areas of critical facilities that would allowing the use of steam or hot water the mobile boiler plants to back up utility heat sources or building site boiler (Figures 3a and 3b). A mobile boiler is a trailer or a container in which a fully functional heating system (hot water or steam) is installed. It consists of a boiler, burners, control equipment (continuously adjustable), all safety devices, pumps, and heating oil tank (natural or liquefied petroleum gas upon request). The unit is connected to the building or utilidor via flexible connection hoses to reliably supply hot water or steam. The capacity of mobile steam boilers may range between 30,000 lbs/h and 150,000 lbs/h at 350 psi (13,608 kg/h and 68,039 kg/h at 2413 kPa), and the capacity of hot-water boilers may range between 125 kBtu/h (50 HP) and 2500 kBtu/h (1000 HP) (Taylor 2020). The connection to the building glycol system could be simple valved tees at the building glycol distribution pump station and building controls contingency programming (Figure 3c). The connection to the building glycol system could be simple valved T's at the building glycol distribution pump station and building controls contingency programming. This strategy would require only a small additional capital investment of limited piping and valves, but would require additional level of

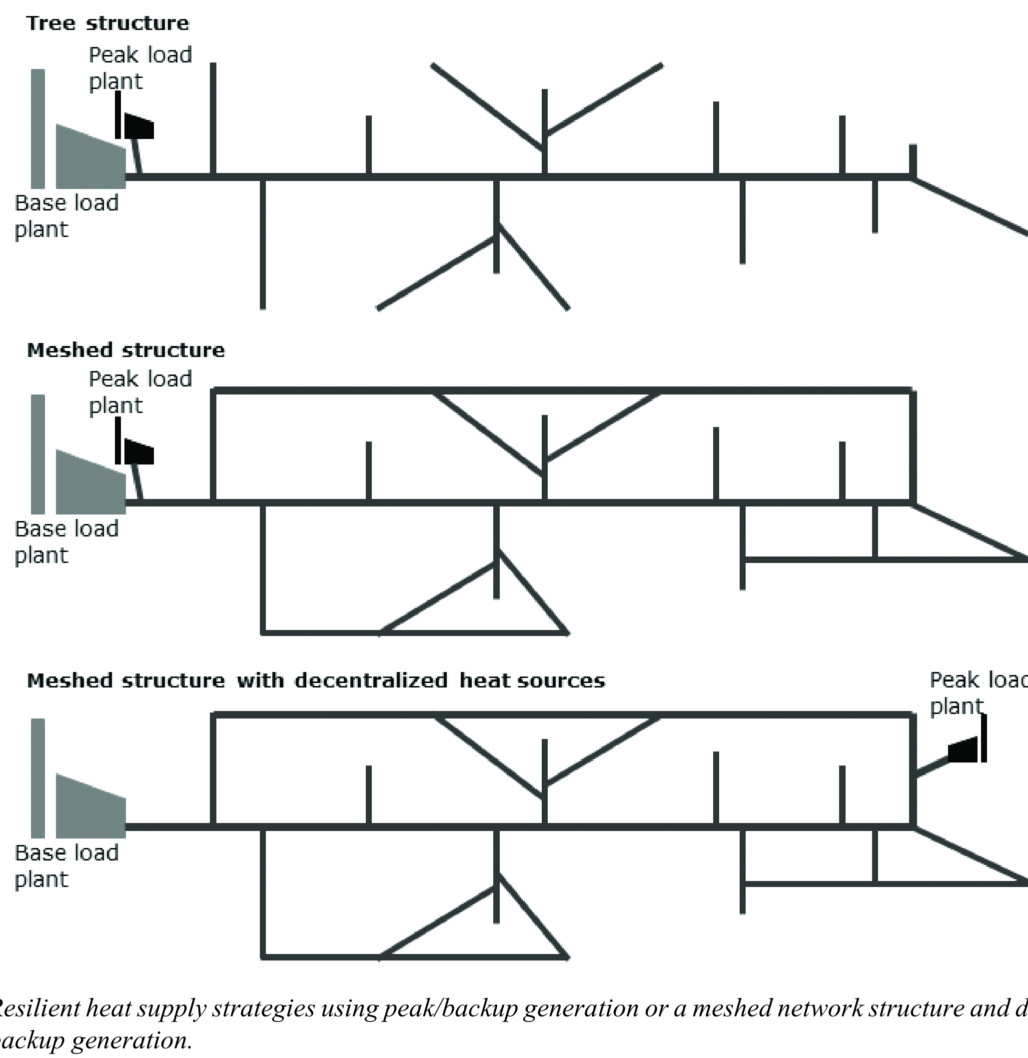

Figure 2 *Resilient heat supply strategies using peak/backup generation or a meshed network structure and distributed peak/backup generation.*

effort to operate in a contingency (finding/storing available boilers, connecting them to the system, and so on). Using mobile boilers may require the installation of several connections to an external wall, e.g., steam or hot-water supply line; fuel line (natural gas or oil) unless the mobile boiler has its own fuel tank; makeup water line, condensate/hot-water return line; power (panel box) for external hook up; blow down or drain line, and so on.

The following actions should be considered to implement this concept:

- Each campus/military base could obtain a boiler trailer with a boiler sized for the scale of a single building configured for low pressure steam or hot water/glycol to protect against service failure.
- Purchase a large medium pressure steam or hot-water boiler(s) to protect the base due to power plant or distribution system failure.

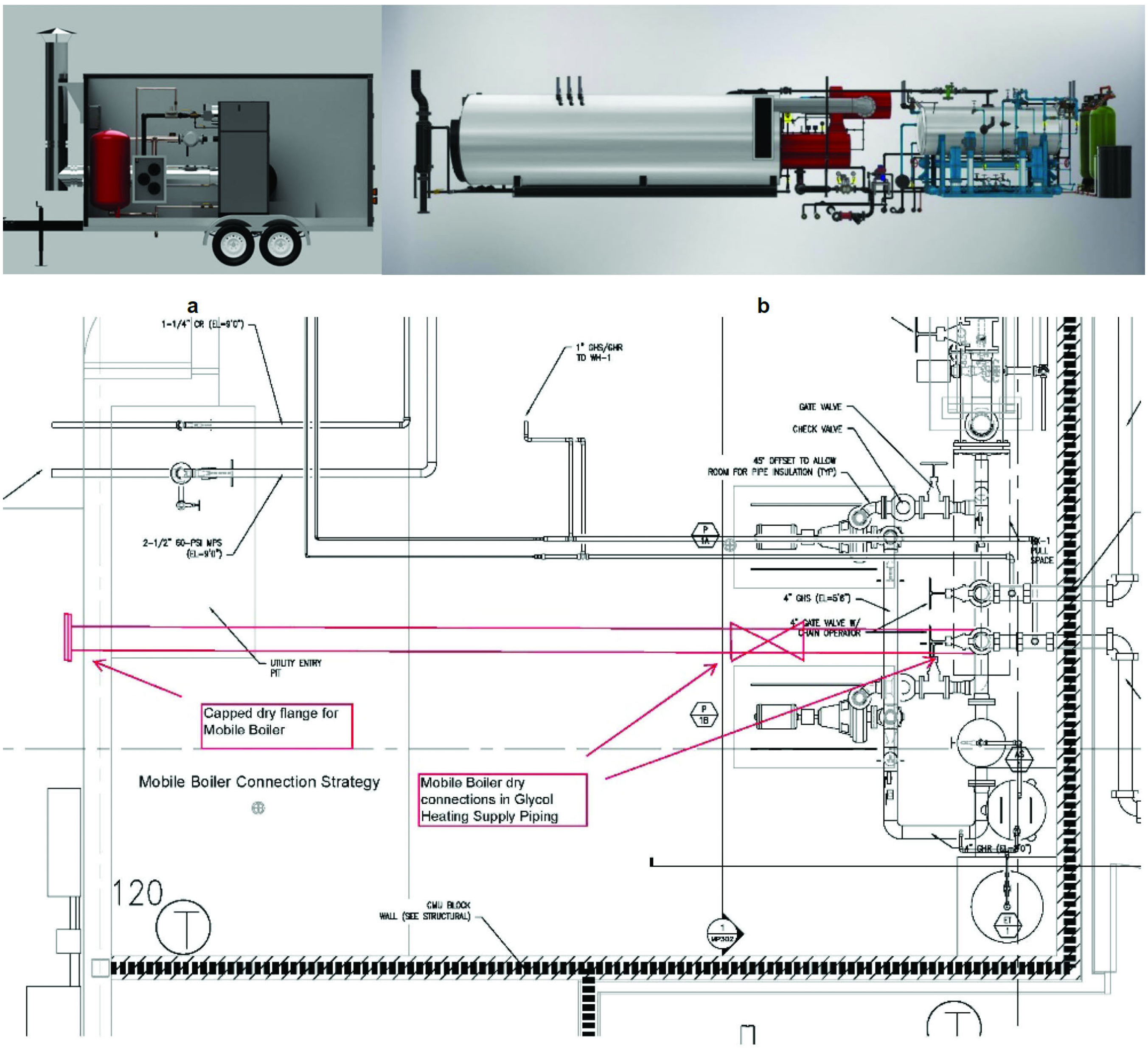

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Figure 3 *Mobile boiler: (a) schematic of hot water mobile boiler (Taylor 2020), (b) schematic of steam mobile boiler (Taylor 2020), (c) example of building interface for connecting to emergency mobile boiler.*

- Condensate collection points should be located within the underground utilidor system. These would likely consist of condensate return pumps in combination with a condensate return tank configured so that power can be switched over to trailer-mounted generators.
- A level pad should be constructed to support the boiler trailer, fuel tanker, and possibly a job or man shack.
- The total wasting of condensate could be considered on an emergency basis, but does not seem appropriate for a planned response. Condensate removal within the steam distribution system is a life safety concern and must be reliably maintained.

Although the use of large trailer-mounted boilers has not been tested at Alaskan military installations, it is expected that the trailer module would include a small fuel oil day tank that would allow the oil tanker to be hydraulically uncoupled from the boiler fuel delivery system. Similar large trailer-mounted boiler systems are currently in use in Alaska and have proven effective. These trailers would likely be set up to operate as trailer-mounted generators. Provisions for connection to commercial power is probably not warranted.

Safety concerns with steam distribution (i.e., the need for absolute reliability in the condensate removal system) would likely discourage the use of multiple heat source locations. If the use of trailer-mounted boilers is pursued, isolation points within the distribution system would need to be carefully considered.

Emergency Electrical Heating Element

Another option would be to install emergency electric heating elements in the HVAC system to provide supplemental heat (first stage) alone without the use of heat from the main source, e.g., boiler or district heat (second stage heat) (Figure 4). This would allow the emergency power supply to be connected for use in emergency situations to cover the minimum mission critical load when there is a problem with the first-stage heating to keep space temperature above minimum requirement to maintain space habitability or prevent building water pipes from freezing (Zhivov 2021). Great care should be taken when designing the electrical power source to disallow the system's use during nonemergency or testing conditions since this could result in significant impacts to the electrical utility bill. If a standby generator is not available on site to energize the coil(s), then external connections for a portable generator may be desired.

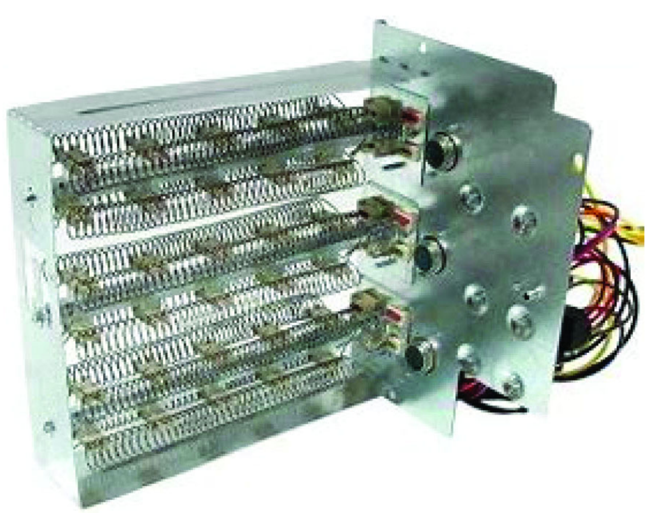

Figure 4 *Example of emergency electrical heating element (https://www.warrenhvac.com/).*

A design impact of this approach is an increased pressure drop and consequent increased energy use of the HVAC system as a result of the coil in the air stream. Equipment should be sized to accommodate both the primary and backup coils unless a bypass is provided (which would require additional controls and footprint to reroute flow to the backup system).

COOLING

Although the Alaskan interior has high record temperatures exceeding 90°F (32°C), the number of annual hours of mechanical cooling that is required is low, with about 70°F (21°C) days above a 65°F (18°C) base annually. Therefore, the least expensive form of mechanical cooling, direct expansion (DX) refrigeration, is typically most appropriate.

DX systems function through the refrigerant vapor expansion and compression cycle. Refrigerant in the evaporator coil, often located within an air-handling unit, cools air passing across the coil by absorbing heat from the airstream. Refrigerant is returned to the condenser to reject the absorbed heat to the ambient environment. Typically, a condenser is located on a pad outside where it can reject heat to the ambient environment; however, this can pose some challenges.

Because of the low angle of the sun during the winter and shoulder seasons as well as the amount of time on the horizon, many buildings will require cooling even when the outdoor air temperature is below the occupied space temperature. The preferred method of cooling during these conditions is through the use of an economizer function that increases the percentage of outdoor air in central ventilation systems. Other systems, e.g., data centers, which require year-round cooling, may not be conducive to either the low-humidity air from a central ventilation system or the limited occupancy schedule; in such cases, a mechanical cooling system is preferred. Depending on the operating temperature range of the outdoor condenser, it may not be recommended to run the condenser with these outdoor air temperatures. This situation can be mitigated to some extent by selecting condensers that include the option to run at low ambient temperatures, which would extend their operating range.

One benefit of DX systems is that they provide high performance at a relatively low installation cost. Moreover, they have a low noise level compared to chillers.

For larger, year-round cooling loads, a closed loop, chilled glycol system may be desired. The preferred exterior heat rejector is a multifan, dry cooler rather than the use of cooling towers due to the potential for freezing. Piping can be configured to bypass the chiller during the winter months and use "free-cooling" through the dry coolers to reject the heat.

Mini split systems, sometimes referred to as ductless or split A/C units, have been successfully used particularly in renovation projects where retrofitting a cooling coil into an air-handling unit or ductwork is not feasible. In this application, small wall- or pad-mounted condensers are located outside or in a mechanical space. Evaporators are located in occupied spaces and can be integrated into the ceiling grid or mounted on the wall. Routing condensate to a mop sink or floor drain can be a challenge depending on the location of the evaporator; therefore, selecting a unit with a small condensate receiver and pump provides more flexibility in pipe routing for condensate disposal.

Other Cooling Systems to Satisfy Year-Round Loads. Technologies such as chilled beams might save energy and offer a quick payback, but they are often not adopted due to their increased maintenance requirements and high first cost. Well water cooling systems have been successful, particularly in applications where the rejected water can be discharged to the storm drainage system. Reinjection has also been successful but is coming under greater regulatory scrutiny regarding its interaction with groundwater pollution sources that might be moved or influenced by the system. All designs that intend to use well or domestic water for cooling should be first vetted by the local utility and by the local environmental permitting agency.

VENTILATION SYSTEMS

Low outdoor air temperatures increase the heating load from heating outdoor air to distribution temperature high. This load can be offset by recovering the heat in the exhaust air stream. Heat recovery ventilators (HRVs) can be used to reduce the size of coils and the load on the heating plant by extracting heat from the exhaust airstream that would otherwise be discharge to the outside (Figure 5).

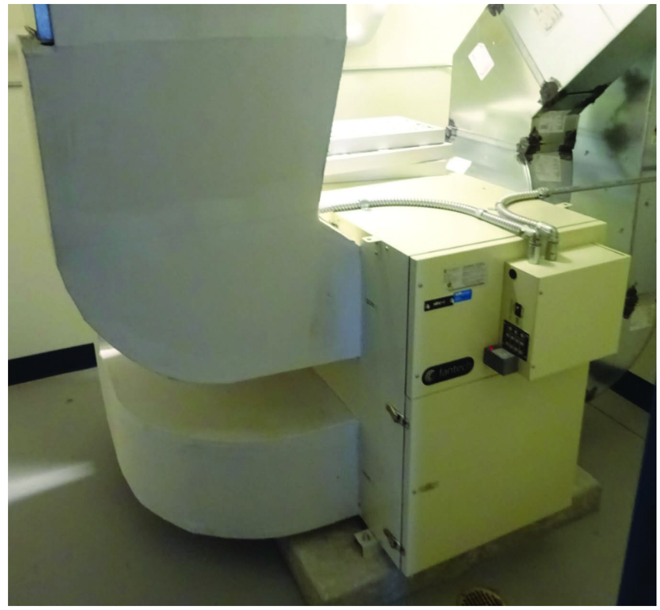

Figure 5 *Small light commercial HRV.*

Several different types of air-to-air heat recovery cores and systems are available. ASHRAE's *Cold-Climate Building Design Guide* (2015) provides additional information. Air-to-air heat recovery systems have their use and, depending on the application, one technology may be more appropriate than others. The most common technology used in cold climates is the plate style, heat recovery core.

Certain considerations must be made when using HRVs. Due to low outdoor air temperatures, the exhaust airstream through the heat recovery core can frost to the point that air is restricted or completely blocked. A common packaged controls method of defrosting the heat exchanger in commercial equipment is to turn off the outdoor air and allow warm exhaust air to defrost the exhaust airstream. In a commercial building where ventilation is required by code, it is typically not acceptable to have no outdoor air ventilation during occupied periods. ASHRAE Standard 62.1 (2019) does have an exception that allows temporary loss of outdoor air ventilation; however, the conditions are limited and often cannot be met in an office space. In smaller residential type units, the defrost function is done by recirculating the exhaust back into the supply air system. Since the exhaust side of a HRV is typically taken from restrooms, this is functionality is not code compliant in commercial and multifamily type applications.

To prevent frosting of the heat recovery core, hydronic preheat coils can be installed in the outdoor air duct before the HRV heat exchanger. These coils must have glycol. The use of preheat coils in a ventilation system is a common strategy in cold-climate mechanical system design to increase energy efficiency and to control the addition of heat to the airstream. With preheat coils, two filter banks are provided. The "summer filter," which is located upstream of the coil, protects the coil from dirt in the summer; the "winter filter," which is located after the preheat coil, protects the coil in the winter when extreme cold temperatures can frost and plug filters installed upstream of the preheat coil. The winter filter is typically located where the airstream temperature is above freezing. A filter is only located in one of these locations and is switched seasonally. ASHRAE's *Cold-Climate Building Design Guide* (ASHRAE 2015) provides for more information and control strategies for preheat coils and summer/winter filter configurations.

For HRV defrost control, preheat coils should be sized to heat incoming air to keep the exhaust airstream just above freezing. The higher the temperature delta across the core, the more efficient heat transfer will be; therefore, incoming outdoor air should be heated only as much as needed to prevent frosting. A heating coil will be needed after the core to bring the final delivery temperature to an appropriate range for occupied spaces.

Due to the exceptionally dry air in cold-climate buildings, some control strategies have extended the frost control strategy to using dew point of the exhaust stream as the control set point. This allows the exhaust air to be below the dry-bulb freezing temperature without frosting (because it is above dew point), increasing the temperature differential and thereby increasing the heat exchange efficiency. This can also result in very low supply air temperatures downstream of the heat exchanger, so this needs to be taken into account in the sizing of the main heating coil; alternatively, a secondary stage of preheat coil control can be added to maintain a set inlet air temperature on the main heating coil or discharge air temperature set point.

Note that the outdoor airstream may be below freezing after the preheat coil and in some extreme locations, even after the heat exchanger. Therefore, the "winter filter" may need to be located after the heat exchanger to prevent frost. The operating conditions should be carefully modeled by the designer and equipment manufacturer to ensure that the heating coil is adequately sized to bring the air up to discharge temperature set point.

While HRVs do not eliminate the need for heating coils, they can offset the load, which saves energy and reduces the facility's operating costs. It is not uncommon in extreme cold environments for the ventilation system to be the highest heating load in the building, even more than the heating load across the building envelope. Heat recovery systems should be designed with the capability to bypass or turn off the heat exchange function when the outdoor air temperature is above the supply temperature set point. ASHRAE's *Cold-Climate Buildings Design Guide* discusses best practices related to air intake designs specific to cold regions (ASHRAE 2015).

PLUMBING SYSTEM DESIGN

Due to low ambient temperatures, location of plumbing piping in exterior walls is considered a freeze-up risk. Typically, significant design effort is spent locating fixtures such that plumbing piping in interior walls or within chases. In the context of resiliency, even piping located within a chase on an exterior wall may be vulnerable to freezing if enough temperature degradation occurs before the heating system can be restored. It is not uncommon for plumbing chases on the exterior of the building to have a heat source with a local thermostat.

Construction of the building envelope can significantly affect plumbing walls. For instance, plumbing wet walls that are built perpendicular to an exterior wall without a continuous vapor barrier between the wall and the exterior wall will allow cold air to enter the wall and freeze water piping. The same is true for interior plumbing walls where the roof vapor barrier has been compromised.

Mechanical rooms pose a freeze potential for water piping as this is typically the location of the water entry and water heater. Mechanical rooms with fuel-fired equipment require combustion air that is typically brought into the space through a passive opening. If handled inadequately, the cold air can sink to the floor and form pockets of low temperature that is missed by the room temperature sensor. A method to reduce this risk is to provide a hydronic or electric unit heater oriented such that the discharge faces the combustion air opening. In this case, air is heated as it comes into the space, which reduces the potential for development of pockets of air cold enough to freeze piping.

The International Plumbing Code (IPC) and the Uniform Plumbing Code (UPC) indicate minimum vent through roof (VTR) sizes according to connected drainage fixture units and piping length. In the Arctic climate, the saturated vapor discharged through a VTR quickly freezes and generates frost on the outlet pipe. A frosted-over vent can disrupt system drainage resulting in dry fixture traps that allow sewage odors to enter the building. Some local code authorities in Alaska have instituted an amendment for the VTR to be increased by two pipe sizes prior to leaving the building to reduce the likelihood of frost closing the outlet. For commercial buildings, it is recommended to use a 4-in. (102 mm) VTR if possible, as even 3-in. (76-mm) outlets have been observed to have frosting issues at prolonged cold temperatures. It is recommended that the vent lines be insulated a minimum of 3 ft (1 m) from the roof penetration and continuously through unheated spaces like attics. In extreme cold locations, the pipe above the roof can be insulated and even electrically heat traced to ensure that the vent remains open.

Roof drains are also prone to freezing in extreme climates, resulting in water buildup and potential structural failure. It is recommended that roof drains, and their associated overflow drains if applicable, be located above the heated portion of the building. If the space below the drain is unheated, such as in building canopies or cold roofs, then the designer should consider adding electric heat trace. Overflow drains or roof scuppers within 2 in. (51 mm) of the normal roof drain are recommended. It is possible that a stormwater system can freeze underground outside of the building. Overflow spouts on the main stormwater line at the building exit point can help protect against such a freeze and to prevent it from plugging the line and creating an overload condition on the roof. Typically, a heat tracing system is provided at the overflow outlet.

The critical nature of domestic hot water depends on the type of facility. Office buildings may be able to function without hot water, but hotels and commercial kitchens cannot. Where resiliency/redundancy is needed in domestic hot water, the use of multiple water heaters is desired. Where natural gas is available, gas-fired water heaters are preferred. Where buildings are heated with fuel-oil-fired boilers or a district heating system, the preferred system is one that uses indirect-fired water heaters. This reduces the number of fuel-fired appliances, which has traditionally meant less maintenance. With indirect-fired water heaters, the hydronic supply temperature must be hot enough to provide the desired hot-water temperature. Redundancy is needed in all components of indirect system, including multiple boilers and individual pumps for each water heater.

REMOTE SITE CONSIDERATIONS

Nowhere in Alaska are energy costs higher than in a remote Alaskan village located off the road system. In such locations where fuel must either be flown or barged into the village, fuel costs three to four times that of fuel in a city on the road system. Schools located in such villages must have more systems and are therefore more complex than city schools. Besides being required to meet nearly all the same codes, such systems must also be able to operate in a self-contained mode that does not rely on a separate municipal utility system to provide power, potable water, and sewage treatment. The school district maintenance department in Fairbanks has approximately 30 technicians who maintain the schools for an approximate population base of 120,000 people. Most of these school district employees have been trained in a trade, and many have specialties and certifications, such as plumbers, locksmiths, boiler mechanics, generator technicians, controls technicians, and fire alarm technicians. On the other hand, a village often has only the school principal, a maintenance employee, and a janitor supplemented by roving maintenance employees who fly in if there is a major problem.

Therefore, even though energy costs are high, critical systems must be simple enough to be maintained at a very basic level. Components that are not critical for basic function tend to fall into disrepair as they often not adequately maintained due to the extremely high cost of flying a technician to the site to troubleshoot and repair an issue. Mission critical facilities in remote location can benefit from the use of modern reliable building automation systems that allow remote monitoring of HVAC and standby power generation so that failures (and potential failures) can be addressed before real critical problems occur.

BEST PRACTICES FOR HVAC DESIGN IN ARCTIC CLIMATE REMOTE SITES

- Many of the schools were previously designed using commercially sized oil-fired furnaces, reducing the possibility of heating fluid freeze-ups and flooding due to circulating air as the heating medium. This practice has now shifted more to oil-fired boilers, which can deliver heat far more efficiently, particularly if the combustion side of the forced air heat exchanger is not regularly cleaned.
- The boiler header temperature set point should be reset on outdoor air temperature by the direct digital control (DDC) system. However, there must be a labeled switch at each boiler that allows a mechanic to easily override the computer control system, allowing the boiler mechanic to be independent of the controls technician.
- Radiant in-floor heating is not typically used in remote villages due to permafrost, which forces the building to be built on structural piling. This in turn causes the floors to be plywood. A level rock or gypsum concrete layout is required as a location for the tubing in this case; however, this is often too expensive and is eliminated due to cost constraints. FTR then becomes the heating terminal unit of choice.
- Utilities are often run aboveground due to permafrost. The interface between the aboveground utilities and the building structure must account for differential movement. The sewer or waste piping within a facility is a challenge for a facility built on pilings. The interstitial area below the warm floor and the bottom of the floor structure is typically inaccessible. If piping is routed in this area, the below-floor envelope must be cut out to find and repair any leak. After this is done, the below-floor construction is usually not repaired well, causing infiltration-related problems. In one successful project, a central interstitial corridor with a height of about 48 in. (1.2 m) was constructed with nearly all plumbing tight to this corridor. Sprinkler piping was avoided by cladding the metal floor joists with insulated metal panels below and with the use of fire-treated plywood for the floor structure above. The interstitial cavity was heated at the lowest point within the corridor allowing heated air to circulate out to the perimeter below the occupied floor and then flow back to the corridor on top of the insulated metal panels making up the lower envelope. This provided reasonable access to nearly all below-floor piping.
- Room thermostats should be simple low voltage thermostatic switches used in conjunction with two position control valves. Glycol is used as the heating fluid with a relatively high flow prior to turbulent flow. Almost no heat transfer occurs prior to turbulent flow, which causes the control to act like two position control whether a modulating valve is used or not. Night setback becomes proportionally less valuable as envelope insulation increases. One can argue that the system simplicity gained without use of night setback can outweigh the potential energy savings for remote applications.
- The DDC controls controlling the ventilation systems should allow easy manual override to prevent override using wire nuts and vise grips. One example of this is to use spring-wound timers for occupancy override of large portions of the building. An LED light panel, tied to the DDC system, can provide simple operational verification including alarm conditions.
- The communications from the DDC system to the outside world is vital; the connection should be via telephone modem rather than the Internet, so that it is not subject to poor or inconsistent information technology

(IT) practices. Many issues with a facilities HVAC system can be remotely troubleshot and, in many cases, fixed by a remote DDC technician using these connections.

- It is recommended that the control system programming at the time of owner acceptance be kept copied and kept with the operation and maintenance (O&M) manual. It is common for these systems to be changed by the owner to the point of nonfunctionality. Having the copy of the original control language allows a technician to restore the system to its original condition, often remotely.

The subarctic interior environment poses many design challenges. Energy conservation is of the highest importance. However, if the systems become so sophisticated that they require specialists to perform maintenance rather than available maintenance staff, or if the systems fail prematurely due to complex construction, the design will ultimately have done a disservice to the end user of the facility. When good design comes together, it resonates throughout the life of the facility.

OPERATION AND MAINTENANCE AND RESILIENCY

When it comes to system resilience, an important first step is to minimize the chance of unexpected system failure that will lead to the need to implement resiliency measures. This is the basis of developing and administering a proactive O&M program. The term *operation and maintenance* covers many facets of facility management. A common definition is the administration of programs that complete preventative maintenance and reactive repair of systems. But it also includes the lobbying of proper funding budgets both in annual funding to complete regularly scheduled maintenance as well as long-term capital improvement project planning that allows for predictive replacement of equipment and systems before they fail. It includes the development of written standards and active involvement in the design of projects to ensure that systems are constructed with maintenance in mind and to minimize long-term operational costs. It includes the ongoing training of both facility maintenance staff and user groups to ensure that systems operate efficiently and effectively.

O&M is vital to a successful resiliency plan. It is more likely that the event that generates the need for resilience is caused by the failure of a piece of equipment or system rather than an outside force such as a natural disaster. A robust O&M program will minimize these system failure occurrences.

Energy system resilience can be enhanced by using backup equipment such as generators and secondary sources of heat, and by maintaining the ability to quickly get systems back online quickly. O&M is critical to ensure that these secondary systems will operate when needed. This includes regular testing of equipment such as standby generators, and completing scheduled maintenance and overhauls of that equipment and its supporting systems. Standby generators must have adequate amounts of clean fuel available. For fuel-oil-based systems, this would include regular inspection and testing of the stored fuel to remove water and ultimately to replace old fuel with new fuel.

Training, a vital part of O&M, is needed so that operators know how to implement resiliency plans. There must be clearly written checklists, supplemented with photos and/or diagrams, available to on-site personnel to help them implement the various plans that should be in place to address multiple threats. The operators must be familiar with the location of key components in the facility, such as diverting valves or exterior portable generator connections, and must know how to manipulate those components to implement a resiliency plan.

If there is a failure and a resiliency plan must be initiated, the ability to quickly get the original/primary systems operational requires a combination of both training and access to the appropriate tools and spare parts. Aside from static measures, most resiliency plans are based on activities that are intended to be temporary. The backup solutions are also typically sized to only maintain minimum critical infrastructure, such as maintaining a building temperature just above freezing temperatures. The resiliency solution will likely not be sized to provide full indoor air quality or environmental control, leaving occupants with a less than ideal working and living condition. Most secondary systems, such as electric heat, can be very expensive to operate; therefore, the need to get the original systems fixed and back to normal operation is vital.

In cold climates, power outages may have a great number of causes. For example, accumulation of snow and ice, and high velocity wind storms can cause trees to fall on power lines, resulting in extended outages. In Alaska, avalanches have destroyed high voltage power distribution systems, and the occasional wildlife mishap can result in power loss. Most commercial facilities commonly maintain a standby generator or the ability to plug into a portable standby generator. As noted above, performing regular maintenance on these standby generators will ensure they will operate when needed. There are several steps to take to prepare for urgent maintenance events, including:

1. Identifying points of failure.
2. Having an accurate set of record drawings of the facility systems design available both in paper and electronically. This will help locate important features such as isolation valves or system diagrams to better evaluate system functionality. Having an electronic copy available will benefit remote technicians in helping with troubleshooting issues.
3. Having maintenance documentation available on-site for at-risk systems and materials. This is traditionally the operation and maintenance manual. This includes information about the product, exploded view of parts with part numbers, troubleshooting guide, warranty information, and preferably contact information for the local

supplier of parts and maintenance technicians (if applicable). This is also beneficial to have electronically and in hard copy.

4. Identifying and having on-hand spare parts and tools that will be needed for critical system repair.
5. Having an organized spare part location so that parts and tools can be readily found. Complete regularly scheduled inventory of tools and parts to ensure they are available when needed. Keeping track electronically of what spare parts are available and when they are used on a project to ensure that replacement materials are ordered so that they are ready for the next incident.
6. Providing training and/or having training videos available on-site that can show how to perform needed maintenance/repair to the system.

Having static resilience measures in place, like a robust building envelope, provides much needed time when a heating system is down. Having established training and thorough O&M and resiliency plan documentation in place expedites the initiation of backup procedures and gets the primary systems quickly back online.

CASE STUDIES

Lessons Learned from Military Installations in Alaska

Military bases in cold and Arctic climates have established (either centralized or decentralized) heating systems. Modeling the energy performance can be useful to find bottlenecks in the system that can negatively affect system recovery.

All boiler systems have an upper (100%) and lower limit (0%). To model systems operating between 0% to 100%, we can use a form of a cumulative probability curve called the "Logistic" equation:

$$f(T) = \frac{A}{1 + B \cdot e^{\gamma \cdot T}} + \Delta \tag{1}$$

where

T = temperature variable (in °F or °C), and

A, B, γ, Δ = system constants.

Between the lower and upper limits, the model is linear and converges to these limits at extreme cold or warm temperatures:

$$\text{Lower Heating Limit:} \quad \lim_{T \to \infty} \left(\frac{A}{1 + B \cdot e^{\gamma \cdot T}} + \Delta \right) = \Delta \tag{2}$$

$$\text{Upper Heating Limit:} \quad \lim_{T \to -\infty} \left(\frac{A}{1 + B \cdot e^{\gamma \cdot T}} + \Delta \right) = A + \Delta \tag{3}$$

The model can also be used with heating degree days (HDD) as the climate variable instead of temperature. In this case, however, the system constants will change in sign and in magnitude.

Using the logistics model, several areas should be examined closely:

- *Fuel/Energy Supply Limits.* All fuel types have capacity limits. Systems fueled by natural gas, for instance, are usually supplied by gas mains. These mains have limited capacity. When that capacity is reached, the heating systems are unable to deliver another increment of heat regardless the system demand. For example, a plot of natural gas consumption versus monthly HDD at an Air Force base in Montana reveals a possible system limitation emerge.

  As the month gets colder, the natural gas consumption appears to approach a limit. This could point to a physical natural gas (NG) supply limit or it could point to a natural maximum consumption limit for the base NG systems. In either case, base heating capacity is reaching a limit. Taking the ratio of the upper bound convergence with the maximum monthly demand, this base has 4% excess capacity in its NG supplied heating systems.

  Conversely, the NG consumption at an Air Force base in Anchorage, Alaska has a more linear profile indicating a greater excess capacity. This analysis shows that this base's NG systems can absorb a 38% greater load than the maximum monthly load.
- *System Limitations.* For central heat plants, more detailed information is usually available from boiler logbooks. The input and output energy flows can be mod-

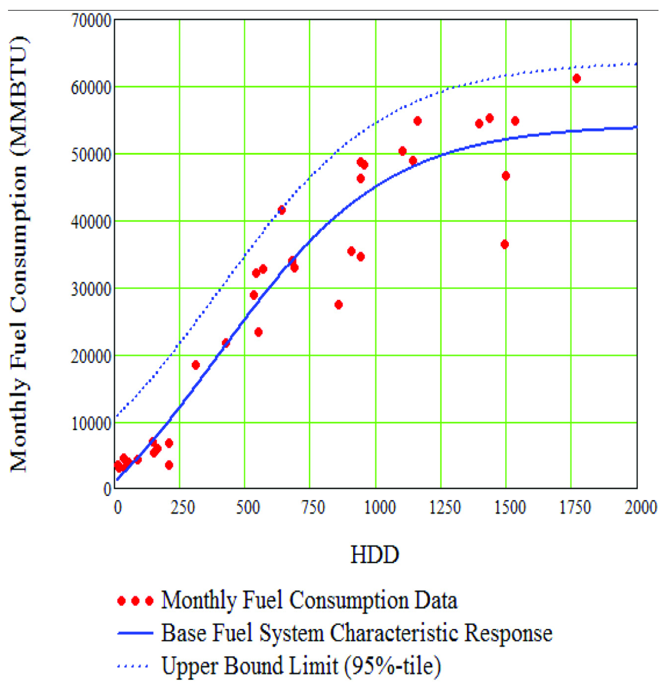

Figure 6 *Montana Air Force base FY17-19 fuel consumption.*

eled, and overall efficiency calculated; automated combustion efficiency calculations may be available to address boiler combustion performance, makeup water is usually tracked to assess distribution system leakage, and so on.

Consider, for example, an Air Force Station (AFS) in Alaska that has a steam boiler plant consisting of three Burnham fire-tube boilers, each rated at an output of 13,390 MBtu/h (39,205,920 kWh/h). On the surface, it appears the plant can supply steam at a maximum rate of 40 MMBtu/h (12 MWh/h) to the base. But the FY16 heat load (steam supply rate) profile indicates otherwise.

The maximum capacity of the distribution system is estimated at 17.3 MMBtu/h (5 MWh/h). This could be due to the size of the distribution lines, size of the facilities' heat-transfer terminal equipment, or possibly a response lag from the boiler plant itself. Regardless, the plant does not appear to have the ability to deliver 40 MMBtu/h (12 MWh/h) to the base. We would deduce that at most, two boilers would ever operate together—the third is a spare in case of a failure in an N+1 scenario.

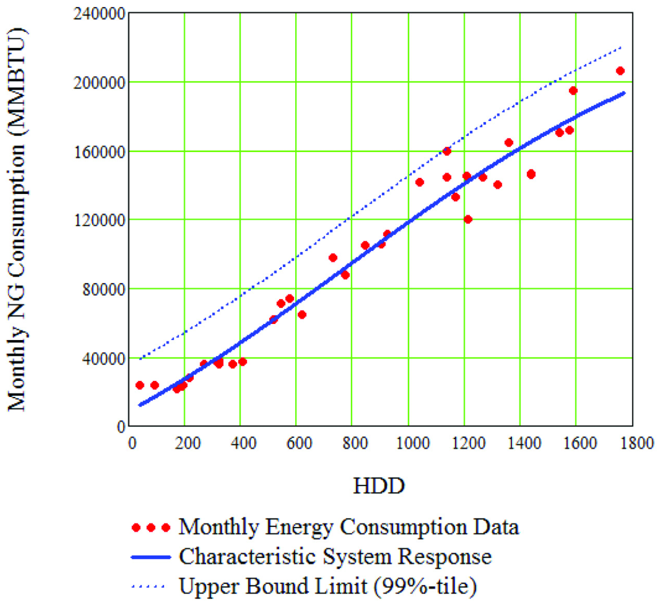

Figure 7 *FY17-19 NG system response at Air Force base in Anchorage, Alaska.*

- *Facility Factors.* It is also important to consider facility factors impacting energy consumption. The heat plants models listed above, for instance, can be used to estimate the average combined conductance of all the installation facilities. This can in turn be used to estimate the indoor temperatures during periods of extreme temperatures. This type of resiliency analysis can assess the need for facility leak testing, insulation improvements, or fenestration improvements (e.g., door, window seals).

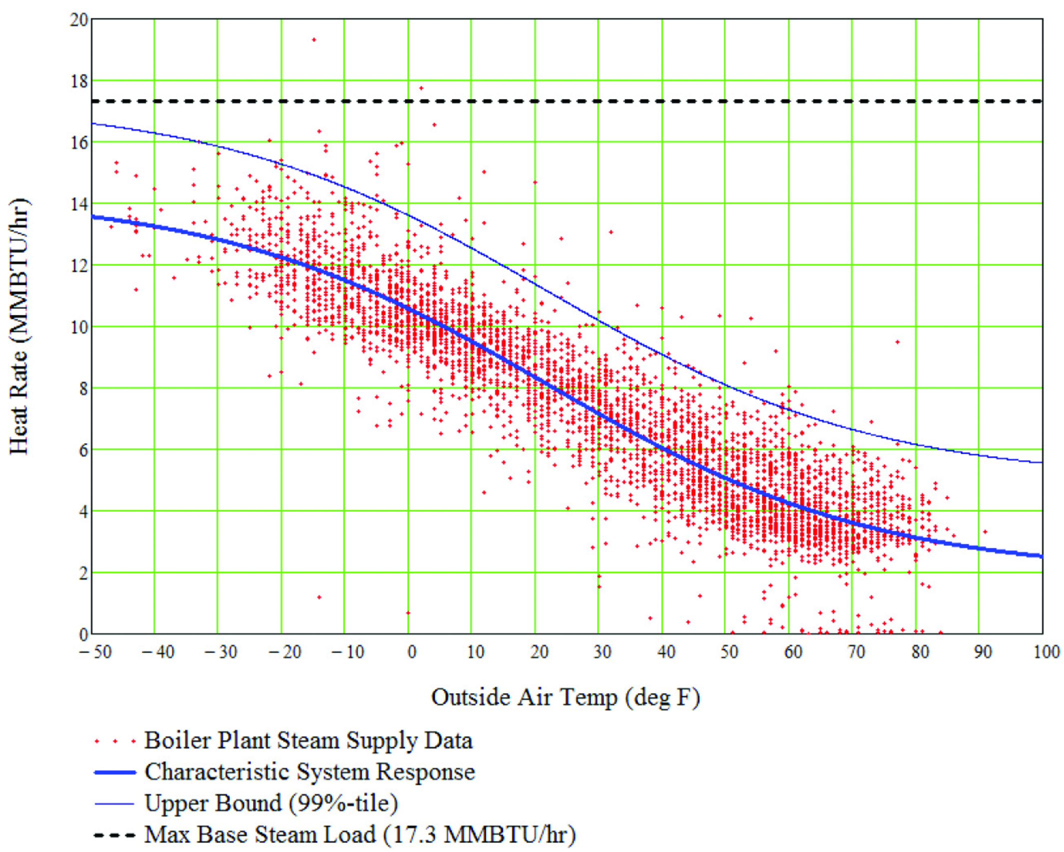

Figure 8 *FY16 heat load at an Alaskan Air Force Station.*

Using $q = U \cdot A \cdot \Delta T$, we have only one unknown—conductance, U. Consider the Alaskan AFS. The 99% design outdoor air temperature (OAT) is –38°F (–39°C), the design inside set point is 68°F (20°C), the total facility area is 578,000 ft^2 (53,754 m^2), and the heat input has been calculated according to the model (minus ~15% for losses at the terminal equipment). Solving for U (and assuming that the facilities have been sized correctly),

$$\begin{aligned} U &= \frac{f(-35°\mathrm{F})\mathrm{MMBtu/h}}{5.78 \cdot 10^5\ \mathrm{ft}^2 \cdot [68°\mathrm{F} - (-35°\mathrm{F})]} \\ &= \frac{13.05\ \mathrm{MMBtu/h}}{5.78 \cdot 10^5\ \mathrm{ft}^2 \cdot [68°\mathrm{F} - (-35°\mathrm{F})]} \qquad \text{(I-P)} \\ &= 0.219\ \mathrm{MMBtu/(h{\cdot}ft^2°F)} \end{aligned}$$

$$\begin{aligned} U &= \frac{f(-37°\mathrm{C})\mathrm{MWh/h}}{5.38 \cdot 10^4\ \mathrm{m}^2 \cdot [20°\mathrm{C} - (-37°\mathrm{C})]} \\ &= \frac{4\ \mathrm{MWh/h}}{5.38 \cdot 10^4\ \mathrm{m}^2 \cdot [20°\mathrm{C} - (-37°\mathrm{C})]} \qquad \text{(SI)} \\ &= 0.064\ \mathrm{MWh/(h{\cdot}m^2°C)} \end{aligned}$$

To assess the impact of meeting the demand in an extremely low temperature (–47°F [–43°C]), we solve for the inside temperature:

$$\begin{aligned} T_i &= T_{oa} = \frac{f(T_{oa})}{U \cdot A} \\ &= -47°\mathrm{F} + \frac{f(-47°\mathrm{F})\mathrm{MMBtu/h}}{(0.219\ \mathrm{MMBtu/(h{\cdot}ft^2°F)}) \cdot (5.78 \cdot 10^5\ \mathrm{ft}^2)} \qquad \text{(I-P)} \\ &= 59.4°\mathrm{F} \end{aligned}$$

$$\begin{aligned} T_i &= T_{oa} = \frac{f(T_{oa})}{U \cdot A} \\ &= -44°\mathrm{C} + \frac{f(-43°\mathrm{C})\mathrm{MWh/h}}{(0.064\ \mathrm{MWh/(h{\cdot}m^2°C)}) \cdot (5.38 \cdot 10^4\ \mathrm{m}^2)} \qquad \text{(SI)} \\ &= 15.2°\mathrm{C} \end{aligned}$$

In other words, this base suffers a Δ5.6°F (Δ3.1°C) degradation in indoor temperatures during periods of extreme low outside temperatures.

Also note that the units of conductance × area, $U \cdot A$, have the same units as the slope of the system response curve, MMBtu/h·°F (see Figure 8). Therefore, we can deduce that a steep slope would indicate low thermal resiliency (high heat loss) for the average facility. Conversely, a mild slope would indicate higher thermal resiliency (or lower heat loss).

Energy Systems in Greenland

Greenland has its own building code from 2006, with requirements for insulation level of building components and overall energy demand by the building.

The power system in Greenland is divided into microgrids, in general one for each town or settlement. The power is generated by hydropower in the larger towns and diesel engines in the smaller. All networks have emergency generators.

In many towns, district heating hot-water networks supply the densely populated part of the towns. The production is based on surplus heat from the power plants and heat from waste incineration or from oil boilers. Buildings without district heating are supplied with oil boilers. In Nuuk, which has surplus hydropower, some buildings are also supplied with electric boilers.

The water supply is drawn from lake water and transported in pipes protected from frost, typically preinsulated pipes with electric cable at the steel pipe.

Buildings are mainly supplied with hydronic heating systems with radiators connected to district heating or oil boilers. Some new buildings, e.g., in Nuuk, use water-based underfloor heating. In the coldest regions, some heating systems are protected with glycol. All heating systems are balanced with thermostatic valves.

In old buildings, ventilation air supply is provided by mechanical ventilation systems and air is exhausted through openings in external walls. This creates problems in winter with cold drafts, and therefore the ventilation rate is often reduced. This in turn creates problems with a poor indoor climate and parts of the building may be damaged. In new buildings, mechanical ventilation systems provide both air supply and air exhaust. These systems have heat recovery. Supply air is heated in a hydronic coil connected to a closed loop glycol circulation system.

Case Study from Quaanaaq

The local community of Quaanaaq in Greenland was established in 1952 to host the native population formerly residing at the nearby U.S. Air Base. The settlement's infrastructure was designed as a campus that offered a good opportunity to optimize the infrastructure and take advantage of synergies and potential symbioses between different systems. Resilient energy systems and energy efficiency are key parameters to the settlement's survivability. North Star Bay, where Quaanaaq is located, is ice locked nine months out of the year. To ensure the operational effectiveness of the air base and livable environment for the local population, the energy infrastructure must be operational at all times and must operate at maximum fuel efficiency to minimize both the cost of imported fuel and the risk of fuel shortages due to long severe winter storms and the extreme cold. In fact, the U.S. Air Base welcome package document (Chickery 2017) informs newcomers that storm class Alpha is considered "business as usual," meaning storms are generally expected in any 12-hour period, and that there are only two seasons in Quaanaaq (Thule), light and dark.

The key technology required to fulfill resilience requirements of the main infrastructures of Quaanaaq is its district heating system (Figure 9a), which uses waste heat from the three diesel power generators and provides 82 Btu/min (1.436 kW) power and 9 MMBtu/h (2.5 MW) thermal capacity at normal

Figure 9 *Heating system in Quaanaaq, Greenland: (a) combined heat and power (CHP) plant (cooling fans are used only for emergencies), and (b) above-ground utilidors.*

operating conditions. Additionally, there are three peak load heat-only boilers with a capacity of 5 MMBtu/h (1.5 MW) and two emergency power generators of 34,152 Btu/min (600 kW). The annual heat and power demands are 1,531 Btu (5.230 MWh) and 805 Btu (2.750 MWh), respectively. The combined heating and power system has a fuel efficiency of 80% to 85% lower calorific value (LCF) as end-use measured per fuel consumption. When restricted to power-only generation and building heat-only boilers, the combined efficiency would be only 55%.

The Arctic climate and permafrost requires that the district heating and other infrastructure be located above ground in ducts (Figure 9b). The relatively low (15%) heat loss from the district heating distribution system provides frost protection service to other infrastructure, wastewater pipes, and fresh water pipes. The ducts and the heat loss further contribute to safer walking paths within the community than would otherwise be possible. Lessons learned from Quaanaaq show that it is possible to plan and operate an efficient and resilient energy supply in combination with water and wastewater services in the Arctic; however, it also demonstrates how difficult it can be to keep and attract qualified staff to ensure efficient operation and a high maintenance standard. More information about this case study can be found in Dyrelund et al. (2021).

CONCLUSIONS

Due to the cold temperatures experienced for sustained periods of time in Arctic climates, the importance of resilient, robust, and maintainable HVAC system is imperative. The design process must identify points of failure and implement features to limit system downtime and reduce impacts on the facility's ability to maintain temperatures during planned or unplanned outages.

Redundancy provides a high degree of reliability. Heating system components such as hydronic circulation pumps and boilers should be designed with redundancy such that a failure does not result in a full system failure. Such redundancy provides building owners with a method of maintaining the building heating system by taking some equipment offline without impacting building functions.

Where practical, it may be necessary to take emergency measures such as establishing connections to remote boilers to ensure functionality of the facility or campus in the case of an equipment or infrastructure failure in the district heating system.

In remote locations where the availability of maintenance personnel is limited and where spare parts may need to be delivered by air, building systems should be designed with as little complexity as possible, and a supply of spare parts should be stored on site.

Glycol should be used as the heating system fluid in hydronic systems to prevent freezing, and the de-rate in performance should be accounted for when sizing terminal units.

Freeze protection best practices for plumbing piping should be followed, e.g., piping should be located in interior walls or plumbing chases. Avoid locating pipes in exterior walls.

The strategies outlined in this article improve the resilience of a building, which in turn provides protection to the infrastructure and contents of these facilities. Frozen pipes and damage to contents can be extremely costly and in some cases can cause irreparable damage to the programming activities housed in the building. It is the responsibility of the designer in partnership with the owner to identify the sensitivity of the facility and to build in resiliency features appropriate to its acceptable level of risk while still managing project costs. This may result in shifting priorities from other features to cover resiliency measures if the owner determines that the acceptable level of risk is low.

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