

**ARMY TM 5-852-5
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TECHNICAL MANUAL

**ARCTIC AND SUBARCTIC CONSTRUCTION
UTILITIES**

**DEPARTMENTS OF THE ARMY, AND THE AIR FORCE
AUGUST 1987**

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ARCTIC AND SUBARCTIC CONSTRUCTION: UTILITIES

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CHAPTER 1

GENERAL

1-1. Purpose.

The purpose of this manual is to provide criteria and guidance for design of utility systems for military facilities in arctic and subarctic regions. Only design criteria unique to cold regions (the Arctic and Subarctic) are provided. Where conventional practice is acceptable, appropriate references are given.

1-2. Scope.

This manual applies to all U.S. Army and U.S. Air Force installations in the Arctic and Subarctic. Topics covered include water supply, wastewater collection, treatment and disposal, fire protection, utility distribution systems and the thermal calculation techniques needed for their cold regions design.

1-3. References.

Appendix A contains a complete list of references for this manual. The bibliography lists additional selected technical information on the subject.

1-4. Environmental conditions in the Arctic and Subarctic.

The design, construction and maintenance of utility systems are all affected by the special environmental conditions found in the Arctic and Subarctic. These conditions include adverse temperatures, wind, and snow; high costs; remoteness of locations, limited availability of construction materials and labor; need for fuel additives, synthetic lubricants, oils and greases for construction equipment; thermal stresses; frost heaving and permafrost.

a. Temperature. The low temperature prevailing in the cold regions is the most critical environmental factor. The intensity of the cold is important, but equally critical is the duration of the cold period. Mean annual air temperatures in the Northern Hemisphere are presented in TM 5-852-1/AFR 88-19, Vol. 1. Air temperatures in arctic locations range from highs of 80 degrees F in summer to lows of -75 degrees F in winter. Interior locations away from the tempering effects of oceans or large water bodies tend to have the greatest extremes. Sub-zero temperatures can persist for months and it is not

uncommon for air temperatures to remain below -30 degrees F for a week or more at many locations in Alaska.

b. Permafrost. Permafrost is defined as any perennially frozen ground. The presence of frozen soil has the greatest impact on design and construction, so permafrost is typically a major design consideration. Figure 4-1 in TM 5-852-1/AFR 88-19, Vol.1, illustrates the approximate distribution of permafrost in the Northern Hemisphere. In the zone of continuous permafrost, frozen ground is absent only at a few widely scattered locations such as at the bottoms of lakes and rivers. In the discontinuous zone, permafrost is found intermittently. TM 5-852-1/AFR 88-19, Vol.1, contains detailed discussion on both permafrost and seasonal frost.

c. Wind and related factors. Mean annual wind speeds for most arctic and subarctic locations are usually about 5 to 10 miles per hour in the interior and 10 to 20 mph at coastal locations. The combination of wind and low temperatures results in very large heat losses from exposed facilities and presents hazards for personnel. Blowing and drifting snow can create major construction and operational problems even when the total precipitation is low. The location and layout of utility systems and access points for operation and maintenance must be given careful consideration during planning and design to avoid problems with drifting snow.

CHAPTER 2

PLANNING UTILITY SYSTEMS

2-1. General considerations.

In the Arctic and Subarctic, utility systems are usually the most costly component in construction of military installations. The layout of a new installation is often controlled by the type of distribution and collection systems selected for the utilities network. As a result, planning for a new installation in the cold regions must include consideration of utilities at a very early stage to ensure overall cost effectiveness.

a. Useful life. The useful life for utility systems and equipment in cold regions is shorter than for the same units operated in more temperate climates. Items of equipment that must operate throughout the winter are particularly critical. Trucks used for water delivery or waste collection are examples. Table 2-1 presents typical useful lives for some utilities components in the Arctic and Subarctic.

Table 2-1. Approximate useful life of utility system components in cold regions

Component	Useful Life (years)
Wells	30
Pumps and controls	5
Storage tanks	40
Water distribution lines	40
Meters	10
Valves	10
Sewage collection lines	30
Lift stations (not pumps)	30
Buildings	30
Paint (exterior)	10
Service connections	10-15
Trucks	4
Tracked vehicles	2-3
Backhoe (occasional use)	6-10
Compressor	5

b. Construction methods. The three basic construction techniques used are modular, stick built, and prefabricated. The method selected must depend on site conditions and transportation facilities available. Modular construction, where the entire facility or a major component is preassembled and shipped via barge to the point of use, has been widely used at oil field developments on the northern coast of Alaska. It is advantageous in these locations since large barges can be used, the construction season is short, and labor is very expensive. Barges can usually begin to arrive in Barrow, Alaska, and the Eastern Arctic around the

first of September. This means that non-modular construction materials must be shipped a year in advance and stockpiled for the next construction season. The stick-built approach, where all fabrication is done on site, and the prefabrication approach, where some components are preassembled at the point of manufacture, are more common at interior locations where transport is limited to air or small rivers. Prefabrication of insulating piping units has been shown to be cost effective for remote locations. The normal construction season varies from two or three months along Alaska's Arctic Coast to six or eight months in southern areas of Alaska.

2-2. Installation layout.

The arrangement of buildings and other facilities at military installations must be as compact as possible to reduce utility construction and operation and maintenance (O&M) costs. Unserviced areas and large open spaces such as storage yards, parks and playgrounds must be located on the outskirts of the installation. If possible, buildings must be located so as not to "shade" smaller structures from either sun or wind. Improper location of large buildings results in excessive snow drifting and burial of smaller structures. Doors and entry-ways to buildings must not be on the windward or leeward sides if possible to avoid drift interference. Orientation of the structure with the long axis parallel to the prevailing wind direction will reduce drifting problems. Roads and walkways will be constructed slightly above the general ground surface to avoid drifting problems, and construction in cut sections will be avoided if possible. Access points (manholes, service boxes, etc.) for utility system maintenance must be located so that entry can be guaranteed during the winter months.

a. Utility networks. The truck delivery of water and collection of wastes is still used at many civilian communities in Alaska, Canada and Greenland. However, at most U.S. military installations in the Arctic and Subarctic it will be more cost effective to provide piped systems for water supply and wastewater collection. The capital costs for piped systems are higher than for the truck delivery but operation and maintenance costs are significantly lower. The critical planning decisions for utility networks are (1) whether the pipes should be above or below ground, and (2) whether the pipes should be

installed as individual units or combined with other utility services in a utilidor. Above-ground utilidor systems offer easier access for maintenance and repair, and are cheaper to build where site conditions are poor. However, there are disadvantages. Above-ground units are exposed to extreme winter conditions and must have additional thermal protection (see chapter 12) as compared to a buried system. Above-ground systems are susceptible to vandalism and traffic damage, they disrupt pedestrian and vehicle traffic patterns, and create snow removal problems. In general, below-ground installation will be adopted wherever possible. In the Subarctic, an unfrozen zone may exist between the maximum seasonal frost penetration and the top of the permafrost. This condition can also exist in the Arctic near lakes and rivers, and on slopes with southern exposure. Pipes buried in permafrost or in the seasonal frost zone must not only be protected from freezing but must also resist the structural effects of heaving in the seasonal frost zone or thawing of permafrost. The terrain is relatively flat in much of the Arctic, and maintenance of the necessary grades for gravity sewers in either the above-ground or buried mode is difficult. Small pump stations, or pressure or vacuum sewer systems must be used to overcome these constraints.

b. Network layout. A compact installation layout will make a central heating plant practical. This will reduce costs and energy consumption and also reduce the risk of fire. Service lines from utility mains to individual buildings are the main source of freezing problems. Buildings will be as close to the mains as possible with service lines 60 feet or less in length. It is typical practice in temperate climates to bury most utility lines in the streets. However, there are thermal disadvantages to this practice in cold regions since clearing the roads of snow will allow greater frost penetration. Burying water and sewer mains in the front or back yards of dwellings, and in open areas where snow will not be removed, will maintain warmer ground and pipe temperatures. Installation layouts should not be designed with dead-end streets. Dead-ends are difficult and expensive to service with circulating water systems and snow removal is more difficult. The largest consumers of water will be located at the extremities of the distribution system, if possible.

2-3. Equipment.

For remote arctic installations the initial cost of most utility equipment is not as important as its reliability. A large inventory of critical spare parts is recommended and standardization of equipment to reduce the parts inventory will prove economical.

Standby units for critical equipment are essential and are particularly important for emergency power and for heating systems. Humidity is a critical factor in enclosed spaces and both high and low extremes can be experienced in arctic situations. Since natural humidity is extremely low due to the low winter temperatures, humidifiers (to maintain humidity at about 30 percent) may be desirable in personnel spaces. Very high humidity is experienced in pump stations and enclosed treatment works, and thus condensation may occur on cold surfaces causing damage and inconvenience.

2-4. Revegetation.

Areas excavated and backfilled for utility systems must be revegetated to prevent erosion. A revegetation procedure is summarized in table 2-2 for tundra areas. These grasses will die out in four to five years but the natural vegetation will have developed by that time. The initial seeding and fertilization will take place after the ice breaks up on local streams but before mid-summer. As indicated in table 2-2, a nitrogen-phosphorus-potassium (N, P, K) fertilizer will be applied with the initial seeding and then supplemental nitrogen at the beginning of the second growing season.

Table 2-2. Revegetation for tundra areas

Grass Seed Type	Rate (lb/acre)
Meadow foxtail (common)	18
Hard fescue (Durar)	18
Red fescue (arctared)	27
Annual ryegrass (<i>Lolium multiflorum</i>)	27
Total	90

Fertilizer	Rate (lb/acre)
First year (apply with seed) 10(N) - 20(P) - 10(K)	358
Second year 33 - 0 - 0	90

CHAPTER 3 WATER SOURCE DEVELOPMENT

3-1. General.

The water requirements and design capacity factors for domestic, fire and other functional uses are specified in TM 5-813-1/AFM 88-10, Volume 1. Both ground and surface waters are available in the Arctic and Subarctic but the environmental conditions require somewhat special approaches for their development. In addition, ice and snow are sometimes used for water supply augmentation or as emergency or stand-by sources.

3-2. Environmental constraints.

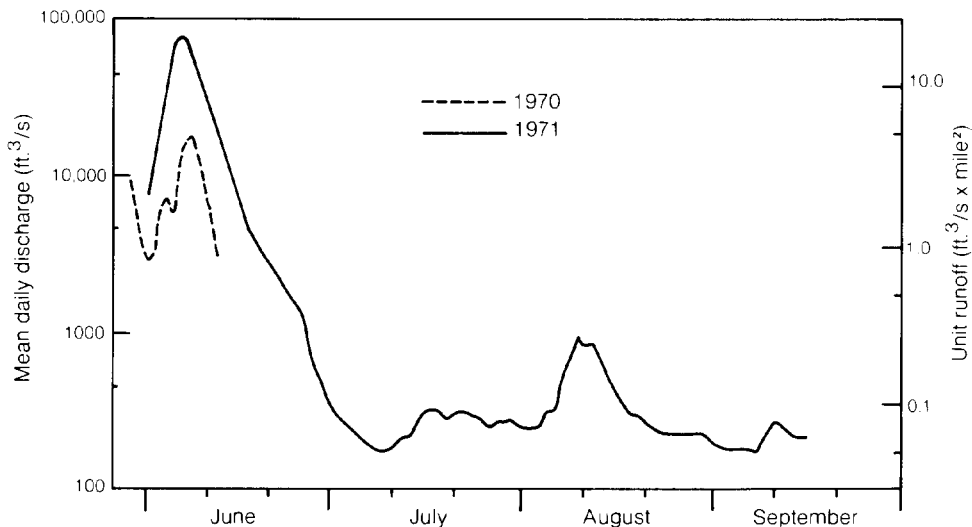
In most of the Arctic and Subarctic, precipitation is light, terrain is relatively flat and runoff is concentrated in the short period during ice breakup. There are many small, shallow lakes and ponds and numerous rivers and streams. Ice cover varies according to local conditions but generally lasts from 6 to 10 months and approaches 6 feet in depth in small quiescent water bodies (see paragraph 12-9a for procedures to estimate thickness of ice formation). Hydrologic data for these regions are scarce so it is difficult to predict reliable yields. Permafrost is essentially impermeable so there is little direct recharge of most aquifers. Any penetra-

tion of the permafrost for exploration or for well development requires special engineering consideration and is costly.

3-3. Surface waters.

Many shallow lakes and small streams freeze completely in the winter, eliminating them temporarily as a water source. Some installations pump water from such sources in the summer months and store the winter supply. Larger streams and deep lakes can have liquid remaining beneath the ice but the volume available is limited since there is no contribution from precipitation in the winter. The large quantity of ice and snow results in major annual flows occurring during the spring "break-up." Figure 3-1 shows a hydrograph for a typical medium-sized arctic river.

a. Rivers. The volume of flow is low in the winter but water quality is excellent since sediment transport from glacial sources is minimal and surface runoff recharges do not occur. Winter water temperatures are very low (33 degrees F), which creates difficulties for treatment, and intakes can clog due to formation of frazil ice. Floating ice during freezeup and breakup periods can damage or



U.S. Army Corps of Engineers

Figure 3-1. Hydrograph of mean daily discharge, Kuparuk River.

destroy intake structures. Some facilities remove the intake structure during those periods and rely on temporary storage. Development of intake galleries or wells in the stream bottom is successful for avoiding ice problems, but it is difficult to locate the permanent channel in alluvial and braided streams. The summer flows are higher in volume than the winter flows but they are poorer in quality, containing sediments and glacial silts which may be difficult to remove. For example, the Kenai River near Soldotna, Alaska, has suspended sediment concentrations up to 151 milligrams per liter (mg/L) in the summer months. These sediments are primarily glacial silts and are almost colloidal in size.

b. Lakes. Deep lakes are a reliable, continuous source of water. The quality of any liquid beneath the ice in a shallow lake or pond is typically poor. Impurities, such as most salts, are rejected from the freezing water, making the ice relatively pure but concentrating the impurities in the remaining liquid. A survey is required to identify lakes and ponds that may freeze deeply enough to create this condition. Chapter 12 discusses the thermal aspects of such an analysis.

c. Saline waters. Distillation or reverse osmosis is used to treat saline or brackish waters; these procedures are costly and energy intensive, so such sources will be avoided except as the last resort.

d. Augmentation. In the Arctic most of the annual precipitation is in the form of snow. Although total precipitation is low, advantage can be taken of the windy conditions to induce snow drifting at selected locations. Collection of the melting snow augments the summer water supply. Snow fences were used to induce drifting in the watershed of the Barrow, Alaska, water reservoir. It was shown that at least 800 gallons of water was collected for every linear foot of 5-foot-high snow fence that was installed, with the fences about 250 feet apart.

3-4. Ground water.

Ground water can be a more reliable water source than surface supplies. It is usually available on a year-round basis and is more consistent in its temperature and mineral quality than surface sources. Very shallow ground waters are unsuited for potable water supplies without extensive treatment and the yield is limited. Subpermafrost ground water or permafrost zones thawed by large rivers and lakes are the most reliable sources. Subpermafrost wells are technically feasible when the permafrost extends to a depth of a few hundred feet or less and they have been successfully used in central Alaska. Costs for drilling and maintenance of

such wells are high. The water must be protected from freezing and the permafrost must be maintained in a frozen condition. This requires special well casings or grouting methods and unique operational methods. Subpermafrost water is generally deficient in dissolved oxygen and can also contain high concentrations of dissolved iron and manganese salts. Hardness is also common. Dissolved organics can also create serious treatment problems due to interactions with the dissolved iron and the color imparted to the water. The most reliable and economical ground water sources in the Arctic and Subarctic are in the thawed zones adjacent to large rivers and lakes. Most of the rivers are braided streams and have shifted their channels many times. The former stream channels may still be underlain by thawed material and represent a potential water source depending on the type of soils involved.

3-5. Other water sources.

Snow, ice and direct catchment of rainfall are potential water sources that must be considered for augmentation or emergency supplies and for small or temporary facilities. The natural quality of these sources is good but a stockpile of snow or ice can be easily contaminated. Large volumes of snow are required to produce even small quantities of water and the costs for harvesting and melting are high. It is estimated that 4 to 5 cubic feet of snow are required for every 5 gallons of water produced, and to melt this volume of snow would require about a pint of diesel fuel for the snow melter. Brackish and saline ponds have been improved in quality by pumping out the concentrated brines that remain under the ice near the end of the winter and allowing fresh spring runoff to recharge the pond. If repeated several times the procedure allows the use of an initially unacceptable water source.

3-6. Structures.

Structures range from wells and their appurtenances or simple temporary intakes on river ice to a complex dam structure located on permafrost. The complete structural design of any of these is beyond the scope of this manual (TM 5-852-4/AFM 88-19, Chap. 4, discusses embankment construction on permafrost). It is the intent of this section to point out those features that may require special attention in the cold regions.

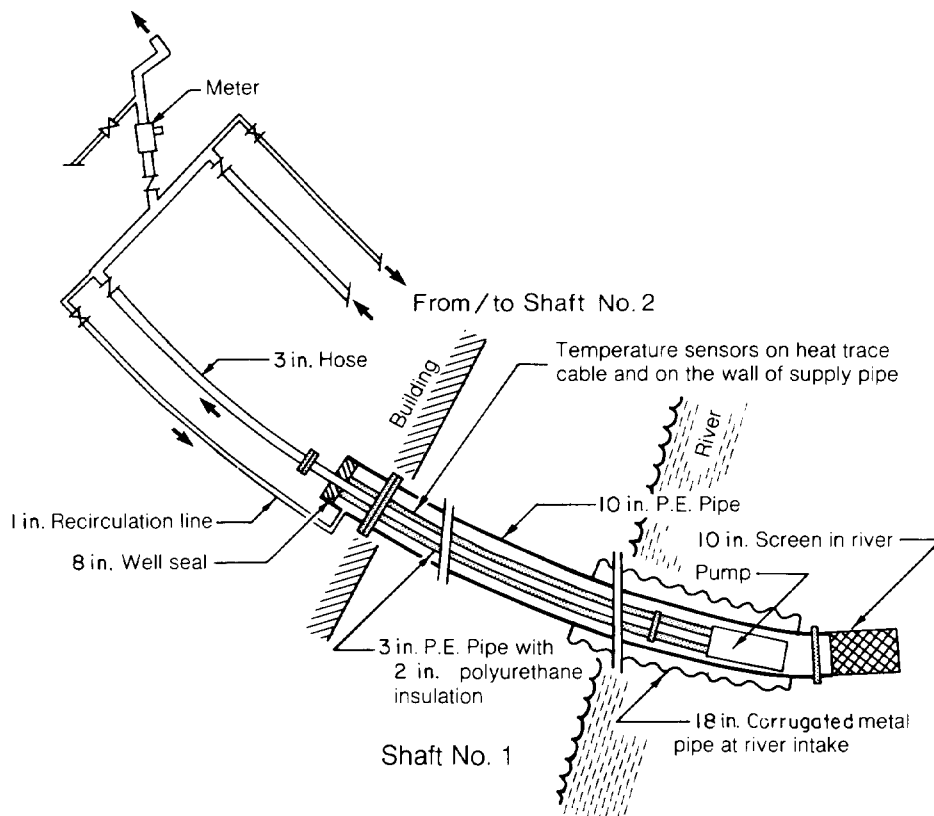
a. River intakes. A permanent intake structure will usually be employed for large-scale permanent military facilities in the Arctic. Structural damage from moving ice in the spring and in the fall is the major concern.

(1) *Temporary intakes.* These are less expensive, and are removed from the river during spring

ice breakup, and storage is relied on as the water supply. This approach is suitable for small populations. A temporary intake consists of a pump and a simple shelter.

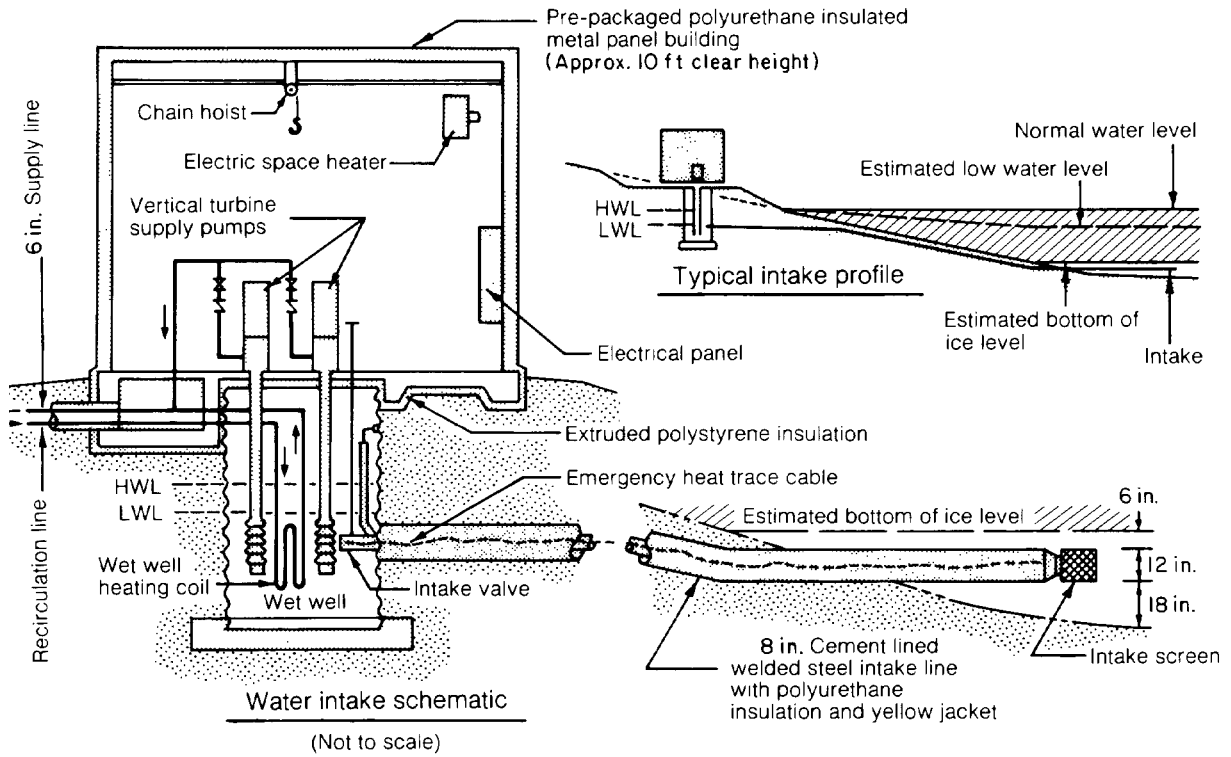
(2) *Permanent construction.* Numerous arrangements and configurations have been designed. Figure 3-2 illustrates the intake in the river at Fort Norman, Northwest Territories, Canada. Figure 3-3 illustrates the water intake at Cambridge Bay, Northwest Territories, Canada. Special features of this design include the insulation provided, heat tracing in the wet well and in the intake line, and the recirculating line from the town site. Dual intakes are recommended to ensure reliability. Continuous water circulation is then used to prevent freezing.

Frazil ice can be a serious problem for intakes during the freeze-up period. Frazil ice occurs as small crystals in flowing water slightly below 32°F in temperature. It will adhere to and accumulate on any submerged object it contacts. Water intakes, trash racks and similar structures can become completely choked by frazil ice in a few hours. It can be avoided by locating the intake in a long calm reach of the river where surface ice will occur before the water becomes supercooled. The surface ice cover then prevents rapid heat loss and precludes frazil ice formation. Heating the intake and bar screens to about 33 degrees F will prevent formation of frazil ice. This can be done electrically or by backpumping hot water or steam.



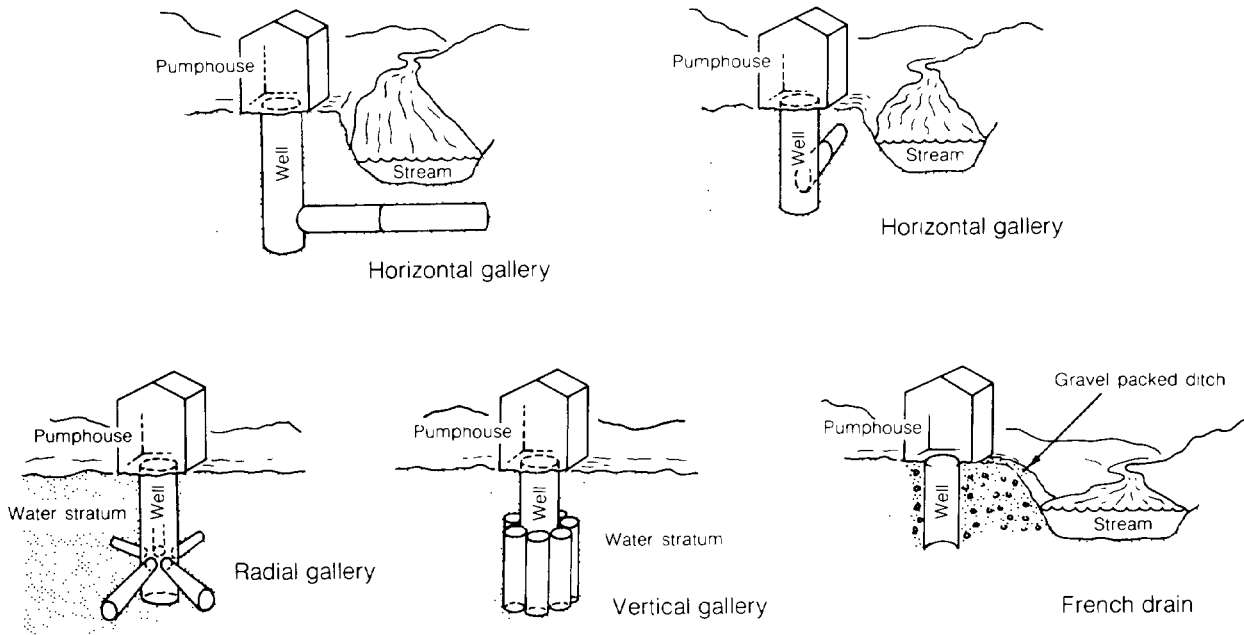
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Figure 3-2. Piping schematic for water intake.



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Figure 3-3. Water intakes.

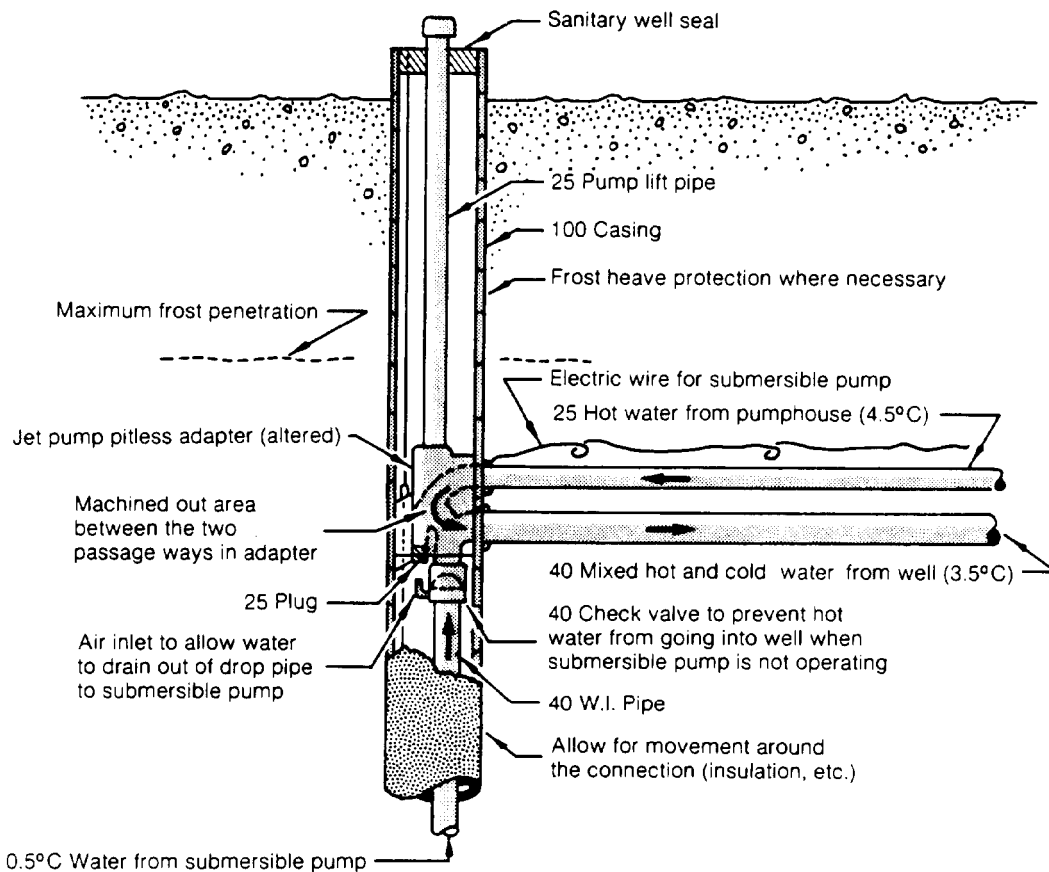


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Figure 3-4. Infiltration galleries.

b. Infiltration galleries. Infiltration galleries remove the structure from risk of ice damage and thereby offer advantages over direct intakes. Figure 3-4 illustrates several configurations of infiltration galleries that have been used successfully in the cold regions. The gallery is placed in thawed material in the stream bed or adjacent to it. The yield will depend on the type of soil present. Importation of coarse-textured material will be necessary for gallery construction in fine-textured silty and clayey soils. Both electrical and steam lines have been used in galleries to prevent freezing. Steam lines are usually placed on the upper surface of the intake laterals and on a second level about 1.5 feet above that. The heating elements or steam lines are not normally operated continuously but are used only in emergencies to restore a frozen or partially frozen system. Springs can also be developed with these same techniques.

c. Wells. The basic procedures for water well design are discussed in TM 5-813-1/AFM 88-10, Vol.1. The special concern for subpermafrost wells is not to allow thawing of the permafrost during drilling and during operation of the well. The former may require either compressed air or non-toxic drilling muds or fluids with rotary drilling procedures. Avoidance of permafrost thawing during well operation may require multiple casings so that cold air can circulate in the annular spaces. Concurrent with protection of the permafrost is the necessity of maintaining the water in an unfrozen state and this will require heat addition for an intermittently used system. Figure 3-5 illustrates a typical cold regions well with a submersible pump in non-permafrost conditions but designed for frost and heave protection in the surface soils. Bentonite, mixtures of oil, wax and sand, and various plastic coatings have been used on these casings to prevent

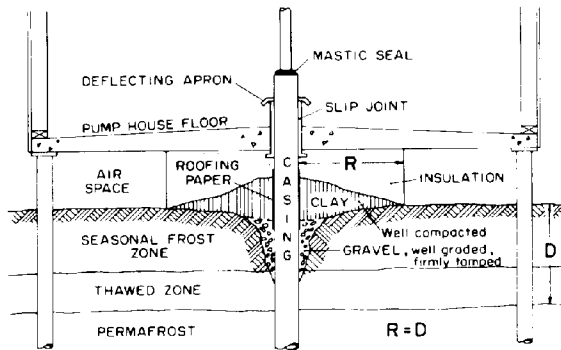


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Figure 3-5. Well seal.

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the bonding between the frozen soil and the pipe and thereby eliminate heave damage. Figure 3-6 illustrates the critical features in the well head and pump house design for larger facilities.



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Figure 3-6. Casing head construction for water well in shallow permafrost when surface soils are susceptible to heaving.

CHAPTER 4

WATER TREATMENT

4-1. General.

The basic requirement, criteria and procedures for water treatment systems for military facilities are covered in TM 5-813-1/AFM 88-10, Vol. 1. This chapter will discuss only those aspects unique to the Arctic and Subarctic. There are three major process concerns: the low temperature of the raw water, removal of glacial silt from surface sources and removal of dissolved minerals and organics from surface or groundwater sources.

4-2. Temperature effects.

The temperature of surface water sources during winter will be at or very near 32 degrees F, while ground-water sources in permafrost regions may be a few degrees warmer and maintain that level year-round. The water must be preheated to at least 40 to 50 degrees F or the unit processes must be designed for low temperature operation. The effect of low temperatures on equipment operations must also be evaluated during facility design.

a. Preheating. A number of methods have been successfully used to heat water in arctic systems. Safeguards are necessary to avoid contamination (and cross connections) during the heating process and the corrosion induced if dissolved oxygen is released from solution. Very cold surface waters may be at or near saturation with respect to dissolved oxygen. Oxygen is then released as a gas as the water is warmed and can cause severe corrosion in iron and steel pipes, pumps, and tanks. Use of non-ferrous metals in the heating stage and controlling the release point for this oxygen will reduce corrosion problems.

(1) *Liquid-liquid heat exchangers.* Hot water is the preferred source of heat for these devices to eliminate problems from tube leakage and contamination. The source of hot water might be a central heating system or cooling water from an engine. Double wall, or double liquid to liquid exchangers are necessary to prevent any possibility of contamination of potable water.

(2) *Blending.* In some cases a source of clean hot water may be available and can be blended directly with the cold water to achieve the desired temperatures. Condenser water from a steam system was successfully used in this way in Fairbanks, Alaska.

(3) *Direct-fired boiler.* These systems use oil, gas or coal furnaces to maintain the contained water at just below boiling temperature. This is then blended with the cold water source or used in a heat exchanger.

4-3. Low temperature treatment.

Almost all of the physical, chemical, and biological processes used in water treatment are sensitive to temperature either through viscosity effects or as an influence on reaction rates. Figure 9-1 illustrates the influence of viscosity, and the multiplier shown must be used to adjust the design of a water treatment process component for temperature.

a. Mixing. Mixing is strongly dependent on temperature because of viscosity changes in the water. The power input for mechanical flocculation is directly dependent on fluid viscosity as defined by:

$$P = G^2 V \mu \quad (\text{eq 4-1})$$

where P = power input
 G^2 = velocity gradient
 V = tank volume
 μ = absolute fluid viscosity.

To maintain the same velocity gradient in the tank as the liquid temperature decreases, it is necessary to adjust the 68 degree F power requirement by the multiplier from figure 9-1. This relationship will be valid for any kind of mechanical mixing. Detention time for mixing is determined separately. Detention times for flocculation range from 15 to 30 minutes and tend to be arbitrarily based on successful performance. The multiplier from figure 9-1 must be used for this adjustment. Multiple basins are recommended when surface water is the source and warmer temperatures are expected in the summer. In this way some of the units can be taken out of service when not needed.

b. Sedimentation. Settling of discrete particulate material is retarded by the increased viscosity in cold waters. As shown in figure 9-2 the effect of low temperature decreases as the solids concentration increases. Plain gravity sedimentation of individual particles would be subject to full viscosity effects and the detention time must be adjusted with the multipliers from figure 9-1.

Upflow and sludge blanket clarifiers are not as sensitive to viscosity effects and the multipliers from figure 9-2 will be used in these cases (solids concentrations >2000 mg/L). Another concern for any type of clarifier is the presence of density currents induced by strong temperature differences between the incoming fluid and the tank contents. These currents will disrupt the settling process and are particularly critical for upflow clarifiers. If possible these units will be maintained at nearly constant temperature and the incoming fluid adjusted to that same level.

c. *Filtration.* Filtration is influenced by low temperature since the head loss through the filter is proportional to viscosity. Mixed media filters will provide a more efficient use of space in cold regions facilities. The multiplier values from figure 9-1 will be used to adjust filtration efficiency. Backwashing of filters is also affected since power for pumping will vary with temperature, due to the increased water viscosity. The minimum upflow velocities will be reduced because of the increased fluid density at low temperature.

d. *Disinfection.* TM 5-813-3/AFM 88-10, Vol. 3, should be consulted for basic criteria on disinfection procedures, chlorine dosages and residuals. The solubility rate of chlorine decreases at very low water temperatures, but for practical purposes this will not occur at the dosage rates commonly used. The effectiveness of chlorination is hindered in cold water, and the exposure times must be increased in order to provide adequate disinfection. Contact time of about 1 hour is recommended for cold water below 40 degrees F.

e. *Fluoridation.* If fluoridation is practiced at remote cold regions facilities, the U.S. Public Health Service (USPHS) recommends that the dosage should be increased since the actual per capita consumption of drinking water tends to be somewhat less than in temperate locations. Fluoride concentrations of about 1.4 mg/L are recommended for the Arctic and Subarctic. Table 4-1 relates the

USPHS recommended fluoride limits to the annual average air temperature at the design location. (See TM 5-813-3/AFM 88-10, Vol.3, for specific guidance at military installations.)

4-4. Removal of minerals and organics.

Ion exchange water softening is commonly used at smaller installations with hard water. Lime-soda softening is frequently used when the water is both turbid and has a high hardness. Dissolved iron is common in cold regions ground waters and can foul zeolite and greensand ion exchange resins so that it must be removed prior to ion exchange processes. Aeration or chemical oxidation with chlorine have been successful for precipitation of elemental iron. However, iron/organic complexes are present in many cold regions groundwaters. Ozone has been shown to be effective in treating such waters. Ozone and carbon adsorption are very effective for color and organics removal.

4-5. Treatment of brackish and saline waters.

Distillation, reverse osmosis and freezing have all been used in the cold regions to reduce salt concentrations to potable levels.

a. *Distillation.* Distillation is expensive, requiring relatively high skill levels to accomplish, and will be considered only if other alternatives do not exist.

b. *Reverse osmosis.* Reverse osmosis (RO) is temperature sensitive, with best results obtained when water temperatures are in the range of 68 to 85 degrees F, and the cost is also high. Packaged reverse osmosis units are available from about 1000 to 1,000,000 gallon/day capacity (gpd). Power requirements are approximately one kilowatt-hour of power for each 100 gallons of potable water produced. These RO systems must be protected from freezing at all times, from the point of manufacture, during storage and during use.

c. *Freezing.* This process takes advantage of natural low temperatures to separate the saline brine from the ice which is then melted (naturally in the spring and summer) and used for water. Trenches have been filled with brackish water, allowed to freeze several feet deep, and then the remaining liquid under the ice pumped out. Spray freezing involves sprinkling brackish water through a nozzle to form a large cone of ice, with the brine draining away continuously during the winter. In a pilot-scale test in Saskatchewan, chloride content was reduced from 2000 mg/L to 500 mg/L in the melted ice. The recovered water represented about 75 percent of the volume sprayed.

Annual Average (5 yr +) Maximum Air Temperature (° F)	Fluoride Limits (mg/L)		
	Lower	Optimum	Upper
54	0.9	1.4	2.4
54-58	0.8	1.1	2.2
58-63	0.8	1.0	2.0
63-70	0.7	0.9	1.8
70-80	0.7	0.8	1.6
80-90	0.6	0.7	1.4

CHAPTER 5 WATER STORAGE

5-1. General.

Basic criteria for determination of capacity requirements and for design and construction of water storage facilities can be found in TM 5-813-4/AFM 88-10, Vol. 4. This section discusses only those aspects unique to the Arctic and Subarctic. Water storage is provided for domestic and fire protection services. The requirements for water will typically be lower at remote facilities in the Arctic and Subarctic than at similar operations in the temperate zone due to conservation and lower external water needs. The water needs will vary with the type of facility, so general criteria are not possible. A special design study to determine specific water needs will be undertaken for each new facility so that cost-effective designs for water supply, water storage and wastewater systems can be ensured.

5-2. Tank materials.

Common construction materials for water tanks include wood, steel, and concrete. Wood stave tanks are constructed with prefabricated pieces that can be shipped relatively easily to any remote site. Leakage is a problem with intermittent or fill-and-draw operations since the joints can open slightly if the wood is allowed to dry. Figure 5-1 illustrates the cross-sectional details of a wooden tank with an internal liner and insulation constructed in the Canadian Arctic on a pile foundation. In Alaska welded steel tanks are most commonly used. Tanks have been insulated with polystyrene or polyurethane boards or with sprayed-on polyurethane. Figure 5-2 shows a welded steel tank with board insulation and metal cladding resting on an insulated gravel pad. Concrete tanks have been used

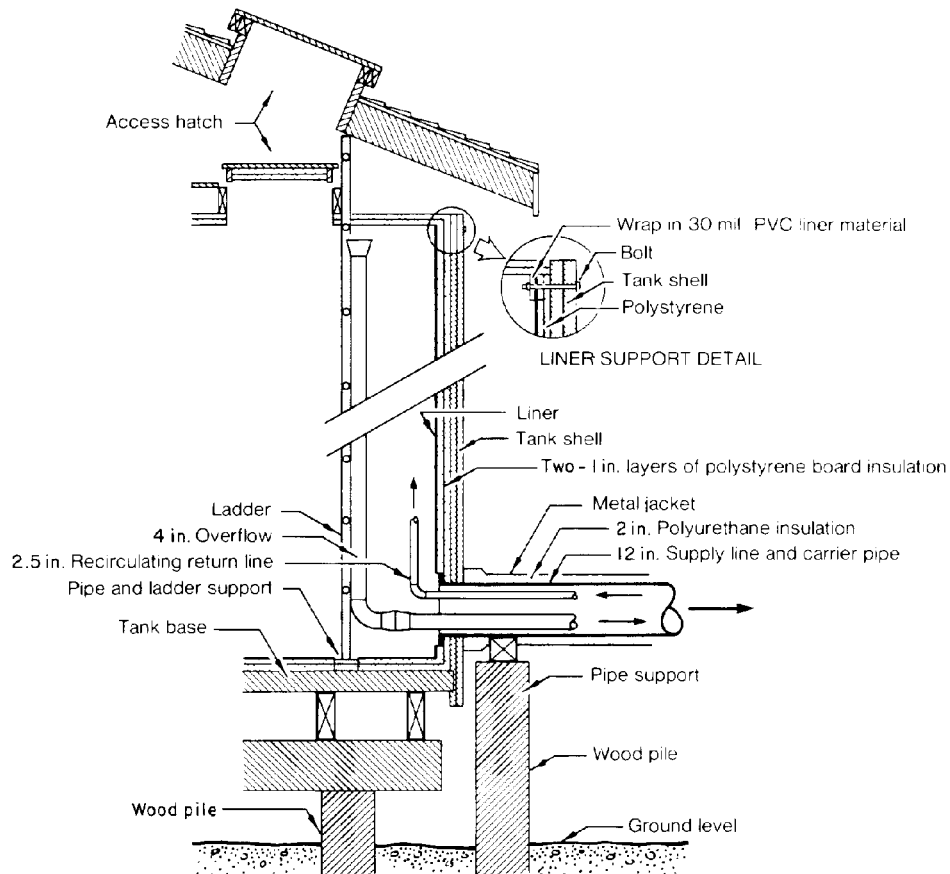
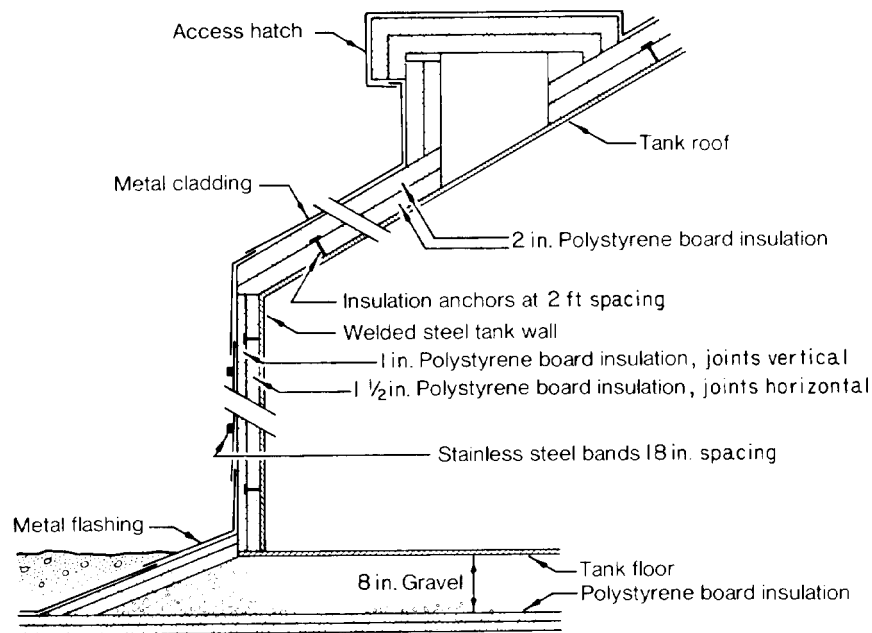


Figure 5-1. Wood tank with insulation and liner on inside.

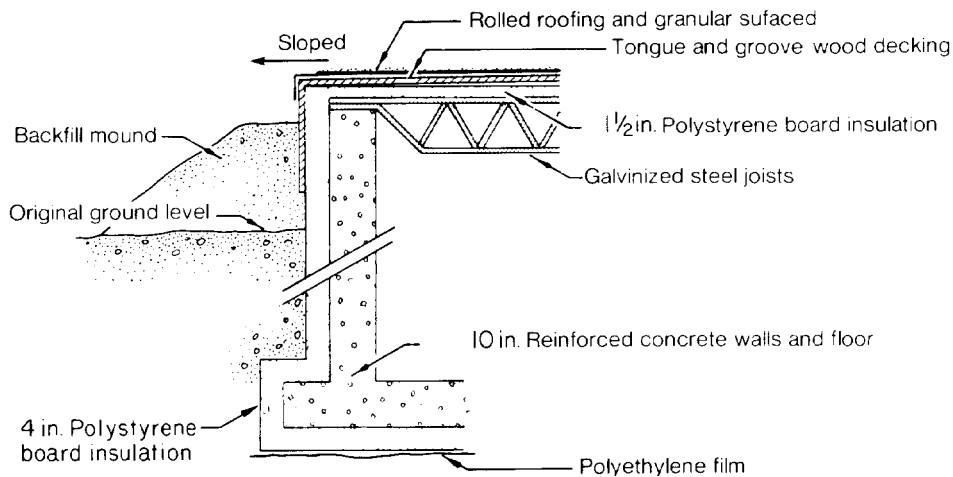
where aggregate is available and the foundation conditions permit slab construction. Concrete tanks will be covered with earth and insulated if necessary to reduce heat losses as shown in figure 5-3.

replacement is very high in remote locations so that the type of coating initially selected should be of high quality and properly applied. Cathodic protection is also required.



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Figure 5-2. Steel tank with board insulation and metal cladding.



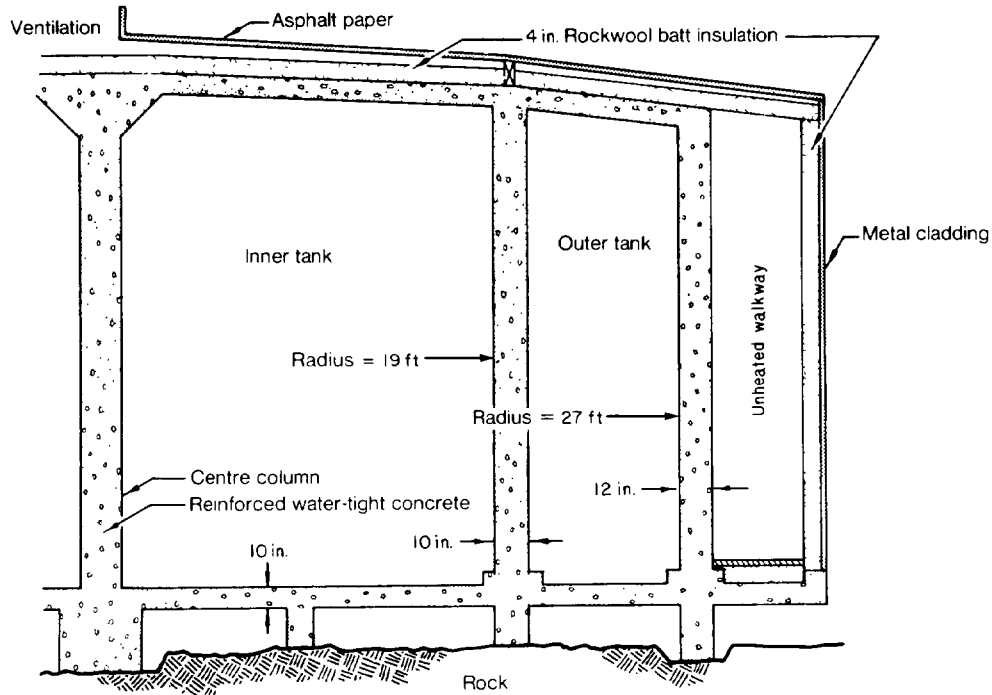
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Figure 5-3. Insulated buried concrete tank.

Seismic conditions must be evaluated prior to selection of a rigid concrete tank. Welded steel tanks are more cost effective for high-risk seismic areas.

a. *Corrosion protection.* Steel water tanks must be painted in accordance with applicable standards. Manufacturers' recommendations regarding acceptable temperature limits for the application of these paints must be strictly followed to avoid premature failure. The cost of sandblasting and liner

b. *Insulation.* Successful tank insulation has been provided by earth cover, wood, glass fiber, cellular glass, polyurethane and polystyrene block materials. Tanks can also be enclosed with a protective shell. Such an exterior shell is either constructed against the tank or a walkway provided between the tank and the exterior wall as shown in figure 5-4. The air gap and the wind protection will reduce heat losses,



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Figure 5-4. Above-ground concrete tank, Greenland.

and this heat loss reduction can be further enhanced by installing insulation. Moisture-resistant insulation materials must be installed in contact with the tank at inaccessible locations since moisture from leaks, condensation, rain or ground water can drastically reduce the insulating effect.

c. *Foam insulations.* Near-hydrophobic plastic foam insulations are readily available and commonly used. Polyurethane can be obtained as either prefabricated boards or foamed in place by spraying directly onto the tank. The latter has been the more common approach in Alaska. To ensure a good bond all loose scale or paint flakes are removed, the surface solvent-cleaned if it is oily, and a compatible primer applied. Foaming-in-place requires a dry surface, winds less than 3 miles per hour, air temperatures above 36 degrees F and tank surface temperatures above 50 degrees F. The hardened foam must then be protected from vandalism, weather and ultraviolet light. This is commonly done with low temperature elastomers or similar coatings compatible with polyurethane that are sprayed onto the insulation. Two or three coats are recommended with the first application within one day of foam application. Polystyrene or polyurethane boards can be glued and strapped (with 1-1/2 inch wide stainless steel banding, 18 inches on center) to the exterior of the tank. Large tanks will require clips. The insulation boards will be less than 3 inches thick

to allow installation on a curved tank surface. Two layers of insulation are preferred so that the joints between boards can be staggered (see figure 5-2). Sheet metal cladding is then applied for weather and vandal protection. Insulation boards composed of high density foams (compressive strength about 1500 psi) are sometimes placed under a tank (figure 5-3) for protection of the frozen subgrade.

5-3. Tank design.

Water storage tanks must be designed to prevent the formation of ice in the tank under all foreseeable circumstances and tanks must be completely drainable. Floating ice in the tank can destroy interior appurtenances, and ice formed on the walls can collapse and cause structural failure or punctures in the tank bottom. Surface icing can be avoided by maintaining the water temperature above 39 degrees F and there will be a continuous circulation. In some cases the return line of a circulating water distribution system is discharged to the storage tank to promote circulation and maintain temperatures. In other cases a small amount of water is withdrawn, heated with a boiler or heat exchanger and pumped back into the tank.

a. *Appurtenances.* Breather vents will be located on the inside of the tank and vented into an attached pumphouse or building rather than directly to the outside. Ice will form in an exposed vent due to

condensation and a vent blocked with ice will result in a vacuum in the tank as water is withdrawn and possibly cause the tank to collapse. Overflow piping will either be inside the tank or protected with insulation and heat tracing if placed on the exterior. Since ice can damage float type water level indicators, the pressure transducer type is recommended. Temperature monitoring at various levels for control and for alarms will be included in the design.

b. Thermal considerations. Whenever practical, tanks must be buried or covered with soil to reduce the effect of low air temperature. Elevated tanks must be avoided unless they are absolutely necessary for the water distribution system since they expose the greatest surface area to the worst climatic conditions. All exposed tank surfaces and risers for elevated tanks must be insulated. The economical thickness of insulation can be determined by the calculation procedures in chapter 12, paragraph 12-9*i*. Thermal calculations are also necessary to size the heating systems used to replace heat losses or to heat the water for distribution. The unit capacity of a heat exchanger or boiler must be equal to the maximum rate of heat loss.

5-4. Tank foundations.

Foundation considerations are similar to those for

other arctic and subarctic structures and are covered in TM 5-852-4/AFM 88-19, Chap. 4. Foundation design for tanks is complicated by the very high loads imposed by the stored water and the need to keep the water in the unfrozen state. The unfrozen water is a heat source that can have an adverse effect on the underlying permafrost and must be considered during design for a tank on grade.

5-5. Earth reservoirs.

Water impoundments for domestic and industrial water supply and for hydropower have been successfully constructed in the Arctic and Subarctic. The most likely configuration for military facilities is an earthen embankment to either increase the storage capacity of an existing lake or stream or to impound water in a natural drainage swale. Construction of these embankments must be in accordance with TM 5-852-4/AFM 88-19, Chap. 4. A liner is necessary within the embankment or to seal the entire reservoir, when permeable soils are present or used for construction. Successfully used liner materials include Hypalon synthetic rubber, chlorinated polyethylene (CPE) and elasticized polyolefin. (See EPA 600/8-79-027 for further detail on linings.)

CHAPTER 6

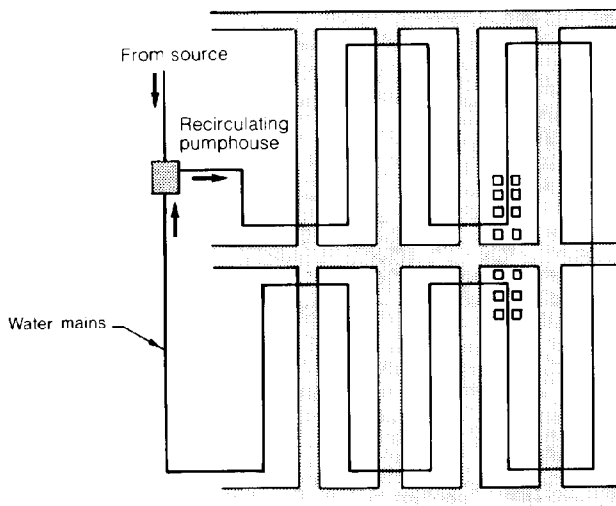
WATER DISTRIBUTION

6-1. General.

The basic criteria for design and construction of water distribution systems can be found in TM 5-813-5/AFM 88-10, Vol. 5. This section presents information that is unique to the Arctic or Subarctic. Pressurized, pipe distribution systems are used for exterior utilities and interior plumbing in most military facilities in the cold regions. An exception might be small facilities at locations remote from the main distribution network. If individual wells are not feasible then vehicle delivery of water would be necessary. Truck delivery systems are common at remote civilian communities in Alaska, Canada and Greenland. Vehicle specifications for this special purpose can be obtained from the U.S. Public Health Service-Indian Health Service, 701 C St., Box 65, Anchorage, Alaska 99513. The location of pipe distribution systems and whether they should be buried or above ground are discussed in chapters 2 and 12 of this manual.

6-2. Single pipe recirculation system.

The single pipe recirculation system is recommended for arctic conditions. As shown in figure 6-1 it consists of one or more uninterrupted loops originating at a recirculation facility and returning to that point without any branch loops. This layout will



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Figure 6-1. Layout and location of mains for single pipe recirculation.

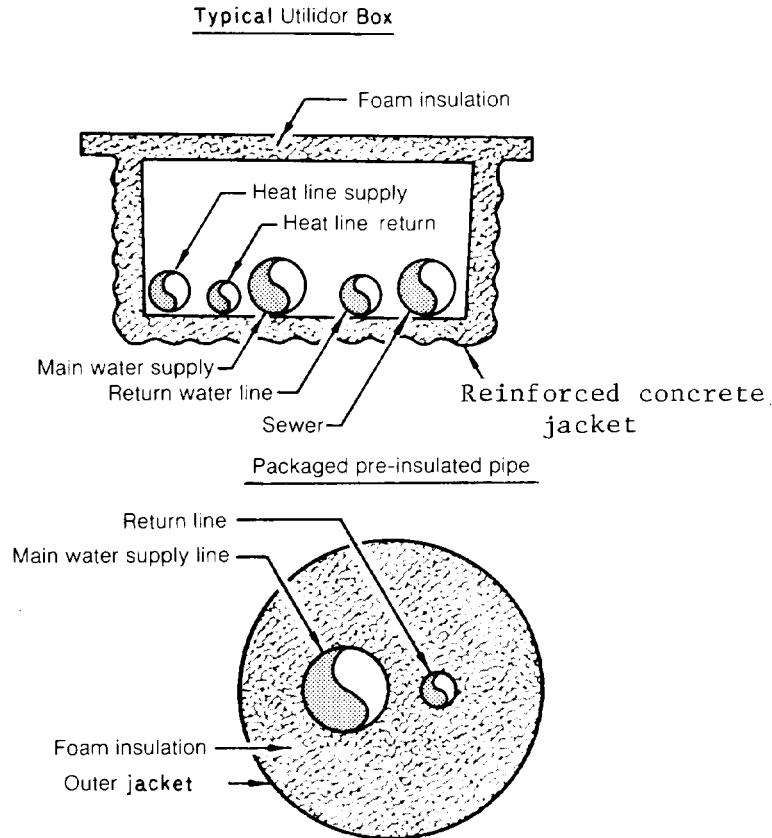
eliminate dead ends and related freezing problems and requires the minimum amount of piping as compared to other circulation methods. A simple, positive control of distribution is possible with flow and temperature indicators on the return lines at the recirculation facility. Normally water is pumped out at between 39 and 45 degrees F and returns at 33 to 39 degrees F. Pipe network design uses the same procedures used for standard water systems. The return line does not have to be of the same size as the delivery pipe because of withdrawals in the network. Expansion of the system is provided by construction of temporary links to close the loops at the end of the present system when the system is expanded, the link is valved off and the pipe link left empty. If possible, the mains will be located at the rear of buildings, rather than in the streets, as shown in figure 6-1. This will provide greater thermal protection (since snow is not typically removed), result in less risk of damage to manholes and other appurtenances, and will allow shorter, less costly service connections to the buildings. There are special advantages to this approach for barracks and family housing areas where large numbers of similar structures tend to be laid out in a regular pattern.

6-3. Alternative systems.

Conventional water pipe mains with no recirculation are possible in very special situations, but require careful planning in the initial site layout for military installations. In these cases, there may be enough flow in the system so that return loops are not needed if a high volume consumer is placed at the ends of the main line. Sizing of the pipe network and other design details follow conventional practice. A dual pipe system relies on a large diameter supply line and a small diameter return line placed side by side in a utilidor or a preinsulated conduit as shown in figure 6-2. The return line is sized to maintain the desired flow in the system. Figure 6-3 is a schematic illustration of typical service connections from a dual system. The service lines are taken off the main and returned to the smaller diameter return line. The pressure differential between the delivery and the return line must be sufficient to induce circulation in the service loop. The system is complex and control mechanisms tend to be elaborate. For example, varying consumption in different

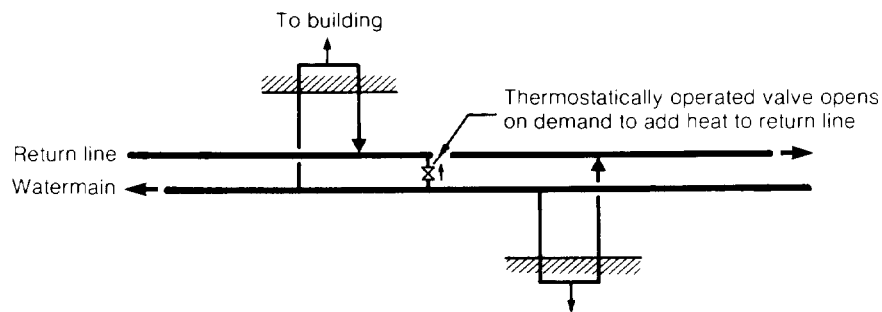
locations can result in stationary water in certain areas at certain times. As shown in figure 6-3, thermostatically controlled solenoid valves are used at regular intervals to overcome this problem. Some

facilities have utilized seasonal transmission mains to convey the water from a summer source to storage tanks. Such lines do not need special thermal considerations.



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Figure 6-2. Typical utilidor and packaged preinsulated pipe.



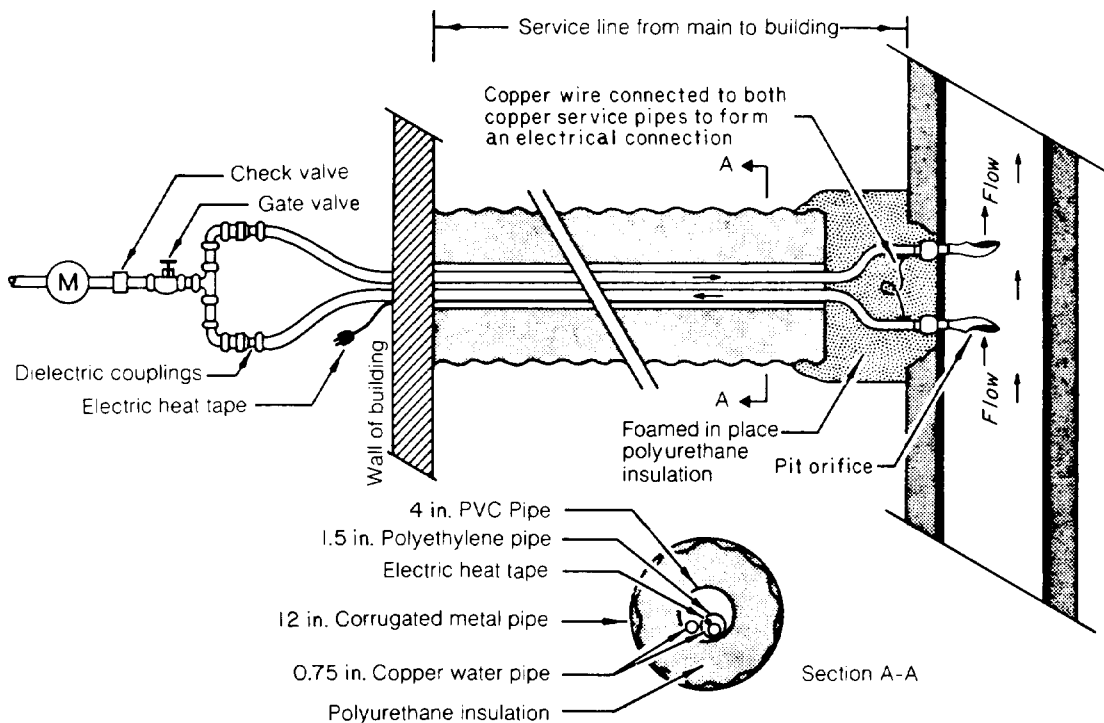
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Figure 6-3. Schematic diagram of a dual pipe system.

6-4. Service lines.

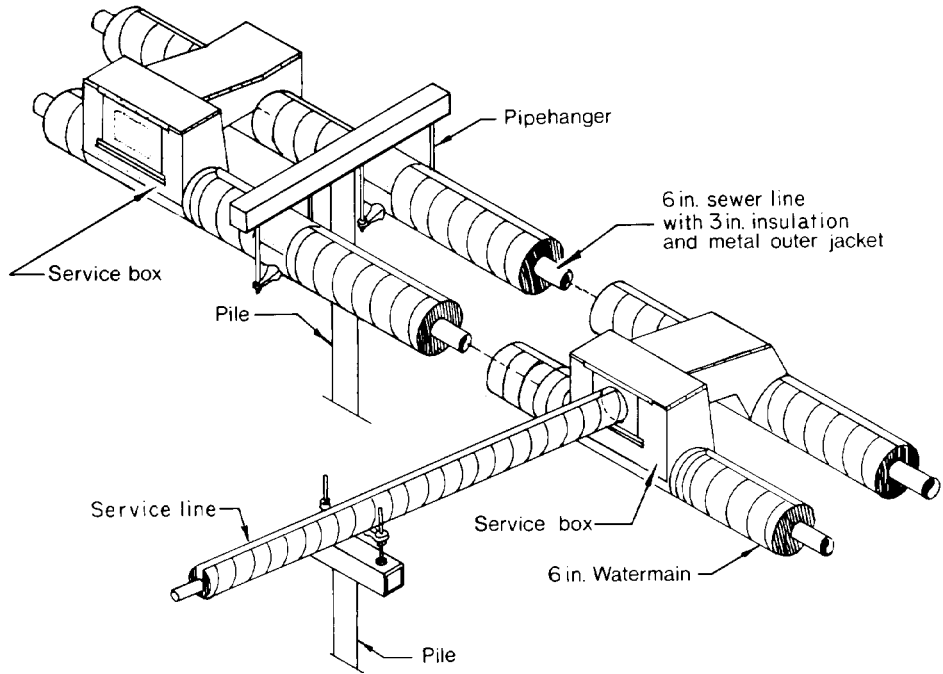
The design of service lines must prevent freezing of the contained water but must also consider the effects of permafrost thawing, frost heaving and differential settlements between the pipes and the building. These structural concerns are covered in TM 5-852-4/AFM 88-19, Chap. 4. Circulation in these service connections is the recommended method to prevent freezing. Heat tapes are also commonly installed as a backup. The two most common methods for circulation are either a small pump inside the building or the use of pit orifices. A typical pit orifice installation is shown in figure 6-4. There will be a small velocity-induced pressure differential between the upstream and downstream orifices, which in turn induces flow in the service loop. To operate properly, the flow velocity in the main must be at least 2 feet per second and this can be technically difficult and energy intensive for large diameter water mains. If the service lines are longer than 80 feet, the pressure differential in the main is not sufficient and the pit orifice will not function. A small circulation pump must be added in the building for longer distances. The presence of these pit orifices will result in head losses in the main. A head

loss of about 0.2 feet per service connection is suggested as a conservative design value. The head losses in the plumbing in the pumphouses used for circulating water in the mains must also be considered as they are substantial on most systems. Backup freeze protection is usually provided by a thermostatically controlled electrical heat tracer. If copper pipe is used for the service lines, an electrical connection between the two service pipes at the main will allow electrical resistance thawing from within the building as a second backup system. Figure 6-4 illustrates both of these approaches. Typical details of above-ground service lines and connections are shown in figures 6-5 and 6-6. Figure 6-7 illustrates the details of an underground valve and box on water mains. The valve box assembly should be packed with a low temperature non-hardening grease to prevent infiltration and freezing of water around the mechanism in the winter. A pair of adjacent buildings can employ a common service loop as shown in figure 6-8. This will be less expensive than individual service connections and will be more reliable because of the two circulation pumps on the single loop.



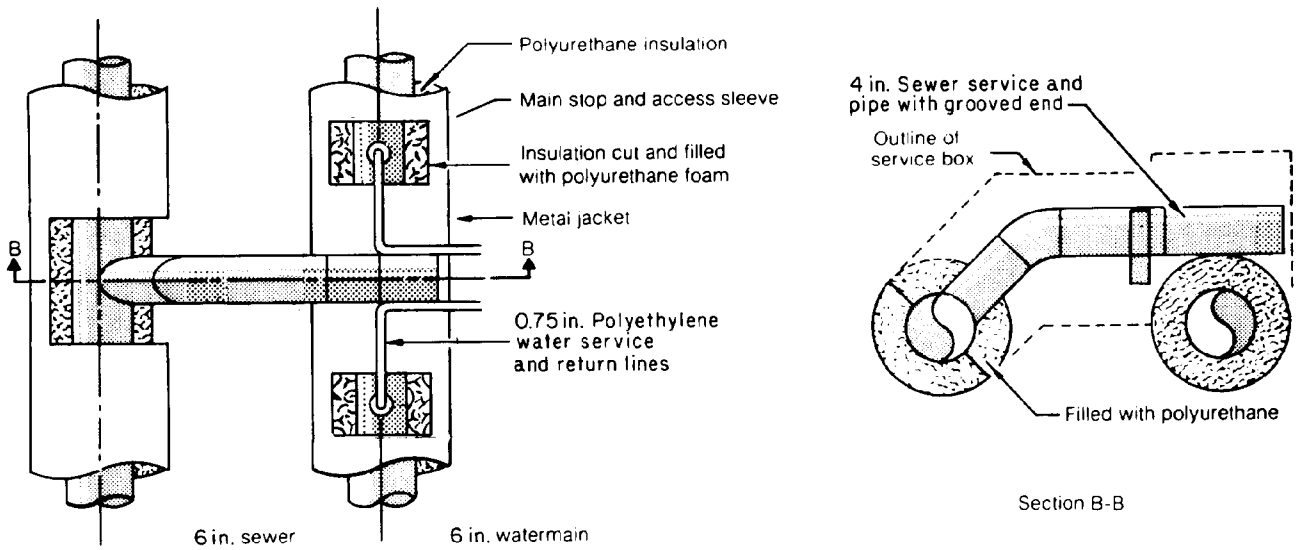
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Figure 6-4. Water service line, with pit orifices.



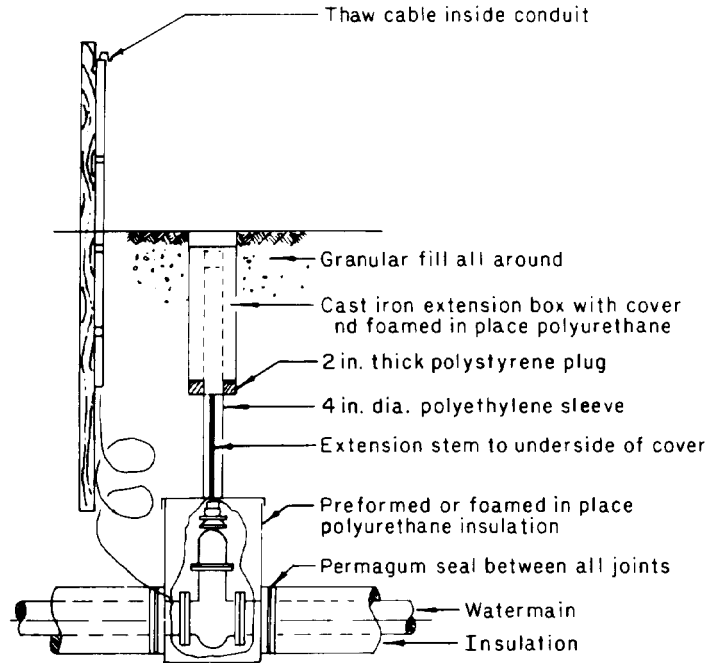
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Figure 6-5. Typical above-ground service line takeoffs.



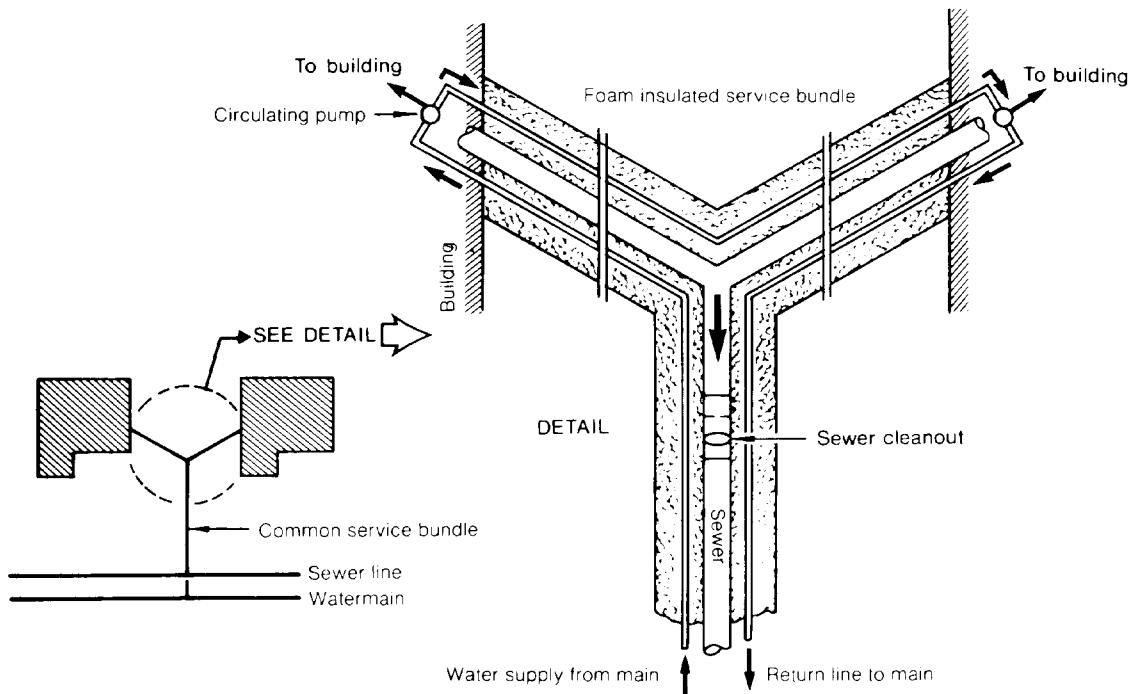
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Figure 6-6. Typical above-ground service line.



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Figure 6-7. Underground valve and box.



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Figure 6-8. Dual service.

6-5. Materials.

The basic selection of pipe materials will be in accordance with TM 5-813-5/AFM 88-10, Vol.5. The discussion that follows is intended to give some indication of the performance of these materials in the Arctic and Subarctic.

a. Copper. Type K copper is commonly used for service lines because it can be thawed by using electrical resistance while plastic pipes cannot be thawed in this manner.

b. Ductile iron. Ductile iron pipe can take some shock loadings and is slightly flexible. It has poor corrosion resistance and lining is necessary. It is a heavy, durable pipe often used in rocky areas or where adequate pipe bedding materials are not available. Ductile iron pipe with special joints is used where bridge strength is required to span piles or where differential settlements are anticipated in buried systems. It can be thawed with electrical resistance.

c. Steel pipe. Steel pipe is lighter, more flexible, and more corrosion resistant than ductile iron. Continuously welded steel pipe has been used to obtain maximum span between piles. It can also be thawed using electrical resistance. Expansion and contraction, including necessary thrust anchors, must be considered. The differential expansion and contraction between a steel pipe and rigid heat tracing components or insulations attached to the pipe must also be considered.

d. High density polyethylene (PE). Pipe of this material is very flexible and impact resistant, with a high coefficient of expansion and contraction, high corrosion resistance and a smooth interior, but it cannot be threaded. Butt-fused polyethylene pipe has been used extensively in Canada for water and sewer mains. Typically the water pipe is insulated with urethane and then covered with a thin polyethylene jacket. Field joints are insulated and covered with heat shrink couplings. The most common use has been in buried systems, and experience has shown that the pipe and contained water can freeze solid without breaking the line.

e. Polyvinyl chloride (PVC). This is the most common type of plastic pipe used for water mains. It can be threaded, is corrosion resistant and has a smooth interior but is not as flexible as PE, and may rupture if pipe and contents freeze. As a result PVC pipe is not the best choice for single pipe systems buried in permafrost areas.

f. Acrylonitrile-butadiene-styrene (ABS). This pipe has a higher impact strength and flexibility but a lower mechanical strength than PVC. It has a smooth interior and does not become brittle at cold temperatures. ABS pipe has mostly been used for

non-pressure drainage, sewer and vent piping. It is not recommended for single pipe systems buried in permafrost areas.

g. Asbestos-cement (AC). This pipe is relatively inexpensive, light weight, corrosion resistant and has a smooth interior. However, it is brittle and is not suited for buried installations in the Arctic or Subarctic where differential settlements and frost heaving are expected.

h. Others. Reinforced concrete is usually used for large transmission lines. Wood stave piping has been successfully used in the past. It is corrosion free, has a smooth interior and can usually be restored after a freezing event, but cannot be thawed electrically.

i. Insulation. Pipe units composed of the materials (except wood and concrete) described above are typically insulated with high density urethane foam at the factory and covered with either a steel or a 40-mil high density polyethylene jacket, depending on the final conditions of exposure in the field. Design calculations to determine insulation thickness are described in section 12 (see example in para 12-91). These prefabricated pipe units are then shipped to the job site with preformed half shells of urethane insulation for the joints. Heat shrink sleeves or special tape is used to complete the field joint when PE is used as the outer jacket. Prefabricated sections are used for steel-jacketed pipes. Pipe insulation is not normally done on-site because of high costs and labor. Factory prefabrication will usually ensure a better quality insulation. Exceptions are appurtenances such as hydrants where foamed-in-place urethanes are commonly employed.

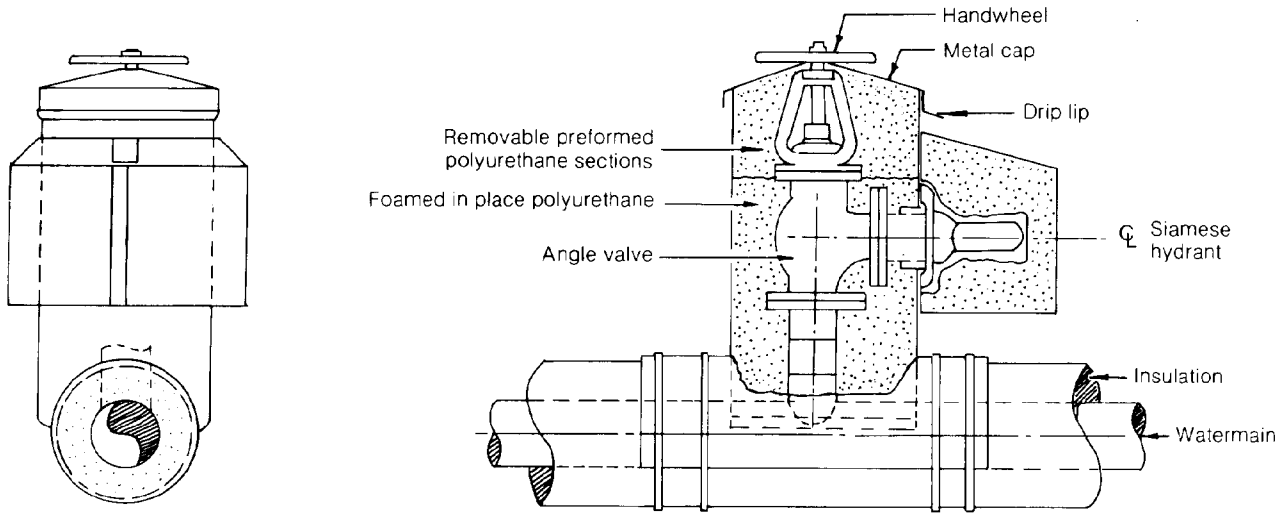
6-6. Appurtenances.

On typical water distribution system these include hydrants and valves.

a. Hydrants. Figure 6-9 illustrates the typical details of a hydrant installed on an above-ground water main. The insulated hydrant box must be specially designed and fabricated to fit the equipment to be used and the particular location. The riser from the main to the hydrant base will be as short as possible so that heat conducted from the water flowing in the main can keep the hydrant from freezing. A typical hydrant connection to a buried water main is shown in figure 6-10. The hydrant is normally on-line to minimize the possibility of freezing, with a frost-isolating gasket between the hydrant barrel and the tee into the main. The hydrant barrel is insulated with 3-inch prefabricated polyurethane inside a polyethylene sleeve. The annulus between the sleeve and the insulated barrel is filled with an oil and wax mixture to prevent frost

heave damage. Isolating valves are typically put in the main or both sides of the tee to allow for hydrant repair or replacement. After use the hydrant

the pipe with or without heat contact cement. Common wattages used are 2.5 watts per foot for service lines and 4 watts per foot for main lines.



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Figure 6-9. Above-ground hydrant.

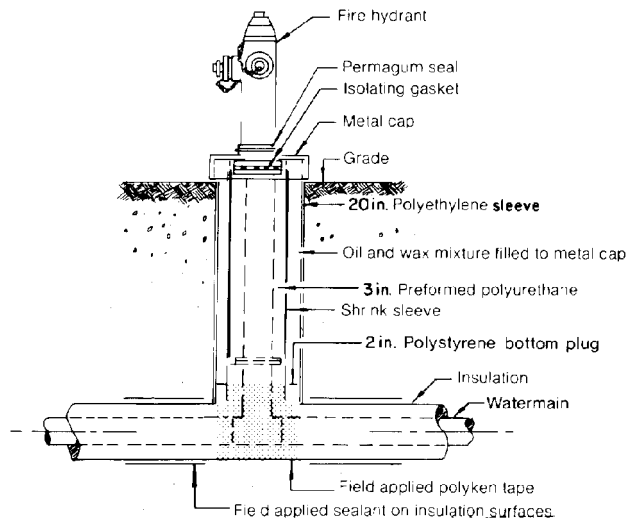
must be pumped out since frozen ground conditions may prevent self draining.

b. *Valves.* Typical details for valve installations are shown in figures 6-5 and 6-7. The riser stem for buried valves is insulated in a manner similar to that described above for hydrants. Non-rising stem-gate valves are most practical for buried or completely insulated locations.

6-7. Backup freeze protection.

These are reserve systems to either prevent freezing if circulation stops in the lines or to thaw the system if freezing occurs. The procedures apply to both main lines and service piping. These include electrical heat or steam tracing to prevent freezing or to thaw, and electrical resistance heating and steam or hot water to thaw systems.

a. *Heat trace systems.* A heat trace system is the standard back-up used in most piped water distribution systems. While it is effective, both the initial capital cost and operating cost for this type of protection are substantial. Constant monitoring must be carried out on such electrical systems if they are to perform as intended. If the controlling thermostats are not working properly or the sensing bulbs are in the wrong location, either too much electric energy will be expended at great cost or it will fail to do the job when required. Easy replacement of heat trace lines should be a standard feature of any system. The heat trace normally used is the constant watt per foot type placed in a conduit or channel next to



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Figure 6-10. Below-ground hydrant.

This method is less efficient on plastic piping. In Greenland and northern Scandinavia the heat trace is placed inside plastic pipes. The calculation procedures presented in chapter 12 can be used to determine heat tracing design requirements.

b. *Steam or hot water thawing.* This system uses a source of steam, such as a portable steam jenny, or hot water introduced under pressure into the frozen pipe via a suitable hose or tube to thaw out the pipe. This system can be used with most types of pipe

materials. It is not recommended for plastic pipes which could melt or be damaged if the procedure used is improper.

c. *Service line thawing.* Small-diameter service lines of any material may be quickly thawed by pushing a flexible 0.5 in. or smaller, plastic tube into the frozen pipe while pumping warm water into the tube. Water pressure can be obtained from a nearby building, either directly or by connecting to the building plumbing. A conventional hand pump filled with warm water can also be used (fig. 6-11). A commercial unit produces a pulsating stream of water to pump warm water through a tube attached to the frozen pipe by a special fitting to ease the installation and reduce spillage.

d. *Electrical resistance thawing.* The thawing of metal pipes using electricity is fairly common. Either portable gasoline or diesel generators, welders, or heavy service electrical transformers (110 or 220 volt) have been used (fig 6-12). AC or DC current at high amperage and very low voltage (seldom more than 15 volts) can be used. The amount of heat generated when current is passed through a pipe is

$$W = I^2R \quad (\text{eq 6-1})$$

where W = heat or power in watts (or joules/second)

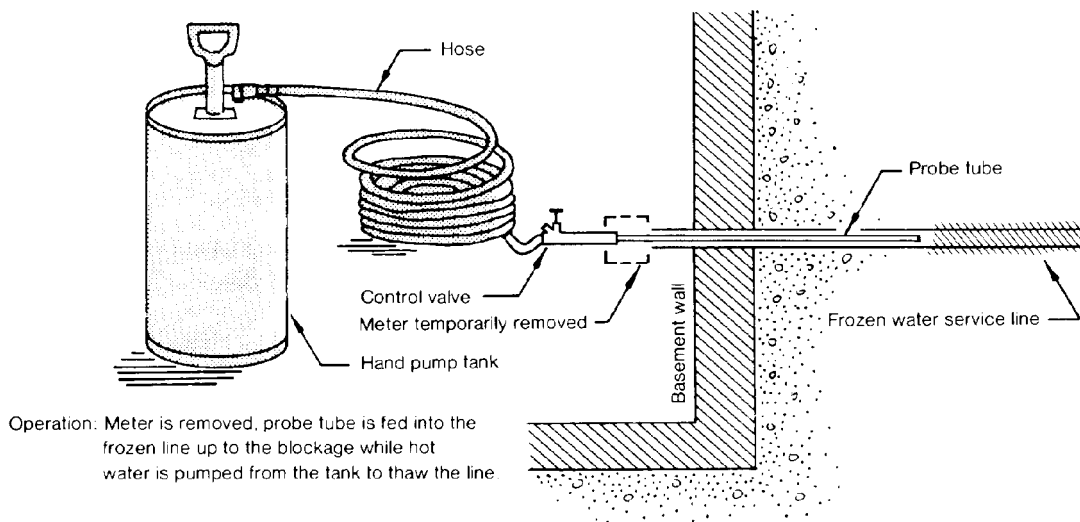
I = current in amps

R = resistance in ohms.

The rate of thawing of a frozen pipe is directly proportional to the square of the current applied, the mass of the pipe (cross-sectional area times length), and the material's effective resistance to the passage of electricity. For example, doubling the current (I)

will increase the heat generated by a factor of four. Generally, as much current (heat) as practical, with safety limits, must be provided so that the thawing time is reduced. The approximate times required to thaw different sizes of steel pipe using different currents are given in figure 6-13. Copper pipe has about one-ninth the resistance of steel and a smaller cross-sectional area. Therefore, when thawing copper pipes, these current values must be increased by about 10 percent for 1/2-inch pipe, 25 percent for 1-inch pipe, and higher values for larger copper pipes. However, when copper pipe with soldered joints is to be thawed, it must not be heated to the point where the solder melts (silver solder can be used to alleviate this). Steel lines with continuous joints can be expeditiously thawed with welders. The following precautions must be taken when thawing pipes electrically:

- (1) Use on underground or protected pipe only (not indoor plumbing).
- (2) Don't use a high voltage. Twenty volts with 50 to 60 amps is sufficient. (Do not use a constant voltage power source because there is usually no control for limiting the current.)
- (3) Make good, tight connections to the pipeline.
- (4) When conventional arc welders are used for thawing, do not operate them at their maximum rated amperage for more than five minutes. Only use about 75% of rated amperage if longer times are needed.
- (5) Disconnect electrical wires grounded to the water pipes in the buildings, or disconnect the



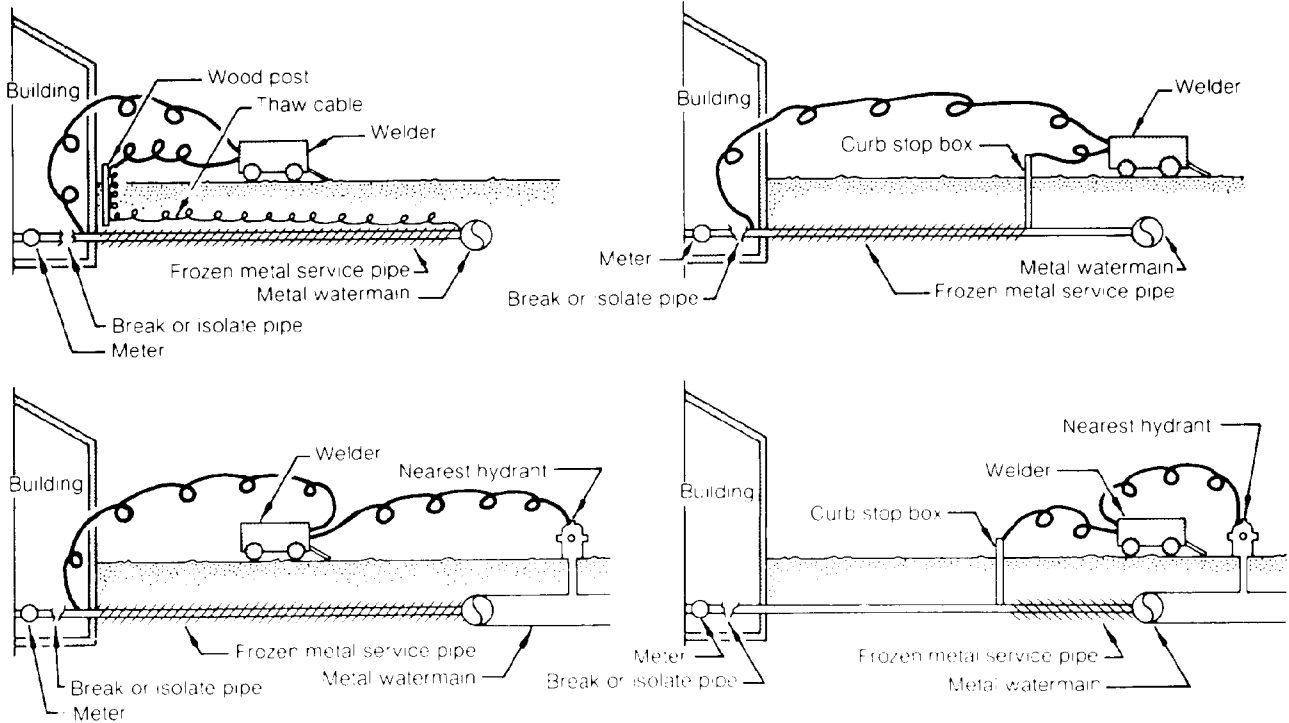
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Figure 6-11. Thaw tube, thawing method.

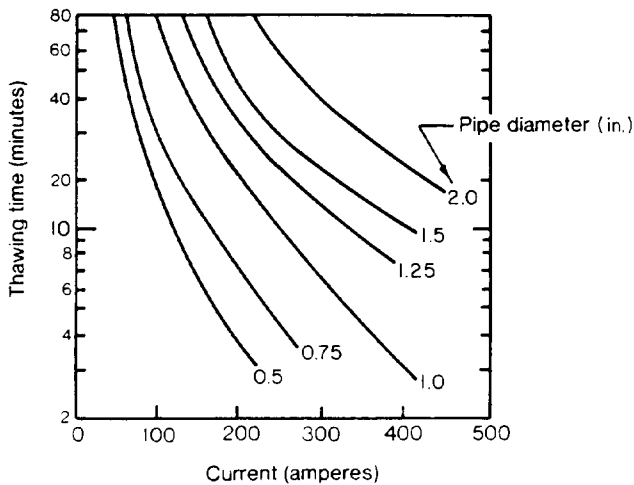
service pipe from the house plumbing. Failure to do this could cause a fire.

(6) Remove meters that may be in the service line.

(7) A problem may be encountered with the thawing current jumping from the water service line into nearby gas or other lines. These should be separated by a 1-inch wood block or wedge.



U.S. Army Corps of Engineers *Figure 6-12. Alternatives for thawing service lines.*



U.S. Army Corps of Engineers *Figure 6-13. Approximate times and current for thawing steel pipes.*

CHAPTER 7 WASTEWATER COLLECTION

7-1. General.

The basic criteria for design of sewerage systems for military facilities are in TM 5-814-1/AFM 88-11, Vol.1, and TM 5-814-2/AFM 88-11, Vol.2. The unique aspects of design and construction of these systems in the cold regions are in this section. In addition some further detail is included on the use of pressure and vacuum sewers since the flat terrain and permafrost make it difficult to design a conventional gravity sewer system in the Arctic. Combined utility systems called utilidor are covered in chapter 8. Table 7-1 compares the characteristics of gravity, vacuum and pressure systems for use in cold regions. Vehicle hauling of water and wastewater is still used at some remote sites, but for the general case, military facilities will be serviced by piped collection systems. Normally, a conventional gravity sewer system will have the lowest life-cycle cost and must be used whenever practicable. Gravity systems have an additional advantage over pressure systems in that they seldom flow full. As a result gravity pipes are less likely to break if freezing occurs.

7-2. Design considerations.

As described in chapter 2, the location of the pipe, above or below ground, is critical to satisfactory performance. An above-ground location with the piping installed on piles may be necessary because of soil conditions. However, the grades necessary for gravity flow are difficult to maintain with above-ground sewers. Above-ground sewers also hinder transportation, block surface drainage and snow removal, have high heat losses, and are more susceptible to vandalism. The operation and maintenance costs for above-ground systems are about three times higher than those for similar systems buried underground. Above-ground construction costs for a single pipe depend on the foundations required. If the pipe can be laid directly on the surface, construction costs will be 20 to 40 percent of that required for the same pipe installed on piling.

a. Sewage temperatures. Domestic wastewater from barracks, mess halls and family housing on military installations in the cold regions will range from 50 to 60 degrees F at the source. Wastewater from facilities not having hot water heaters can be as

Table 7-1. Characteristics of wastewater collection systems.

Type	Soil Condition	Desirable Topography	Economics	Other
Gravity	Non-frost-susceptible or <i>Slightly</i> frost susceptible with gravel backfilling material.	Gently sloping to prevent deep cuts or lift stations.	Initial construction costs high but operational costs low unless must install above ground or use lift stations.	Low Maintenance. Must have adequate grade. Flushing of low use lines may be necessary. Large diameter pipes necessary.
Vacuum	Most useful for frost susceptible or bedrock conditions, but can be used with any soil conditions.	Level or gently sloping.	Initial construction cost moderately high. Operational costs moderate.	"Traps" every 300 ft. Low water use. Must have central holding tank for each 30 to 50 services with additional pumps to pump waste to treatment facilities. Can separate gray and black water. Uses small pipes. No exfiltration.
Pressure	Most useful for frost susceptible or bedrock conditions, but can be used with any soil conditions.	Level, gently sloping or hilly.	Initial construction costs moderate. Operational costs moderately high.	Low water use if water use fixtures are installed. Number of services not limited. No infiltration. Uses small diameter pipes.

low as 35 degrees F. The temperature of wastewater in utilidor (chapter 8) can be increased if steam or hot water lines are also included in the utility package. The thermal design of the sewer piping (chapter 12) must include these wastewater temperatures for cost-effectiveness. Storm water will not be admitted to sewers in cold regions. It lowers the temperature of the wastewater and increases the cost of pumping, treatment, and disposal.

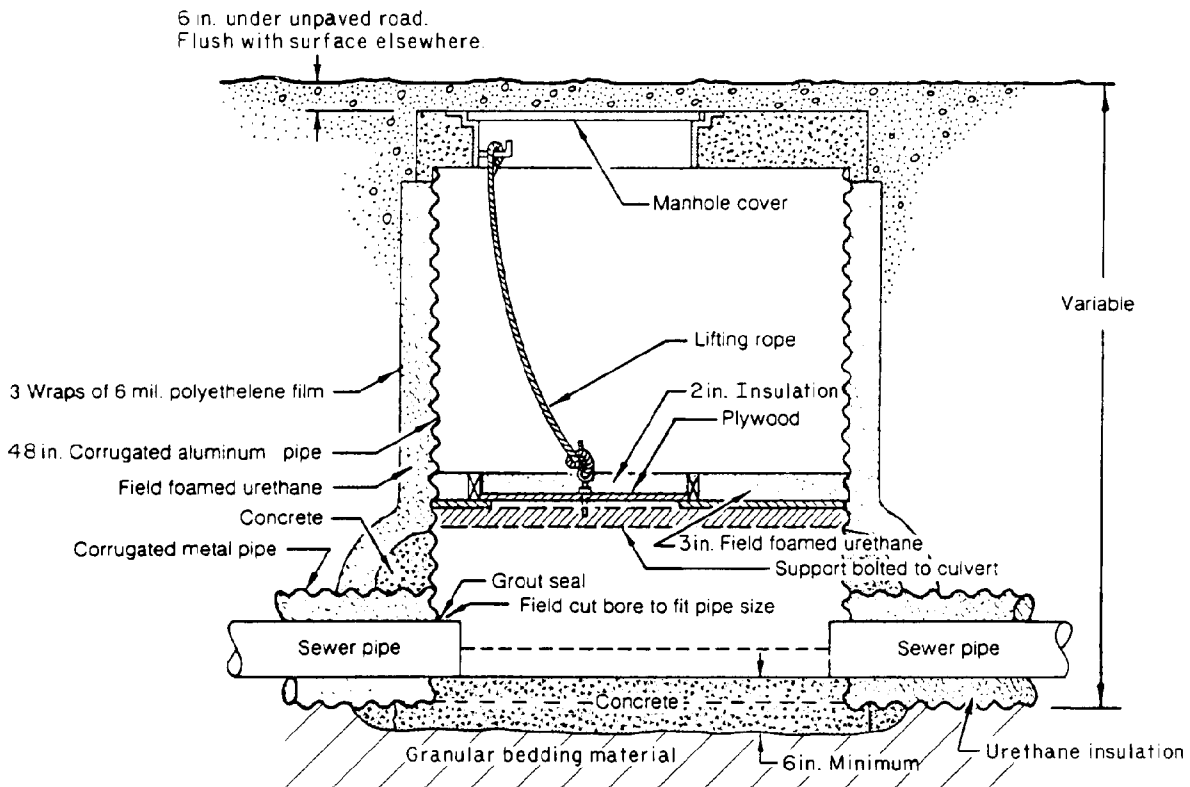
b. Pipe materials. The materials selected for sewerage systems will be in accordance with the criteria given in TM 5-814-1/AFM 88-11, Vol.1. Paragraph 6-5 in section 6 of this manual discusses the cold climate aspects of these materials.

7-3. Appurtenances.

These include manholes, cleanouts, building or service connections, and flushing siphons.

a. Manholes. Figure 7-1 illustrates typical details for a buried sewer manhole structure in the cold

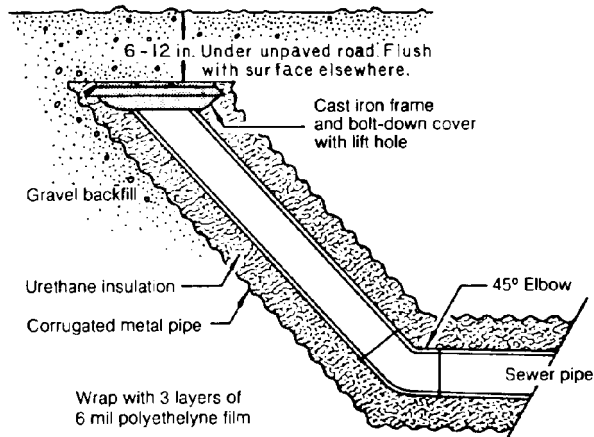
regions. A plastic film wrapped around the outside of the manhole will be required to prevent bonding of the soil to the structure and thereby prevent damage from frost heaving. Typically, such manholes have been insulated with a minimum of 3 inches of polystyrene or urethane around the outside, with a plastic film or other external coating to prevent moisture damage to the insulation. An insulated cover will be provided over the wastewater chamber to further reduce heat loss. A firm foundation is essential, and may require either piling or excavation, and then sand and gravel backfill. If a poured-in-place concrete invert is used in the manhole as shown in figure 7-1 and permafrost is at a relatively shallow depth, the concrete will be placed on insulation board to reduce the downward heat losses. Spacing of manholes will be in accordance with TM 5-814-1/AFM 88-11, Vol.1. Solid manhole covers will be required to prevent entry of surface water.



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Figure 7-1. Typical sewer system manhole.

b. *Cleanouts.* Cleanouts are typically used in building connections and in some cases are installed in place of manholes as described in TM 5-814-1/AFM 88-11, Vol.1. They must be used with caution in cold regions since they are difficult to protect and are susceptible to frost heaving. Figure 7-2 illustrates details of a cleanout that has been successfully used in Canada.



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Figure 7-2. Typical cleanout.

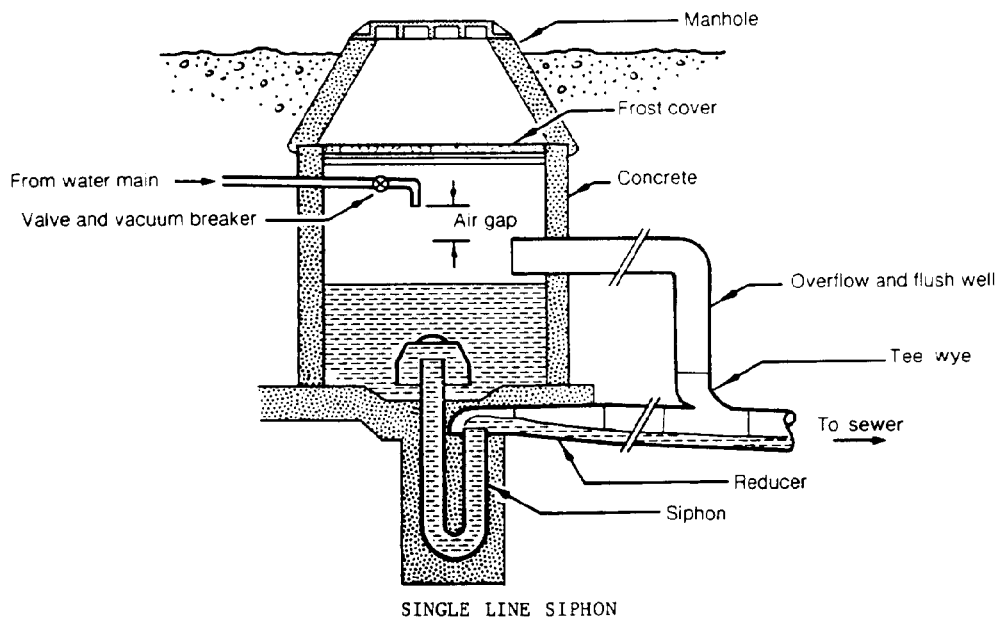
c. *Siphons.* Sewers subject to low flows and velocities must be avoided if possible in the system design since a trickle flow may result in gradual freezing and ice build-up in the pipe. If such sewers are necessary, then a pump station or a flushing siphon must be included. These must be designed to discharge a slug of relatively warm water into the system. If there is insufficient wastewater available to operate the siphon frequently enough to avoid freezing, it may be necessary to add water as shown in figure 7-3, with proper precautions taken to prohibit cross connections.

d. *Building connections.* Figures 7-4 and 7-5, for buildings on pile or post foundations, show typical connections for a gravity sewerage system in cold regions. The wall penetration shown in figure 7-4 is more flexible than the floor penetration in figure 7-5, and will permit more differential settlement without damage to the sewer line.

7-4. Pump stations.

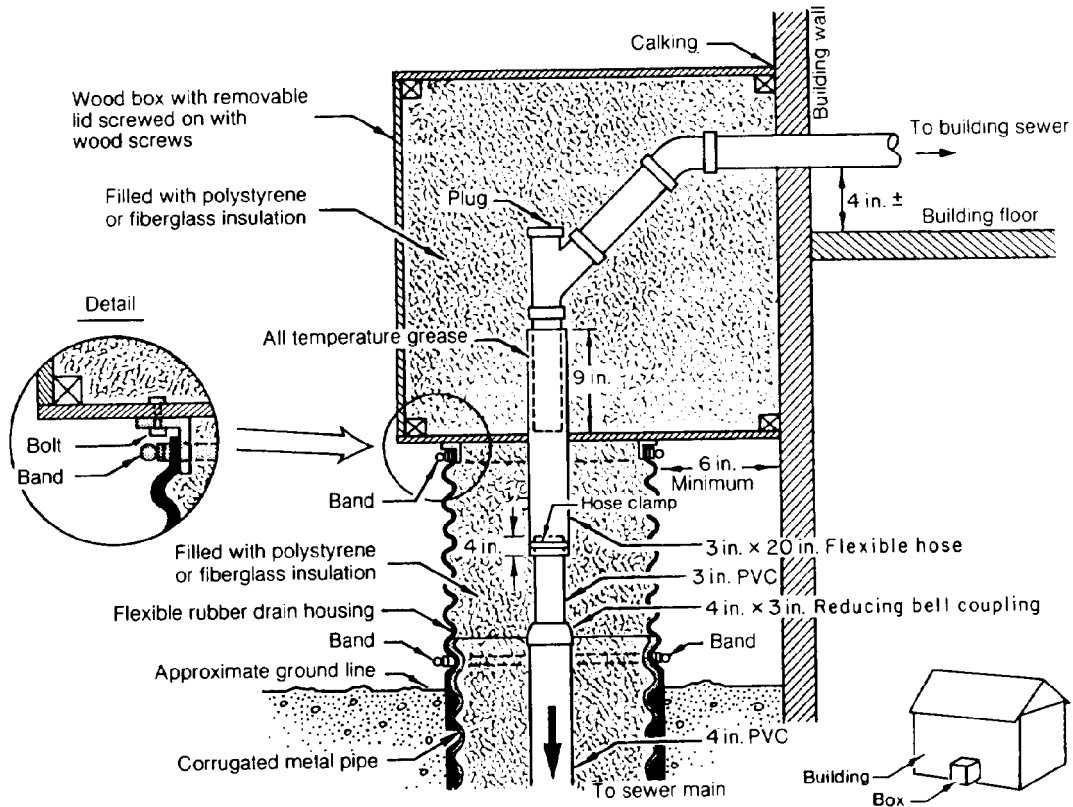
The basic hydraulic design of pumping stations will be in accordance with TM 5-814-2/AFM 88-11, Vol. 2. Special requirements and concerns for use in cold regions are discussed below.

a. *Insulation.* The outside of the station structure will be insulated with at least 3 inches of urethane or polystyrene, with an outer covering to protect the



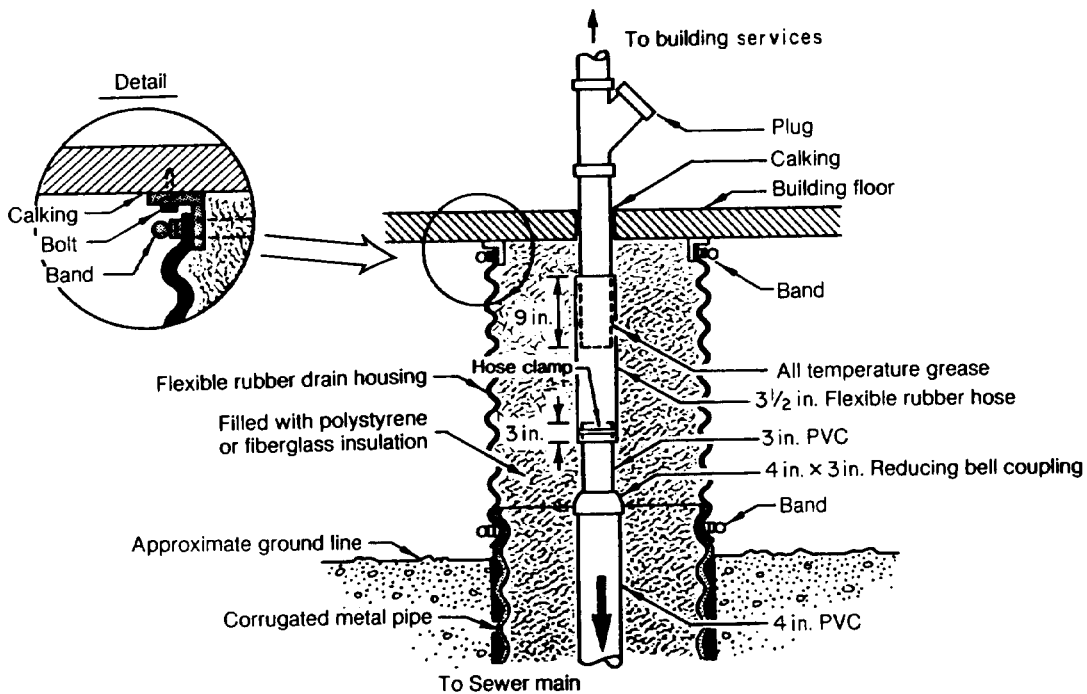
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Figure 7-3. Typical siphon.



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Figure 7-4. Typical service connection (wall).



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Figure 7-5. Typical service connection (floor).

insulation from moisture. Insulation will also be placed beneath the station when permafrost is present at a shallow depth to prevent settling due to ground thaw. A plastic film or some other bond breaker will be required to reduce frost jacking in the active layer (see further discussion, para 11-3). If thawing and settling under the station are anticipated, pile foundations extending well into the permafrost will be required. All stations must be attached to concrete base slabs to provide sufficient weight to overcome the buoyancy of the station. Pressure couplings or flexible connections are required for the inlet and outlet pipes to prevent station differential movement from breaking the lines.

b. Condensation. A prefabricated, below-grade pumping station must not be installed without immediately placing the heater and dehumidifier into operation. Condensation caused by the surrounding cold earth could corrode the controls and electrical equipment before the system is actually put into service.

c. Alarms. Alarms must be provided in accordance with the requirements of TM 5-814-2/AFM 88-11, Vol. 2. All critical components, such as pumps and compressors, must be duplicated in each station. In addition, alarms must be set to warn of freezing temperatures in the station and to warn of sump pump malfunctions. Alarms must be annunciated as described in TM 5-814-2/AFM 88-11, Vol.2.

d. Standby power. Due to the dangers of freezing associated with extremely low temperatures, standby power facilities must be provided for each major pump station.

e. Maintenance. During freezing conditions, each pump station must be checked daily by the operator. All entrance manholes must extend sufficiently above the ground surface to be above any flooding or snow drifts. All pump stations will be supplied with devices for measuring flow rates. Corrosion protection must be provided in accordance with TM 5-814-2/AFM 88-11, Vol.2. Sacrificial anode type systems do not work well when the ground surrounding the anode or pump station is frozen.

f. Force mains. Force mains will be designed to have scour velocities during pumping (2.5 to 3.5 feet per second) and to drain between pumping

cycles. This can be accomplished by an electrically operated ball valve in the line to allow drainage back into the wet well between pump cycles. If this is not possible the line must be placed in a heated utilidor or heat traced. Another option would be to time the pumping cycle so that wastes stay in the line for a calculated period, and to size the wet well at the pump station to hold at least the volume of the force main.

7.5 Pressure sewerage.

The main advantage of pressure sewers is that specific grades need not be maintained throughout the system. Typically grinder pump units are used so that smaller diameter pipes can be installed without the risk of clogging. Grinder pumps may be installed in each building or in a holding tank serving several buildings. An alternative to grinder pumps is to install a two-compartment septic tank with a conventional submersible pump in the second compartment. The hydraulic design of these pressure systems is not unique in the cold regions and criteria found in TM 5-814-2/AFM 88-11, Vol. 2, will be used. The pressure piping must be designed to drain by gravity to a low point or sump in case the system has to be shut down in the winter. The grinder pump units, holding tanks and septic tanks must have a firm foundation and must be protected from frost heaving as discussed previously for manholes (para. 7-3a). Water conservation measures in each of the buildings served is required to reduce the costs of equipment and energy for pumping.

7-6. Vacuum sewerage.

Vacuum sewers do not depend on a specific grade for successful operation. They operate at a vacuum of 8-10 psi, and so are limited to an elevation difference of 15 to 20 feet within the system. The hydraulic design is not unique to the cold regions. The concept depends on providing traps in the system to maintain a vacuum. Since these traps are full of water for extended periods, they must be insulated and/or heated for extreme low temperature conditions. The traps should also be drainable under emergency situations. A 50 house vacuum system in Noorvik, Alaska, was installed in 1977 and has operated successfully, since that time.

CHAPTER 8

UTILIDORS

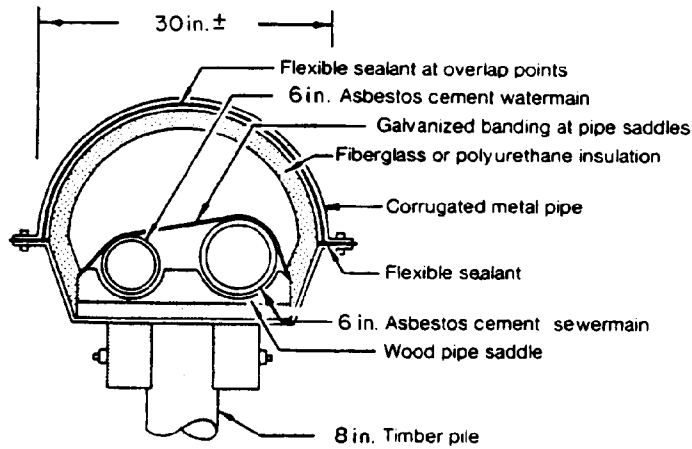
8-1. General.

A utilidor is a conduit that contains multiple utility systems such as water, sewerage, fuel oil, gas, electrical power, telephone, and central heating in various combinations or in some cases all together. They have been used at a number of military installations and civilian communities in the North American Arctic. Utilidors are very expensive and can only be justified for special situations. In most cases individually insulated pipes in a common trench or on a common pile will be more economical. Utilidors have been constructed above and below ground, and range in size from a simple insulated conduit to a walk-through passageway. Figures 8-1 and 8-2 illustrate typical utilidor configurations that have been constructed recently in the cold regions. These new designs typically incorporate lighter construction materials than the reinforced concrete used previously at many military installations.

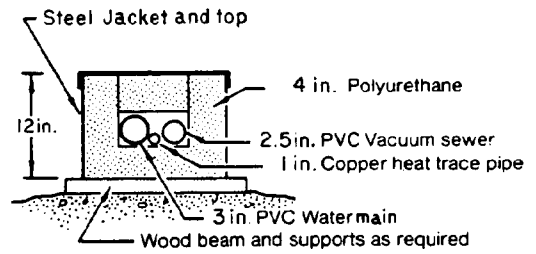
8-2. Design considerations.

The thermal design of the utilidor is made in accordance with the procedures in chapter 12. The foundation design must be in accordance with TM 5-852-4/AFM 88-19, Chap. 4. Both designs are influenced by the types of utilities that are included. The inclusion of power, telephone, and gas lines along with water and sewerage in a utilidor will not cause design or operational problems. However, the inclusion of central heating lines is more complex. Their heat losses are usually great enough to protect the water and sewage pipes from freezing but the utilidor usually has to be much bigger to provide continuous easy access to steam and condensate lines, and therefore construction costs will increase. Problems also occur because this heat source is constant and must operate all or most of the year. In the summer, undesirably high domestic water supply

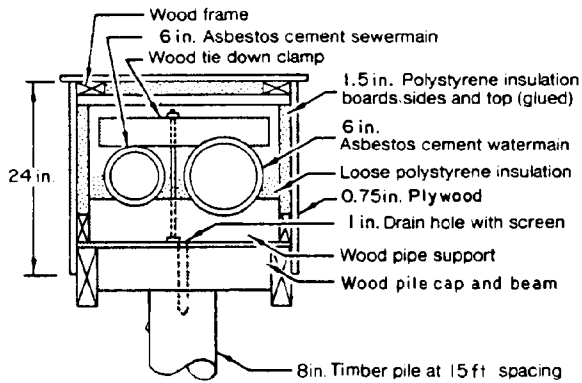
temperatures can result due to exposure to the excess heat (<80°F). The heating of a large air space in the utilidor is less efficient than direct heating and circulation of the water supply in the winter. Thermal stratification can cause freezing of the lower pipes in large utilidors even when the average air temperature is adequate. Figure 8-3 illustrates the temperature variation within a small utilidor. The cold water line was placed on one side to maintain desirable temperatures for the consumers and the hot water lines on the other side. Under extreme conditions this cold water line froze and burst due to the thermal shielding, in spite of the continuous circulation of hot water. When transport methods permit prefabrication of the major utilidor components is recommended to reduce construction costs in the field. The heat sources for freeze protection should be located near the bottom of large utilidors if possible to ensure distribution of heat. Sensitive piping (e.g. water) should not then be shielded from these heat sources. If the heat sources (i.e. steam and condensate lines) are operational all year, separate insulation of domestic water lines is recommended to maintain acceptable cold water temperatures for domestic use. The utilidors shown in Figure 8-1 all have prefabricated components. All of these units can be entirely prefabricated in a convenient unit length. A hydrant unit on an above-ground utilidor of the type in figure 8-2b is shown in figure 8-4. When both water and sewage lines are exposed in the same utilidor, the sewer access cleanouts must be sealed to prevent cross connections. Flanged elbows or pipes larger than 8 inches in diameter are large enough to insert cleaning or thawing equipment. Standard fittings or smaller pipes do not provide adequate access in both directions. Figures 8-5 illustrates details of sewer cleanouts that have been used for this purpose.



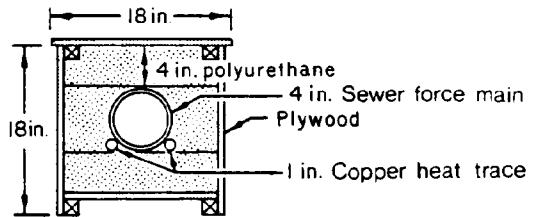
Utilidor, Inuvik, N.W.T.



Utilidor with vacuum sewer, Noorvik, Alaska



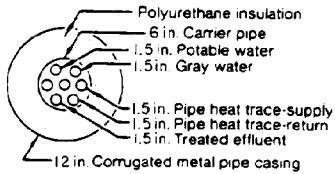
Plywood box utilidor, Inuvik, N.W.T.



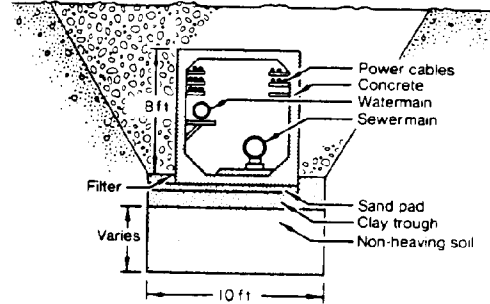
Single pipe with heat tracing, Noorvik, Alaska

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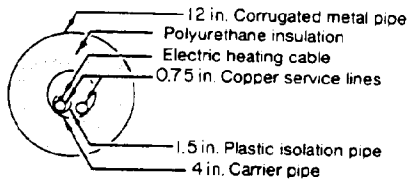
Figure 8-1. Various utilidors installed in cold regions.



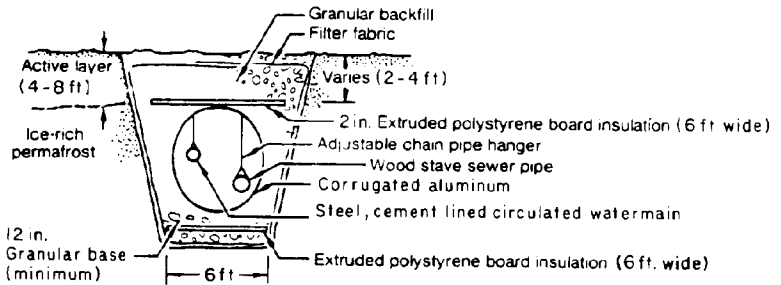
Utilidor with many small pipes, Wainwright, Alaska



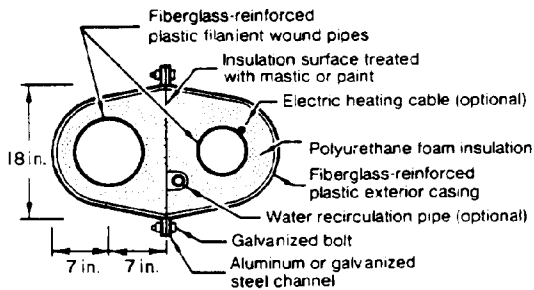
Buried accessible utilidor, Mirryl, U.S.S.R.



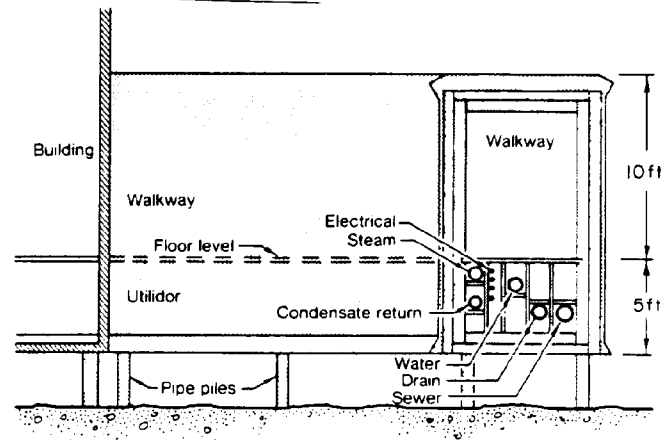
Service connection



Buried accessible utilidor, Nome, Alaska



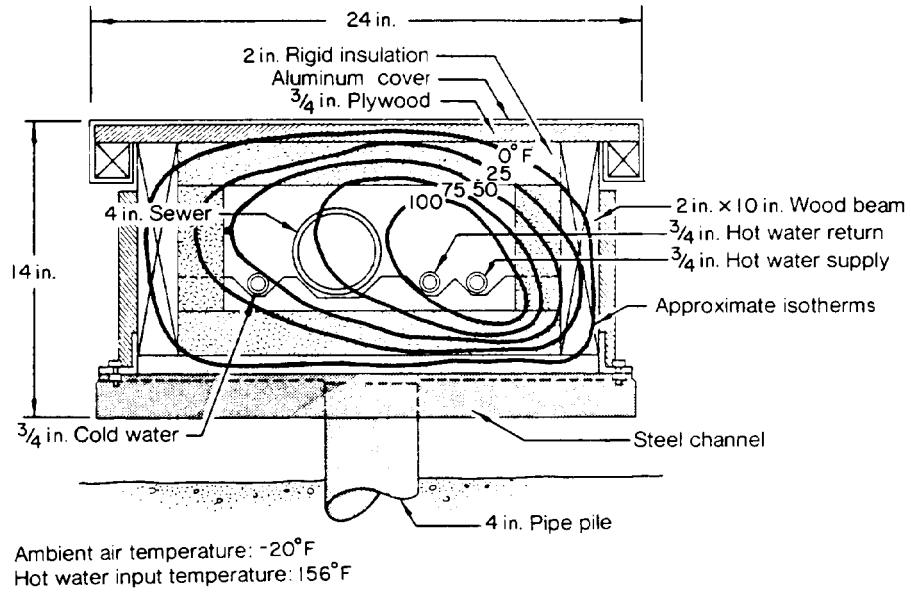
Prefabricated utilidor



Walkway utilidor, Cape Lisburne, Alaska

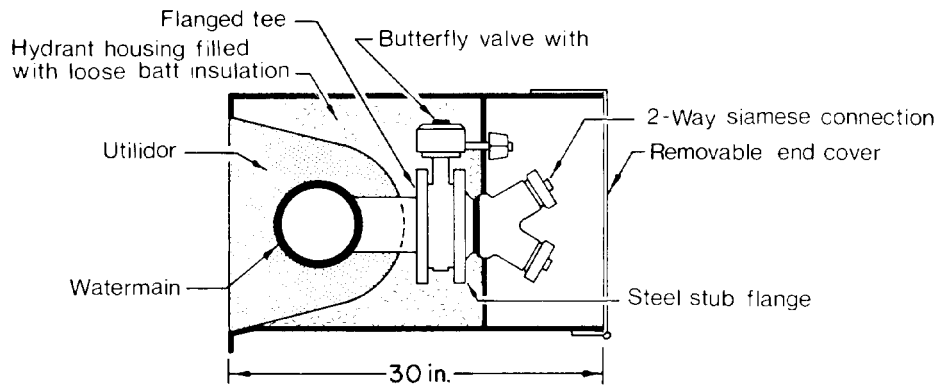
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Figure 8-2. Typical utilidors.



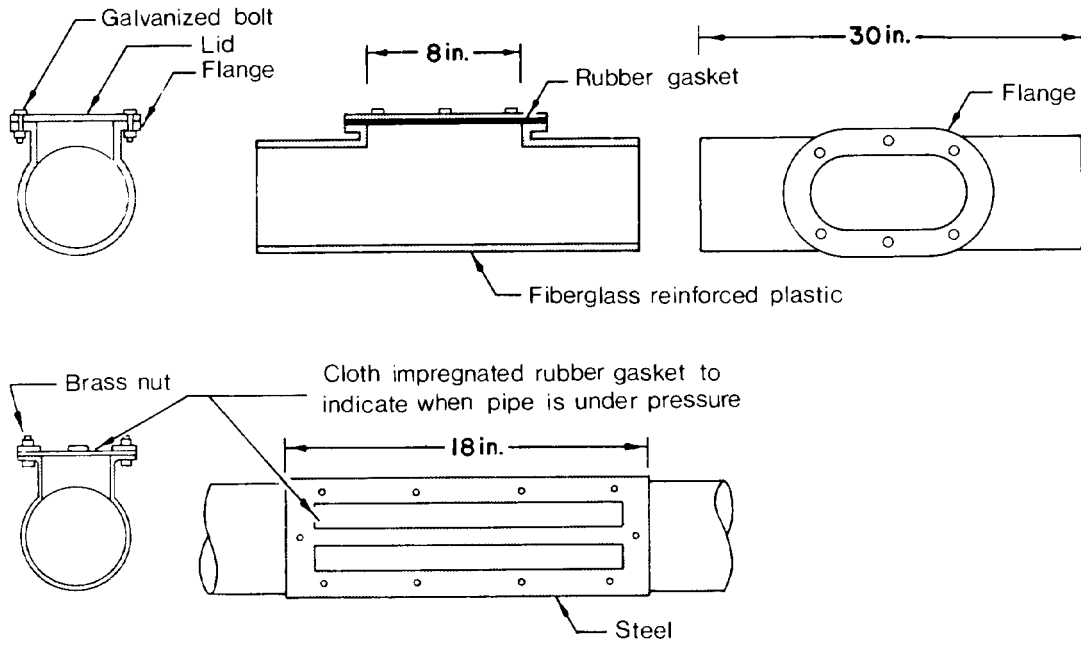
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Figure 8-3. Temperature variation in a small utilidor with central hot water distribution.



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Figure 8-4. Above-ground utilidor hydrant.



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Figure 8-5. Sewer cleanouts.

CHAPTER 9

WASTEWATER TREATMENT

9-1. General.

Basic design criteria for domestic wastewater treatment systems can be found in TM 5-814-3/AFM 88-11, Volume 3. This chapter provides information and guidance on those aspects unique to cold regions and presents general design criteria for those treatment systems most commonly used in the Arctic and Subarctic.

9-2. Wastewater characteristics.

Wastewater characteristics in the cold regions will generally be different from those in temperate regions, with respect to quantity, quality, and temperature. The total quantity of wastewater discharged at military installations in cold regions tends to be very close to the quantity supplied for potable water use since there is little external or industrial use, storm water is usually excluded, and groundwater infiltration is not a factor in the newer insulated and tightly sealed pipe systems. As a result wastewater in the Arctic and Subarctic tends to be more domestic in nature and higher in strength than at comparable facilities elsewhere.

a. Quantity. The determination of design flows should be based on a special analysis of the installation. The population equivalents and capacity factors presented in TM 5-814-3/AFM 88-11, Vol.3 will tend to overestimate the volume of flow to be expected at remote installations in the Arctic and Subarctic with small populations. This may result in operational problems with some biological treatment units. Selection of less sensitive processes or use of two smaller units in parallel will avoid the problem if the design cannot be based on actual flows.

b. Quality. The mass of pollutants in cold region wastewaters is comparable to that in other locations but the concentration will generally be higher because of lower water usage rates. For example, TM 5-814-3/AFM 88-11, Vol.3 allows a biochemical oxygen demand (BOD) loading of 0.2 pound per capita per day. At flow rates of 100 gallons per capita per day, that results in a BOD concentration of about 240 milligrams per liter (mg/L). At remote installations in the cold regions the BOD concentration will normally be over 300 mg/L for domestic wastewater, at the typical flow

rates ranging from 60 to 80 gallons per capita per day.

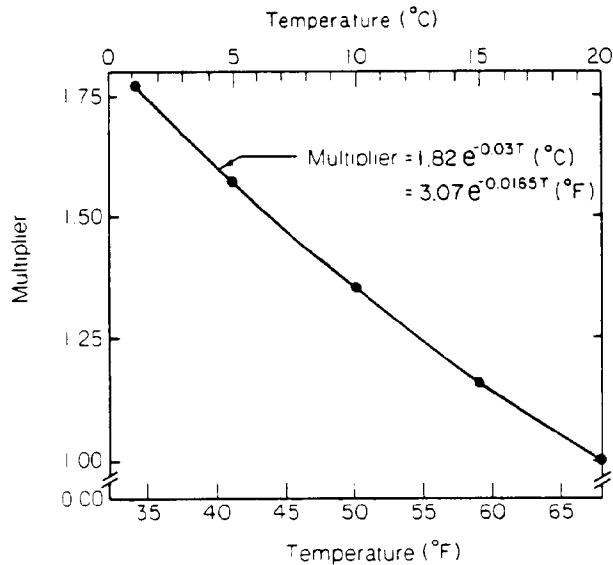
c. Temperature. The wastewater temperature at many cold region facilities tends to be at least 50 degrees F due to transmission in insulated and sometimes heated lines. The heat available in this incoming wastewater should be considered during process design.

d. Flow variations. The diurnal flow pattern at military installations tends to be the same regardless of climate and TM 5-814-3/AFM 88-11, Vol.3 must be used to determine peak and minimum flow ratios for design purposes.

9-3. Unit operations.

Practically all of the basic unit operations used in waste water treatment are affected by temperature through liquid viscosity changes or changes in chemical reaction rates. An analysis during the early stages of design is required to predict the thermal status of major components in the treatment system. If wastewater temperatures above 50 degrees F are expected and the entire system is to be housed in a heated building, then conventional practice as defined in the TM 5-814-3/AFM 88-11, Vol. 3 will be used. If temperatures below 50 degrees F are expected, or significant temperature changes are allowed to occur within the system, then adjustments will be necessary in the design of the unit operations. Figure 9-1 will be used to make the necessary adjustments in design to compensate for viscosity effects. The power requirements for mixing, the detention time or size of grit chambers and primary clarifiers and the efficiency of gravity filters will all be adjusted using figure 9-1 where low temperature liquid is expected. For example, a detention time of 2 hours is typically specified for primary clarifiers. If wastewater at 35 degrees F is expected, then the detention time will be increased as follows:

$$\begin{aligned} \text{Multiplier} &= (3.07) e^{-0.0165T} \text{ (from figure 9-1)} \\ \text{At } 35^{\circ}\text{F} &= (3.07) e^{-0.0165(35)} \\ \text{Adjusted time} &= (2 \text{ hr})(1.723) \\ &= 3.45 \text{ hr.} \end{aligned}$$



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Figure 9-1. Viscosity effects vs. temperature.

a. *Gas transfer.* The solubility of oxygen and other gases in water increases as the liquid temperature decreases. However, the viscosity of the liquid also increases so that the opportunity for contact between gas bubbles and liquid molecules is decreased. The net practical effect is little improvement in overall gas transfer in cold wastewater without additional mixing.

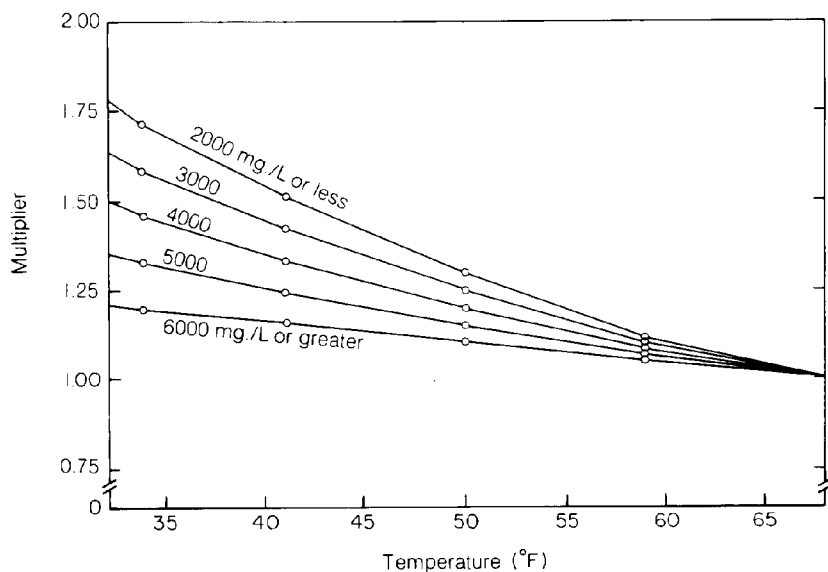
b. *Adsorption and chemical reactions.* Adsorption is not affected by low temperatures, with the

range of values experienced in wastewater treatment. Most chemical reaction rates are slower at low temperatures. This can affect treatment and must be considered in preparing chemical solutions for use in wastewater treatment. The solubility of some common treatment chemicals is given in table 9-1.

Table 9-1. Solubility of common treatment chemicals

	Pounds per gallon at	
	32°F	60°F
Alum	6.0	7.3
Ferrous sulfate	0.5	2.0
Sodium hydroxide	2.4	4.4
Calcium hypochlorite	1.8	1.9

c. *Flocculent sedimentation.* Secondary clarifiers and sludge thickeners generally receive relatively high concentrations of solids and are not dependent on temperature as predicted by Stoke's law. The multipliers shown in figure 9-2 will be used to adjust the size or detention time of these units, depending on the design solids concentration. At solids concentrations of 2000 mg/L or less, and for primary clarification, temperature effects are close to that predicted by figure 9-1, but as the solids concentration increases, the influence of temperature decreases and figure 9-2 will be used. Density currents can completely disrupt the operation of settling tanks and thickeners, so protective ele-



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Figure 9-2. Settling detention time vs. temperature.

ments will be required in cold regions to maintain the temperature of tank contents as closely as possible to that of the incoming liquid.

9-4. Unit processes.

These include preliminary treatment, primary treatment and a variety of biological or chemical processes for secondary treatment. All are subject to temperature influences on their performance.

a. Preliminary treatment. This commonly includes screening, grit and scum removal and grinding or comminution. Conventional equipment can be used and basic design criteria will be in accordance with TM 5-814-3/AFM 88-11, Vol.3; adjustment in grit chamber detention time will be as described in paragraph 9-3 above. Protective, insulated shelters will be constructed over trash racks, bar screens, and grit chambers to avoid icing problems in the winter. Where structures are unheated, condensation and icing may occur on the inner surfaces of exterior walls. In these instances, materials and coatings will be selected accordingly and controls will be located on dry interior walls, or in another remote location.

b. Primary treatment. The design detention time of primary clarifiers will be adjusted, as described in paragraph 9-3 above. In general the tanks will be designed in the conventional manner as buried or partially buried structures. However, the presence of shallow permafrost, particularly ice-rich, fine-textured soils, will require above-ground tanks or special foundations (see TM 5-852-4/AFM 88-19, Chap. 4). Temporary covers for heat retention purposes are recommended for winter operation of buried and exposed tanks in the Arctic and Subarctic. Tanks above grade will also require sidewall insulation or enclosure in a protective structure. Construction details are similar to the procedures described for water tanks in chapter 5.

c. Biological processes. Biological systems for secondary treatment that have been successfully used in cold climates include lagoons or ponds, both facultative and aerated, several activated sludge variations, and attached growth systems. Each has special requirements for successful cold regions performance.

(1) *Facultative lagoons.* Where sufficient land area and suitable soil conditions exist, facultative lagoons are the most economical alternative in the cold regions because of their low construction cost and simplicity of operation. Treatment performance during winter is greatly reduced by low temperatures and by ice and snow cover, with re-

moval rates roughly comparable to those of primary treatment alone. Total retention of wastewater during winter months will be required with controlled discharge commencing in late spring and in early fall. This is a common practice in Canada and the north-central United States. Three or more cells will be used to avoid short circuiting. Each cell will be isolated briefly and then discharged in turn during the specified period. Rectangular cells with a minimum 3:1 length to width ratio are recommended to further reduce short circuiting. For a three-cell system, approximately one half of the total volume needed will be provided in the primary cell, with the remainder equally divided among the other cells (a four-cell system will have two-fifths the volume in the first cell). The design BOD₅ loading over on the total area will be 20 pounds per acre per day maximum. The design volume for controlled discharge ponds will be fixed by the time interval between discharges, and not by the minimum detention for BOD₅ reduction. The BOD₅ loading on the first cell in controlled discharge systems will not exceed 50 pounds/acre/day to avoid odor problems.

(a) Design depth. The design depth will be based on winter conditions and will allow a free-board of 1 foot plus the ice thickness, plus 5 feet from the underside of the ice to the lagoon bottom. Adjustable weirs will be provided at the outlet so that the water level can be raised to provide the necessary depth at the start of winter, and then lowered to the normal operating depth in the summer. Ice thickness will be best determined from actual records or from observations made at small ponds or lakes in the area. An approximation of the maximum ice cover that can occur will be calculated with the following equation, applicable only to unaerated ponds:

$$d = m(I_A)^{1/2} \quad (\text{eq 9-1})$$

where

- d = maximum ice depth, inches
- m = coefficient depending on site conditions
 - = 0.8 for windy site, no snow cover on ice
 - = 0.68 for moderate snow cover (see table 12-4 for other conditions), in (°F•d)^{-1/2}
- I/A = the annual air freezing index, in degree days, °F•d). See TM 5-852-1/AFR 88-19, Vol. 1 for procedure to determine the air freezing index and for typical values.

For example, if Fairbanks, Alaska, has a mean air freezing index of 5500°F•d, and a moderate snow cover on the lagoon is assumed, then the

$$\begin{aligned} \text{maximum depth of ice} &= 0.68 \sqrt{5500} \\ &= 50.4 \text{ inches.} \end{aligned}$$

See section 12, paragraphs 9a and b for additional detail on ice formation.

(b) *Special construction features.* Standard construction techniques can be used except where permafrost is present. Fine textured, ice-rich permafrost must be avoided if possible, since thawing will result in failure, or at least require frequent repair of dikes and berms. Lagoons may be installed in permafrost that is physically stable after thawing. Construction techniques for dikes and berms, and the use of lining materials are essentially the same as those described in chapter 5. Synthetic rubber has been most commonly used for lagoon liners at military installations in Alaska (see EPA report MCD 54 for additional information). Details of inter-basin transfer structures and outlet works are shown in figure 9-3. The use of the stop-log

manhole concept as shown in this figure will permit easy control of depth in the lagoon cells and is an alternative to adjustable weirs.

(2) *Aerated lagoons.* Partially mixed aerated lagoons, also called facultative-aerated ponds, have been used successfully in cold regions. They require less land area, but more energy and more operational attention than facultative lagoons. Basic process design criteria are similar to those of temperate regions. The design is based on:

$$\frac{S_e}{S_o} = \frac{1}{1 + kt} \quad (\text{eq 9-2})$$

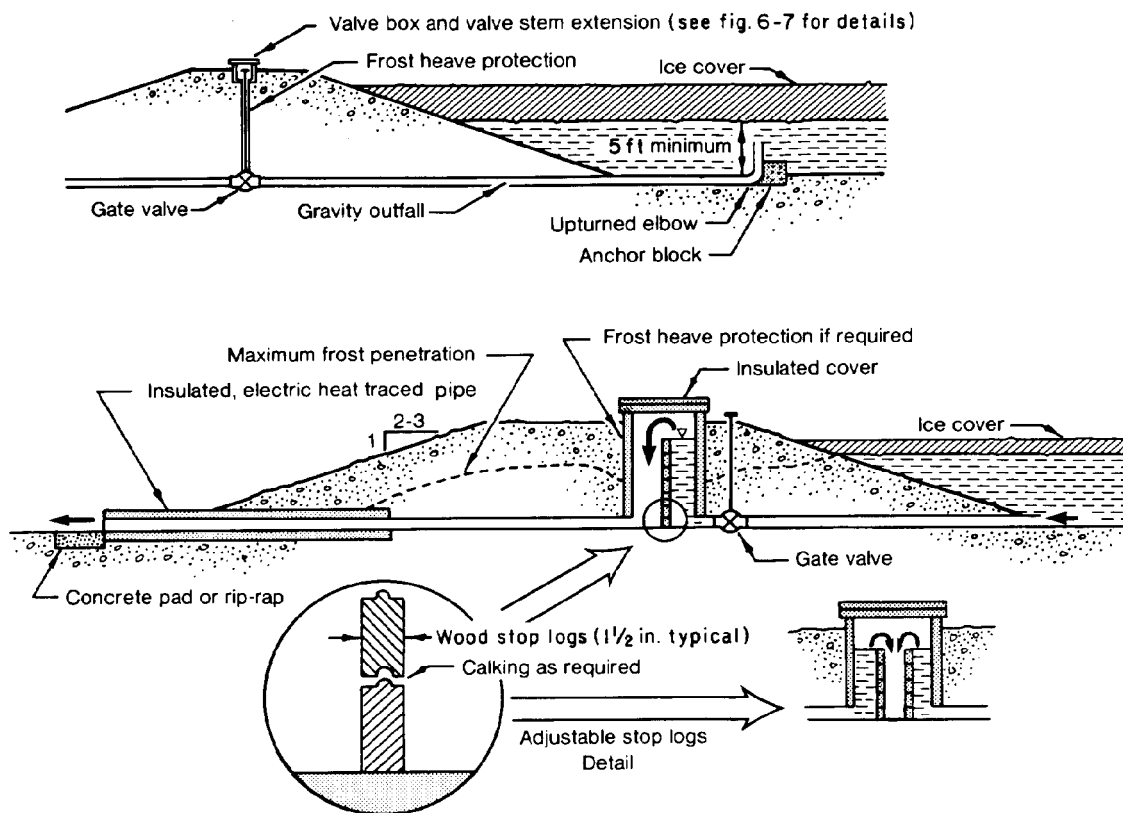
where

S_e = effluent BOD₅, mg/L

S_o = influent BOD₅, mg/L

t = total detention time, days
= V/Q

V = Total volume of lagoon,
millions of gallons (mg) or ft³



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Figure 9-3. Lagoon construction details.

- Q = average daily flow, millions of gallons per day (mgd)
- k = overall reaction coefficient (base e), days⁻¹ as used in Alaska and northwest Canada:
 typical winter value = 0.14 (≈ 33°F)
 typical summer value = 0.28 (60°F-70°F)
 One can also use: $k_T = k_{20}(\theta)^{(T-20)}$
 with $k_{20} = 0.28$, $\theta = 1.036$, see table 9-3.

For several cells in series, the equation becomes

$$\frac{S_e}{S_o} = \frac{1}{[1 + \frac{kt}{N}]^N} \quad (\text{eq 9-2})$$

where N = number of cells (other terms are defined above). This equation can be solved to determine the optimum number of cells in the system. In general, winter conditions will determine the number and size of cells and summer conditions will control the design of the aeration equipment. For example, assume the following conditions:

- influent BOD = 240 mg/L
- effluent BOD₅ = 30 mg/L
- k_{winter} = 0.14.

Then determine the optimum number of cells using equation 9-3. For one cell:

$$t = \frac{1}{0.14} \left[\left(\frac{240}{30} \right)^{\frac{1}{N}} - 1 \right] = 50 \text{ days}$$

and other combinations are shown in the following table.

Number of cells	Total detention time
N	t, days
1	50
2	26
3	21
4	19
5	18

There is no further significant decrease in total detention time after three cells, so the design should be based on three. The first cell in a three-cell unit should contain about half of the design volume.

(a) *Design depth.* The effective lagoon depth must allow for ice cover in the winter and sludge accumulation on a year-round basis. Ice will not form continuously over the surface of aerated lagoons. Even under extreme winter conditions

(-50°F) there will be small areas of open water where air will bubble to the surface from a submerged aeration system. Aerated lagoons in central Alaska (freezing index >5000°F days) have been successfully designed assuming a 12-inch ice cover. A single-cell lagoon near Anchorage, Alaska (freezing index 2500°F days), receiving warm sewage has an ice cover of less than 3 inches in the winter. If specific values are not available from similar lagoons in a similar climate, an assumed value of 15 percent of the total for design depth is recommended for ice cover allowance in arctic and subarctic regions. About 5 percent will be allowed for sludge accumulation on the bottom. The depth required for treatment in the winter is in addition to both of these factors.

(b) *Aeration design.* A submerged aeration system is required for year-round operation in arctic and subarctic regions since icing problems can interfere with performance of surface aerators. The aeration design for these partial mix lagoons is based on supplying the required oxygen, not on keeping all of the solids in suspension. As a result, there will be settlement of sludge on the bottom of the lagoon, and some algae growth in the liquid portion. Summer conditions control aeration design since biological reaction rates are the highest and the amounts of oxygen that can be dissolved are the lowest. The oxygen required for partial-mix lagoons will be set at double the organic loading:

$$O_2 = 2(\text{BOD})(Q)(8.34) \quad (\text{eq 9-4})$$

where

- O₂ = oxygen required, lb/day
- BOD = influent BOD₅, mg/L
- Q = design flow, mgd.

Under standard conditions, air contains about 0.0175 pounds per cubic foot (pcf) oxygen (specific weight of air at standard temperature and pressure is 0.0750 pcf, with 23.2 percent oxygen), so the air required in cubic feet per minute (cfm) is

$$\begin{aligned} \text{Air required (cfm)} &= \frac{2(\text{BOD})(Q)(8.34)(60)}{(E)(0.0175)(86,400 \text{ sec/day})} \\ &= \frac{(0.662)(\text{BOD})(Q)}{E} \end{aligned} \quad (9-5)$$

where E = efficiency.

The aeration efficiency depends on the depth of water, type of diffuser, mixing turbulence and basin configuration. For example, a typical efficiency (E) of submerged tubing is 16 percent. Therefore, for a design flow of 1 MGD and a BOD₅ of 240 mg/L, the air requirements would be

$$\begin{aligned} \text{Air required} &= \frac{(0.662)(240)(1)}{(0.16)} \\ &= 993 \text{ cfm.} \end{aligned}$$

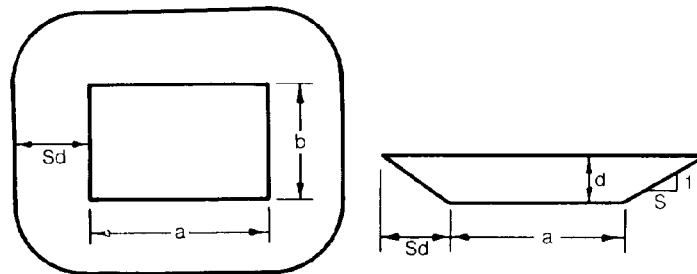
(c) *Aeration system operation.* Aeration systems that have been successfully used in cold region lagoons include perforated tubing, tubing with diffuser inserts, air guns, and helical diffusers, all available from a number of commercial sources. Table 9-2 summarizes the characteristics of these devices. The values in the table along with equation 9-4 will be used for a preliminary estimate of the number of devices and length of tubing that will be required for a particular system. Manufacturers' literature is then consulted for the final design of a specific system. About 65 percent of the aeration capacity will be located in the first cell of the lagoon system. Submerged tubing and, to a lesser degree, air gun systems are susceptible to clogging due to precipitation of carbonate and bicarbonate salts around the air outlets. The potential severity of the problem increases with the hardness of the sewage. A number of tubing systems in Alaska have been replaced because of this problem. The problem is overcome by including a gas cleaning system using anhydrous hydrogen chloride gas. The acid produced at the air outlets dissolves the incrustations.

(d) *Configuration and construction.* The prevention of short circuiting and minimization of heat losses must both be considered in design. The optimum configuration for minimal heat loss would be a circular basin with vertical side walls, but construction costs would be prohibitive. A square basin with sloping sidewalls would be slightly more efficient thermally than a rectangular basin of the same volume, but would be prone to greater short circuiting. In general, hydraulics will control design and long rectangular cells (length to width ratio greater than 3:1) will be used to reduce short circuiting. A maximum slope of 1 on 3 is required for interior sidewalls. Figure 9-4 will be used to calculate dimensions of the cells. Inlet and outlet structures, and other construction details, are the same as those described in paragraph 9-4 (1)(6) for facultative lagoons. The general provisions for construction of dikes and lagoon structures will be as required in TM 5-814-3/AFM 88-11, Vol.3.

Table 9-2. Typical aeration equipment.

Equipment	Oxygen Provided* (lb/day)	Common Depth (ft)
Submerged tubing	3-10/100 LF	8-15
Air gun	80-150/unit	12-20
Helical Diffuser	100-400/unit	10-20

*These values can be used to estimate the number of units or linear feet (LF) of tubing required to satisfy the oxygen requirements as defined by equation 9-4. Manufacturers, literature should be consulted for absolute aeration efficiency ratings.



$$\text{Volume} = V = d [(a + Sd) (b + Sd) + .333 S^2 d^2]$$

Note: The last term (.0472 S² d²) can be dropped for preliminary estimates

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Figure 9-4. Dimensions of lagoons.

(3) *Activated sludge systems.* Systems that have been successfully used in cold regions include conventional and pure-oxygen activated sludge, contact stabilization, and extended aeration concepts, both in package plants and in oxidation ditches. Basic design criteria for these processes can be found in TM 5-814-3/AFM 88-11, Vol.3. When the system is enclosed and incoming waste-water temperatures exceed 50 degrees F, basic design criteria will apply. Special measures are necessary only when incoming wastewaters are below 50 degrees F or if a significant temperature drop is expected within the system. All of the biological reaction rates involved are temperature sensitive, and must be adjusted using:

$$k_T = k \theta^{(T - 20)} \quad (9-5)$$

where

- k_T = reaction rate coefficient at temperature T
- k_{20} = reaction rate at 20 degrees C
- T = design wastewater temperature, degrees C
- θ = temperature coefficient.

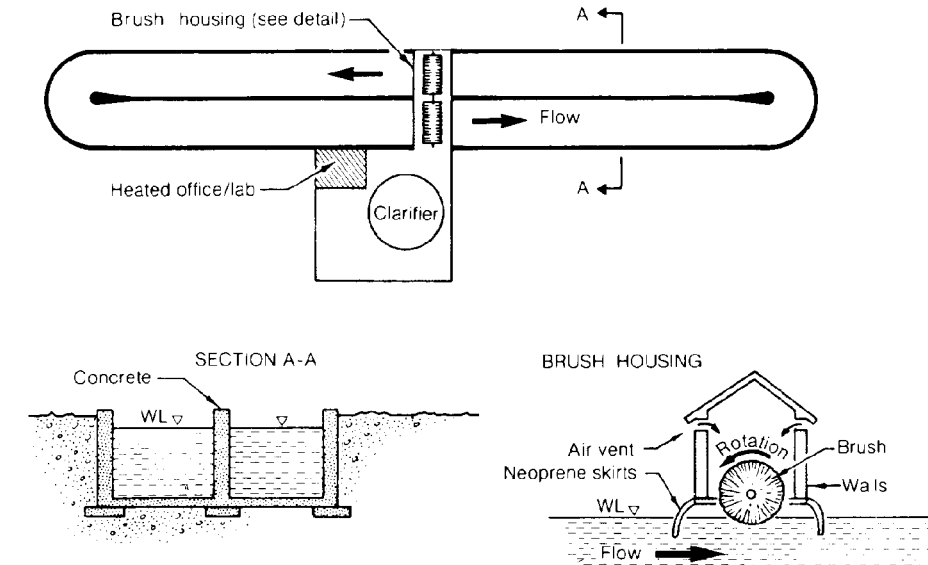
The θ values given in table 9-3 will be used in equation 9-5 to adjust the reaction rate for the design wastewater temperature. The basic reaction rate coefficients are found in TM 5-814-3/AFM 88-11, Vol.3.

Table 9-3. Temperature coefficients for biological treatment.

Process	θ	Temperature Range (°F)
Oxidation pond	1.072-1.085	37-95
Facultative lagoon	1.06 -1.18	39-86
Anaerobic lagoon	1.08 -1.10	41-86
Aerated lagoon	1.026-1.058	36-86
Activated sludge	1.00 -1.041	39-113
Extended aeration	1.037	50-86
Trickling filter (conventional)	1.035	50-95
Biofilter (plastic media)	1.018	
Rotating disc		
Direct filter	1.009	50-86
recirculation		
Final effluent	1.009	55+
recirculation		
Final effluent	1.032	40-55
recirculation		

(a) *Special requirement.* A permanent ice cover must be avoided in the aeration compartments of activated sludge systems. An ice cover will inhibit atmospheric aeration and will entrap solids, both of which reduce treatment efficiency. The design must provide for a minimum of exposed liquid surface area to reduce heat losses. An unheated shelter, a temporary tank cover or a wind break is required during the winter. Clarifiers associated with these systems will require similar protection to avoid freezing and to inhibit density currents. A continuously heated building is not necessary to maintain treatment efficiency. Operator comfort and convenience are the only justifications for such energy inputs. If the incoming sewage is 50 degrees F or warmer there is sufficient heat in the liquid to sustain a protected treatment process. A standby heat source and emergency power are recommended for extended power failures and other emergencies.

(b) *Extended aeration.* Extended aeration units have been successfully operated with liquid temperatures as low as 33 degrees F and have still produced high quality effluent. Design organic loadings (food/microorganism ratio) of up to 0.08 lb BOD (biochemical oxygen demand)/lb MLSS/day, and mixed liquor suspended solids (MLSS) concentrations of 3000-40000 mg/L are recommended for low temperature operation. Small packaged treatment units must be covered and must be protected from the wind. Pumps, motors, blowers, external pipes, valves and similar appurtenances will require heat as well as a protective shelter. These systems must not be oversized or overdesigned with respect to hydraulic capacity, because low organic loadings usually result in poor performance. Dual units are required for low, intermittent flows at remote installations. Only one unit is operated during low flow periods. This unit is operated with a MLSS concentration. Sludge is then transferred to the second unit during peak flow periods allowing an immediate start-up. Figure 9-5 illustrates the special features of an oxidation ditch in the Subarctic. The aeration basin has vertical sidewalls and a vertical central divider. This reduces exposed surface area and heat losses by about 32% as compared to the conventional ditch with sloping sidewalls and center island. The only heated space in this treatment system is the office/laboratory clarifier equipment and aeration brushes are housed in simple concrete block construction. Condensation and ice forms on the interior surfaces of exterior walls. Thus switches, control panels, etc., must be located on dry interior walls. These features are not unique to oxidation ditches and can usually be incorporated into other systems as well.



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Figure 9-5. Oxidation ditch for the Subarctic.

(4) *Attached growth systems.* These include trickling filters, rotating biological discs, and other devices with plastic, rock or wooden media. Effective treatment depends on maintaining a thin film of liquid over the media. These units are susceptible to freezing and must therefore be enclosed in a protective structure. Criteria from TM 5-814-3/AFM 88-11, Vol.3, will be used for design, along with the temperature coefficients given in table 9-3. The need for additional heat in the protective structure will depend on the temperature of incoming waste-water and on the degree of treatment required.

9-5. Sludge management.

Large-scale, conventional treatment facilities and those operating in a heated environment can be expected to produce sludge at rates similar to those of conventional temperate zone practice. Typical values for systems in use in the cold regions are presented in table 9-4. Thickening, digestion, and dewatering of sludge all follow temperate zone practice as defined in TM 5-814-3/AFM 88-11, Vol.3.

a. *Freeze-thaw dewatering.* Sludges from water or waste water treatment operations can be flooded onto conventional open sand drying beds in layers and allowed to freeze. The depth of sludge that can be frozen (or thawed) is calculated with:

$$X = m_s (I_A)^{1/2} \quad \text{(eq 9-6)}$$

where:

X = depth of sludge that can be frozen, inches

m_s = proportionality coefficient for sludge, use 0.6 for sludge concentrations in range 0-7 percent solids (higher concentrations are difficult to spread on bed), in $(^\circ\text{F}\cdot\text{d})^{-1/2}$

I_A = Air freezing (or thawing) index, $^\circ\text{F}\cdot\text{d}$ (use warmest winter of record for freezing calculations)

(1) Sludges with an undrainable jelly-like consistency will dewater immediately upon thawing and then have a granular consistency.

Table 9-4. Typical sludge production rates^a.

Process	Dry solids lb/person/day	Solids content of wet sludge (%)
Primary settling	0.12	6
Trickling filter (TF)	0.04	4
Secondary		
Primary plus TF	0.16	5
Secondary		
Conventional activated sludge (AS), secondary clarifier	0.07	0.5-1
Primary plus conventional AS secondary	0.19	2-3
Extended aeration	0.09	2
Lagoons	0.13	20 ^b

a Average, 24-hr values, from temperate climate experience.

b High value due to long-term consolidation of sludge on lagoon bottom. Data from partial-mix aerated lagoons in Alaska.

(2) Solids concentrations of 20-25 percent immediately after thawing are typical and after a few more weeks of drying will approach 50 percent. The total depth of sludge that can be frozen is related to the depth of frost penetration that will occur in a particular location. Repeated applications in thin layers is recommended to ensure that each layer freezes completely. The following equation can be used to estimate the potential total depth of sludge that could be frozen (applied in 3-inch layers) if the maximum depth of frost penetration for a site is known:

$$\Sigma X = 1.76 (f_p) - 40 \quad (\text{eq 9-7})$$

where:

ΣX = total depth of sludge that could be frozen in 3 inch layers, in.

F_p = maximum depth of frost penetration for area (see TM-5-852-1/AFR 88-19, Vol. 1), in.

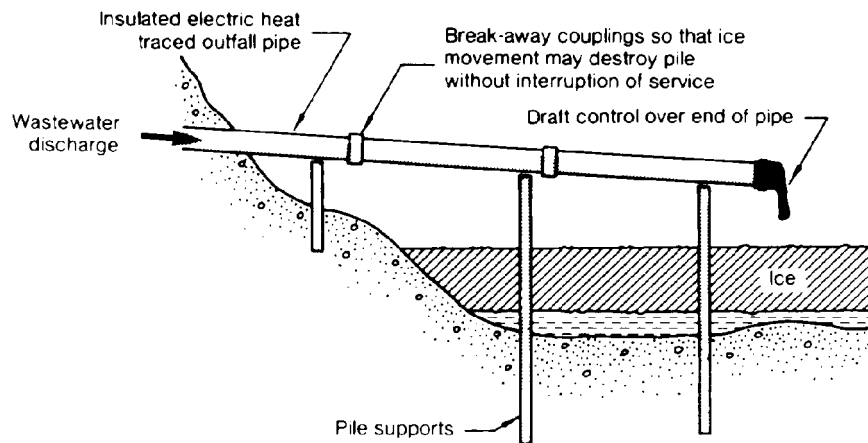
(3) At most facilities it will not be cost-effective to depend entirely on freezing since this would require sludge storage during the warmer months. The optimum design, to avoid storage, will determine the amount of material that can be frozen and then thawed by early summer so that the beds can be used in the conventional drying mode for the balance of the warm season. Polymer additions (in the summer only) will be necessary to condition alum and other metallic hydroxide sludges for conventional dewatering on the sand beds.

b. Sludge disposal. Landfills or land application of sludge are the most appropriate techniques for disposal in cold regions. Temporary sludge storage will be necessary where winter conditions or frozen

ground prevent surface application or landfill operations.

9-6. Outfalls.

Outfall structures require special consideration to prevent freezing of the effluent and to prevent structural damage from ice in the receiving waters. In some cases these problems can be avoided by designing for seasonal discharge. However, an unused outfall is still exposed to damage by ice in the winter and during spring thaw. Exposed outfall piping will be insulated and heat-traced. The thermal design will be accordance with section 12. A submerged outfall is recommended wherever possible. However, in shallow streams the pipe must be protected from ice scour that can occur during spring breakup. If possible, the pipe will be installed underground with the outlet completely submerged in water and below the maximum penetration depth of winter ice. If these conditions cannot be satisfied an elevated outfall will be required. Figure 9-6 illustrates a typical elevated outfall detail. The support piling will be designed in accordance with TM 5-852-4/AFM-88-19, Chap. 4, to resist the uplift forces generated by a floating ice sheet. This is particularly critical at coastal locations with significant tidal action. It is usually not practical to design simple pile supports to resist the lateral forces from ice movements during spring breakup. As shown in figure 9-6, break-away couplings will be used to prevent complete destruction of the outfall structure. Elevated outfalls will, in general, be designed to discharge on top of the ice since an open water surface cannot always be maintained. Most of the effluent will then freeze and form a large mound of ice as the winter progresses.



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Figure 9-6. Example of an elevated outfall design.

The pipe must be of sufficient height so that the ice mound does not plug the outlet. A dual outlet constructed as a wye with a valve on each branch has been successfully used to overcome this problem. When the ice mound approaches one outlet, discharge is shifted to the other leg for the remainder of the winter. Figure 9-3 illustrates design details for the buried outfall for a typical cold regions lagoon. A submerged outfall will be similar in concept to the water intake shown in figure 3-3.

9-7. Alternatives to treatment/disposal.

At many remote installations that have small populations or with intermittent usage, it may not be cost effective or technically feasible to construct one of the treatment/disposal options discussed above. Small-scale on-site systems may be feasible for these situations and will be considered. Conventional septic tanks and soil absorption systems have been used throughout Alaska with mixed results. Sludge

accumulates at high rates in septic tanks in low temperature soils. Annual sludge removal is required to avoid clogging problems in the adsorption field. Design procedures are similar to conventional practice for these systems. Insulation of the septic tank is desirable; a 2-inch thickness of rigid polystyrene board will retain heat and is recommended for intermittently operated systems. Where feasible, deep seepage pits are preferred over conventional absorption fields because of their greater thermal efficiency. In locations where in-ground disposal is not practical or feasible, vault storage and truck haul will be required. Electric incinerator toilets have been successfully used since 1977 at remote Alaskan stations. These units are not recommended for recreational areas or for transient users. The "grey water" (kitchen, bath and laundry wastes) at these remote stations is discharged to a gravel pad on the ground surface.

CHAPTER 10

FIRE PROTECTION

10-1. General.

Requirements for fire protection are covered in MIL-HDBK-1008. Protection of Air Force installations should be in accordance with AFR 88-15.

10-2. Hydrants.

Fire hydrants were discussed in chapter 6 paragraph 6-6a, and special features for cold regions use shown in figures 6-9 and 6-10. Hydrants must be accessible and operable at all times (regardless of frost depth, snow cover and temperature).

10-3. Truck systems.

Motorized fire pumping apparatus with booster tanks and hoses will normally be provided for protection of remote buildings not serviced by the water distribution system. Winter operation in the Arctic will require tank trucks on standby in heated garages and a protected water point with a pumping capability of at least 350 to 500 gallons per minute for refilling the tank trucks if hydrants are not available.

10-4. Chemical and gas methods.

A halon gas system is recommended in high hazard

buildings where sensitive electrical or mechanical systems could be destroyed by water. Guidance and criteria for systems of this type can be found in DOD 4270.1. Foaming equipment will not function at optimum levels below -15 degree F air temperatures since aspiration of the foam is not complete. Standard carbon dioxide fire extinguishers will also not function properly at below-freezing temperatures. Dry chemical extinguishers have been used successfully and range in size from hand-held units to large dolly-mounted units containing about 350 pounds of chemical.

10-5. Alarm systems.

Central alarm systems must be designed in accordance with TM 5-813-3/AFM 88-10, Vol.3. In many cases it is advantageous to integrate the systems with other utility system sensors for protection of the water distribution network and sewage transmission lines (see section 6 and 7). All of these signals can be transmitted to the fire department and other central alarm centers where appropriate action can be initiated.

CHAPTER 11

POWER DISTRIBUTION AND COMMUNICATION SYSTEMS

11-1. General.

The basic design requirements for wire and cable networks for power transmission and communication Systems are not unique in the cold regions and TM 5-811-1/AFM 88-9, Chap. 1, should be used for the design of these systems. Special concern is needed to ensure proper grounding in permafrost areas, to maintain stability of towers, poles, guy wires and anchors, and for direct burial of cables.

11-2. Grounding.

Areas with permafrost do not provide acceptable grounding conditions due to the high resistance of frozen ground. In these locations all the facilities are tied together, including electrical wiring, petroleum, oil, and lubricant (POL) piping metal building, POL storage tanks, water and sewer lines, etc., to form one large grid network. This network is then connected to a water well casing that penetrates the permafrost layer and results in an acceptable ground. If no well casing exists, the grid system is connected to a ground rod that does not penetrate the permafrost. This will provide a common floating ground with everything at the same electrical potential. This is an acceptable approach as long as everything is bonded to that common ground. Another possibility is to place a grounding cable

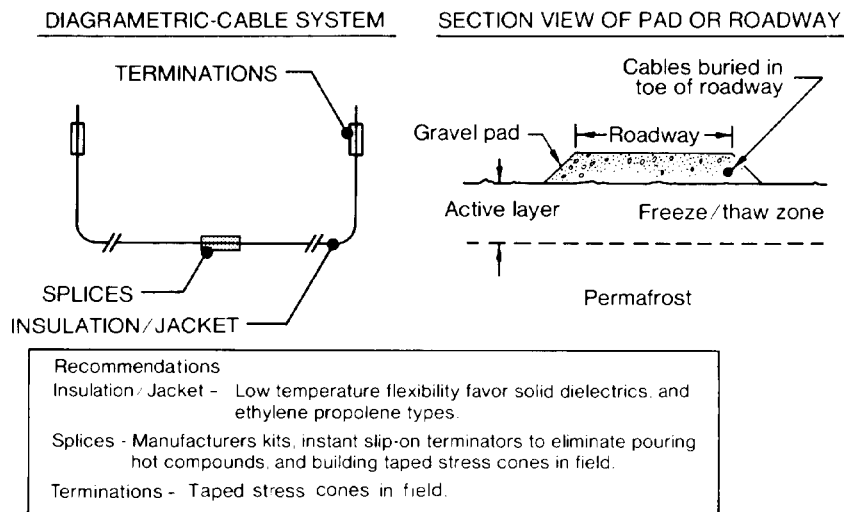
grid into a nearby lake.

11-3. Underground Systems.

Power and communication networks have been successfully installed in the utilidor systems described in chapter 8. The direct burial of cables in the active layer in frost-susceptible soils must be avoided. The freezing and expansion of these soils will result in structural failure of the cable or severe mechanical damage. Buried conduits or ducts must be placed in non-frost-susceptible backfill materials. Prime consideration will be given to placing a gravel and non-frost-susceptible material pad on the existing ground surface and burying the cables in this new pad if a buried system is required. As shown in figure 11-1, the gravel pad also serves as a road or walkway.

11-4. Aerial Systems.

Ice buildup will be a problem for aerial cables, particularly in coastal locations. Preventive measures have included the use of a steel conductor to increase tensile strength and to allow resistance thawing. The major engineering problem with aerial systems in the cold regions is the stability of the supporting towers or poles. The upper soil layer, known as the active zone, goes through a freezing



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Figure 11-1. Underground cable guidelines.

and thawing cycle on an annual basis. In the spring this zone may go through several freezing cycles due to warm days and cold nights. This freezing causes significant expansion, depending on the soil type and moisture content. The expansion is very significant with fine-textured silty soils when a source of unfrozen water is available. Further details on this soil "heaving" can be found in TM 5-852-4/AFM 88-19, Chap. 4. The practical effect on towers and poles is to apply an upward force to the unit that may result in overstress and mechanical failure or in differential vertical movement between components. It is necessary to design the towers or poles to resist these upward forces, or to allow the units to "float" up and down with the expansion and contraction caused by heaving of the active layer, or to replace the frost-susceptible soils with clean gravel. In many cases the utility pole will move up due to the heaving forces but cannot return to its original position because of the flow of soil into the void. The net effect is an annual increment of upward movement that will eventually "jack" the pole out of the ground.

a. Towers. Typical designs for tower foundations on gravel pads and on or in frost-susceptible soils are shown in figures 11-2 and 11-3. Technical details for these designs are discussed in TM 5-852-4/AFM 88-19, Chap. 4. The above-surface gravel pads provide some surcharge for resistance to heaving forces but some vertical movement is likely. At the end of the thaw period the pad will settle to its original position. The anchors for guyed towers provide the major resistance to uplift and provide lateral stability. If the footings for towers are placed in the frost-susceptible material they will be moved upward during the heaving phase, but as described in the previous section, the footing will not then settle back to its original position when seasonal thawing is complete. A progressive failure will result because the footing will be moved upward another increment each year until the resistance to overturning is insufficient.

b. Poles. A very strong bond can develop between the frozen soil and the surface of an imbedded power pole. This bond, if developed in the active layer with frost-susceptible soils, will lift the pole out of the ground. Wooden poles are commonly used for both power and communications systems. Two measures are commonly taken for permanent construction where permafrost is relatively close (3-5 feet) to the surface:

- Sufficient imbedment in permafrost is provided so that the bond developed in that zone can resist the uplift forces due to heaving in

the active layer.

- The active zone portion of the hole is backfilled with non-frost-susceptible materials or this portion of the pole is wrapped with a 10-mil polyethylene sleeve to prevent development of a bond.

The "rule-of-thumb" for poles in the 50-foot range is to place 10 percent of the above-ground height plus another 4 feet into the permafrost (example-50 feet above ground height would require 9 feet of embedment). A "rule-of-thumb" for shorter poles is to provide an embedment in permafrost for a depth equal to about 2-1/2 times the thickness of the active layer. Holes for these poles or support piles are made with a drill or soil auger and are made slightly larger (3-4 inches) than the diameter of the pole. A slurry of native soil or sand with water is then placed around the pole to the top of permafrost. This construction is often done in the winter when the active layer is also frozen. This will allow easier access with minimal environmental disturbance. Rock-filled cribs (fig 11-3) are used where permafrost is very deep, or rock very shallow, or for temporary or semi-permanent construction. Tripod or "teepee" pole configurations using local tree saplings or poles in gravel-filled drums have been used for lightweight wires and cables in expedient situations.

c. Anchors. Anchors for tower guy wires will be designed in accordance with TM 5-852-4/AFM 88-19, Chap. 4. The major concern is progressive movement or "creep" of the anchor in ice-rich soils with temperatures just below the freezing point. Manufacturers' ratings for design capacities of commercially available earth anchors will be reduced by 75% if placed in thawed soil above the permafrost layer. As described in TM 5-852-4/AFM 88-19, Chap. 4, special helical anchors have been developed for installation in permafrost.

11-5. Special considerations.

There are other special considerations that relate to construction of electrical distribution systems in the cold regions due to responses to low temperatures or other environmental factors:

a. Nylon-jacketed conductors (type THWN), when used at low ambient temperatures, tend to experience separation of the insulation from the jacket.

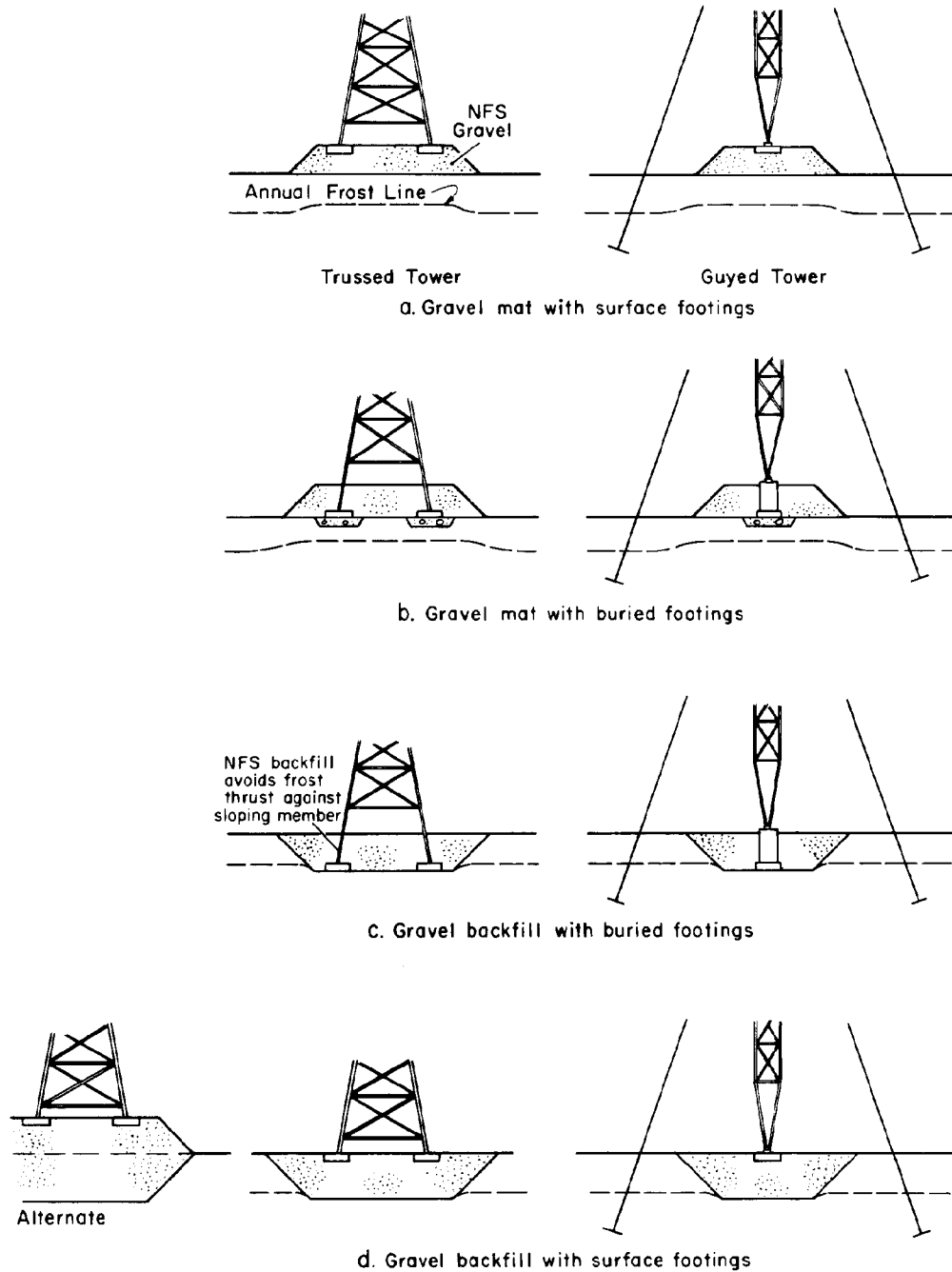
b. Molded case circuit breakers and stored potential switches are not always dependable at extremely low temperatures. The alternative use of fuses should be considered or supplemental heat provided to raise the ambient temperature of the

equipment enclosure.

c. Low temperature, special alloy steel is frequently used for transformers, circuit breakers and other exterior electrical distribution apparatus.

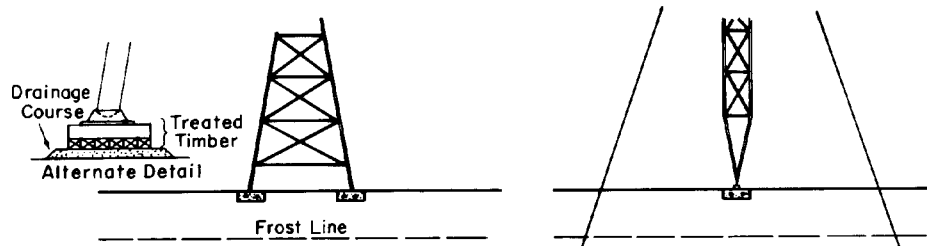
d. Cold weather starting of street lighting can be a problem. Mercury vapor lights are especially dif-

ficult to start. Either the lights must remain energized continuously during extreme low temperatures or provided with integral thermostats to turn on the lights when the temperature drops below -22 degrees F, the present low limit of the typical ballast manufacturer's ratings.

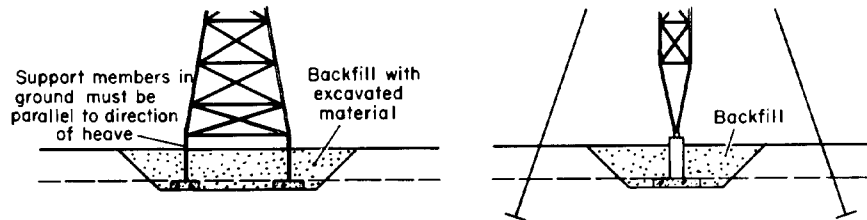


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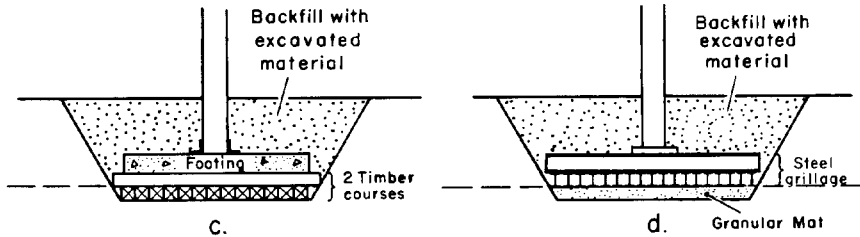
Figure 11-2. Granular pad utility tower foundations (NFS = non-frost-susceptible material).



a. Non-frost-susceptible (NFS) foundation with shallow footings.



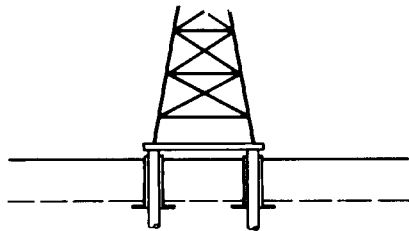
b. Frost susceptible foundation with footings below frost line.



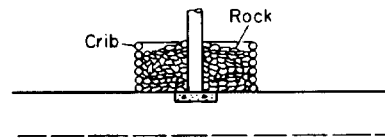
c.

d.

Alternate foundation details.



e. Pile foundation



f. Crib foundation

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Figure 11-3. Foundation designs employing minimum and no granular material for utility towers and power poles.

CHAPTER 12

THERMAL CONSIDERATIONS

12-1. General considerations.

The thermal aspects of utility system designs are among the most critical elements for cold regions systems. The potential problems are failure of pipes due to freezing of water, thaw settlement or heaving of foundation soil, thermal strains and the associated stresses, the cost-effective selection of materials and insulation thicknesses, and economical operation. This chapter presents criteria and design examples for the most critical thermal calculations that might be required for design of pipes, utility structures and appurtenances.

12-2. Freezing of pipes and tanks.

Damage or failure occurs due to the expansion of water changing to ice. The hydrostatic pressure on the still-unfrozen liquid can reach several hundred atmospheres and it is this pressure, not the contact of the ice, that typically causes pipe failure. Prevention of freezing is accomplished via the most cost-effective combination of insulation, heat trace, circulation, etc., using the methods presented in this section. Insulation alone will not necessarily prevent freezing. It reduces the rate of heat loss and extends the freeze-up time. Small diameter service connections may have a freeze-up time measured in minutes or a few hours. These are the most vulnerable portion of the system and will usually freeze first. Thawing capability is mandatory for these small diameter pipes.

12-3. Thawing of frozen pipes.

Remote electrical thawing methods that can be incorporated in the original design include skin effect, impedance, and various resistance wire and commercial heating cable systems. Frozen wells have been thawed by applying a low voltage from a transformer to a copper wire located inside the riser. Once a small annulus is melted, the flow can be restarted and it will thaw the remaining ice. Chapter 6 contains details on thawing of frozen pipes.

12-4. Heat loss from pipes.

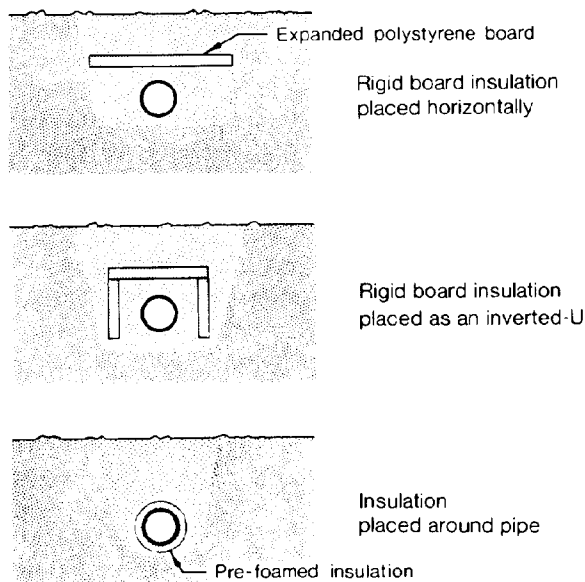
The total heat loss and the freeze-up time are dependent on the ambient and internal temperatures in the pipe system. Above-ground piping systems must be designed for the lowest expected air

temperatures, which range from -40 to -75 degrees F. These extreme surface temperatures are attenuated by burial depending on the thermal properties of the soil. For example, the air temperature at the surface might have an annual range of 150 degrees F. At a depth of six feet the temperature may vary slightly with the season, and at 30 feet seasonal temperature fluctuations are negligible. Frost penetration will be greatest in rock or bare, dry soils. A snow cover will typically reduce the depth of frost penetration by an amount equal to the snow depth. Locating utility lines away from snow-plowed surfaces will take advantage of this potential. There is a time lag involved with frost penetration so that maximum depth of frost penetration will occur long after the extreme winter temperatures. At a depth of six feet the lag time may be one to five months after the onset of freezing conditions at the surface. The specific time depends on soil properties and moisture conditions.

a. Direct burial. Water and sewer mains are typically buried below the maximum depth of seasonal frost. In cold regions, the frost penetration is often greater than the common pipe burial depths of 6 to 10 feet, and may be 20 feet or more in exposed dry soil or rock. Deep frost penetration, high groundwater, hilly terrain, rock or other factors will make it more practical and economical to install all or portions of the utility system within the frost zone. In these cases, the degree of freeze protection necessary will depend upon the ground temperatures at the pipe depth. Where pipes are only intermittently or periodically within frost, conventional bare pipes will be adequate, provided a minimum flow can be maintained by circulation, bleeding or consumption. Frost-proof appurtenances, stable backfill and some heating will also be necessary. Heat loss and freeze danger are significantly reduced by insulating the pipes. Insulated pipes can be installed in shallower trenches or within berms at ground surface. In these cases, the minimum depth of cover would be 1.5 to 3.0 feet for exposed ground surfaces. Greater depths will be necessary if heavy surface traffic is expected.

b. Insulation barrier far buried pipes. Buried pipes within seasonal frost can also be protected by placing a layer of insulation board, usually polystyrene, above the pipe (fig 12-1). This method, using

bare pipes and fittings and board insulation, is often less expensive (for materials) than use of prefabricated insulated pipe; however, the construction cost will be higher and the effectiveness of the insulation is lower than direct insulation on the pipes. The board method has been used where the soils underlying the pipe are frost-susceptible, since frost penetration beneath the pipes can be prevented by the insulation board. The necessary thickness and width of the board increases for shallower pipes and deeper frost penetration, such as dry soils or rock. The relative economics, compared to that for insulated pipes, is improved when pipes are placed in a common trench under a board and when warm sewer or central heating lines are included. Generally, the insulation should be a minimum of 4 feet wide for a single pipe, and the thickness will be determined by the proposed depth of burial and the expected or calculated frost penetration. In terms of reducing frost penetration, two inches of polystyrene foam insulation ($k = 0.02 \text{ BTU/hr}\cdot\text{ft}\cdot\text{°F}$) is roughly equivalent to 4 feet of sand or silt or 3 feet of clay cover over the pipe. The heat loss and trench width will be reduced by placing the insulation in an inverted U. The design example in paragraph 12-9c illustrates frost penetration calculations beneath an insulation board.



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Figure 12-1. Methods of insulating buried pipe.

c. *Deep burial.* Deeper pipes will experience less extreme ambient temperatures, lower maximum rates of heat loss and a longer safety factor time for freezing. However, the heating period will be longer, and pipes installed in permafrost will require freeze-protection all year.

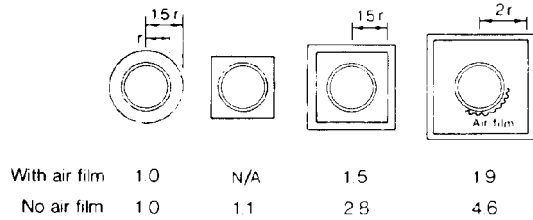
12-5. Physical methods for reducing heat loss.

The primary physical method of reducing heat loss is insulation. It is impractical to prevent ground moisture, humidity or water from pipe failures from reaching the insulation and, since moisture content is a key factor in determining the thermal performance of insulations, only near-hydrophobic insulations will be used. Even these insulations will usually require some physical and moisture protection.

a. *Amount of insulation.* An economic analysis to balance heating and insulating costs must be performed to determine the minimum amount of insulation that is required (see para 12-9i) and will include factors, such as the freeze-up time, the maximum rate of heat loss and practical dimensional considerations. Heat loss estimates for pipe systems must consider exposed sections of pipes, joints and appurtenances, and thermal breaks such as at pipe anchors. For example, a 5-inch gate valve has a surface area equivalent to 3 feet of bare pipe. If this valve were left exposed it would lose as much heat as about 200 feet of 5-inch pipe insulated with 2 inches of polyurethane insulation and freezing would occur at the valve first. To ensure a safe design, the thermal resistance around appurtenances must be 1.5 times that required around the adjacent pipe sections.

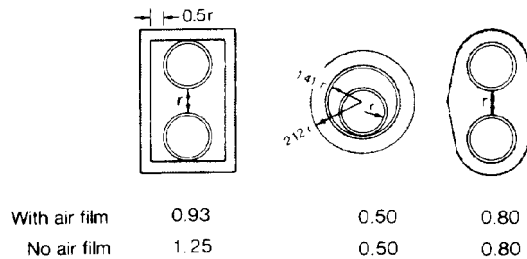
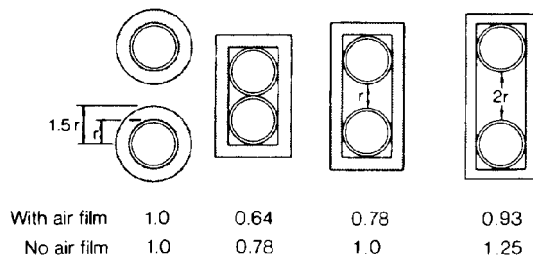
b. *Location of insulation.* Heat loss and the volume of materials will be reduced by minimizing exposed surface area. This is most important for above-ground pipes and facilities. Insulation is most effective when it is placed directly around the source of heat. These characteristics are illustrated by the simple shapes in figures 12-2 and 12-3. Where there is an air space, the thermal resistance of the pipe air film can be quite significant and must be considered. For a single pipe, insulation is best applied in an annulus directly around the pipe. Heat loss from several pipes in a compact utilidor is less than that of the same number of separate pipes insulated with the same total volume of insulation. Heat loss will also be reduced and freeze protection improved by installing one water pipe inside of a larger one, rather than using two separate pipes. This technique is applicable for freeze protection of small-diameter recirculation pipes used to maintain a flow in supply

lines, or dead ends within a water distribution system.



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Figure 12-2. Relative heat loss from single pipes insulated with same volume of insulation.



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Figure 12-3. Relative heat loss from two pipes insulated with same volume of insulation.

12-6. Heat loss replacement.

If ambient temperatures are below 32 degrees F, freezing will eventually occur in the pipe unless heat is added to the fluid. Heat can be added either continuously or at point sources.

a. *Fluid replacement.* Freezing will not occur if the liquid residence time in the pipeline is less than the time necessary for it to cool to the freezing point. The quantity and temperature of the replacement water must be sufficient and the flow must be reliable. Operation without additional heating is restricted to situations where relatively warm water supplies, such as ground-water, are used or where the flow rate is reliable and high, such as in some water supply pipelines or mains. Bleeding

of water has been used to maintain or enhance the flow in service lines, dead ends and intermittent flowing pipelines, but the wasting of large quantities of water is inefficient and results in water supply and wastewater treatment problems. Recirculation will maintain a flow and a uniform temperature within the system, and prevent premature freezing at locations with lower-than-average ambient temperatures or at poorly insulated sections. However, the water temperature will still decline unless warmer water is added or the recirculating water is heated.

b. *Point sources of heat.* Water may be heated at the source, treatment plant, pumping stations, or along the pipeline or within distribution systems as required. Heat is commonly obtained from oil-fired boilers; however, simple electric water heaters have been used where the heat requirements are very low. The heating of water can be practical with low-temperature waste heat, such as from electric power generation. There must also be sufficient flow within the piping system to distribute the heat. If the normal water demand is too low or is intermittent, then bleeding or recirculation is necessary. A minimum water temperature will be maintained with the piping system by increasing either the flow rate or the input water temperature while keeping the other parameters constant, or by adjusting them simultaneously. As a general rule, the temperature drop along a pipeline must always be kept to less than 10 degrees F, and preferably less than 5 degrees F, by insulation, higher flow rates, or intermediate heating along the pipeline. Velocities greater than 0.3 foot per second for 6-inch pipes and 1.5 feet per second for 2-inch pipes are of little benefit in reducing total energy input to maintain a specified minimum water temperature. Higher velocities must be balanced with the electrical energy requirements for pumping and are not usually practical for large diameter mains.

c. *Heat tracing.* Replacement of heat losses and maintenance of a minimum temperature can also be accomplished with heat tracing systems. Circulation of warm air has been used in large, open utilidor but the most common heat tracing systems are either separate fluid or electrical lines as the heat source.

(1) *Fluid tracers.* For pipe heat tracing, hot water, generally between 175 and 200 degrees F, is much simpler to use than either steam or higher temperature water. The use of an antifreeze solution protects the heat trace piping, allows start-up during winter and provides a means of thawing frozen pipes. The viscosity of low freezing point glycol and water mixtures is greater than that of water; therefore, the required pumping capacity and friction losses will be higher. The heat transfer

characteristics are also poorer than for water. For example, a 50% mixture of glycol and water would require a 15% increase in flow rate to achieve the same heat transfer. Design information on these heating systems is available from the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) (ethylene glycol is toxic and cross-contamination must be prevented). Propylene glycol, which is non-toxic, but more expensive, can be used. Glycol solutions are corrosive to zinc and can leak through joints and pump seals that will not leak water at the same pressures. Some boiler manufacturers void their warranty if glycol solutions are used. Mechanical seal pumps should be utilized to prevent leakage. Special organic fluids can also be used instead of water-glycol solutions.

(2) *Electric heat tracing.* Electric heat tracing systems are relatively easily installed and controlled. They can be installed continuously on water and sewer pipelines, or only at freeze-susceptible locations, such as road crossings, service connections or at appurtenances such as fire hydrants. Because of the relatively high cost of electrical energy, these systems are usually installed for freeze-prevention or system restoration in the event of operating upset, such as a prolonged no-flow condition, rather than as the primary method of maintaining a minimum operating temperature in the system.

(a) *Types.* A variety of electric heat tracing systems and products are available from a number of manufacturers. Resistance-type cables and wires are available for installation with pipes or for exterior tracing. Small-diameter metal pipes, such as service lines, can be heated or thawed by induction heating from an alternating current in a wire wrapped around the pipe which induces eddy currents within the pipe. The most common electric heat tracing systems used are zone-parallel and self-limiting continuous parallel heating cables and strips. Since they contain separate conductor and resistance buss wires or conducting material in the same casing, they produce a constant heat output per unit length, and can be conveniently cut to the desired length. Maximum lengths are usually 250 feet to 650 feet. One type has a carbon-filled polymeric heating element with self-adjusting properties that decreases heat output as the temperature increases. This cable will not burn itself out or overheat plastic pipes, and the heat output modulates, to some extent, with temperatures along the pipe.

(b) *Location.* Maximum heat transfer efficiency will be obtained if the heating cables are installed inside the pipe. However, the coating and joints of only a few cables, such as mineral insulant

(M.I.) resistance cable, are approved for installation within water pipes or for submerged conditions. In-line cables are more practical for long water supply transmission mains, but are impractical in the distribution network because valves and other fittings must be bypassed. They may be subject to vibration damage when fluid velocity is greater than 4 feet per second, and the cables must be removed to clean the pipes and when some types of pipe repairs are made. Heating cables are more conveniently and commonly located on the outside pipe surface. The required capacity for heating cables must be increased by a factor of 1.5 unless flat or wide heating strips or adequate contact between the cable and the pipe, preferably with heat transfer cement, is maintained. Exterior cables for pre-insulated pipe are commonly installed within a raceway or conduit attached to the pipe surface, which facilitates fabrication, installation, removal and replacement. In this configuration, the air space and poor contact of the heating cable with the pipe can further reduce the heat transfer efficiency and the heat input for plastic pipes may need to be two to six times that for a heating cable within the pipe. It is difficult to make the joints in the exterior heating cable channel watertight, as is required for most cables or their joints when used underground.

(c) *Overheat protection.* Plastic pipes, insulations and the electric heat tracing system itself must be protected from overheating unless the self-limiting heating cable is used. For conventional cables, a high temperature thermostat cut-off is usually installed and set at about 85 degrees F and the sensor is placed on the surface of the heat cable.

(d) *Controls.* To provide freeze protection, automatic control systems must activate the electric heat tracing system at a set point above 32 degrees F to provide some lead time and allow for variances in the temperature detection sensitivity of the thermostat and sensor. To provide economical operation, the controls also cut off the power supply when heating is not required. These controls are often a major cause of malfunction and wasted energy. Mechanical thermostats with capillary tube sensing bulbs are limited to about 16 feet in length and temperature control is only possible within a few degrees. Electronic thermostats are much more sensitive but they are expensive. The resistance sensors they use can be located any practical distance from the controller and the system can be selected to maintain fluid temperatures within 0.1 degree F. This type of system, which is commonly used in Greenland, allows the utility system to be reliably operated at near-freezing temperatures. The sensors must be located with care to provide proper control, freeze-protection, and prevent the waste of

energy. To accurately measure the fluid temperature, they should be put in a pipe well or attached to the pipe surface with heat transfer cement, particularly for plastic pipes. They should be located where the lowest pipe temperatures within the section being controlled are expected, such as at exposed windswept areas or shallow buried sections.

(3) Pipe friction. Friction heating is negligible for smooth pipes with fluid velocities less than 6 ft/s (feet per second), which is about the desirable upper limit for flow in pipes. At high velocities frictional heat is significant, but deliberately increasing the velocity for this purpose is an inefficient method of heating since the energy is supplied by pumping. The equations for frictional heat input are presented in figure 12-4.

12-7. Insulation materials.

Common insulating materials are plastics, minerals and natural fibers, or composite materials. For design purposes, the structural and thermal properties for the worst conditions must be used. These conditions occur after aging, compaction, saturation and freeze-thaw cycles. Other selection considerations are ease of installation, vapor transmission, burning characteristics, and susceptibility to damage by vandals, animals, chemicals and the environment. The insulating value of a material depends more or less directly on the volume of entrapped gas in the material. If the material becomes wet and the voids filled with water, the insulating properties are lost since the thermal resistance of air is about 25 times that of water and 100 times that of ice. In the past, the lack of a near-hydrophobic insulation made the design of piping in moist environments very difficult and is a major reason for the development of above-ground utilidor.

a. Polyurethane foam is used extensively in cold regions to insulate pipes and storage tanks, and is also used in some buildings and foundations. Urethane will bond to most materials. Piping or other components can be pre-insulated or polyurethane can be applied on-site from the raw chemicals, which are about 1/30th the final volume. Field applications are restricted by climatic conditions, and the density and thermal conductivity will often be higher than values attainable under factory conditions. The foam must be protected from ultraviolet radiation. A metal skin has proven effective to prevent the loss of entrapped heavy gas which can increase the thermal conductivity by about 30% above the theoretical minimum value. Densities over 6 pounds per cubic foot are essentially impermeable, but lighter foams, which are better insulators,

require coatings to prevent water absorption, since freeze-thaw cycles of the moisture can lead to deterioration of the insulation.

b. Extruded polystyrene, particularly the high density products (3 pounds per cubic foot), suffer the least from moisture absorption and freeze-thaw but the outer 0.25 inch of unprotected buried insulation should be disregarded in thermal analyses. Molded polystyrene will absorb some moisture and should not be used in moist conditions. Polystyrene is available in board stock or beads. The former has been extensively used to reduce frost penetration. Beads are useful for filling voids in utilidor while retaining easy access to pipes. Although the thermal conductivity of polystyrene is higher than that of urethanes, the volumetric cost is usually lower.

c. Glass fiber batt insulation is the most common building insulation, primarily because it is fire-resistant and relatively inexpensive. Its insulating value is significantly reduced when wet, and is reduced by half if 8% by volume is water. For this reason, glass fiber should not be used underground but may be considered wherever dry conditions can be ensured. Cellular glass is very water-resistant but is seldom used because it is brittle and difficult to work with. Lightweight insulating concrete made with polystyrene beads, pumice or expanded shale can be formulated with relatively high strength and thermal resistance. It can be poured in place around piping but must be protected from moisture to prevent freeze-thaw deterioration.

12-8. Thermal calculations.

The analytical thermal equations presented below use a number of simplifying approximations. The user must determine their applicability for particular problems and consider the various models and a range of values for physical and temperature conditions. This chapter includes time-independent steady-state heat flow procedures as well as calculations to determine ground temperature and the depth of freezing and thawing. The symbols used are defined in table 12-1 and the thermal conductivity of common materials in table 12-2. Solutions to typical utility system problems are given to illustrate the procedures involved.

a. Steady-state pipeline heat loss. These include typical cases for bare and insulated pipes, and single and multiple pipes in above- and below-ground configurations. These methods are presented in figures 12-5, 12-6 and 12-7.

(1) Figure 12-5 deals with heat flow from a bare pipe, an insulated pipe, a single pipe in an insulated box, and a utilidor carrying multiple pipes. In each case, some of the major approxima-

Heat Loss and Temperature Drop in a Fluid Flowing Through a Pipe	Freeze-Up Time For a Full Pipe Under No-Flow Conditions ($V = 0$)
<p>Comments: The above sketch is schematic. R and T_A appearing in these equations can be replaced by the thermal resistance and corresponding exterior temperature for any shape or configuration</p>	
<p>$D = \pi r_w^2 V \cdot C \cdot R$</p> <p>Calculate T_1 or T_2, Given R, T_1 or T_2, T_A</p> <p>$T_1 = T_A \cdot (T_2 - T_A)^{-1} \exp(-\ell/D)$ $= T_A + (T_2 - T_A) (1 - \ell/D)$ if $\ell/D < 0.1$</p> <p>$T_2 = T_A + (T_1 - T_A) \exp(-\ell/D)$</p> <p>Calculate R, Given T_1, T_2, T_A</p> <p>$R = -\ell / (\pi r_w^2 \cdot V \cdot C \cdot \ln[(T_2 - T_A) / (T_1 - T_A)])$ $= \ell(T_1 - T_A) / (\pi r_w^2 \cdot R \cdot C (T_1 - T_2))$ if $\ell/D < 0.1$</p> <p>Calculate V, Given T_1, T_2, T_A, R</p> <p>$V = -\ell / (\pi r_w^2 \cdot R \cdot C \cdot \ln[(T_2 - T_A) / (T_1 - T_A)])$ $= \ell(T_1 - T_A) / (\pi r_w^2 \cdot V \cdot C (T_1 - T_2))$ if $\ell/D < 0.1$</p> <p>Calculate Heat Loss (Q), Given T_1 or T_2, T_A, V, R</p> <p>$Q = (D/R)(T_1 - T_A) [1 - \exp(-\ell/D)]$ $= (\ell/R)(T_1 - T_A)$ for $\ell/D < 0.1$ $= D/R (T_1 - T_A) [\exp(\ell/D) - 1]$</p> <p>Calculate Friction Heating, Given V, f</p> <p>$Q_f = F \cdot r_w^2 \cdot V \cdot f$</p> <p>Where Q_f = BTU h · ft $F = 0.2515 \text{ BTU} \cdot \text{ft}^2$ r = ft V = ft h f = friction head loss, ft / ft length Not significant for $V > 2.3 \times 10^{-4} \text{ ft} \cdot \text{h}$</p> <p>or Q_f = J s · m $F = 3.074 \times 10^{-4} \text{ J} \cdot \text{m}^2$ r = m V = m s f = friction head loss, m / m length Not significant for $V > 2 \text{ m} \cdot \text{s}$</p>	<p>Freeze-Up Times; Given R, T_1, T_A</p> <p>Assume that thermal resistance of the ice, as it forms, and the heat capacity of the pipe and insulation are negligible.</p> <p>Design Time (Recommended)</p> <p>t_D = Time for the fluid temperature to drop to the freezing point.</p> <p>$t_D = \pi \cdot r_w^2 \cdot R \cdot C \cdot \ln[(T_1 - T_A) / (T_2 - T_A)]$</p> <p>Safety Factor Time</p> <p>t_{SF} = Time for the fluid to drop to the nucleation temperature. Same as t_D but with T_C replaced by 27°F</p> <p>Complete Freezing Time</p> <p>t_F = Time for the fluid at freezing point, 32°F, to completely freeze solid.</p> <p>$t_F = \pi \cdot r_w^2 \cdot R \cdot L \cdot (T_C - T_A)$</p>

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Figure 12-4. Temperature drop and freeze-up time in pipes.

Table 12-1. List of symbols used in thermal calculations

Symbols

A = Amplitude
 A = Thermal factor = $T' \operatorname{arccosh} H_p/r_p$
 B = $[\pi C_p/k \cdot p]^{-1/2}$
 C = $[H^2 - r^2]^{1/2}$ ft
 c_m = Mass heat capacity, BTU/lb·°F
 C = Volumetric heat capacity, BTU/ft³·°F
 d & t = Thickness, ft
 D = Scaling parameter, ft
 E = Young's modulus, lb/ft²
 F = $\operatorname{arccosh} (H/r)$
 h = Thermal film coefficient (or surface conductance), BTU/h·ft²·°F
 H = Depth of burial, ft
 I = Freezing or thawing index, °F·h
 k = Thermal conductivity, BTU/h·ft·°F
 l = Length, ft
 L = Volumetric latent heat, BTU/ft³
 p = Period, sec, hr
 P = Perimeter (mean), ft
 q = Fluid flow rate, ft³/sec
 Q = Rate of heat loss per unit longitudinal length, BTU/ft·hr
 r = Radius, ft
 R = Thermal resistance of unit longitudinal length, hr·ft·°F/BTU
 t = Time, sec, hr
 T = Temperature, °F
 $T^* = (T_1 - T_G)/(T_0 - T_G)$
 u = Coefficient of thermal expansion, ft/ft·°F
 w = Moisture content of dry weight, %
 V = Velocity ft/hr
 x = Depth
 X = Depth to freezing (32°F) plane, ft
 α = Thermal diffusivity, ft²/hr
 γ = Unit weight (density), lb/ft³
 a, μ , λ = Coefficients in modified Berggren equation

Subscripts

A - refers to air
 α = thermal diffusivity, ft²/hr
 γ = unit weight (density), lb/ft³
 a, μ , λ = ground freezing index
 G - refers to ground
 h = refers to heating index
 I - refers to insulation
 j - denotes 1,2,3,
 L = refers to thermal lining (of utilidor)
 m - refers to mean
 0 - refers to (zero) freezing point of water
 P - refers to pipe
 S - refers to soil
 t - refers to thawed soil
 U - refers to utilidor
 W - refers to water (fluid) within a pipe
 x - refers to depth
 Z - refers to zone of thaw

Table 12-2. Thermal conductivities of common materials


Material	Unit Weight (dry) lb/ft ³	Specific Heat Capacity	BTU/ft·h·°F
Air, no convection (32°)		0.24	0.014
Air film, outside, 15 miles·hr wind (per air film)			0.50
Air film, outside (per air film)			0.14
Polyurethane foam	2	0.4	0.014
Polystyrene foam	1.9	0.3	0.020
Rock wool, glass wool	3.4	0.2	0.023
Snow, new, loose	5.3	0.5	0.05
Snow, on ground	19	0.5	0.13
Snow, drifted and compacted	31	0.5	0.4
Ice at -40°F	56	0.5	1.54
Ice at 32°F	56	0.5	1.28
Water at 32°F	62.4	1.0	0.34
Peat, dry	16	0.5	0.04
Peat, thawed, 80% moisture	16	0.32	0.08
Peat, frozen, 80% ice	16	0.22	1.0
Peat, pressed, moist	71	0.4	0.40
Clay, dry	106	0.22	0.5
Clay, thawed, saturated (20%)	106	0.42	1.0
Clay, frozen, saturated (20%)	106	0.32	1.2
Sand, dry	125	0.19	0.06
Sand, thawed, saturated (10%)	125	0.29	1.9
Sand, frozen, saturated (10%)	125	0.24	2.4
Rock typical	156	0.20	1.3
Wood, plywood, dry	37	0.65	0.10
Wood, fir or pine, dry	31	0.6	0.07
Wood, maple or oak, dry	44	0.5	0.10
Insulating concrete (varies)	12		0.04
	to 94		to 0.35
Concrete	156	0.16	1.0
Asphalt	156		0.42
Polyethelene, high density	59	0.54	0.21
PVC	87	0.25	0.11
Asbestos cement	119		0.38
Wood stave (varies)	—		0.15
Steel	486	0.12	25
Ductile iron	468		30
Aluminum	169	0.21	115
Copper	550	0.1	220

(1) Values are representative of materials but most materials have variable properties.

	(a) Bare Pipe	(b) Insulated Pipe	(c) Single Pipe in a Box	(d) Multiple Pipe Utilidor
Sketch				
Assumptions	Thin walled pipe (i.e., $r_p \ll 2r_w$) R_W is negligible, $R_p \ll R_A$	All thermal resistances but that of the insulation are neglected.	Convection ensures the temperature inside the utilidor, T_U is uniform. Utilidor air films neglected.	Same as (c).
Thermal Resistance	$R_p = (r_p - r_w) / (k_p \cdot \pi \cdot r_w)$ $R_A = N \left(\frac{T_w - T_A}{r_p} \right)^{0.25}$ $R_W = \frac{1}{2\pi r_p h_A}$ $R_C = R_p + R_A$ $N = 0.23 \text{ Btu} \cdot \text{h} \cdot \text{ft}^{7/4} \cdot \text{ft}^{-2} \cdot \text{ft}^{-1/4} \cdot \text{ft}^{-1/4}$ $W = \sqrt{12.5 V + 1}$ for $V = \text{miles/h}$ $N = 1.12 \text{ J} \cdot \text{s} \cdot \text{m}^{7/4} \cdot \text{m}^{-2} \cdot \text{m}^{-1/4} \cdot \text{m}^{-1/4}$ $W = \sqrt{0.56 V - 1}$ for $V = \text{m/s}$	$R_C = R_I + \frac{\ln(r_i/r_p)}{2\pi k_i}$ $R_I = \frac{(r_i - r_p)}{(k_i \cdot \pi \cdot r_p)}$ if $r_i \leq 2r_p$ Or given r_i/r_p and k_i , read off R_I from graph, Fig. 12-8.	Calculate R_C , the thermal resistance of the interior conduct by: using (b) if insulated or using (a) if bare and replacing T_A in the formula for h_A by an estimate for T_U (i.e., T_U) $R_L = t_L / (P_L \cdot k_L)$ $R_E = t_E / (P_E \cdot k_E)$ $R_U = R_L + R_E$ $R = R_C + R_U$ $T_U = \frac{(T_W/R_C) + (T_A/R_U)}{(1/R_C) + (1/R_U)}$ if bare pipe, iterate T_U	Calculate R_i for each pipe as in (c) to get R_{ij} (i = 1, 2, 3, ...) Calculate R_{Uj} as in (c) $T_U = \frac{\sum_i (T_i/R_i) + (T_A/R_U)}{\sum_i (1/R_i) + (1/R_U)}$ if bare pipes present, iterate T_U
Rate of Heat Loss	$Q = (T_W - T_A) / R_C$	$Q = (T_W - T_A) / R_I$	$Q = (T_U - T_A) / R$	$Q_i = (T_i - T_U) / R_i$ (per pipe) $Q = \sum_i Q_i = (T_U - T_A) / R_U$
Insulation Thickness (given Q)	N/A	$r_i - r_p = r_p \left\{ \exp \left[2\pi k_i (T_W - T_A) / Q \right] - 1 \right\}$ $= \pi k_i (T_W - T_A) Q$ if $r_i \leq 2r_p$ Or given R_I and k_i , read off r_i/r_p from Figure 12-8.	Obtain R_E and R_C as above $T_U = P_L k_L \left[\frac{(T_W - T_A)}{Q} R_E - R_C \right]$ if bare interior pipe, iterate T_U , R_C and hence t_L	Given acceptable Q_i , calculate R_{ij} as above and evaluate $T_U = T_i - R_{ij} Q_i$ for each pipe for which Q_i is known. Using the maximum T_U found, calculate new Q as above. Using these Q_i and the same T_U , evaluate $t_L = P_L k_L \left[\frac{(T_U - T_A)}{\sum Q_i} R_E \right]$ if bare pipes present, iterate T_U , R_i and hence t_L
Comments	Often, for metal pipes, R_p may be neglected. If R_p is significant, the expression above for R_A will generate an overestimate of Q . If $T_A > T_W$ switch T_A and T_W in the expression for R_A .	The neglected thermal resistances given in (b) may be included if desired. Estimate a value for the insulation surface temperature and calculate h_A and R_A . Iterate.	The value of h_A and hence R_A is fairly insensitive to the choice of T_U , and so one iteration on T_U is usually sufficient. Often R_E may be neglected. Similar calculational procedure may be performed for pipes and utilidors of different cross-section.	as (c) If it is clear that one pipe dominates the heat loss process, (c) may be used to estimate T_U . It is wise to consider the heat loss from the various pipes if certain other pipes cease to function.

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Figure 12-5. Steady-state thermal equations for above-surface pipes.

	(a) Bare, No Thaw	(b) Bare, With Thaw Zone	(c) Insulated, No Thaw	(d) Insulated, With Thaw Zone
<p>Sketch</p> 	<p>Neglect all thermal resistances except that of the soil</p> $R_S = \frac{\text{arccosh}(H_p/r_p)}{2\pi k_S}$ $= \ln \frac{(H_p/r_p) + \sqrt{(H_p/r_p)^2 - 1}}{2\pi k_S}$ $\approx \frac{\ln(2H_p/r_p)}{2\pi k_S} \text{ if } H_p > 2r_p$	<p>Same as (a), but accounting for the different conductivities of thawed and frozen soil</p> $T_W = \frac{k_f(T_W - T_0) + T_0}{k_f}$ $T' = \frac{T_p - T_0}{T_W - T_0}$ $c = \sqrt{H_p^2 - r_p^2} > H_p \text{ if } H_p/r_p > 7$ $A = T' \text{arccosh}(H_p/r_p)$ $= T' \ln(2H_p/r_p) \text{ if } H_p > 2r_p$ <p>Use Fig. 12-9 to read off arccosh(H/r_p), then solve for A, then use Fig. 12-10 for H_z and r_z.</p> $H_z = c \coth A \quad r_z = c \text{csch} A$ <p>R_f, R_i and R_S (= R_f + R_i) as given in (d) but with r_f replaced by r_p.</p>	<p>Neglect all thermal resistances except those of the soil and insulation. Outer surface of insulation assumed to be isothermal. r_f = r_p = H_p.</p> <p>R_f as given in Figure 12-8 (b).</p> <p>R_S as given in (a), but with r_p replaced by r_f.</p> $T_1 = T_W - \frac{R_i(T_W - T_0)}{R_S + R_i}$ <p>For known T_W, T_0 and R_S, the minimum insulation thickness to prevent thaw (i.e. T_1 = T_0) is given by:</p> $R_f = \frac{T_W - T_0}{T_0 - T_0} R_S$	<p>Same as (c) but accounting for the different thermal conductivities of thawed and frozen soil.</p> <p>R_f as given in Figure 12-8 (b). T_W, T', c, H_z, r_z and R_S as in (b) but with r_p replaced by r_f and using</p> $A = T' \text{arccosh}(H_p/r_p) + 2\pi k_f R_f$ $R_f = \frac{R_i(T_W - T_0)}{R_S + (k_f k_i) R_i}$ <p>Also:</p> $R_f = \text{arccosh}(H_p/r_f) \text{arccosh}(H_z/r_z) / (2\pi k_f)$ $= \ln(H_p/r_f) \ln(2H_z/r_z) / (2\pi k_f) \text{ if } H_z > 2r_z$ $R_f = \ln(2H_z/r_z) / (2\pi k_f)$ $= \ln(2H_z/r_z) / (2\pi k_f) \text{ if } H_z > 2r_z$ $R_S = R_f + R_i$
<p>Assumptions</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>
<p>Thermal Resistance and Thaw Zone Parameters</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>
<p>Rate of Heat Loss</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>
<p>Insulation Thickness</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>	<p>N/A</p>
<p>Comments</p>	<p>For calculations of heat loss when there is a temperature gradient in the soil and H_p > 2r_p, T_g may be replaced by T_g0, the undisturbed ground temperature at the pipe axis depth. For an upper limit on heat loss use k_S = k_f, otherwise use k_S = (k_f + k_i)/2.</p>	<p>The thawed zone is a circle in cross-section.</p>	<p>May be used to approximate (d) if k_f = k_i and/or r_z = r_f, and thaw zone parameters are not required. Use k_S = k_f or k_S = (k_f + k_i)/2 as in (a).</p>	<p>Often the above expressions for H_z, H_i and R_S are not required.</p>

U.S. Army Corps of Engineers Figure 12-6. Steady-state thermal equations for below-surface pipes.

Condition	Sketch	Thermal resistance																														
Square insulation		$R = \frac{1}{2\pi k_1} \ln 108 \frac{a}{2r}$																														
Rectangular insulation		$R = \frac{1}{2\pi k} \ln \left(\frac{4a}{\pi r} - 2S \right)$ <table border="1"> <thead> <tr> <th>b/a</th> <th>S</th> <th>b/a</th> <th>S</th> <th>b/a</th> <th>S</th> </tr> </thead> <tbody> <tr> <td>1.00</td> <td>0.08290</td> <td>2.00</td> <td>0.00373</td> <td>4.00</td> <td>6.97×10^{-6}</td> </tr> <tr> <td>1.25</td> <td>0.03963</td> <td>2.25</td> <td>0.00170</td> <td>5.00</td> <td>3.01×10^{-7}</td> </tr> <tr> <td>1.50</td> <td>0.01781</td> <td>2.50</td> <td>0.00078</td> <td>∞</td> <td>0</td> </tr> <tr> <td>1.75</td> <td>0.00816</td> <td>3.00</td> <td>0.00016</td> <td></td> <td></td> </tr> </tbody> </table>	b/a	S	b/a	S	b/a	S	1.00	0.08290	2.00	0.00373	4.00	6.97×10^{-6}	1.25	0.03963	2.25	0.00170	5.00	3.01×10^{-7}	1.50	0.01781	2.50	0.00078	∞	0	1.75	0.00816	3.00	0.00016		
b/a	S	b/a	S	b/a	S																											
1.00	0.08290	2.00	0.00373	4.00	6.97×10^{-6}																											
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1.50	0.01781	2.50	0.00078	∞	0																											
1.75	0.00816	3.00	0.00016																													
Eccentric cylindrical insulation		$R = \frac{1}{2\pi k_1} \ln \frac{\sqrt{(r_2+r_1)^2 - s^2} + \sqrt{(r_2-r_1)^2 - s^2}}{\sqrt{(r_2+r_1)^2 - s^2} - \sqrt{(r_2-r_1)^2 - s^2}}$ $= \frac{1}{2\pi k_1} \operatorname{arccosh} \frac{r_1^2 + r_2^2 - s^2}{2r_1 r_2}$																														
Two buried pipes		<p>Where $H_1 \geq 3r_1$, $H_2 \geq 3r_2$ and $p \geq 3(r_1 + r_2)$</p> $R_{1-2} = \frac{1}{2\pi k_s} \cdot \frac{\ln \frac{2H_1}{r_1} \cdot \ln \frac{2H_2}{r_2} - \left[\ln \frac{\sqrt{(h_1+h_2)^2 + p^2}}{\sqrt{(h_1-h_2)^2 + p^2}} \right]^2}{\ln \frac{\sqrt{(h_1+h_2)^2 + p^2}}{\sqrt{(h_1-h_2)^2 + p^2}}}$ $R_{1-T_G} = \frac{1}{2\pi k_s} \cdot \frac{\ln \frac{2H_1}{r_1} \cdot \ln \frac{2H_2}{r_2} - \left[\ln \frac{\sqrt{(h_1+h_2)^2 + p^2}}{\sqrt{(h_1-h_2)^2 + p^2}} \right]^2}{\ln \frac{2H_2}{r_2} = \ln \frac{\sqrt{(h_1+h_2)^2 + p^2}}{\sqrt{(h_1-h_2)^2 + p^2}}}$																														
Buried rectangular duct		$R = \frac{1}{k_s \left(5.7 + \frac{b}{2a} \right)} \ln \frac{3.5H}{b^{0.25} \cdot a^{0.75}}$																														
Surface thermal resistance		<p>Surface thermal resistance between ground and air can be approximated as the equivalent thickness of the underlying soil equal to</p> $H_o = \frac{k_s}{h_c}$																														
Composite wall		$R = \frac{1}{h_1} + \frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2}$																														

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Figure 12-7. Steady-state thermal resistance of various shapes and bodies.

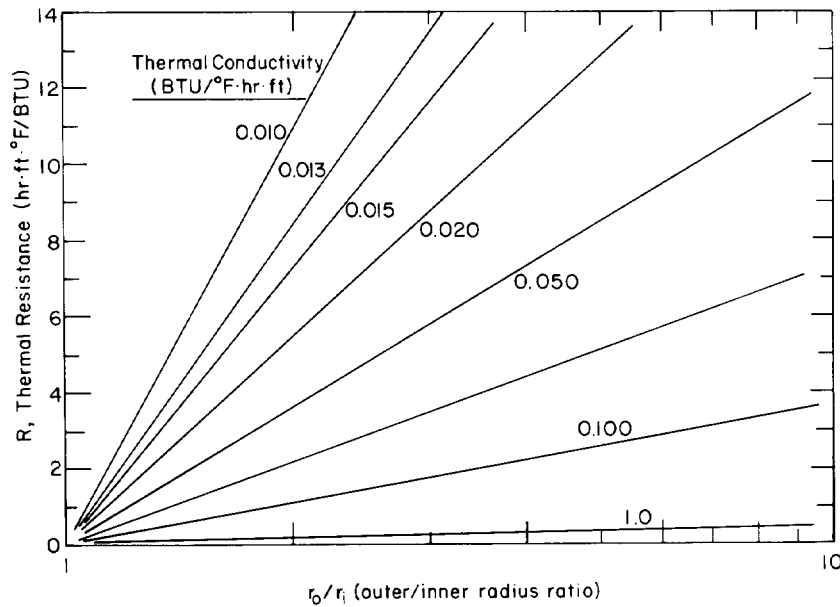
tions, in addition to the implied time-independent steady-state assumptions, are indicated. Some comments intended to facilitate application of the equations are also included. Where applicable, procedures are given for relevant thermal resistance, rates of heat flow and insulation thicknesses.

(2) Figure 12-6 gives similar information for uninsulated and insulated buried pipes. In each of these two cases, the presence of thawed ground around the pipe is considered, and equations are included to determine the dimensions of the resulting thaw cylinder.

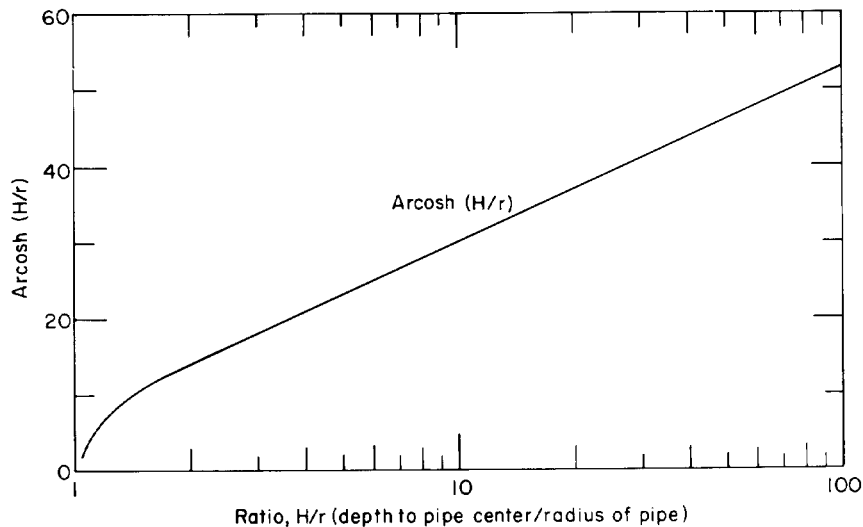
(3) Figure 12-7 presents procedures for cal-

culating the thermal resistance of typical shapes and bodies. Equations are given in figure 12-4 for estimating the temperature drop (or gain) along a pipeline system, and simple procedures to determine freeze-up times under no-flow conditions are included.

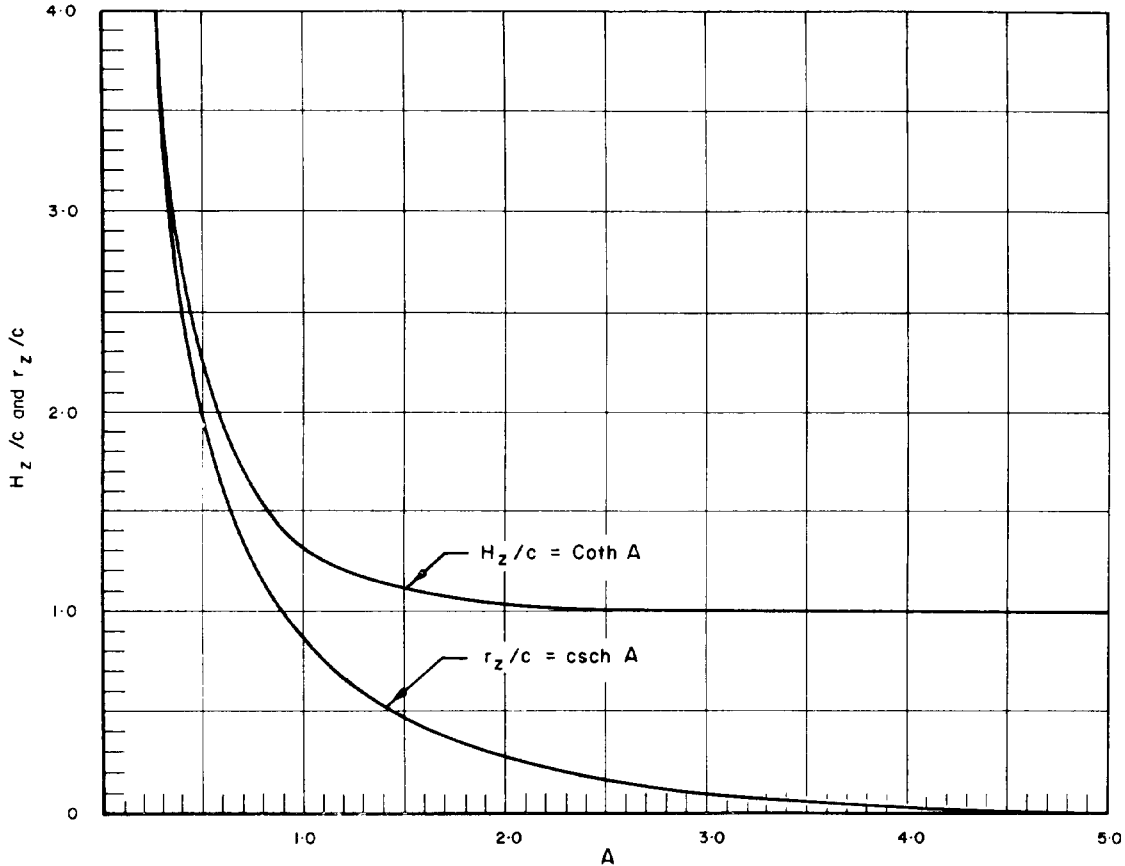
(4) To facilitate computation, numerical values for certain variables in some of the calculations may be read directly from figures 12-8, 12-9 and 12-10. These curves present a partial solution for some of the heat loss equations. Their use is demonstrated in paragraphs 12-9d and f.



U.S. Army Corps of Engineers *Figure 12-8. Thermal resistance of a hollow cylinder, solution to the equation $R = \ln(r_o/r_i)/2\pi k$.*



U.S. Army Corps of Engineers *Figure 12-9. Arcosh (H/r) versus H/r for solution of thaw zone equations.*



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Figure 12-10. (H_z/c) and (r_z/c) versus A factor for solution of thaw zone equations.

(5) Steady-state thermal influences in isotropic, homogenous soils can be summed and geometric modifications and approximations can be made to the basic steady-state equations. For example, a layered soil can be represented by an “effective” soil thickness with the same total thermal resistance as the layered soil. When pipes are buried below the area influenced by short-term air temperature fluctuations, the ground temperatures around the pipeline resemble a slowly changing series of steady-state conditions. The heat loss from deeply buried pipes can be calculated from steady-state equations for a cylinder of material around a pipe if the fluid temperature and the soil temperature at a known distance from the pipe are measured, and the soil and insulation thermal conductivities are known. Heat loss from deep pipes can also be conveniently estimated by replacing the ground surface temperature in the steady-state equations with the undisturbed ground temperature at the pipe depth. Heat loss from a buried pipe over a time

period can be calculated from the heating index during that period (see paragraph 12.9h):

$$\text{Heat loss} = \frac{I}{R} \quad (\text{eq 12-1})$$

$$\text{or} = \frac{\Sigma (\text{Pipe temperature} - \text{Ambient temperature})}{\text{Thermal resistance}} \quad (\text{eq 12-2})$$

where

- I = heating index °F (time period).
- R = thermal resistance hr•ft•°F/BTU.

b. *Depth of freezing or thawing.* The depth of freezing or thawing of soil and the ice thickness on water bodies are best obtained by field measurements, but they can be estimated using one of the many analytical solutions available. Because of the assumptions necessary in these analytical

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solutions, such as assuming a step change in surface temperature or neglecting the soil temperature changes, they generally overestimate the maximum freezing isotherm depths for the given conditions and are, therefore, conservative for engineering applications. They are generally Neumann or Stefan-based solutions which have the basic form:

$$X = m(I_g)^{1/2} \quad (\text{eq 12-3})$$

where

X = depth of freezing or thawing, feet

m = coefficient of proportionality

I_g = ground surface freezing (I_f) or thawing (I_t) index, $^{\circ}\text{F}\cdot\text{hr}$

The following equations incorporate various assumptions, and are useful for specific conditions:

$$X = \left(\frac{2k \cdot I_g}{L} \right)^{1/2} \quad (\text{eq 12-4})$$

$$X = \left(\frac{2k \cdot I_g}{L + C \left(T_m - T_o + \frac{I_g}{2t} \right)} \right)^{1/2} \quad (\text{eq 12-5})$$

$$X = \left(\left(\frac{k_2}{k_1} d_1 \right)^2 + \frac{2k_2 \cdot I_g - \frac{d_1^2 \cdot L_1}{2k_1}}{L_2} \right)^{1/2} - \left(\frac{K_2 - 1}{K_1} \right) (d_1) \quad (\text{eq 12-6})$$

$$X = \left(\frac{2k \cdot I_g}{L} \right)^{1/2} \left(1 - \frac{C \cdot I_g}{8L \cdot t} \right) \quad (\text{eq 12-7})$$

$$X = \lambda \left(\frac{2k \cdot I_g}{L} \right)^{1/2} \quad (\text{eq 12-8})$$

where

k = thermal conductivity of the material above the freezing isotherm, k_f for frost penetration and k_t for thawing calculations, BTU/hr·ft· $^{\circ}\text{F}$.

L = volumetric latent heat of the material undergoing phase change, BTU/cf (for water $L = [(144 \text{ BTU/lb}) (62.4 \text{ pcf})] = 8986 \text{ BTU/cf}$)

C = volumetric heat capacity of the material above the freezing isotherm, C_f or C_t . For thawed soil: $C_t = \gamma [C_s + C_w (w/100)]$ and for frozen soil: $C_f = \gamma [C_s + C_i (w/100)]$

γ = dry unit weight of soil, pcf

C_s = mass heat capacity of mineral matter in soil; assume a value of 0.2 BTU/lb

C_w = mass heat capacity of water = 1.0 BTU/lb

C_i = mass heat capacity of ice, assumed value of 0.5 BTU/lb

w = moisture content of soil, %

T_m = mean annual site temperature, $^{\circ}\text{F}$

t = freezing or thawing period, consistent units

T_o = freezing point, 32°F for water

d = thickness of layer of material, feet

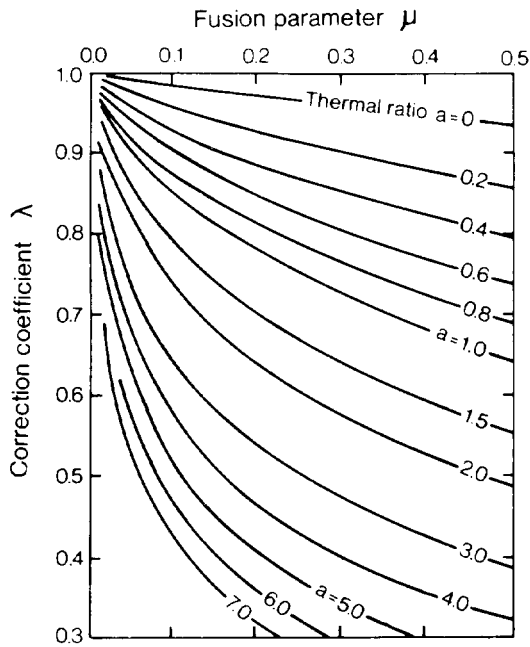
λ = a correction coefficient which takes into consideration the effect of temperature change in the soil, and primarily accounts for the volumetric specific heat effects. It is a function of two parameters: the thermal ratio (a) and the fusion parameter (μ), and is determined from figure 12-11:

$$a = \frac{(T_m - T_o)}{T_m} = \frac{(T_m - T_o) \cdot t}{I_g}$$

$$\mu = \frac{C \cdot I_g}{L \cdot t}$$

T_s = I_g/t , surface freezing or thawing index divided by the time period t , $^{\circ}\text{F}$.

Subscripts f and t refer to freezing and thawing, and subscripts 1 and 2 refer to the surface layer and the underlying material (all symbols are also defined in table 12-1).



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Figure 12-11. Correction coefficient λ, for use in Berggren equation.

(1) Equation 12-4 is the Stefan solution for a homogeneous material with a step change in surface temperature (see example 12-9a). This is modified in equation 12-5 to account for the temperature change in the freezing or thawing soil. Equation 12-6 is a two-layer solution of the Stefan equation that is useful for calculations involving snow cover, a gravel pad or a board of thermal insulation, in which the surface layer has no latent heat and the equation is simplified (see para 12-9b and c). Equation 12-7 is a close approximation of the Neumann solution when the ground temperatures are near freezing. Equation 12-8, the modified Berggren equation, is perhaps the most commonly used approach for determining thermal responses of soils. When the soil has a high moisture content the X coefficient approaches unity, and the equation is identical to the Stefan approach (equation 12-4). In climates where the mean annual temperature is near or below freezing, the thermal ratio approaches zero and the [A] coefficient is greater than 0.9. In very dry soils, the soil warming or cooling can be significant and should be included. Multilayered soil systems can be solved by determining that portion of the surface freezing or thawing index required to penetrate each layer. The sum of the thicknesses of the frozen or thawed layers whose indices equal the total index is equal to the depth of freeze or thaw. The partial freezing or thawing index to penetrate the nth layer is

$$I_n = \frac{L_n \cdot d_n}{\lambda^2} \sum_{1}^{n-1} R + \frac{R_n}{2} \quad (\text{eq 12-9})$$

where

I_n = the partial freezing or thawing index required to penetrate the nth layer, °F•hr

L_n = volumetric latent heat in the nth layer, BTU/ft³

d^n = thickness of the nth layer, ft

λ = the coefficient based on the weighted average values for μ down to and including the nth layer (see figure 12-13)

$\sum_{1}^{n-1} R + \frac{R_n}{2}$ = the sum of the thermal resistances of the layers above the nth layer

$R_n = d_n/k_n$, the thermal resistance to the nth layer, hr • ft • °F/BTU.

(2) The solution for multi-layered systems is facilitated by tabular arrangement of the intermediate values. The penetration into the last layer must be solved by trial and error to match the total freezing or thawing index at the site. It is necessary to determine the temperature condition at the ground surface to determine subsurface thermal effects, including the depth of freezing and thawing. Since air temperatures are readily available, but surface temperatures are not, a correlation factor which combines the effects of radiation, and convective and conductive heat exchange at the air-ground surface is used:

$$I_g = n \cdot I_a \quad (\text{eq 12-10})$$

where

I_g = ground surface freezing or thawing index, °F • hr

I_a = air freezing or thawing index, °F • hr

n = n-factor, ratio of the surface and air temperature indices.

The n-factor is very significant in analytical ground thermal considerations. It is highly variable and is usually estimated from published observations such as the values listed in Table 12-3.

Table 12-3. Typical values of the n-factor for correlation of air temperature with surface temperature of various materials (see eq 12-10).

Surface	n-factors		
	Thawing	Freezing	
Snow	.....	1.0	General application
Pavement free of snow and ice	.....	0.9	General application
Sand and gravel	2.0	0.9	General application
Turf	1.0	0.5	General application
Spruce	0.35 to 0.53	0.55 to 0.9	Thompson, Manitoba
Spruce trees, brush	0.37 to 0.41	0.28	Fairbanks, Alaska
Above site, cleared, moss surface	0.73 to 0.78	0.25	Fairbanks, Alaska
Stripped, mineral soil surface	1.72 to 1.26	0.33	Fairbanks, Alaska
Spruce	0.76	.....	Inuvik, NWT
Willows	0.82	.....	Inuvik, NWT
Weeds	0.86	.....	Inuvik, NWT
Gravel fill slope	1.38	0.7	Fairbanks, Alaska
Gravel road	1.99	.....	Fairbanks, Alaska
Concrete road	2.03	.....	Fairbanks, Alaska
Asphalt road	1.74 to 2.70	.....	Fairbanks, Alaska
White painted surface	0.76 to 1.25	.....	Fairbanks, Alaska
Peat bales on road	1.44 to 2.28	.....	Fairbanks, Alaska
Dark gravel	1.15 to 1.73	.....	Fairbanks, Alaska

(3) Ice thickness on water bodies can be estimated from the previous depth of freezing equations or from equations 12-3 with the m values in table 12-4 (see example 12-9a). Snow cover has a significant insulating effect and can significantly reduce the maximum ice thickness (see example 12-9b). The ice formation can be greater than calculated if the weight of snow or the lowering of the water level causes cracks in the ice and water overflows onto the surface. This water is drawn into the snow and the mixture refreezes and bonds to the original ice.

Table 12-4. m-factors for ice thickness estimation

m-factor inch [°F·d] ^{1/2}	Conditions
0.9 - 0.95	Practical maximum for ice not covered with snow
0.8	Windy lakes with no snow
0.7 - 0.8	Medium-sized lakes with moderate snow cover
0.6 - 0.65	Rivers with moderate flow
0.4 - 0.5	River with snow
0.2 - 0.4	Small river with rapid flow

12-9. Design examples.

Eight typical examples are given below to illustrate the utilization of the calculation procedures described above.

a. Estimate the practical maximum ice thickness on a water reservoir with no snow cover when the annual air freezing index (I_g) is 3000 °F · d. Use equation 12-3:

$$x = m(I_g)^{1/2}$$

—From table 12-4, m = 0.95 inch/(°F)^{1/2}(d)^{1/2}

$$\begin{aligned} x &= (0.95)(3000)^{1/2} \\ &= 52 \text{ inches} \\ &= 4.33 \text{ feet.} \end{aligned}$$

—The Stefan equation (equation 12-4) can also be used:

$$x = \left(\frac{(2k)(I_g)}{L} \right)^{1/2}$$

where

k = thermal conductivity of material above the freezing isotherm, ice in this case, so from table 12-2:

$$k_{\text{ice}} = 1.28 \text{ BTU/ft} \cdot \text{hr} \cdot \text{°F}$$

L = volumetric latent heat of material undergoing phase change, in this case water, so:

$$\begin{aligned} \text{Latent heat of water at } 32\text{°F} &= \\ &144 \text{ BTU/lb} \end{aligned}$$

$$\text{Density of water at } 32\text{°F} = 62.4 \text{ lb/ft}^3$$

$$L = (144 \text{ BTU/lb})(62.4 \text{ lb/ft}^3) = 8985.6 \text{ BTU/ft}^3$$

$$I_g = (3000\text{°F} \cdot \text{d})(24 \text{ hr/day}) = 72,000 \text{ °F} \cdot \text{hr}$$

$$\begin{aligned} X &= \left[\frac{(2)(1.28 \text{ BTU/ft} \cdot \text{hr} \cdot \text{°F})(72,000 \text{ °F} \cdot \text{hr})}{8986 \text{ BTU/ft}^3} \right]^{1/2} \\ &= 4.5 \text{ ft.} \end{aligned}$$

b. Estimate the ice thickness on the reservoir when there is an 8-inch snow cover on top of the ice and $I_g = 3000 \text{ }^\circ\text{F} \cdot \text{d}$.

—From equation 12-3, and Table 12-4:

$$\begin{aligned} X &= m(I_g)^{1/2} \\ &= 0.7(3000)^{1/2} \\ &= 38 \text{ inches} \\ &= 3.2 \text{ ft.} \end{aligned}$$

—Or, use the Stefan equation (equation 12-6) for a two-layer system:

$$X = \left[\left(\frac{k_2}{k_1} d_1 \right)^2 + \frac{(2k_2)(I_g) - \frac{(d_1)^2(L_1)}{2k_1}}{L_2} \right]^{1/2} - \left(\frac{k_2}{k_1} - 1 \right) (d_1)$$

—The first layer is snow, $d_1 = 8 \text{ inches} = 0.667 \text{ feet}$, assumed to be drifted and compact. From table 12-2, $k_1 = 0.4 \text{ BTU/ft} \cdot \text{hr} \cdot \text{ }^\circ\text{F}$. Since no phase change occurs in the snow, $L_1 = 0$.

—Ice: $k_2 = 1.28 \text{ BTU/ft} \cdot \text{hr} \cdot \text{ }^\circ\text{F}$
 $L_2 = (144)(62.4) = 8986 \text{ BTU/ft}^3$

$$\begin{aligned} X &= \left[\left(\frac{1.28}{0.4} \right) (0.667) \right]^2 + \frac{2(1.28) \cdot (3000)(24)}{8986} \right]^{1/2} \\ &\quad - \left(\frac{1.28}{0.4} - 1 \right) (0.667) \\ &= \sqrt{4.55+20.5} - 1.47 \\ &= 3.5 \text{ ft (includes the 8 in. of snow).} \end{aligned}$$

c. The Stefan equation (equation 12-6) can also be used to estimate the depth of frost penetration beneath a gravel pad or an insulation board. The L_1 in either case would be zero. The L_2 in this example would be the latent heat of fusion for the soil and would be dependent on the moisture content in the soil.

—Assume: sandy soil, dry density 125 pcf, moisture content 6% and a freezing index (I_g) = 3000 $^\circ\text{F} \cdot \text{d}$

—Find depth of frost penetration under 3-inch-thick polystyrene board. From table 12-2:

$k_1 = 0.020 \text{ BTU/ft} \cdot \text{ }^\circ\text{F} \cdot \text{hr}$ (for polystyrene),
 $k_2 = 1.0 \text{ BTU/ft} \cdot \text{ }^\circ\text{F} \cdot \text{hr}$ (for sand) and thus
 $d_1 = 3/12 = 0.25 \text{ feet}$. The moisture content in the soil = $(0.06)(125 \text{ pcf}) = 7.5 \text{ lb water/ft}^3 \text{ soil}$.

Latent heat of water = 144 BTU/lb

$L_2 = (144 \text{ BTU/lb})(7.5 \text{ lb/ft}^3) = 1080 \text{ BTU/ft}^3 \text{ of soil}$

$L_1 = 0$

$$X = \left[\left(\frac{k_2}{k_1} d_1 \right)^2 + \frac{2k_2 I_g}{L_2} \right]^{1/2} - \left(\frac{k_2}{k_1} - 1 \right) (d_1)$$

$$\begin{aligned} X &= \left[\left(\frac{1.00}{0.020} \right) (0.25) \right]^2 + \frac{(2)(1.00)(3000)(24)}{1080} \right]^{1/2} \\ &\quad - \left(\frac{1.00}{0.020} - 1 \right) (0.25) \\ &= \sqrt{156+133} - 12.25 \\ &= 4.75 \text{ ft.} \end{aligned}$$

—The depth of frost penetration would be 11.5 feet in the same soil, under the same conditions, if the insulation board were not in place.

d. Determine the rate of heat loss per linear foot of above-ground pipe from a 5-inch-ID (wall thickness 1/2 inch) plastic pipe encased in a 2-inch thickness of polyurethane insulation. Water inside the pipe is maintained at 40 $^\circ\text{F}$, ambient air temperature is -40 $^\circ\text{F}$, and wind speed is 15 mph. Thermal conductivity of pipe material is 0.208 BTU/ $^\circ\text{F} \cdot \text{ft} \cdot \text{hr}$ and thermal conductivity q of the insulation material is 0.0133 BTU/ $^\circ\text{F} \cdot \text{ft} \cdot \text{hr}$.

— Use equations a and b from figure 12-4:

$$\text{Thermal resistance of pipe } R_p = \frac{\ln(r_{out}/r_{in})}{(2)(\pi)(k_p)}$$

Inside radius = $r_{in} = 2.5 \text{ inch}$

Outside radius = $r_{out} = 2.5 + 0.5 = 3.0 \text{ inch}$

$$R_p = \frac{\ln(3.0/2.5)}{(2)(3.14)(0.208)} = \frac{0.182}{1.306}$$

$$= 0.139 \text{ hr ft F/BTU}$$

— Thermal resistance of insulation

$$R_i = \frac{\ln(r_{out}/r_{in})}{2\pi k_i}$$

Inside radius, $r_{in} = 3$ inches
 Outside radius, $r_{out} = 5$ inches

$$R_i = \frac{\ln(5/3)}{(2)(3.14)(0.0133)}$$

$$= 6.115 \text{ hr} \cdot \text{ft} \cdot \text{°F/BTU.}$$

— To determine the thermal resistance of the air film (R_A) it is necessary to estimate the surface conductance (h_a). From figure 12-4a:

$$h_a = N \left[\frac{T_s - T_A}{r_p} \right] W.$$

— From figure 12-4a, $N = 0.23$ and $w = (12.5V+1)^{1/2}$ where $V =$ windspeed, mph:

$$W = ((12.5)(15)+1)^{1/2}$$

$$= 13.73$$

— In this case R_p is to the outer surface of the insulation $= 5/12 = 0.417$ ft. For the first iteration one must assume a surface temperature (T_s). This will be close to air temperature. Assuming $T_s = -39^\circ\text{F}$, then:

$$h_a = (0.23) \left[\frac{-39 - (-40)}{0.417} \right] (13.73)$$

$$= 7.573 \text{ BTU/hr} \cdot \text{°F}\cdot\text{ft}$$

— Then, to calculate thermal resistance of air film:

$$R_A = \frac{1}{2\pi r_p h_a}$$

$$= \frac{1}{(2)(3.14)(0.417)(7.573)}$$

$$= 0.0504 \text{ hr}\cdot\text{ft}\cdot\text{°F/BTU}$$

— Then, check the assumed air film temperature:

$$T_s = T_A + [T_w - T_A] \left[\frac{R_A}{R_A + R_i + R_p} \right]$$

$$= -40 + [40 - (-40)] \left[\frac{0.0504}{0.504 + 6.116 + 0.1396} \right]$$

$$= -40 + (80)(0.00799)$$

$$= -39.4 \text{ vs assumed } -39.0, \text{ which is close enough.}$$

— If the values did not check it would be necessary to repeat the calculation with another assumed T_s until a reasonable check is attained. The combined thermal resistance (R_c) is

$$R_c = R_A + R_i + R_p$$

$$= 0.0504 + 6.116 + 0.1296$$

$$= 6.306 \text{ hr}\cdot\text{ft}\cdot\text{°F/BTU.}$$

—The rate of heat loss (Q) is

$$Q = \frac{(T_w - T_A)}{R_c}$$

$$= \frac{(40 - (-40))}{6.306}$$

$$= 12.7 \text{ BTU/hr}\cdot\text{linear foot of pipe.}$$

—Figure 12-8 can be used to obtain an estimate of heat loss if it is assumed that the thermal resistance of the air film and of the pipe material are negligible:

$$\frac{r_{out}}{r_{in}} = \frac{5}{3} = 1.667$$

$$K_1 = 0.0133 \text{ BTU/f}\cdot\text{°F}\cdot\text{hr.}$$

—Then, enter figure 12-8 with these values and

$$R = 6.4.$$

$$\text{—So: } Q = \frac{[40 - (-40)]}{6.4}$$

$$= 12.5 \text{ BTU/hr linear foot (LF) of pipe.}$$

e. Compare the heat losses for the water pipe in the example above if installed at Barrow, Alaska,

above ground or at a depth of 4 feet. Assume the minimum air temperature is -58°F , and the minimum mean daily soil temperature at a depth of 4 ft is 1.4°F . Thermal conductivity of soil is $1.2 \text{ BTU/ft}\cdot\text{hr}\cdot^{\circ}\text{F}$.

(1) *Above-ground installation.* Assume a 5-inch ID plastic pipe, with 2 inches of polyurethane insulation:

$R_c = 6.306 \text{ hr}\cdot\text{ft}\cdot^{\circ}\text{F}/\text{BTU}$ (from previous example).

—The water inside pipe will be maintained at 40°F , so that the maximum rate of heat loss

$$\begin{aligned} Q &= \frac{(T_w - T_A)}{R_c} \\ &= \frac{[40 - (-58)]}{6.306} \\ &= 15.5 \text{ BTU/hr}\cdot\text{LF pipe.} \end{aligned}$$

(2) *Buried installation.* Assume that the top of the pipe is 4 feet below the surface, the radius to the outer surface = 5 in. = 0.416 feet, the depth to center of the pipe $H_p = 4.416 \text{ ft}$, and the radius of pipe = 0.416 feet (see equations, fig 12-5a) and H_p is $> 2r_p$. So the thermal resistance of the soil (R_s) is

$$\begin{aligned} R_s &= \frac{\ln(2H_p/r_p)}{2\pi k_k} \\ R_s &= \frac{\ln[(2)(4.416/0.416)]}{(2)(3.14)(1.2)} \\ &= 0.405 \text{ hr}\cdot\text{ft}\cdot^{\circ}\text{F}/\text{BTU.} \end{aligned}$$

—The air film is not a factor for a buried pipe of this type so the combined resistance R_c equals

$$\begin{aligned} R_c &= R_p + R_i + R_s \\ &= 0.1396 + 6.116 + 0.405 \text{ (} R_p \text{ and } R_i \text{ from previous example)} \\ &= 6.661 \text{ hr}\cdot\text{ft}\cdot^{\circ}\text{F}/\text{BTU.} \end{aligned}$$

—So, the heat loss Q equals

$$\begin{aligned} Q &= \frac{(T_w - T_A)}{R_c} \text{ (} T_A \text{ in this case is soil temperature } 1.4^{\circ}\text{F)} \\ &= \frac{(40 - 1.4)}{6.661} \end{aligned}$$

$$= 5.79 \text{ BTU/hr}\cdot\text{linear foot (LF) of pipe.}$$

—This is about one-third the heat loss rate calculated for an above-ground installation in the same location. The responsible factor is the attenuation of the extreme surface temperature at the 4-foot depth.

f. Determine the mean size of the thaw zone and the average rate of heat loss from a 6-inch steel pipe buried 4 feet below the surface in a clay soil, where the soil thermal conductivities are k_f (thawed) = $0.60 \text{ BTU/hr}\cdot\text{ft}\cdot^{\circ}\text{F}$ and k_f (frozen) = $1.0 \text{ BTU/hr}\cdot\text{ft}\cdot^{\circ}\text{F}$. Mean soil temperature at the ground surface is 27.5°F and the water in the pipe is maintained at 45°F . (See figure 12-8b, for schematic, symbols and equations.) A bare steel pipe has negligible thermal resistance so

$$R_p = 0.$$

—Outer pipe radius $r_p = 6 \text{ inch}/(2)(12) = 0.25 \text{ ft}$

—Depth to center of pipe $H_p = 4.0 \text{ ft}$.

$$T'_w = \frac{k_t}{k_f} (T_w - T_o) + T_o$$

where

T_w = water temperature inside pipe

T_o = soil temperature at interface of thawed zone

$$= 32^{\circ}\text{F}$$

$$T'_w = \left(\frac{0.6}{1.0}\right) (45 - 32) + 32 = 39.8^{\circ}\text{F}$$

$$T' = \frac{T_o - T_G}{T'_w - T_G}$$

T_G = temperature and ground surface

$$= \frac{(32 - 27.5)}{(39.8 - 27.5)} = \frac{4.5}{12.3} = 0.366^{\circ}\text{F.}$$

—Depth to center of thawed zone, H_2 :

$$H_2 = (c)(\coth A)$$

—Radius of thawed zone, r_2 :

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$$r_2 = (c)(\text{csch } A)$$

$$c = (H_p^2 - r_p^2)^{1/2} = [(f)^2 - (0.25,2)^{1/2} = 399 \text{ ft}$$

$$A = T' \text{ arccosh } (H_p/r_p)$$

—If $H_p \geq 2r_p$

$$A \approx T' \ln (2H_p/r_p)$$

$$= (0.366)(\ln 8/0.25)$$

$$= (0.366)(3.466)$$

$$= 1.268$$

$$H_2 = (3.99)(\text{coth } 1.268)$$

$$= (3.99)(1.172)$$

$$= 4.68 \text{ ft}$$

$$r_2 = (3.99)(\text{csch } 1.268)$$

$$= (3.99)(0.5215)$$

$$= 2.08 \text{ ft.}$$

—The thaw zone, under steady state conditions will be a cylinder of soil enclosing, and parallel to, the pipe. The radius of this zone will be about 2 feet and the axis will be about 5 inches below the bottom of the pipe:

The axis = $H_2 - (H_p + r_p) = 4.68 - 4.25 = 0.43 \text{ ft} = 5.2 \text{ in. below pipe}$

The heat loss (Q) from this pipe would be

$$Q = \frac{T'_w - T_o}{R_s}$$

$$R'_s = \frac{\text{arccosh}(h_p/r_p)}{(2)(k_r)(\pi)}$$

If $H_p \geq 2r_p$:

$$R' = \frac{\ln(2h_p/r_p)}{(2)(k_r)(\pi)}$$

$$= \frac{\ln(8/0.25)}{(2)(1.0)(3.14)}$$

$$= \frac{3.466}{6.28} = 0.552 \text{ hr}\cdot\text{ft}\cdot^\circ\text{F}/\text{BTU}$$

$$Q = \frac{(39.8 - 27.5)}{0.552}$$

$$= 22.3 \text{ BTU/hr LF of pipe.}$$

—Figures 12-9 and 12-10 can be used to assist in calculations of this type:

$$\frac{H_p}{r_p} = \frac{4}{0.25} = 16, \text{ From figure 12-9, arccosh } \left(\frac{H}{r}\right) = 3.48$$

$$A = T' \left(\text{arccosh } \left(\frac{H_p}{r_p}\right)\right) = (0.366)(3.48)$$

$$= 1.27.$$

—Then from figure 12-10, with $A = 1.27$

$$\frac{H_2}{c} = 1.18$$

$$\frac{r_2}{c} = 0.6$$

$$c = [(H_p)^2 - (r_p)^2]^{1/2} = [16 - 0.0625]^{1/2} = 3.99 \text{ ft.}$$

—So:

$$H_2 = (1.18)(3.992) = 4.7 \text{ ft}$$

$$r_2 = (0.6)(3.992) = 2.39 \text{ ft}$$

and

$$R'_s = \frac{\text{arccosh}(H_p/r_p)}{(2)(k_r)(\pi)} = \frac{3.48}{(2)(1)(3.14)}$$

—So:

$$Q = \frac{(39.8 - 27.5)}{0.554}$$

$$= 22.2 \text{ BTU/hr LF of pipe.}$$

This agrees closely with the 22.3 BTU/hr value determined previously.

g. Determine the design time, the safety factor time and the complete freezing time for the pipe designed in paragraph 12-9d if the water stopped flowing. From paragraph 12-9d, assume a 5-inch ID plastic pipe with 2-inch polyurethane insulation, constructed above ground. Water temperature $t_w = 40^\circ\text{F}$, air temperature $T_A = -40^\circ\text{F}$, and wind speed 15 mph. Use equations from figure 12-4.

—Design time = time for water in pipe to drop to freezing temperature (32°F); see figure 12-4 for definition of terms.

$$t_0 = \pi r_w^2 \cdot R \cdot C \cdot \ln [(T_1 - T_A)(T_2 - T_A)]$$

$$\begin{aligned} \text{Design time} &= (3.14)(0.208)^2(6.306)(62.4) \\ &\quad \left[\ln \left(\frac{40 - (-40)}{32 - (-40)} \right) \right] \\ &= (53.5)(0.105) \\ &= 5.6 \text{ hr} \end{aligned}$$

—Safety factor time = time for water in pipe to reach nucleation temperature for ice formation. Assume 27°F .

Substitute 27°F for T_2 in previous equation:

$$\begin{aligned} \text{Safety factor time} &= (3.14)(0.208)^2(6.306)(62.4) \\ &\quad \left[\ln \left(\frac{40 - (-40)}{27 - (-40)} \right) \right] \\ &= (53.5)(0.177) \\ &= 9.5 \text{ hr.} \end{aligned}$$

— Complete freezing time = time for water at 32°F in pipe to freeze completely solid.

$$= \frac{(\pi)(r_w)^2(R_c)(L)}{(T_2 - T_A)}$$

$$\begin{aligned} L &= \text{volumetric latent heat of water} \\ &= (144 \text{ BTU/lb})(62.4 \text{ lb/ft}^3) \\ &= 8986 \text{ BTU/ft}^3. \end{aligned}$$

Other factors are as defined above.

—Complete freezing time

$$\begin{aligned} &= \frac{(3.14)(0.208)^2(6.306)(8986)}{[32 - (-40)]} \\ &= \frac{7698}{72} \\ &= 107 \text{ hours.} \end{aligned}$$

h. Estimate the total annual heat loss from the above-surface pipe design described in paragraphs 12-9d and e if it were located at Barrow, Alaska. The maximum rate of heat loss (Q) was calculated in paragraph 12-9e for extreme winter conditions. Extrapolation of that rate to an annual value would seriously overestimate the total heat losses. An estimate is possible by determining the annual heating index (equation 12-1). Mean monthly temperatures ($^\circ\text{F}$) for Barrow, Alaska, are:

J	F	M	A	M	J	J	A	S	O	N	D
-9	-13	-11	2	11	30	40	37	32	16	5	-6

—The temperature of water in pipe $T_w = +40^\circ\text{F}$
 —Heating index = $\sum(T_w - T_A)$ (equation 12-2)
 —Tabulate heating index by months:

Jan	[40 - (-40)]	= 80
Feb	[40 - (-13)]	= 53
Mar	[40 - (-22)]	= 62
Apr	(40 - 2)	= 38
May	(40 - 11)	= 29
June	(40 - 30)	= 10
July	(40 - 40)	= 0
Aug	(40 - 37)	= 3
Sept	(40 - 32)	= 8
Oct	(40 - 16)	= 24
Nov	(40 - 5)	= 35
Dec	[40 - (-6)]	= 46

—Heating index = $388^\circ\text{F}\cdot\text{month}$

$$\begin{aligned} &= (388^\circ\text{F}\cdot\text{month}) \left(30.4 \frac{\text{average days}}{\text{month}} \right) \\ &\quad (24 \text{ hr/day}) \\ &= 283,0850\text{Fhr} \end{aligned}$$

$$R_c = 6.306 \text{ hr}\cdot\text{ft}\cdot^\circ\text{F}/\text{BTU} \text{ (see example 12-9d)}$$

—Annual heat loss = heating index/ R_c
 $= 44,891 \text{ BTU/yr}\cdot\text{linear foot of pipe.}$

This is considerably less than extrapolation of the

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maximum heat loss rate calculated in paragraph 12-9e (134,904 BTU/yr LF pipe).

i. Determine the economical thickness of insulation for an above-ground 6-inch-OD water main to be located at Barrow, Alaska (temperature conditions as defined in paragraph 12-9f). Assume fuel oil cost (140,000 BTU/gallon) at \$1.05/gallon, and an 85% efficient heating plant. Assumed installed costs of polyurethane foam are tabulated below for various available thicknesses. Thermal conductivity for polyurethane is 0.014 BTU/ft•hr•°F. Assume a 20-year design life at an interest rate of 8%.

—Neglecting air film and steel pipe material, the combined thermal resistance is

$$R_c = \frac{\ln(r_{out}/0.25)}{(2)(\pi)(k)}$$

$$= \frac{\ln(r/0.25)}{(2)(3.14)(0.014)}$$

$$= (11.37) [\ln(r/0.25)]$$

—The heating index for Barrow, Alaska, would be 275,059 °F•hr (see example 12-9g).

$$\text{—The cost of heat} = \frac{\$1.05/\text{gal.}}{(140,000 \text{ BTU/gal})(0.85)}$$

$$= \$0.0000088/\text{BTU}$$

—The economical thickness will have the lowest total cost for construction plus the present worth of the annual heating costs:

Present worth factor

$$(\text{PWF}) = \frac{[(1+i)^n - 1]}{(i)(1+i)^n}$$

where i = interest rate (as a decimal)

n = design period

for i = 0.08 and n = 20

$$\text{PWF} = \frac{[1.08^{20} - 1]}{(0.08)(1.08)^{20}} = 9.818.$$

—Present worth of heating costs = heating index/R_c x (PWF)(cost of heat)

$$= \frac{275,059}{(11.37) [\ln(r/0.25)]} (0.0000088)(9.818)$$

$$= \frac{2.09}{\ln(r/0.25)} \text{ \$/ft}$$

at an insulation thickness of 1 in., r = (1/12 in.) + (0.25 ft) = 0.33 ft. Therefore, the present worth of heating costs

$$= \frac{2.09}{\ln(0.33/0.25)}$$

$$= \$7.53/\text{linear foot.}$$

—Repeat calculations, and tabulate, for typical insulation thickness:

Insulation thickness (in.)	Present worth of heat (\$/ft)
1	7.53
2	4.09
3	3.02
4	2.47
5	2.13

—Installation costs for polyurethane insulation (assumed for this example only, obtain from suppliers in actual case):

Insulation thickness (in.)	Installation Costs (\$/ft)
1	3.60
2	4.70
3	5.40
4	6.20
5	7.10

—Combining heating and construction costs give:

Insulation thickness (in.)	Total Present Worth of Costs (\$/ft)
1	11.13
2	8.79
3	8.42
4	8.67
5	9.23

—Plot these results on arithmetic graph paper to determine the lowest cost. Then select the available nominal thickness of insulation that is closest to the graphical value. In this case a 3-inch thickness would be the most cost effective for the conditions assumed.

APPENDIX A REFERENCES

Government Publications.

Departments of the Army, the Navy and Air Force

TM 5-349	Arctic Construction
TM 5-811-1/AFM 88-9, Chap. 1	Electrical Power Supply and Distribution
TM 5-812-1	Fire Prevention Manual
TM 5-813-1/AFM 88-10, Vol. 1	Water Supply: Sources and General Considerations
TM 5-813-3/AFM 88-10, Vol. 3	Water Supply: Water Treatment
TM 5-813-4/AFM 88-10, Vol. 4	Water Supply: Water Storage
TM 5-813-5/AFM 88-10, Vol. 5	Water Supply: Water Distribution
TM 5-814-1/AFM 88-11, Vol. 1	Sanitary and Industrial Wastewater Collection — Gravity Sewers and Appurtenances
TM 5-814-2/AFM 88-11, Vol. 2	Sanitary and Industrial Wastewater Collection — Pumping Stations and Force Mains
TM 5-814-3/AFM 88-11, Vol. 3	Domestic Wastewater Treatment
TM 5-852-1/AFR 88-19, Vol. 1	Arctic and Subarctic Construction: General Provisions
TM 5-852-4/AFM 88-19, Ch. 4	Arctic and Subarctic Construction: Foundations for Structures
TM 5-852-6/AFR 88-19, Vol. 6	Arctic and Subarctic Construction: Calculation Methods for Determination of Depths of Freeze and Thaw in Soils
NAVFAC OM-9	Cold Regions Engineering Design Manual
<i>U.S. Environmental Protection Agency</i> Cincinnati, OH 45258	Cold Climate Utilities Delivery Design manual (EPA 600/8-79-027) (Reprint of Canadian EPS 3-WP-79-2).
	Manual of Water Well Construction Practices EPA 570/9-75—00 1.
	Process Design Manual for Wastewater Treatment Facilities in Small Sewered Communities, EPA 625/1-77-009.
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