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# A WATER DISTRIBUTION SYSTEM
# FOR COLD REGIONS

## - The Single Main Recirculating Method -

## An Historical Review, Field Evaluation, and Suggested Design Procedures

A water distribution system for cold regions: The Single Main Recirculating method: An historical review, field evaluation and suggested design procedures
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# PREFACE

> *It is difficult to impress upon the public and industry at large that the most essential quality of the Arctic is not cold, or gold, or polar bears, but a central position in the world community. Michael Marsden in* THE ARCTIC FRONTIER(1)*

Students and residents of the Arctic are familiar with the many problems peculiar to the geographical area. This monograph will consider an adequate, safe, and reliable water distribution system. Water supply, together with housing, transportation, and waste disposal, are demanded when a remote area becomes established as a permanent settlement.

As long as the population of the North was widely distributed in small mining camps, villages, and individual cabins, water distribution systems were not necessary, as shallow wells and nearby streams adequately served most needs. With the rapidly increasing settlement of the vast lands of the North, the population is being centered in communities rather than distributed over large areas. The world population explosion will undoubtedly contribute to increasing immigration into Arctic and sub-Arctic areas. These changes have already created a need for modern water distribution systems, a need which will become more critical with time.

This monograph has been prepared with two purposes in mind. First, it historically reviews the development of water distribution practices in the North American Arctic from aboriginal times to the present. Although most of the information presented in the historical sections has appeared in previously published literature, there is a need to present it in a single concise volume. The value of this becomes apparent when one considers the turnover rate of professional personnel in the Arctic. It is not uncommon for a capable man new to the area to expend much effort in the development of a system previously developed by others merely because the information is

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*| *Numbers in ( ) refer to references found in Appendix V.*

scattered or unavailable.

Second, previously unpublished data are presented on the design of what the authors feel is the most satisfactory water distribution system: the single-main recirculation type. Design criteria based upon this type of system are presented. The data were obtained from several prototype operations within the State of Alaska. The second purpose of the monograph, therefore, is addressed to both the recently arrived engineers and the men who have been working in the Arctic for many years.

The authors realize that there are many problems yet to be solved, some of which they recognize and some of which have not been obvious to them. The monograph is presented as a state of the art treatise with the hope it will prevent repetition of work already done and that it will lead to the advancement of the art.

The work is also addressed to the planning of non-institutionalized installations which are not suitable to the more expensive methods developed by the military for camp complexes. It could be said the system described herein is most suitable for the average city where the utility does not have complete control over where buildings are located, versus the institution where the utility may itself be the controlling factor in building size and location.

The research upon which this publication is based was performed in accordance with Contract No. ph 86-67-18 with the U.S. Public Health Service, Department of Health, Education, and Welfare. The use of the facilities of the Arctic Health Research Laboratory (USPHS) and the Alaska Native Medical Service (USPHS) is greatly appreciated.

Special appreciation is due to Dr. William Ryan of the Alaska Native Medical Service for his close cooperation during the field testing performed on this work.

Lastly, the support of the Institute of Water Resources, University of Alaska is acknowledged, through an Office of Water Resources Research grant A-018-Alas. Without the supported and unsupported contributions made by this organization the completion of this work would have been impossible.

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# CHAPTER I

## ARCTIC WATER DISTRIBUTION SYSTEMS

Keeping water in the liquid form throughout a distribution system is the major problem confronting the water supply engineer in the Arctic. Of all the schemes developed for this purpose, basically only two are used. Either enough heat is added to the water to prevent freezing or the system is designed in such a way that the water is removed from the system before it freezes.

As the Arctic and sub-Arctic began to be settled by persons from more temperate climates, greater demands were placed upon adequate and convenient water supplies and distribution systems. The systems developed for these communities are discussed, the good and bad points of each system being reviewed.

Some rather ingenious methods have been developed to accomplish water distribution under arctic conditions. This chapter describes these methods and, in some cases, the locations where applied. Design information on these systems is not presented herein since the primary purpose of this report is the single-main recirculation system. It does seem important to present the historical development of all types of systems, as they have in the past proven useful, and, it is thought, will continue to find some use in particular situations.

### Aboriginal

The first water supplies were those used by the Indians, Eskimos, and Aleuts. Since communities were at best only semi-permanent, there was little need to develop water distribution systems. Water supplies were obtained from warm springs, melting of ice and snow, water obtained beneath the ice during winter months, and, during the summer, from surface streams and rainwater. The collection of this water has always been a time-consuming task, but the quantity of water needed (about 2-5 gallons per capita per day) does not approach that of a modern community. Many individuals and some communities continue to rely on this method as their only source of water.

## Trucking

As communities began to grow and adopt the technology of the rest of North America, the demand for greater quantities of water than obtainable by the individual-hauling method increased. Large trucks, sledges, and other vehicles were fitted with water tanks so that water could be hauled from some central source, whether it be from a treatment plant or a good-quality stream. This water is then pumped into tanks located in a heated part of the consumer's building. The economics of such a system are poor, but the first cost is relatively low when compared to more sophisticated systems. Water becomes a very valuable commodity under such conditions, it being rarely used to the extent found in the more temperate climates. There are a number of relatively large communities in Alaska still using this method for part or all of their water supply.

## Intermittent Pumping

Intermittent pumping has been developed for very small communities and other low consumption establishments where complete control of the water is practical. A distribution system, usually located underground, is installed in such a way that all the lines, including those used as service connections, can be quickly and easily drained. During the summer months the system is operated as any conventional distribution system would be. During the winter, however, the water can not be left in the lines. Therefore, on a predetermined schedule, or on demand, the water is put through the distribution system and each consumer fills a storage tank in his house. This tank is usually located in an attic so that the house will have water pressure without reverting to individual pumps.

When the water to the distribution pipes is turned off, all water is removed from the system either by gravity drainage or, in a few cases, by blowing compressed air through the system and forcing all the water from the pipes.

It is probably safe to say that the above system is inadequate for a community of any size. An additional disadvantage is the lack of fire protection by such a system. However, for two to six homes in a subdivision, certain advantages are apparent, particularly if the cost of a well or other water source is high.

## Conventional System with Bleeding

Dawson City, Yukon Territory, was probably the first city in what is now called the Far North, to install a water distribution system. It was constructed in about 1903. A conventional system was installed, with the provision that water could be bled from each service connection and at the end of each main on a continuous basis during the periods of deep frost penetration. Leaving these valves open allows the water to be in constant motion throughout the system, thereby preventing main freezing as long as the heat lost between the pump and the end of the main is less than the amount required to form ice.

The "bleeding" method of freeze-up prevention has many disadvantages, one being the large quantity of water distributed as compared with the quantity actually utilized for consumptive purposes. In an area of low population with abundant good quality water it may still find some applications. However, if pumping must be used, the cost per customer will be a real economic factor. Needless to say the "bleeding" method would be a completely uneconomic scheme if the raw water quality is such that extensive physical and/or chemical treatment is required. The last disadvantage of "bleeding" concerns itself with the problem of waste disposal. If the wasted water is discharged into a sewerage system, the resulting dilution of the organic wastes will cause an excessive hydraulic load on the treatment plant, undoubtedly reducing the efficiency of the biological processes. In addition, the size of the pipes and treatment facilities will be proportionately larger, increasing the capitalization. Separate sewer systems for wastes and excess water appear to be impractical unless the city also has installed a storm sewer system, which could be used for removing the excess water. However, most communities small enough to take advantage of the "bleeding" process probably rely upon surface storm water runoff rather than a separate storm sewer system.

## Conventional System with Deep Burial and/or Insulation

The system commonly used in the northern United States and the southern areas of Canada is to bury the pipes to a depth greater than the expected seasonal frost line. Such a system is also practical in many Far North areas that are not located in the permafrost regions. However, the farther north one proceeds, the greater is the depth of this frost line, and, at some point, economics will prevent a pipe from being buried to the necessary depth.

Since most water sources, whether surface or well water, are near the freezing temperature during many months of the year, heat must often be added to the water before it is pumped into the distribution system. If heat is not added, the water can lose only a small amount of heat before problems develop.

The quantity of water used in the highly insulated type system often determines whether problems will develop. In densely populated areas, where a large quantity of water is used without much variation in flow rate, the water is in the distribution system the minimum length of time. Hence, the chance of freezing is reduced. As the distribution system becomes extended or the water-use less, heat must be added, the pipe buried deeper, increased insulation added, or a combination of these factors incorporated into the design.

Although the economics of the highly insulated water main often appear to be quite good, the system does not solve the problem inherent in the service connections. The service line still must enter the house at approximately foundation level, which is often at a depth severly influenced by freezing. Experience has shown that there is a tendency to allow the water to run during the night low-use hours to prevent freezing of the service lines. Such practices have the same disadvantage as the "bleeding" type system, namely a rather large amount of wasted water.

Another system which can be classified with the conventional highly insulated type is the so-called Utilidor. A Utilidor is a heated and insulated box-like structure into which all utilities are placed; electric, water, sewer, telephone, steam, gas, etc. Installations of this type have been constructed below grade (University of Alaska, Nome, many military installations) as well as on the surface (Inuvik, N.W.T., some military installations). Surface construction is often necessitated by permafrost.

To protect utilities from freezing a Utilidor is a good system. It is usually built large enough to allow working space inside for maintenance and repair. The amount of heat which must be added to the Utilidor is a function of the amount of insulation, depth, and amount of heat lost by the various utilities themselves. For instance, if steam pipes are included in the services, enough heat can usually be obtained by heat lost from these lines to keep other utilities from freezing. In fact, a case can be cited where the Utilidor is so hot from excessive heat-loss of steam lines that the water lines themselves must be insulated in order to keep the water temperature cool enough to be used without customer complaints. Obviously such installations were not properly designed.

Besides the disadvantage of an extremely high first cost, certain other factors make the Utilidor undesirable for most installations. The presence of permafrost makes construction costs prohibitive unless the Utilidor is placed very shallowly or on the surface of the ground. In the latter case, additional insulation is necessary, and, in all probability much more heat. Conventional waste disposal systems are usually impractical if placed above ground because gravity flow is obviated by the negligible or negative grade between the house fixtures and the sewer line in the Utilidor. Above ground systems also cause serious problems at street crossing, paths, etc.

Because of the cost and the previously mentioned disadvantages of the Utilidor, few of these systems are located at places other than government projects, institutions, small mining facilities, and similar complex-type installations.

## Dual-Main Circulating Systems

One of the disadvantages of all the previously described methods of water distribution is the fact that the water in the service lines between the main and the house remains quiescent during many hours of the day and is subject to freezing, particularly at the point where the line is brought through the foundation into the house. The solution to this problem is either to allow the water to run during periods of extreme cold or to add a large amount of heat to the water. Two methods have been proposed to solve this problem. One method herein designated the dual-main system, is workable but has found little acceptance, mainly because a less expensive and more workable system was developed simultaneously.

The basic goal, as is apparent from the discussion thus far, is to have the water continuously circulating both in the distribution lines proper as well as in the individual house connections. Another desirable feature is a means of reheating the water which has become cooled in the distribution system, should the need arise.

The dual-main system accomplishes both objectives. The water initially leaves the pumphouse in a high pressure line. If thermodynamic conditions warrant, heat may have to be added at this point in the system. The house service comes off the high pressure line, into the dwelling, through a pressure reducing valve, and out of the dwelling, discharging into a second main operating at a lower pressure. Interior house plumbing is taken off the "loop" by a tee, thereby allowing conventional plumbing throughout the house.

The low pressure line returns to the pumphouse, or intermediate pumping station and storage facility, where it is heated, if necessary, and returned to the disrribution network in the high pressure main.

It can be seen that the dual-main system will keep water constantly in motion throughout the distribution system as well as in the service connections. The pressure differentials needed to be maintained are a function of water temperature, ground temperature, pipe insulation, and length of service lines. Because of certain inherent disadvantages of this system, design considerations will not be discussed as it is felt less expensive systems will continue to be built, the dual-main layout being academic at the present stage of technology.

The glaring disadvantage of the dual-main system is the fact that two mains must be installed throughout, thereby nearly doubling the first cost of the installation. In addition, extremely close control of the pressures in both lines must be maintained, requiring extra equipment and man-power.

## Single-Main Recirculating System

It became apparent at the time of the conception of the dual-main system that a more economical solution using a single main was essential to make northern water distribution systems economically feasible. One obvious solution would be a constantly running main, each house being connected to it by a loop in which the water is constantly running, the prime energy input being an individual pump located in the heated part of each building. Although such a system is workable, requiring each customer to install and maintain a pump is not the most economical manner for the distribution of water, particularly in a large city.

The Arctic Health Research Center, U. S. Public Health Service, Anchorage, Alaska, began exploratory studies in 1952 to develop a means of providing a continuously circulating water system which could be operated similarly to the conventional systems in the more temperate climates. After considerable experimentation in their facilities and those of the Washington State College, design criteria were established for a system which would accomplish this goal. The system will be referred to as the single-main recirculation system throughout the remainder of this report.

This method of water distribution consists of one water main through which the water is continuously pumped during periods of extreme cold or in areas of permafrost. The flow loop is from the treatment plant or primary pumping station around the loop and either back into the same pumping station or into another station. Heat is added to the water, when necessary, at the pumphouse.

The above system satisfies the requirement of keeping the water in the mains in motion. The problem of keeping the water in the service connections in motion without reverting to bleeding or individual pumps was solved by the development of a device which has become known in the North as the "pitorifice". The name is derived from both pitot tube and orifice, since their principle of operation involves the fundamentals of each device. The pitorifice is inserted into the pipe as a corporation stop. Since it is impossible to obtain a definite and controllable pressure drop across the house service connections, it is necessary to produce the velocity in the service connections by utilizing the velocity head of the water in the main to produce the necessary flow. A dual service connection is used to accomplish the above: one line in which the water flows from the main to the house; a second return water line from the house to the main. Figure I diagrammatically depicts this system. Figure 2 is a photograph of a pitorifice.

The development of this system has all the advantages of previous systems described but it is more economical than any of the others. It is not to be construed that such a design is cheap, but for the rigorous conditions

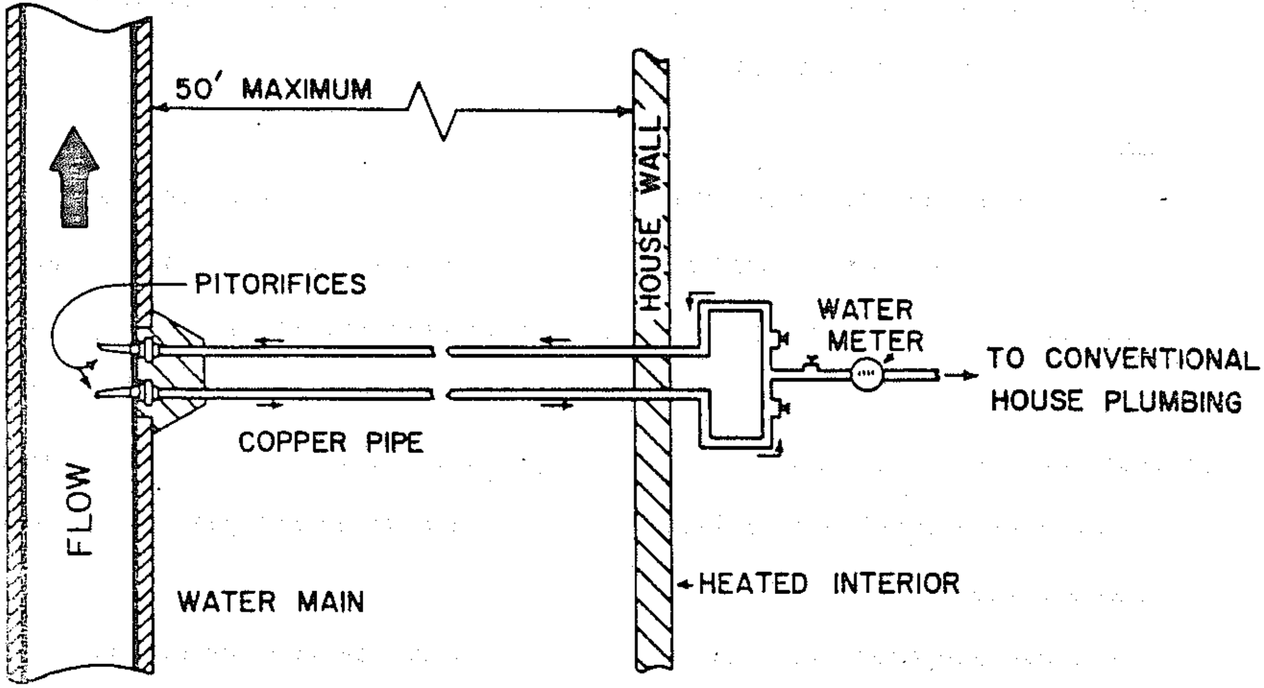
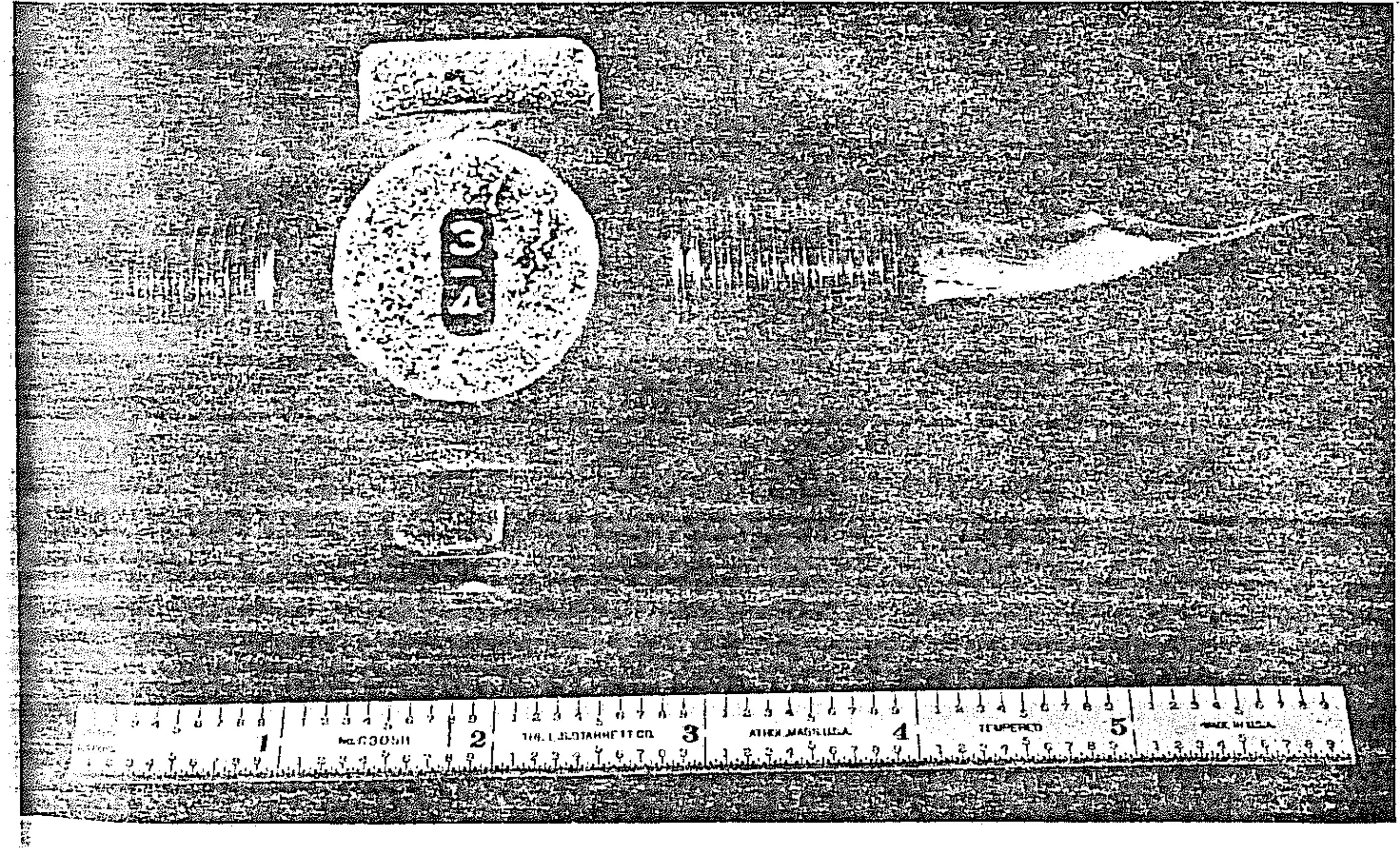


FIGURE 1



A PITORIFICE.

FIGURE 2

of the North it is a reasonable solution for this very important utility. Fairbanks, Unalakleet, and Grayling, Alaska all use this system of water distribution with very successful results.

Summary

This chapter has described the most common water distribution systems found in the Arctic and sub-Arctic areas of North America. All the systems have been or are being used at the time of this writing. It is the opinion of the authors that the single-main recirculation system is the most practical solution for water distribution in the geographic area. All other systems are either more expensive to build or have certain disadvantages which make them uneconomical.

The above statement is restricted to what might be considered the private sector. Institutions, military bases, company facilities, etc. may or may not find this to be the most economical solution. For instance, a military site may house 100 men and be constructed in such a way that the entire complex is one large building with a number of wings. Such construction lends itself to the placement of utilities under the floors, in separate indoor utilidors, and other configurations. However, in the private sector, people demand relatively large lots and homesites, similar to what they were accustomed to in other areas of North America. The most economical solution for such an area is the one which most closely approaches that found in what can be termed a conventional system. Therefore, the statement that the single-main recirculation water distribution system is the best devised to date for the Arctic regions is limited to those installations that are not of the institutional type.

A last remark concerning the use of other types of systems should be made.

As one proceeds from the true Arctic, with permafrost, to more southerly regions, the use of deeply buried, highly insulated pipes, and the heating of the water may become more advantageous than the method which is being discussed in this paper. It should be made clear that the work presented herein is aimed primarily at the severe northern regions rather than at those areas which may have marginal freezing problems with water distribution.

## Chapter 2

## FIELD STUDY AT UNALAKLEET, ALASKA

It was mentioned in Chapter 1 that more than one single-main recirculation water distribution system had been constructed in the State of Alaska. The system at Unalakleet was chosen as a study facility for a number of reasons. Of these, the most important was the fact that all parts of the system were completely separated from any other utility or heat source and, secondly, that nearly the complete construction phase of the system could be observed. Although the City of Fairbanks uses the same method for water distribution, the system is not conducive to a study of this sort because the heat budget for the water mains is very difficult to assess. The local steam plant uses the cold well water as a cooling liquid prior to the water entering the treatment plant and distribution system, thereby making it difficult to determine the cost of heat. In addition, Fairbanks has a much more complete utility system than does Unalakleet, the former having a steam distribution network in the downtown area and a central sewage collection system. Whenever possible the water line was installed as close to these other utilities as possible to take advantage of heat losses from the steam and sewer lines to prevent freezing of the water distribution system.

The system located at Grayling, Alaska was not constructed at the time this study was started.

The Unalakleet system is completely self-contained, the only heat added to the system being through a heat exchanger which is an integral part of the facility. Since the waste system consists of individual seepage pits, no other utilities exist which could add heat.

Unalakleet is located on the extreme eastern end of Norton Sound, an arm of the Bering Sea, at latitude 64°N. (See Figure 3). The area can be classified as subarctic according to the definition given by Washburn (2), wherein the mean temperature is not higher than 50°F for more than four months of the year, and the mean temperature of the coldest month is not more than 32°F. It should be mentioned that, by the above definition, Unalakleet is located within 100 miles of the true arctic region. Temperatures have ranged from a record high of 86°F to a low of -50°F, the annual average temperature being 26°F. Like all coastal areas in the North, the area is subject to high velocity steady winds which are predominantly westerly during the summer months and easterly during the winter. The average annual precipitation is 13 inches, including an average of 34 inches of snow.

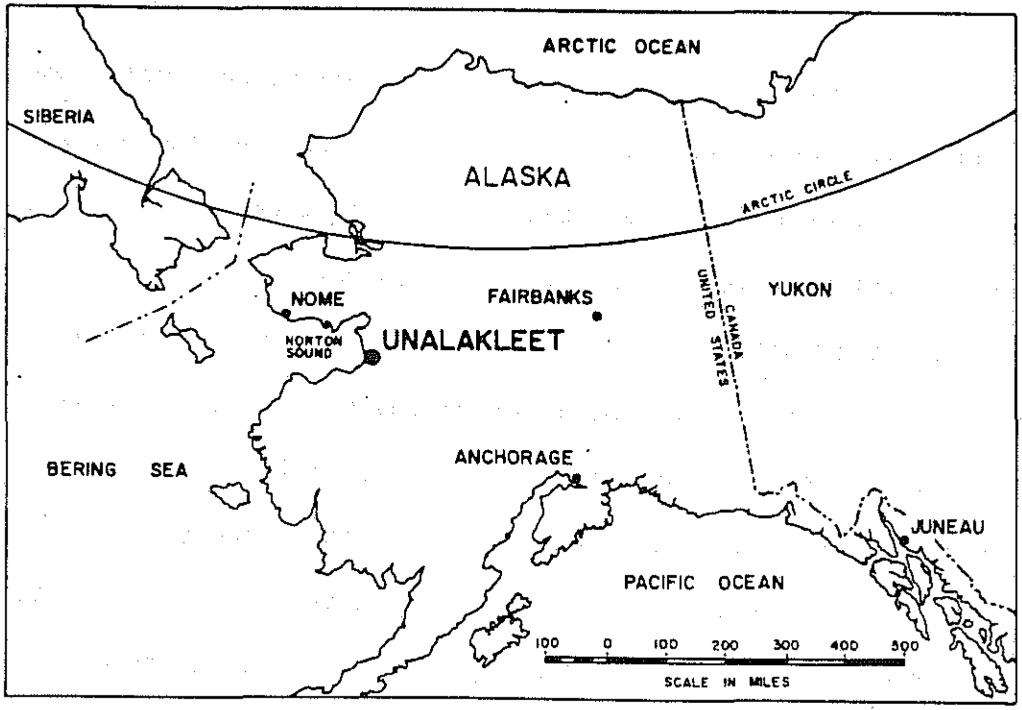


FIGURE 3

Location Map of Unalakleet, Alaska

The townsite of Unalakleet is not located in a permafrost area, although all surrounding terrain is subjected to extensive permafrost conditions. The village is situated on a well drained sand spit which does not retain sufficient moisture to create a permafrost condition. Seasonal frost generally will extend to a depth of eight feet in undisturbed soil sections. A more detailed description and maps of the village are to be found in this chapter under the heading of Description of the System.

The water system was built with funds of the U.S. Public Health Service, Division of Indian Health, Alaska Native Medical Center, Anchorage, under authorization of Public Law 86-121, Project No. A64-440. The original design was made by a consulting engineering firm (3) with many design changes being incorporated by Alaska Native Medical Center engineers. The latter organization was responsible for the final design and construction of the project.

Actual construction work was begun during the summer of 1964. All equipment and supplies were brought into the village during that summer by ship from Seattle. Unalakleet is not served by roads and, therefore, the complete supply inventory for the project had to be ordered and shipped at one time to prevent more expensive airfreight charges.

The actual construction was performed by local labor under the direction of one resident foreman. Occasionally an engineer from the Anchorage USPHS office would be at the site for inspection and supervision of certain complicated details. The fact that the majority of the workers at the site were unskilled at the start of the project had to be considered in the design.

The construction season is relatively short at this latitude. Work could not get underway until the last week in May, and all but minor work had to be completed prior to the end of October.

Because of the short construction season, the use of unskilled labor, and the logistics required for a project at such a remote location, the system was not put on line until November, 1965. The collection of data presented in this report was begun at that time.

The water distribution system operated for the next fourteen months with the normal difficulties inherent in any new system. A fire in January, 1967 destroyed the pumphouse and all its contents, including all the temperature recording instruments used in this study. Therefore, the report will consider the information acquired during the first fourteen months of the system's life. The pumphouse and related equipment have subsequently been rebuilt and the people of Unalakleet have running water at the time of the writing of this report. Special instruments used solely for this study were not replaced as sufficient data had been collected.

The village itself is predominantly Eskimo with a native population of approximately 600. Besides the homes, the village consists of a Bureau of Indian Affairs (BIA) School, a mission, a Federal Aviation Agency (FAA) site, and a store. All but the Federal Aviation Agency facility are presently served by the central water distribution system.

## Description of the System

A plan view of the village of Unalakleet is shown in Figure 4. The primary distribution system has two loops, both of which originate and terminate at the pumphouse. A third loop was constructed between the pumphouse and the wells to the north. The BIA Junior High School, located too far from the mains to take advantage of their water velocity for recirculation, was forced to install a separate loop using a pump to provide the recirculation. The remainder of the system consists of a pumphouse and its

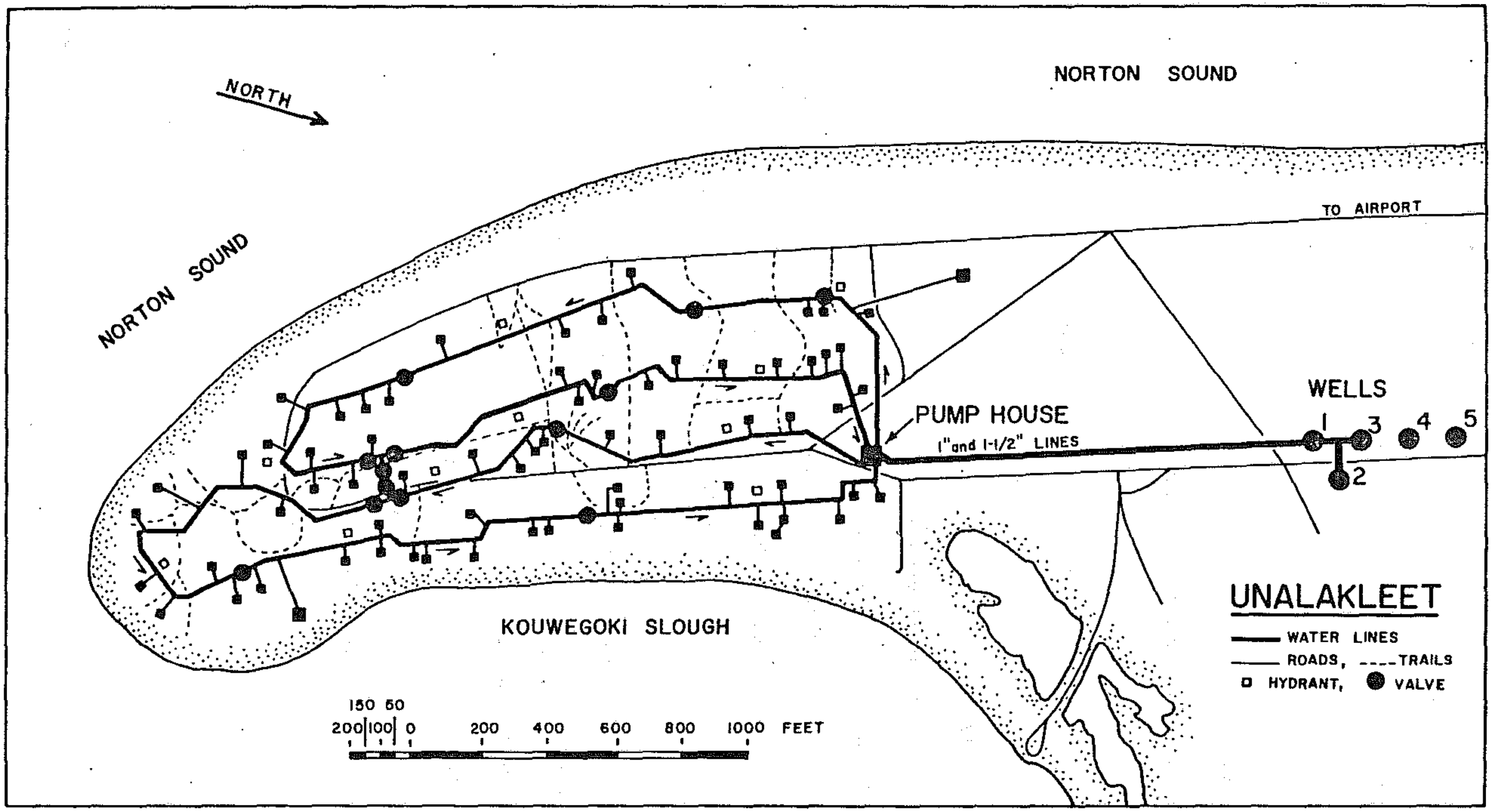

NORTON SOUND
NORTH
NORTON SOUND
TO AIRPORT
WELLS
1
2
3
4
5
PUMP HOUSE
1" and 1-1/2" LINES
KOUWEGOKI SLOUGH
UNALAKLEET
WATER LINES
ROADS, TRAILS
HYDRANT, VALVE
150 50
200 100 0 200 400 600 800 1000 FEET

FIGURE 4

related equipment, fuel storage facilities, and an elevated water storage tank.

Main Circulation Loops: The village plan was such that a single main could not be utilized because the distance from the main to some houses far exceeded the maximum safe distance. Therefore, the primary distribution system consists of two loops, herein called the East and West Loops. The East Loop is 5300 feet in length and the West is 4500 feet. The number of house services from each loop is 39 from the East and 30 from the West.

The construction practice followed called for all lines to be on a grade so drainage to a central point or points would be assured. The minimum depth of cover at any point on the lines was set at five feet, although some points near the pumphouse were constructed at shallower depths. From this high point the lines were laid on grade to fire hydrants, located approximately 1000 feet apart. These hydrants are constructed such that the entire casing remains dry when the valve is closed. If the hydrant is used during the winter months it must be completely drained to prevent freezing. The latter is accomplished by turning the main water supply off, removing the hydrant valve stem, and pumping all the water from the lines between high points by means of a small centrifugal pump.

Although the above procedure appears to be time-consuming and possibly impractical, for a small distribution system the number of occurences calling for hydrant use would be small. The major advantage of the system is the ability to be able to remove all the water from the distribution system in the event of a prolonged power failure, line break, or other repair work when the circulating water must be turned off for long periods during winter months. The usefulness of placing the hydrants at low points on the grade made itself very apparent during the start-up process as well as the time of the January, 1967 fire.

If the water had not been removed, the subsequent freezing of the pipes undoubtedly would have caused complete failure to most of the distribution system.

Four-inch nominal diameter cement-lined cast-iron pipe was used throughout the main loops. These pipes were covered with one and one-half inches of rigid preformed glass insulation (Foamglass; a product of Pittsburgh Corning Corp., Pittsburgh, Pa.). Figure 5 is a photograph of a typical cross section of the pipe and insulation.

<u>Service Connections</u>: The primary advantage of the single-main recirculation system lies in the ability to keep the water flowing between the mains and the house without having to revert to the practice of wasting water or to using individual pumps. Therefore, the success of the system depends to a large degree upon the house-service loops. The major consideration in the placement of these loops is the overall distance that the water must travel. Studies at the University of Washington showed that service lines should not exceed 50 feet. Although most services at Unalakleet did not exceed this value, those that did were found to freeze the most frequently. In the installation at Unalakleet it was not necessary to be careful about easements, right-of-way, etc. because of the Reservation status of the community. Therefore, the main loops could be placed such that they came as close as possible to any one house, cutting across property lines at will. However, this would not be the case in most communities, and on the average, the house loops would undoubtedly be somewhat longer than those reported for this village.

Figure 6 is a detail of the house loop connection into the 4 inch cast-iron main. The holes for the pitorifice were tapped in the field after the main had been installed. Although no exact center-to-center distance was followed between the two pitorifices, they were usually installed not more than eight inches from one another.

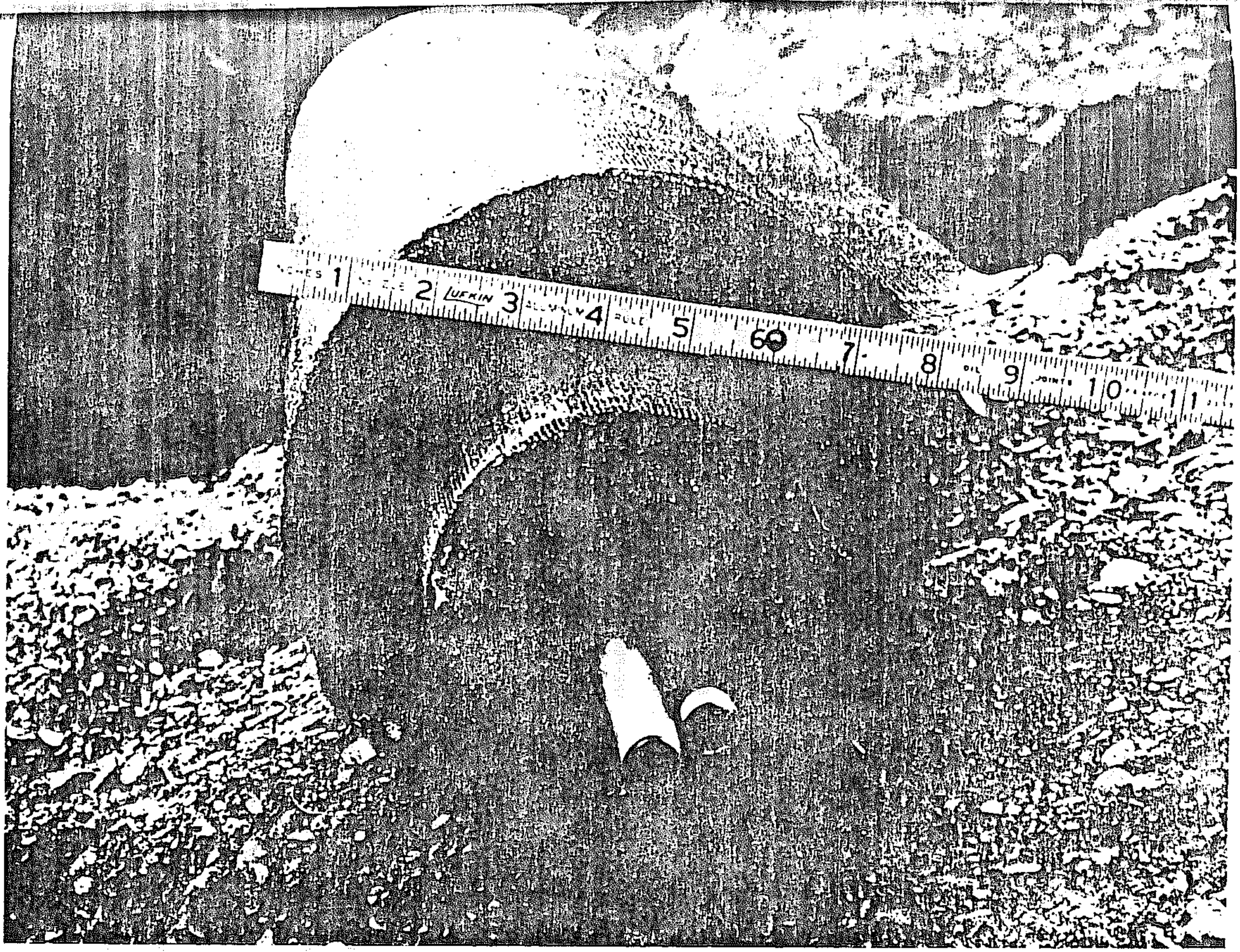


FIGURE 5

The two service lines were electrically insulated from each other by wrapping one line with electrical tape. The lines were then placed next to each other within the casing used for heat-loss insulation. A copper wire was connected between the two pitorifices, as shown in Figure 6.

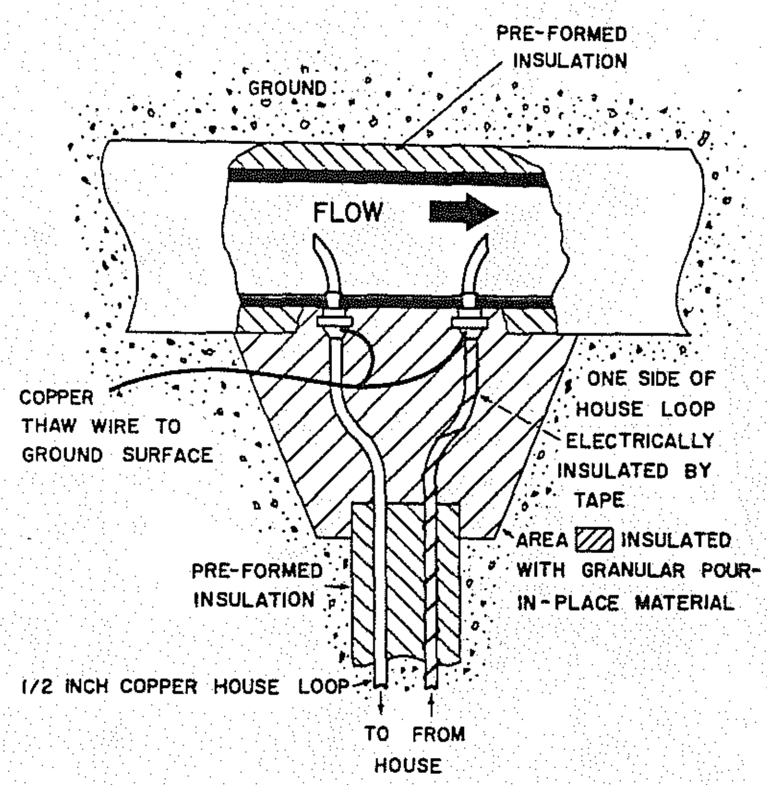


Figure 6

This copper wire was long enough to reach the ground surface after the trench had been back-filled. This arrangement is used for connecting an electric arc welder to the service lines in the event of a freeze-up. One terminal of the welder is connected to the copper cable at the main and the other to the exposed pipe inside the building. The electrical insulation is necessary to prevent short-circuiting of the current during the thawing procedure. This could occur if the two pipes touched each other. One of the connections inside the house can be broken to prevent short circuiting at that point.

The two pipes making up the house loop were installed in a round preformed insulation material similar to that used in the main loop. This insulation material was one and one-half inches thick. The complete pipe was insulated by this material between the point at which the two pipes were brought together to a point inside the residence. Powdered insulating material of a similar composition was poured over the joints where the house loop joined the main loop, thereby insulating the complete service to a minimum thickness of one and one-half inches.

All house loops consisted of one-half inch soft copper tubing. In order to follow the procedure that the entire system can be drained if the need should arise, the entrance depth into the house was set at four feet. Therefore, even at the points where the main was at its minimum depth of five feet, a one foot drop between the house and the main was always present, and each house service had the capability of being able to be drained with the mains.

The valving arrangement in the interior of the house was detailed in Figure I. This series of valves is necessary to shut-off each side of the loop independently if the need to thaw only one side should arise. If a water meter must be installed it would be located on the house side of the loop, as shown in Figure I.

Probably the greatest single problem with an installation of this type is children turning the valves off inside the house. Once a valve is closed the circulation pattern obviously ceases, and a freeze-up occurs soon thereafter. This occurrence then leads to the second problem which becomes apparent when the thawing procedure is started; trying to locate the thaw cable in the snow-covered frozen ground above the main. A valving arrangement which is more difficult to manipulate might well be a worthwhile addition to the system, or the valving arrangement should be installed in a container which can be opened only by employees of the utility.

It was previously mentioned that one loop had to be installed wherein the circulation between the serviced structure and the main was done by a pump. This was the BIA Junior High School. The distance between the heated part of the building and the main was 400 ft. In order to solve this problem a loop was installed which consists of a three inch copper line to carry the water from the main to the school and a two inch copper line which carries the recirculated water from the school back to the main. In order to minimize heat losses, the two inch line, which always would carry the colder water, was placed inside the three inch line, both of which were insulated with one and one-half inches of Foamglass insulation material. A small centrifugal pump located in the school provided the required circulation.

Wells and Well Loops: The well field for this installation is located approximately 1200 feet to the north of the pumphouse, and again, a special system had to be installed to insure that the cold (33°F) well water would reach the pumphouse before freezing. To accomplish this a one and one-half inch galvanized iron line was installed which carries heated water from the pumphouse to the well head. This warmer water mixes with the well water at this point and is returned to the pumphouse in a 3 inch line of the same material. Both lines were insulated with one and one-half inches of insulation.

The well lines were graded to the wells so that if the system were to be shut down for any reason the water in the lines would drain to the wells and return to the aquifer. A special series of valves and fittings had to be installed at each of the three usable wells such that water could flow only in one direction while the pumps were in operation and so that the valves would open to allow the water to drain into the field if it became necessary.

Pumphouse: The original pumphouse was a 1000 sq. ft. prefabricated building. The mechanical equipment consisted of water meters on both loops at the discharge and return points. Total circulated flow and water consumption (including losses) thus could be measured. Two pumps were installed for each loop: a three and a one and one-half horsepower. The original design called for both, which could be operated singly or in series, to give the desired flexibility of increased velocities in mains as well as the availability of a stand-by-unit. Smaller pumps were installed for the well loop.

The building also housed two boilers of 600,000 BTU rated capacity. These units were put into the system to add heat to the water during the winter months. To conserve pumping and piping costs, only a small fraction of the water was brought through the boilers. This water was heated in the range of 40 - 60°F and mixed with the colder water to insure approximately 40°F water entering the distribution loops at all times.

Immediately outside the pumphouse two steel fuel tanks of 10,000 gallon capacity were installed. Since the village is located in a remote area, fuel for an entire year must be brought in and stored at one time during the summer.

Elevated Storage Tank: A 40,000 gallon wood stave water storage tank was built as part of the system in order to serve as a constant head tank during the summer months when no circulation is needed, and to serve as a reservoir for heated water during the winter months. Storage is necessary because the wells have insufficient capacity to supply the demand during peak hours of consumption.

The tank is located on a twenty-five foot tower. Because of extreme cold and the probability of high winds, a 3/8 inch plywood windbreak supported on two-by-fours was constructed around the tank, providing a 3.5 inch dead air space for insulative purposes.

Under normal operating conditions the water from the well enters the tank and is mixed with its contents prior to being discharged into the main distribution system. The water from the distribution system is returned to the storage tank, mixed, and returned to the lines. The heating and heat-loss characteristics of the system will be discussed in detail in the next section of this report.

The piping system between the pumphouse and the elevated storage tank was installed in a 30 ft. long utilidor. The utilidor is unheated, but an electrical heat tape was installed in the event freezing should occur.

## Description of Test Equipment

As stated in the introduction of this report, the primary purpose of the study was to determine the heat-loss characteristics of the overall system so fundamental engineering design values could be developed. In order to determine these characteristics, temperatures of the undisturbed soil versus depth, the soil surrounding the distribution pipes, the temperature of the water leaving and returning to the pumphouse, the temperatures of the water in the elevated storage tank, and the temperature of water in the house loops had to be determined. The following paragraphs describe the instrumentation and procedures used to acquire this information.

Ambient Weather: The Federal Aviation Agency operates a Flight Service Station adjacent to the Unalakleet airport, approximately one mile north of the pumphouse. Hourly weather readings are taken at this facility and are submitted monthly to the U.S. Weather Bureau in Anchorage. All weather data used in this report that were not obtained by project instruments were obtained from this source.

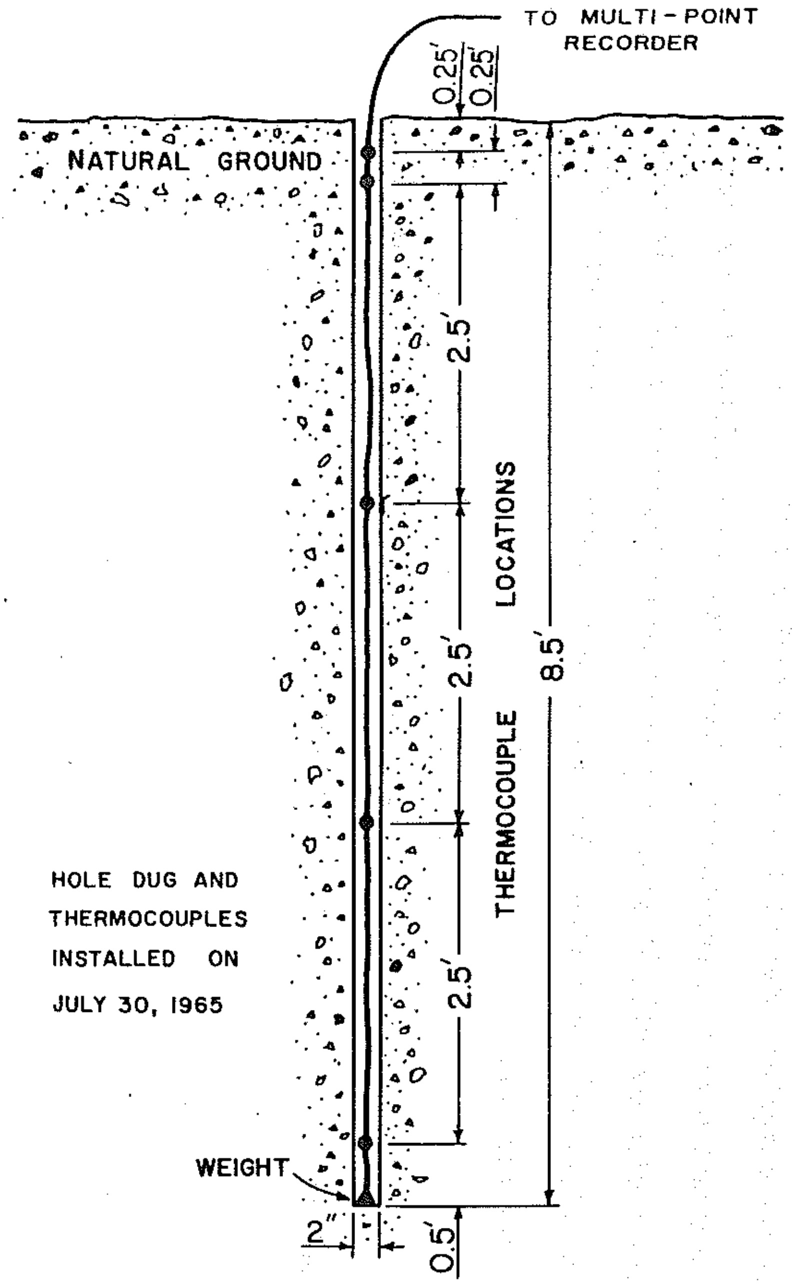
Undisturbed Soil Temperatures: Although it is obviously impossible to obtain an "undisturbed" temperature of the soil at any depth except the surface, a close approximation was made by drilling a two-inch hole in the soil near the pumphouse in an area not subjected to excavation during the construction phase of the project. The spot selected for this hole was in an area that was not likely to be subjected to vehicular traffic during the period of the study.

A series of thermocouples were placed into this hole at the depths shown in Figure 7.

As each thermocouple was placed into the hole, dirt was put in as backfill and tamped. The characteristics of these temperatures were such that it is felt they approximated the normal soil conditions found in the area.

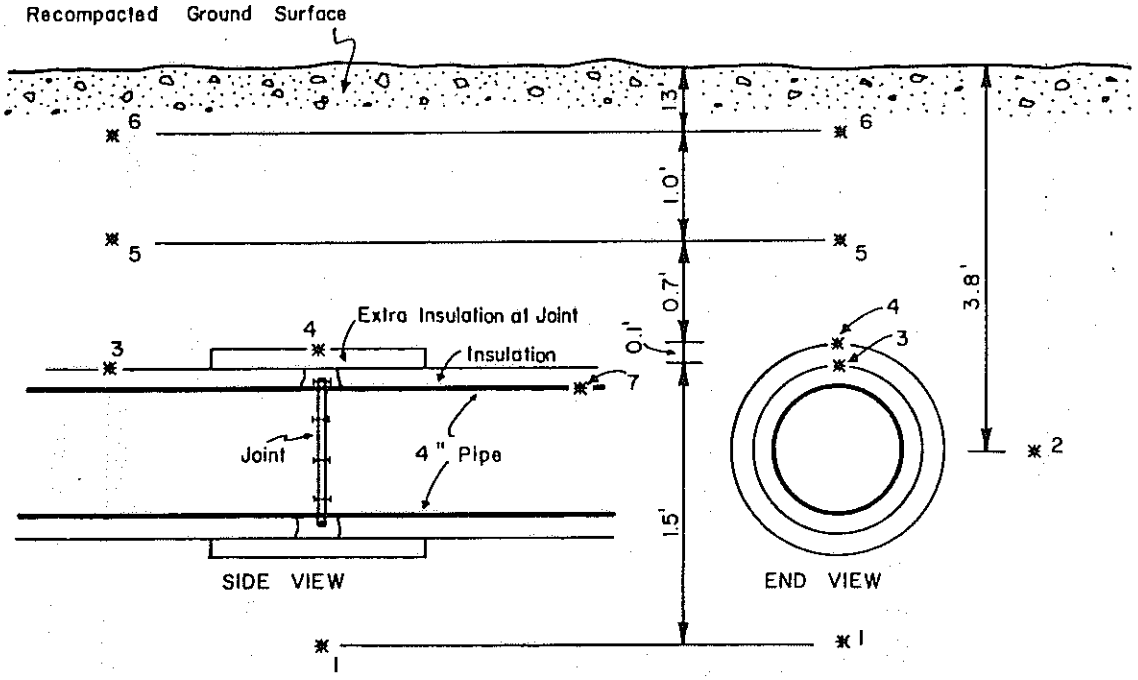
Main Distribution Loop - Soil Temperatures: The amount of heat lost from the water in the distribution system to the soil was determined by placing a series of thermocouples around the outgoing pipe on the West Loop. Since the outgoing water will be at the maximum temperature in the system, the greatest heat loss should occur immediately upon leaving the pumphouse. Figure 8 diagrammatically shows the location of the thermocouples in respect to the pipes and insulation. The units were located at a distance of 65 ft. from the northwest corner of the pumphouse.

These series of thermocouples were located in a disturbed section of soil which ultimately was used as a roadway, thus creating more severe temperatures as compared to undisturbed sections.



HOLE DUG AND
THERMOCOUPLES
INSTALLED ON
JULY 30, 1965

FIGURE 7



Thermocouples # 1-6 Installed July 30, 1965
Thermocouple # 7 Installed Sept. 1966

no scale

FIGURE 8

Main loops - water temperatures: The water temperatures for incoming and outgoing water were obtained by alcohol and mercury thermometers inside the pumphouse.

House loops: In order to test the most severely influenced part of the complete system, individual house loops were installed on the return lines of both the East and West main distribution loops. Since the water returning to the pumphouse will have lost the maximum amount of heat, these test loops were located 60 ft. before the main entered the pumphouse. No thermocouples were installed on the loop, but thermometers were placed inside the pumphouse on these units so the loss between the main and the pumphouse could be determined.

The fact that these loops, both approximately 60 feet in length, would be the coldest section of the entire distribution system made them an ideal operational control, as constant checking of their temperatures would signal an impending freeze-up.

Unfortunately, flow rates through the loops could not be measured accurately without impeding the flow, which would have obviated the value of these individual test loops.

Well loops: Thermocouples were installed near the wells to measure the water temperatures at that remote site. However, they were damaged during the backfilling operations near the completion of the project and no reliable data could be obtained.

The temperature of the well water leaving and returning to the pumphouse was determined by thermometers located inside the building. Fairly good heat loss calculations were therefore able to be obtained from these readings.

Elevated storage temperatures: Water temperatures in the storage tank were determined at different depths and different locations inside the water tank. In addition, thermocouples were located on both the east and west sides of the tank on the outside of the staves, on the inside of the plywood windbreak, and on the outside of the windbreak.

These temperature probes were placed so that heat-losses through the tank walls could be determined, water stratification, if present, could be determined, and the effect of the prevailing winds could be seen.

Procedures used to collect data: All thermocouples described in the previous sections were fed into the pumphouse and connected to a Honeywell multipoint (24 point) recorder. The recorder was constantly checked against a highly accurate laboratory thermometer placed in a water bath in the pumphouse.

Although the recorder was a continuous-duty machine, it was used in this mode only on rare occasions for two reasons: many of the temperatures were nearly identical and could not be differentiated when the machine was running continuously and, secondly, most of the temperatures changed slowly with time, particularly the ground readings. Therefore, the unit was run early every morning and again in the evening. These two daily readings were sufficient to give all the information needed for the purposes of this study.

All the readings on the water-temperature thermometers and the water meters were taken at the same time that the recorder was run, therefore giving complete sets of data for all installed equipment.

Occasionally more intensive readings were made. This was usually done when one of the investigators was on location. During these periods the recorder was often left on continuously and the other readings were made on a schedule varying from every half hour to every two hours. During the remainder of the study a local worker, hired for this project, took the readings and sent them into the Fairbanks office.

# Chapter 3

## Analysis of Unalakleet Field Data

The instruments installed at Unalakleet and described in Chapter 2 were operated for a period of seventeen months. The data collected is presented graphically wherever possible. Predicted heat losses are compared with actual heat losses obtained by the direct measurement of temperatures in both the house loops and the main distribution pipe.

### Ambient Conditions at Unalakleet

Weather: Unalakleet lies in the transition zone between arctic, maritime, and continental influences. Summer temperatures are modified by the cooling effect of the cold Norton Sound waters. During the winter months the ice cover lessens the sea's warming effect creating a more continental climate. Figure 9 shows the daily maximum and minimum temperatures at the Unalakleet airport for a 15 month period beginning in October, 1965 and ending on January 10, 1967, plotted at 10 day intervals.[1] Superimposed are the mean daily air temperatures for the 18 years of record. It can be seen that the temperatures at Unalakleet during the 15 month period were typical, although there was a cold spell in March, 1966.

Because of Unalakleet's relatively unsheltered position, strong winds occur fairly frequently. When persistent high pressure systems dominate the interior of Alaska, and low pressure areas dominate the northern Bering Sea (as in the winter), the wind speed for a month may average as much as 25 miles per hour. The prevailing direction is generally from the west during the summer and the east during the winter.

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[1] *This method of plotting temperature does not necessarily show the extreme highs and lows, but does give a good indication of the temperatures throughout the year.*

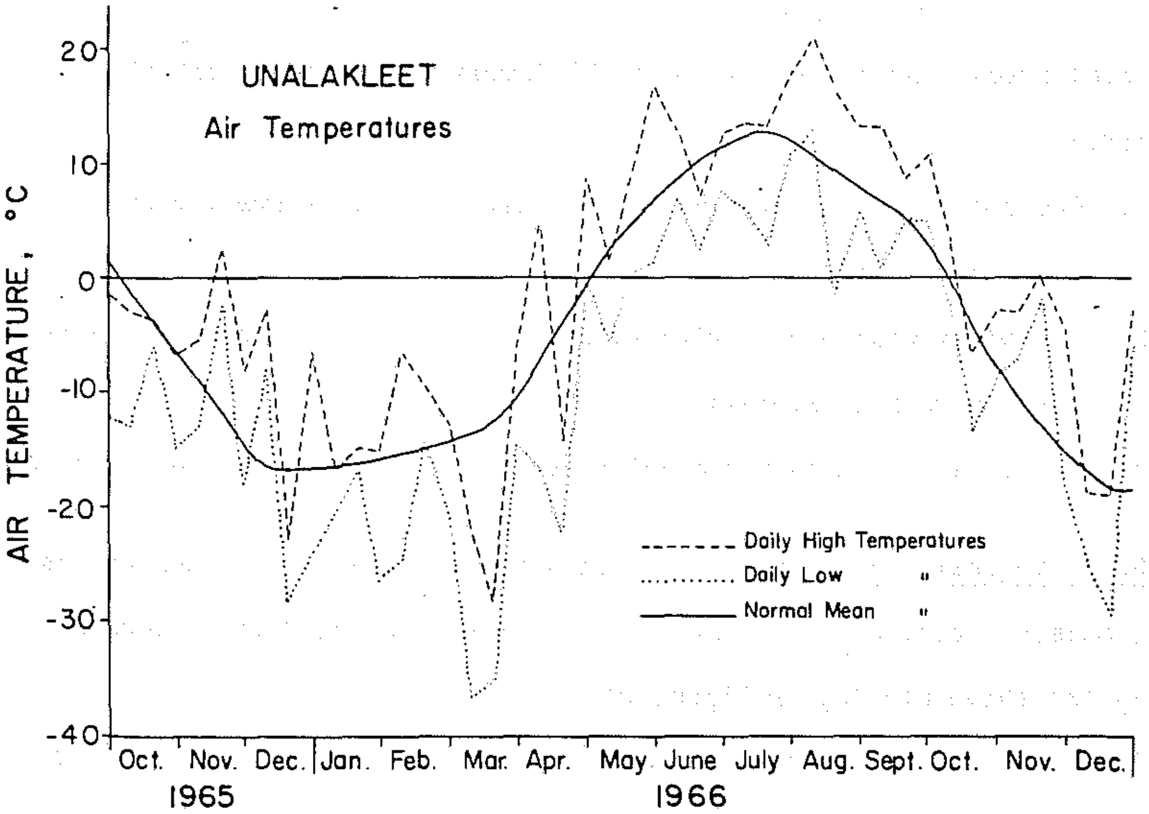

FIGURE 9

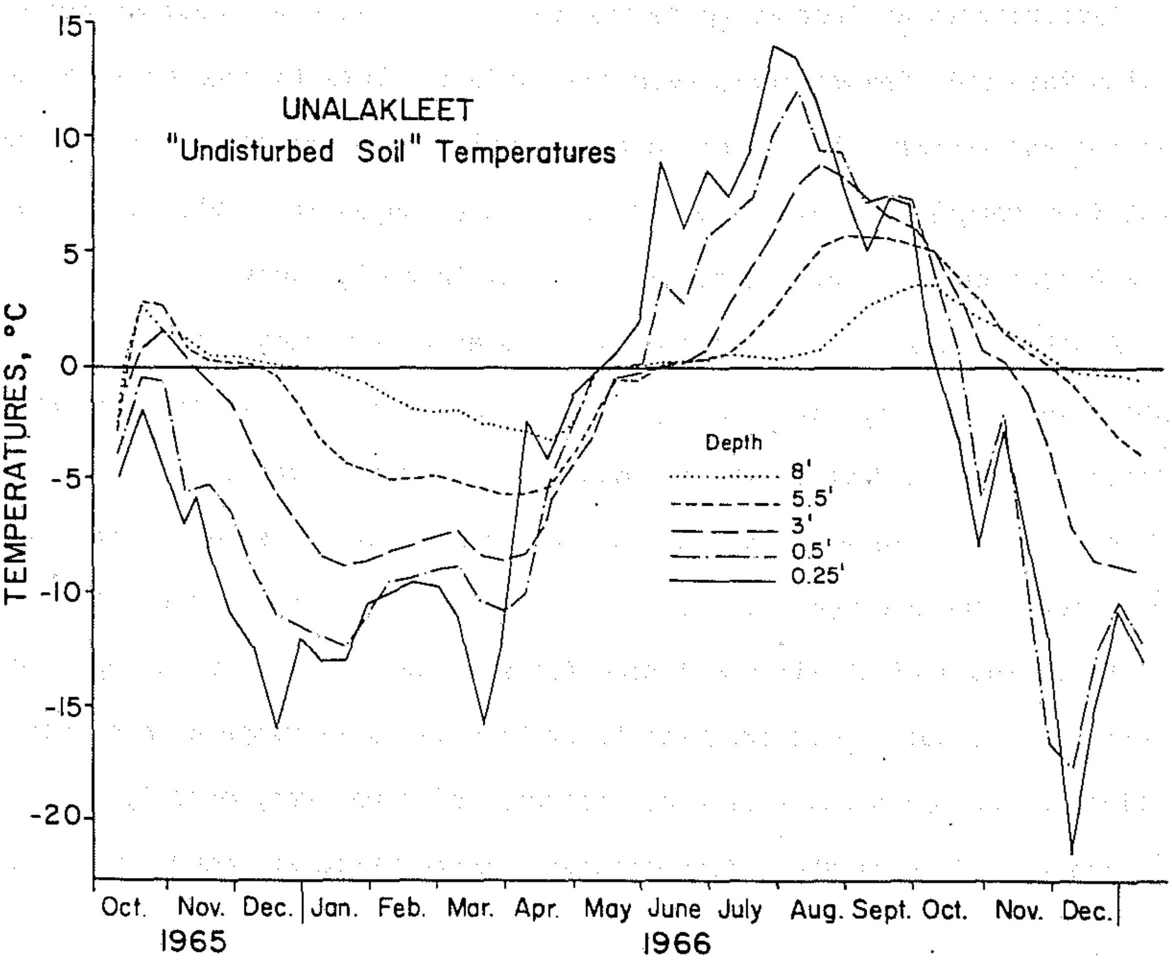

FIGURE 10

Total precipitation is only 10 to 20 inches per year because of two factors:

1. The cool air above the Bering Sea can carry only small magnitudes of water vapor.
2. No inland mountain barrier exists to create conditions favorable for orographic rainfall.

Of the total, approximately two-thirds occur as rain and one-third as snow.

Soil Temperatures: "Undisturbed soil" temperatures at various depths were measured during the 15 month period from October, 1965 to December, 1966. These are shown plotted in Figure 10.

There are several factors typical of soil temperatures in subarctic and arctic regions shown on this graph.

Temperatures at increasing depths have a less extreme seasonal variation than soil temperatures near the surface. This is true both in the winter and summer. Thus, for instance, while the temperature at a depth of 0.5 feet ranges from +13°C to -17°C, it only ranges from +5°C to -2°C at the 8 foot depth. This factor is critical in design work.

Another feature of importance, particularly with regard to operational characteristics, is the time lag behind atmospheric conditions exhibited by soils at a given depth. The minimum temperatures at the 8 foot depth appear to occur approximately six weeks after the minimum atmospheric temperatures. At 5 feet, the average pipe depth, soil temperatures reach their lowest values in March and April. Minimum temperatures appear to be -5°C during a normal year. It is not a good practice to extrapolate soil temperatures from one point to another because several factors, which may vary greatly from place to place, influence these temperatures. Among these are amount of snow cover, amount of soil moisture, and soil composition. Probably more important for pipeline construction is the drastic change in thermal characteristics caused by excavating, backfilling, and recompacting the trench.

When cooled, moist soils steadily decrease in temperature until the freezing point of water is reached. At this point they remain at approximately 0°C until all free water reaches the frozen condition. The reverse occurs when the soil thaws. This appears on the undisturbed soil temperature-time curves as a horizontal line at 0°C and is referred to in the literature as the "zero curtain" or "freeze-thaw curtain." An example of this is evident in Figure 10. The zero curtain was utilized in the Unalakleet field studies to check the original calibration of the thermocouples. During thawing and freezing the length of the zero curtain increases with depth due to a combination of two factors: the increase in total thermal mass above any point with depth, and the increase of soil moisture with depth.

In addition to the temperature measurements referred to in Figure 10, the U.S. Army Cold Regions Research and Engineering Laboratory (Terrestrial Sciences Center) observed ground temperatures at Unalakleet for a period of 10 years. The data obtained are shown in Figure 11. From this data it can be seen that temperatures are such that a permafrost condition does not exist at the normal pipe depth since temperatures above freezing occur during some part of the year.

### Service Loop Heat Losses

Theoretical Losses: The house service loops are the most critical feature in the design and operation of single main recirculating systems. It is quite easy to measure temperatures in the mains and to add more heat when required, but there is no economical method available to measure or monitor the

# UNALAKLEET GROUND TEMPERATURES
## 1947 - 1956

| Depth in Feet | January | | | February | | | March | | | April | | | May | | | June | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. |
| 0.0* | 23.8 | -3.4 | 8.7 | 19.4 | -30.5 | 5.2 | 20.8 | 4.0 | 8.2 | 28.8 | 7.4 | 14.7 | 35.4 | 18.9 | 29.8 | 54.4 | 38.0 | 44.7 |
| 0.5 | | | | | | | | | | | | | | | | | | |
| 1.0 | 24.0 | 1.3 | 10.1 | 21.1 | -11.0 | 8.5 | 23.8 | 6.9 | 10.2 | 27.9 | 11.7 | 16.4 | 33.2 | 26.7 | 30.4 | 46.8 | 31.8 | 41.1 |
| 2.0 | 25.6 | 14.0 | 18.0 | 22.1 | 2.8 | 13.5 | 23.4 | 3.2 | 12.5 | 24.4 | 11.7 | 16.9 | 31.5 | 25.9 | 29.8 | 38.3 | 31.3 | 34.3 |
| 4.0 | 29.7 | 24.6 | 26.9 | 24.3 | 18.1 | 22.1 | 23.4 | 16.4 | 20.0 | 25.6 | 17.3 | 21.5 | 32.2 | 26.8 | 29.9 | 34.5 | 31.1 | 32.0 |
| 7.0 | 32.9 | 29.9 | 31.9 | 32.0 | 30.3 | 31.3 | 31.6 | 20.2 | 27.7 | 29.9 | 25.4 | 27.3 | 31.6 | 28.6 | 30.2 | 32.2 | 27.4 | 31.0 |
| 11.0 | 34.8 | 28.9 | 33.8 | 33.9 | 32.5 | 33.5 | 33.4 | 32.5 | 32.9 | 32.7 | 29.6 | 32.2 | 32.5 | 31.5 | 32.9 | 34.1 | 31.0 | 32.2 |
| 16.0 | 34.8 | 33.0 | 34.3 | 34.1 | 33.8 | 33.9 | 33.8 | 33.0 | 33.4 | 33.4 | 32.5 | 33.1 | 33.0 | 32.5 | 32.8 | 32.9 | 30.0 | 32.3 |
| 22.0 | 34.4 | 32.5 | 33.9 | 34.5 | 33.9 | 34.0 | 34.5 | 32.2 | 33.8 | 34.0 | 32.7 | 33.6 | 36.0 | 33.0 | 33.6 | 35.9 | 32.7 | 33.6 |

| Depth in Feet | July | | | August | | | September | | | October | | | November | | | December | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. |
| 0.0* | 64.8 | 41.9 | 52.7 | 55.8 | 46.6 | 52.5 | 52.3 | 46.4 | 48.8 | 45.3 | 31.2 | 38.2 | 28.4 | 18.9 | 26.4 | 25.6 | -10.5 | 13.5 |
| 0.5 | | | | | | | | | | | | | | | | | | |
| 1.0 | 55.8 | 43.7 | 49.3 | 56.8 | 49.6 | 53.0 | 50.5 | 44.6 | 48.1 | 44.9 | 35.4 | 39.8 | 32.8 | 25.2 | 29.6 | 26.4 | 7.5 | 18.7 |
| 2.0 | 48.5 | 39.0 | 44.3 | 52.5 | 46.6 | 48.9 | 49.1 | 43.9 | 46.5 | 44.6 | 37.7 | 41.9 | 33.6 | 30.4 | 32.5 | 32.7 | 19.0 | 26.1 |
| 4.0 | 39.1 | 34.3 | 36.5 | 44.4 | 39.5 | 42.6 | 46.0 | 41.7 | 44.5 | 43.3 | 39.7 | 41.6 | 36.6 | 33.8 | 34.5 | 33.4 | 27.4 | 31.9 |
| 7.0 | 32.0 | 29.9 | 31.1 | 41.1 | 32.4 | 39.9 | 41.1 | 30.2 | 37.2 | 41.5 | 36.6 | 39.8 | 38.4 | 32.0 | 36.5 | 38.0 | 32.4 | 34.6 |
| 11.0 | 32.7 | 30.8 | 32.0 | 33.4 | 30.0 | 32.1 | 35.9 | 30.0 | 34.4 | 37.9 | 33.4 | 36.2 | 37.7 | 34.3 | 36.2 | 36.2 | 35.2 | 35.6 |
| 16.0 | 33.6 | 31.5 | 32.2 | 32.7 | 31.8 | 32.5 | 33.8 | 30.7 | 32.7 | 34.8 | 31.3 | 34.1 | 35.9 | 31.5 | 33.9 | 36.1 | 33.0 | 34.8 |
| 22.0 | 34.4 | 32.4 | 33.2 | 33.8 | 32.5 | 33.2 | 33.8 | 32.7 | 32.9 | 34.1 | 32.6 | 33.2 | 34.8 | 32.5 | 33.7 | 34.8 | 32.7 | 33.8 |

* Thermocouple installed 1/8-inch to 1/4-inch below ground surface

Temperatures recorded by Cold Regions Research Laboratory, Hanover, New Hampshire heat losses in each individual house connection. Experience has often shown that these flows can be so low that the water in the house loops freezes while little temperature drop in the mains is exhibited.

The conventional method for heat loss determination is based on the steady-state heat flow equations described in Appendix I. This method assumes two layers of insulation; the actual fabricated material and an annular soil section. The thickness of the soil ring must be such that its outer surface temperature is essentially the natural ground temperature. This is about 10 inches for the insulated service lines used at Unalakleet.

When the above method of heat loss calculation is used, the thermal conductivity, k, of the soil surrounding the pipe must be estimated. This factor is a function of density, moisture content, particle size and shape, temperature, and dissolved and gaseous substances.

A test hole bored at Unalakleet by Cold Regions Research Laboratory on July 11, 1958 showed that the soil from 5.5 feet to 8.5 feet in depth consisted of a coarse to medium sand, poorly graded, with an average water content of 3.6% of dry weight. Above the 5.5 foot depth the soil has slightly less moisture, but is similar in composition. The value of k for this type of soil was estimated to be 0.7 BTU/hr.ft.°F for the unfrozen state and 0.5 BTU/hr.ft.°F for the frozen state.

The steady state heat conduction equations formulated in Appendix I are for long cylinders. The geometry of the house loops complicates the use of these equations. In order to simplify these computations, the two pipes were assumed to be equivalent tc an imaginary single pipe having the same total flow. The radius of the imaginary pipe was chosen to be such that its cross-sectional area was equal to that of the two pipes.

A sample calculation of expected heat losses for a given date is shown below. Late March was chosen since the soil temperatures are at a minimum at that time of year. The data is developed for the east test house service loop in order that the results can be compared to measured losses.

In the calculation below, the undisturbed soil temperature of 9°F was taken from Thermocouple #2, in Figure 12, rather than from Figure 10, "Undisturbed Soil Temperatures", from which a higher temperature would have been obtained. This was done because the lack of snow cover over the east test house service loop produced soil temperatures which differed from those in the undisturbed soil section. Thermocouple #2, in Figure 12, was assumed to be essentially at undisturbed ground temperature at that location.

## Sample Calculation

Date: March 24, 1966

Loop: East test house service loop

Equation: 1-4, Appendix 1

The following values are known or measured:

$T_o = 9°F$

$T_i = 42°F$

$k_1 = 0.022$ BTU/ft hr°F

$k_2 = 0.6$ BTU/ft hr°F

$r_1 = 0.353$ in

$r_2 = 1.853$ in

$r_3 = 11.85$ in

$L = 60$ ft

From Appendix I, the equation for heat loss is:

$$\dot{q} = \frac{2\pi L(T_i - T_o)}{\ln(r_2/r_1)/k_1 + \ln(r_3/r_2)/k_2}$$

Substituting,

$$\dot{q} = \frac{2\pi(60)\ (42-9)}{\ln\frac{1.853}{.353} / .022 + \ln\frac{11.85}{1.853} / .6}$$

$$\dot{q} = 159 \text{ BTU/hr}$$

The calculations show that the expected heat loss will be approximately 159 BTU/hr per 60 ft length of service line made of two 1/2" copper tubes covered by 1.5 inches of insulation. It must be emphasized that this value is only approximate due to the estimates and simplifications inherent in the equation used.

An error in estimating the annular soil thickness for the temperature to decrease to that of the unaffected surrounding natural ground will have minimal effects upon resultant calculated heat loss because of the large temperature drop across the insulation. If a soil ring 100 inches thick had been used instead of the 10 inches in the example, the heat loss would be 151 BTU/hr., a five percent difference. The effect of properly estimating the coefficient of thermal conductivity for the soil is much greater.

Measured Losses: Service loop heat losses were measured by the temperature decrease of the water flowing through the pipe, as described in Chapter 2. As predicted by the theory, the greatest heat loss was obtained in March.

The quantity of water flowing through the test house service loops is not easily measured without being impeded to some degree. One set of velocity measurements was made for the east test loop by injecting a dye into a 2 ft. section of clear tubing (4). This test indicated that the velocity in the service was 0.18 ft/sec at a time the velocity in the main was 1.7 ft/sec. This test was performed only once, and that was for only one service length and piping configuration.

All calculations have been made assuming the velocity in the test service line is directly proportional to the velocity in the main. This approximation is quite valid for any given service line, but cannot be extrapolated to other service lines since the velocity also depends on service line length.

The calculations for radial heat loss for the same day and service connection as calculated from theory are shown below using Equation I-5 as outlined in Appendix I.

## Sample Calculation

Date: March 24, 1966

Loop: East test house service loop

Equation: I-5, Appendix I.

Given:

$T_1$ = 44°F (water temperature at beginning of house loop)

$T_2$ = 42°F (water temperature at house)

$v_m$ = 1.25 ft/sec

$v_s$ = 0.13 ft/sec

$C$ = 1 BTU/lb°F

$Q_m$ = 40 lb/hr

From Equation I-5,

$$\dot{q} = CQ_m \Delta T$$

$$\dot{q} = 1 \times 40 \times 2 = 80 \text{ BTU/hr}$$

Since the above loss is for one-half of the house loop, the value is doubled for the total loss in the complete loop. Thus, for March 24 a heat loss of 160 BTU/hr is expected under the prevailing conditions and physical constraints of the system.

A series of similar calculations for heat losses were performed and compared with expected theoretical losses for the east test house loop. Differences were as high as 50 percent between theoretical and actual. This seemingly large error, admittedly of significance, is partially explained by the quality of some of the raw data used as well as some of the assumptions and simplifications inherent in the equations. The manner in which much of the raw data was obtained, i.e., two readings of all meters per day, tended to introduce an error. Average velocities for a 12 hour period were used to calculate mass flow rates. This information was then used to calculate heat losses using an instantaneous water temperature value.

The authors feel the equations used are accurate within ten percent and should be used for calculations of this type.

## Main Loop Heat Losses

Soil Temperature Near Loops: Figure 12 shows temperatures recorded at and around the west main. The location and numbering key for these thermocouples are detailed in Figure 8. Thermocouple No. 4, located on the soil side of the insulation at the pipe joint, is not shown in Figure 8.

The thermal characteristics of the soil surrounding the pipe (shown in Figure 12) are indeed much different than those in the undisturbed ground, as would be expected. The former exhibits shorter lag times at a given depth and a shorter zero curtain length. The characteristics of the soil surrounding the pipe were changed by the excavation and refilling during construction. The magnitude of the changes could not be determined from the collected and collated data.

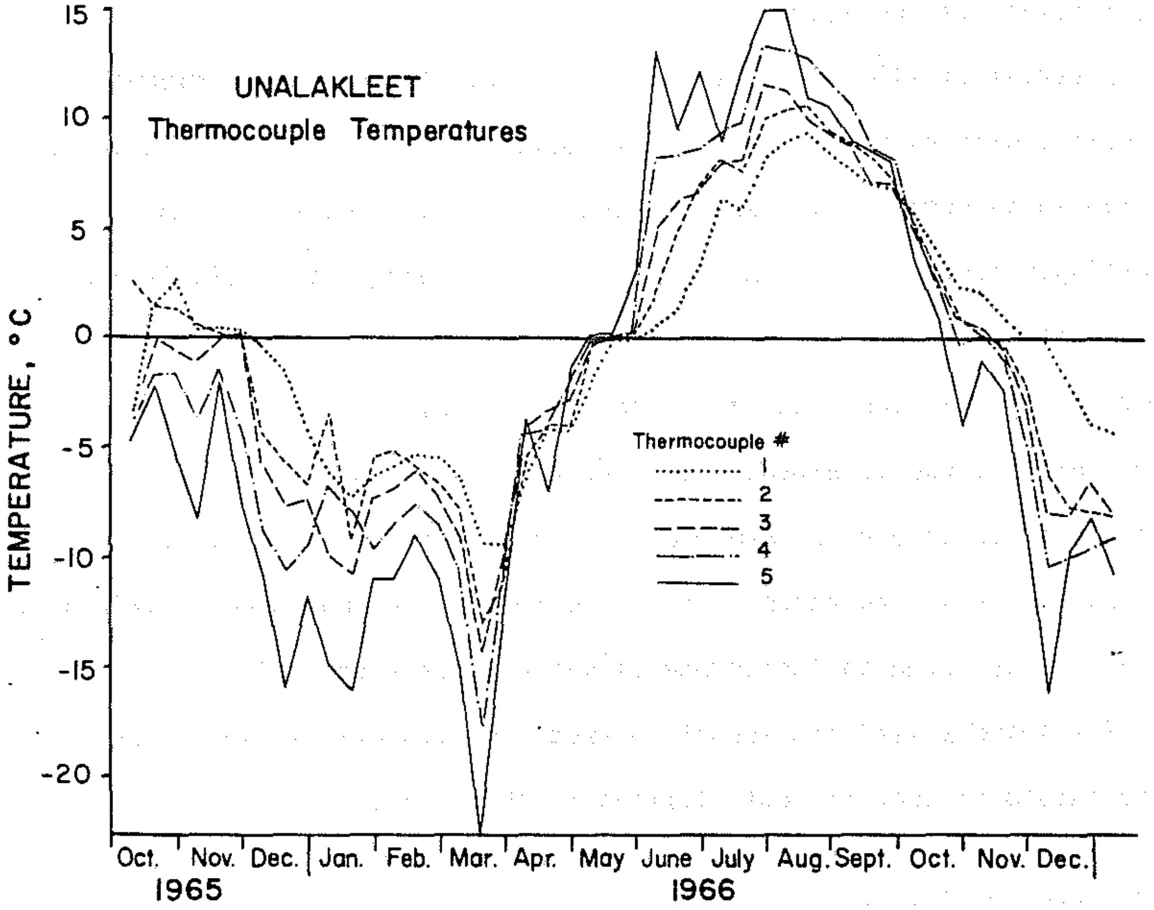

Figure 12

The data indicates that the soil temperatures in the vicinity of the pipe are lower than those at equal depth in the undisturbed ground. This would be contrary to expectations since the soil adjacent to the pipe is receiving heat flowing from the pipe. Construction processes may have caused the above phenomenon by altering the soil characteristics. However, the primary cause is thought to be the use to which the ground surface had previously been put. The pipe is under an area which was heavily used for parking trucks and other machinery. The snow cover was cleared and/or compacted, thereby reducing its insulating properties. The undisturbed measurements were all observed under an area which was not subjected to traffic of any type.

The above implies that the heat losses were calculated for their most severe case if these figures were utilized. At Unalakleet such a situation would result in a conservative design because of the scarcity of roads and the fact that the greatest part of the piping was not built along the existing roads. However, since common engineering practice in the United States is to put water mains under streets, this most severe case may indeed be the one which should be used in design.

Theoretical Losses: Heat loss calculations for the main loop are shown below using the same equations as presented for the house loops.

### Sample Calculation

Date: March 24, 1966

Loop: East main

Equation: I-4, Appendix I

Given:

$T_o$ = 9°F

$T_i$ = 45°F

$k_1$ = 0.022 BTU/ft hr °F

$k_2$ = 0.6 BTU/ft hr °F

$r_1$ = 2.3 inches

$r_2$ = 3.8 inches

$r_3$ = 18.2 inches (Value was used because of placement of #2 thermocouple so known values could be used)

L = 5,300 ft

$\dot{q}$ = 47,400 BTU/hr (calculated by Equation I-4)

Actual Losses: Since the temperature decrease and average flow in the loop were known, heat losses could be computed directly. The accuracy of temperature measurements was limited to 1/2°F.

Date: March 24, 1966

Loop: East Main

Equation: I-5, Appendix I

Temperature decrease in line = 2°F

Temperature decrease due to heat lost in services = 1/4°F
(see following section)

$$\Delta T = 2 - 1/4 = 1.75°F$$

$$Q_m = \frac{35280 \text{ gal}}{12.45 \text{ hr}} \left(\frac{8.34 \text{ lb}}{\text{gal}}\right) = 23700 \text{ lb/hr}$$

$$\dot{q} = CQ_m\Delta T$$

$$\dot{q} = 1(23700)\ (1.75)$$

$$\dot{q} = 41{,}500 \text{ BTU/hr}$$

The above figure compares fairly closely with 47,400 BTU/hr computed using the soil ring method. Other calculations differed by 10,000 BTU, indicating a large degree of uncertainty.

If the total heat loss from the services is compared to that from the main loop, it can be seen that heat loss from the main is the primary cause of the system temperature decrease. However, freezing may be expected to take place first in the service lines, due to the low flow rates.

Losses from Heat Flow in Services: The total heat lost in the main loops is the sum of heat loss from the main loop itself and heat loss from the service loops. That is, the heat lost in each service connection has a cumulative effect on the system as a whole. In order to determine whether this effect was of a significant magnitude, heat loss calculations were made for the composite system. In an analysis of the 5,300 ft east loop, which has 39 service loops averaging 38 ft in length, it was found that the maximum contribution of the service loops to the heat loss of the total system is approximately 6,000 BTU/hr. For normal flows, this means a temperature drop of less than 1/4°F in the main line. However, if the flow through the service loops were greater, or if a system had more and/or longer loops, the heat loss from this part of the system could cause significant temperature drops in the main.

## Heat Losses in the Well Lines

To keep the cold well water from freezing on its way to the pumphouse, a one and one-half inch galvanized iron line carries warm water 1200 feet from the pumphouse to the well head where it is mixed with the cold ground water. The well water and the water from the pumphouse returns in a three inch galvanized iron pipe. One and one-half inches of insulation covers both lines.

The temperature of the water leaving the pumphouse to the wells, and that of the water returning from the wells, was recorded twice daily. The well water was known to remain constant at 33°F.

In order to determine the heat losses in the well loops, three distinct events were considered:

1. The heat losses of the outgoing water were computed and the temperature drop of the water was obtained by means of the steady state conduction formula in Appendix I.
2. When mixing occurs at the well head, a further drop in temperature takes place. The temperature of the water at this time was computed.
3. Using the temperature obtained above, the heat loss of the returning water was computed.

In order to determine the validity of the calculations, the temperature drop which would occur in the return line due to the heat loss was calculated and the final temperature compared to the known temperature recorded at the well house.

## Sample Calculation

## Well Loop Heat Losses - March 24, 1966

1. Outgoing water: Equation I-4, Appendix I

$T_o = 9°F$

$T_i = 47°F$

$L = 1200$ ft

$Q_m = 4560$ lb/hr

$r_1 = 0.95$ inches

$r_2 = 2.45$ inches

$r_3 = 12.45$ inches

$k_1 = .022$ BTU/ft hr °F

$k_2 = .6$ BTU/ft hr °F

$$\dot{q} = \frac{2\pi L(T_2 - T_o)}{\ln(r_2/r_1)/k_1 + \ln(r_3/r_2)/k_2}$$

$$\dot{q} = \frac{2\pi(1200)\ (47-9)}{\ln \frac{2.45}{0.95} \ / \ .022 \ + \ \ln \frac{12.45}{2.45} \ / \ .6}$$

$$\dot{q} = 6250 \text{ BTU/hr}$$

$$T = \frac{6250}{4560} - 1.4°F$$

Temperature at well head = 47 - 1.4 = 45.6°F

2. Mixing at well head

$$T = \frac{4560 \text{ lb/hr} \times 45.6°\text{F} + 2490 \text{ lb/hr} \times 33°\text{F}}{7050 \text{ lb/hr}} = 41.2°\text{F}$$

3. Returning water:

$T_o$ = 9°F

$T_i$ = 41.2°F

$L$ = 1200 ft

$Q_m$ = 7050 lb/hr

$r_1$ = 1.75 inches

$r_2$ = 3.25 inches

$r_3$ = 13.25 inches

$k_1$ = .022 BTU/ft hr °F

$k_2$ = 0.6 BTU/ft hr °F

$$\dot{q} = \frac{2\pi(1200)(32.2)}{\ln \frac{3.25}{1.75} / .022 + \ln \frac{13.25}{3.25} / .6}$$

$\dot{q}$ = 7900 BTU/hr

$$\Delta T = \frac{7900}{7050} = 1.1°\text{F}$$

Final temperature of the water should be 41.2-1.1 = 40.1°F. This compares with a measured temperature at the well house of 40°F.

From the above calculations, it was found that on March 24, 1966 a total of approximately 14,000 BTU/hr was lost from the well lines.

## Heat Losses in the Storage Tank

The 40,000 gallon water storage tank is of wood-stave construction resting on a 25 foot tower. Because of the extreme cold and high winds, the tank was furred and covered with 3/8" plywood to create a dead air space for insulation.

An analysis of the temperature data collected from various points in the storage tank showed that water temperature in the tank was essentially independent of location within the tank.

Since all water is circulated through the tank under normal operating conditions, the water in the tank is being continually changed and mixed. This prevents water stratification from occurring and hides the effect of the wind on the water temperature.

Approximate heat loss calculations showed that at an air temperature of -40°F and a wind velocity of 10-15 mph, approximately 45,000 BTU/hr of heat would be lost from the water in the tower. The greatest heat loss from the tank normally would occur during the coldest month but at a different time of the year than the greatest heat losses in the underground part of the system.

## Summary

Using the data obtained, heat loss calculations were made on all major portions of the water system. Theoretical determinations were made in some cases and compared with the empirical heat losses.

By expanding the calculations made in the examples in previous sections of this chapter, heat losses for the entire system on a day such as March 24, 1966, were found to total approximately 140,000 BTU/hr. This assumes miscellaneous minor heat losses totaling about 10,000 BTU/hr. The heat losses were divided as follows:

| Portion of System | Heat Loss | % of Total |
|---|---|---|
| House loops | 11,000 BTU/hr | 8 |
| Main loops | 75,000 BTU/hr | 54 |
| Well loops | 14,000 BTU/hr | 10 |
| Water Tank* | 30,000 BTU/hr | 21 |
| Miscellaneous | 10,000 BTU/hr | 7 |
|  | 140,000 BTU/hr | 100% |

**The water tank heat loss given here is less than that discussed in the previous section, since air temperatures were warmer.*

# Chapter 4

## Heat Transfer Considerations in Design of System

Many of the factors considered herein will apply to systems other than the single main recirculating system. However, if the utility is to be buried, the single main system will likely be the most economical.

Heat transfer considerations will be very important in the design phase of the system. In areas where the climate causes water freezing in the pipes, underdesign can produce a system which is a failure, while overdesign can make the system uneconomical. Therefore, it is of paramount importance to be as accurate as possible in heat loss estimations. No matter how detailed and painstaking the heat loss calculations are, however, there will be several parameters which will introduce errors into the results. Perhaps the most important of these is the variation in make-up and water content of the earth in which the pipes will be buried. Others which may have importance are variations in land surface and snow cover, and the lack of sufficient temperature data.

The first requirements in the design of a single-main recirculation system would be to determine the soil characteristics in the proposed location of the system. It is then possible to estimate the lowest soil temperatures expected at the pipe depth.

In subarctic regions where there is no permafrost, a first approximation would be to determine the maximum depth of freezing for design purposes. This can be accomplished by use of the modified Berggren Equation discussed later in this section. If the depth of the 32°F isotherm is shallow enough to economically bury the system beneath this depth, a single-main recirculation system is not needed.

If the pipe must go in the seasonal frost zone, a very rough approximation of soil temperatures at a given depth can be obtained by a straight-line interpolation between 32°F at the depth obtained by the Berggren Equation and the design minimum soil surface temperature.

## Design Freezing Index

The surface freezing index of the area must be known to use the modified Berggren Equation. The freezing index is the sum of the differences between the daily mean temperatures and 32°F for one year. Daily mean temperatures above 32°F are not included in the summation. One method of estimating this value is to use monthly averages. For each month where the average temperature (TA) is below 32°F, multiply (32-TA) times the number of days in that month. The sum of all these values over the year is an approximation of the freezing index.

The freezing index to use in the design of a system would, of course, have to be something larger than the average freezing index. Calculation Methods for Determination of Depth of Freeze and Thaw in Soils (5) defines the design freezing index as "...the average air-freezing index of the three coldest winters in the latest 30 years of record. If 30 years of record are not available, the air-freezing index for the coldest winter in the latest 10 year period may be used." The design air-freezing index can be approximated by adding 1,000°F days to the mean freezing index for most locations in Alaska. Figure 13 shows mean air-freezing indexes for Alaska.

Another method of determining a design freezing index would be to plot a probability graph using all available yearly freezing indexes. The freezing index for the probability desired may then be estimated by interpolation.

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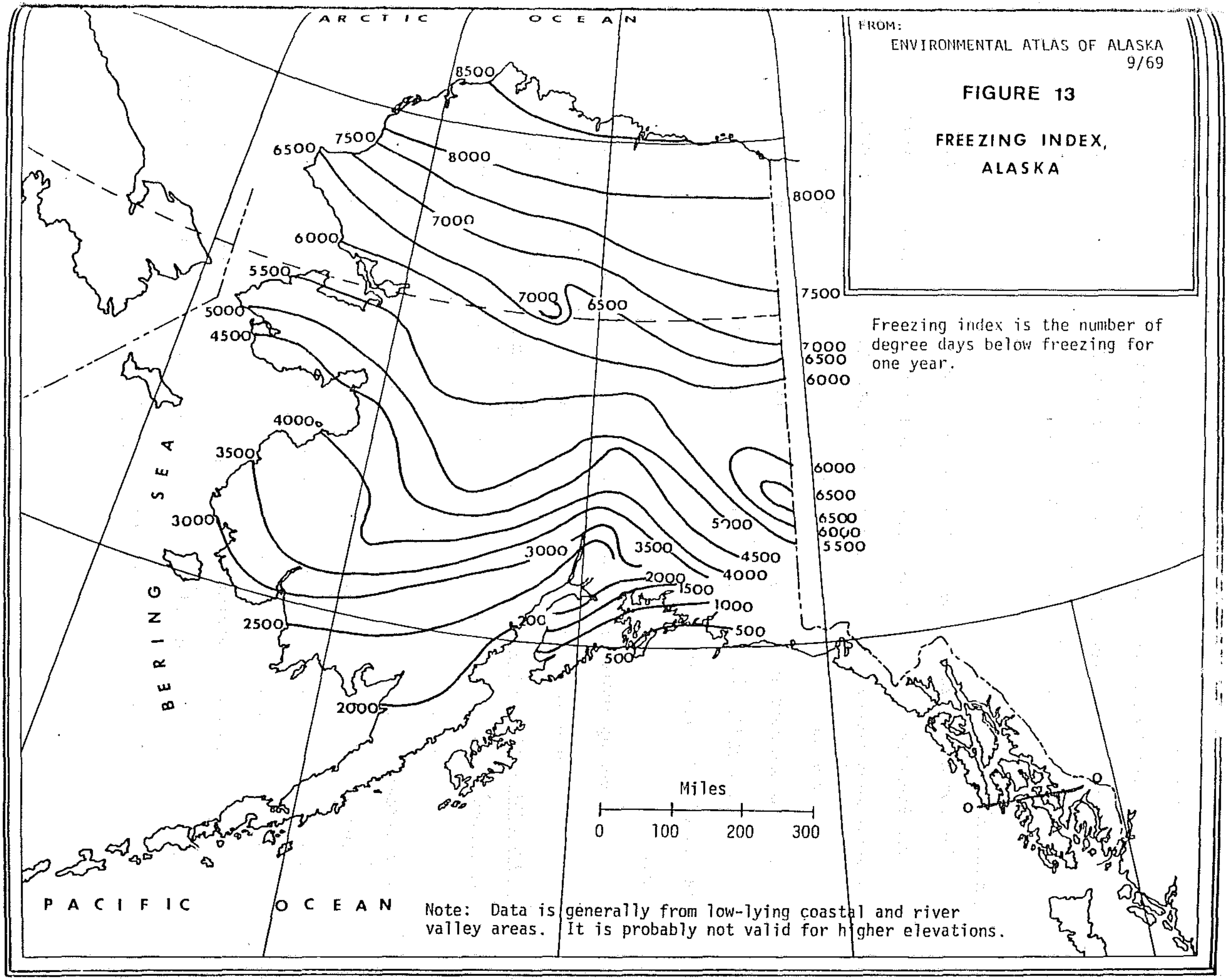
## FIGURE 13

### FREEZING INDEX, ALASKA



Freezing index is the number of degree days below freezing for one year.

Note: Data is generally from low-lying coastal and river valley areas. It is probably not valid for higher elevations.

Modified Berggren Equation (6): The following equation may be used to find the maximum depth of the 32°F isotherm below the surface of the ground.

$$x = \lambda \sqrt{\frac{48knF}{L}} \qquad (4\text{-}1)$$

where
$x$ = depth of freeze (ft)

$k$ = thermal conductivity of soil $\left(\frac{\text{BTU}}{\text{hr ft °F}}\right)$

$L$ = volumetric latent heat of fusion (BTU/ft$^3$)

$n$ = conversion factor for air freezing index to surface freezing index (see Table 4)

$F$ = air freezing index

$\lambda$ = a coefficient which is a function of the freezing index, the mean annual temperature, and the thermal properties of the soil.

The value of $\lambda$ is generally very close to 1.0 in cold climates, but affects the equation increasingly in warmer regions. Two factors, the thermal ratio, $\alpha$, and the fusion parameter, $\mu$, are used to determine $\lambda$.

$\alpha$ is defined by

$$\alpha = \frac{V_o}{V_s} \qquad (4\text{-}2)$$

where
$V_o$ = mean annual site temperature minus 32°F (MAT-32°F)

$V_s = nF/t$

$t$ = length of freezing season

The fusion parameter, $\mu$, is defined by

$$\mu = V_s \frac{C}{L} \qquad (4\text{-}3)$$

where
$C$ = volumetric specific heat of the soil

Figure 14 can be used to obtain $\lambda$ as a function of $\alpha$ and $\mu$.

### Table 4-1*

| Surface type | n-factor |
|---|---|
| snow | 1.0 |
| pavements free of snow & ice | 0.9 |
| sand and gravel | 0.9 |
| turf | 0.5 |

*These values are estimates and should only be used in the absence of better information.

### Example of Use of the Modified Berggren Equation

Problem: To find the depth of freezing, x, during an average year in a deep gravel fill at King Salmon, Alaska.

Given:

$k_{avg} = 1.05$ BTU/ft hr °F

$\gamma_{dry} = 100$ lbs/ft$^3$

$W = 13\%$ water

$F = 2300°$ Days

$T = 180$ Days

$n = 0.9$

$V_o = 34°F - 32°F = 2°F$

$V_s = \frac{0.9(2300)}{180} = 11.5$

$C_{avg} = [0.17 + (.75W)]\ \gamma_{dry}$

$C_{avg} = 27$ BTU/ft$^3$°F

$L = 144(100)\ (0.13) = 1870$ BTU/ft$^3$

$\mu = V_s \frac{(C)}{L} = \frac{11.5(27)}{1870} = 0.166$

$\alpha = \frac{V_o}{V_s} = \frac{2}{11.5} = 0.174$

From Figure 14, $\lambda = 0.94$

$$x = \lambda \sqrt{\frac{48knF}{L}} = .94\sqrt{\frac{48(1.05)\ (.9)\ (2300)}{1870}}$$

$$x = 7 \text{ ft.}$$

Therefore, we would expect approximately 7 ft. of freezing in the gravel fill. For a design year, if the freezing index is increased by 1000 degree-days, x = 10 ft.

In soils which are dry, or in extremely cold areas where permafrost exists and the active layer is thin, the following equation may be used to estimate temperature at a given depth:

$$A_x = A_o \exp\left(-x\sqrt{\frac{\pi}{ap}}\right) \tag{4-4}$$

where $A_x$ = amplitude of temperature wave at depth x, °F

$A_o$ = amplitude of the surface wave above or below the mean annual surface temperature, °F

$x$ = depth below surface, ft

$a$ = thermal diffusivity of the mass, $ft^2$/day

$p$ = period of sine wave, 365 days.

The amplitude of the surface temperature wave is difficult to obtain. It is invariably less than that of air temperatures, and varies with the type of surface. Figure 15 gives a qualitative picture of the wave for various surfaces, drawn about a given vertical axis. Air temperature annual sine wave amplitudes for Alaska are shown in Figure 16. From these, the surface temperature amplitudes can be estimated.

Like the annual surface temperature wave, the Mean Annual Surface Temperature (MAST) is a function of many variables, and is difficult to obtain precisely. It is usually from 2°F to 11°F warmer than the mean annual air

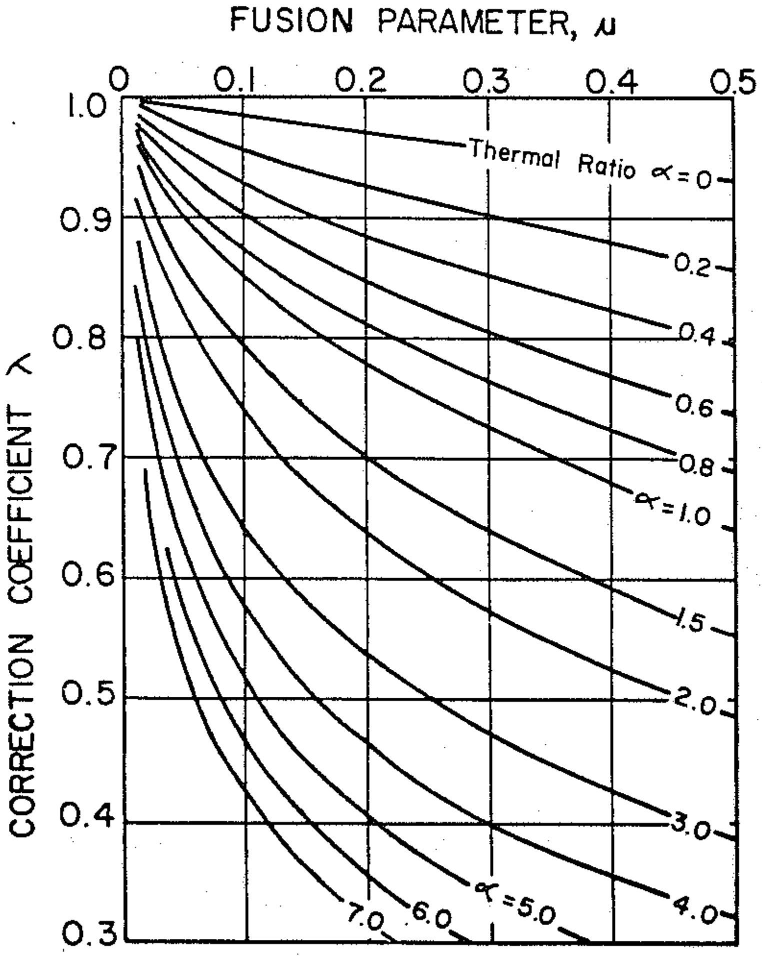


FIGURE 14

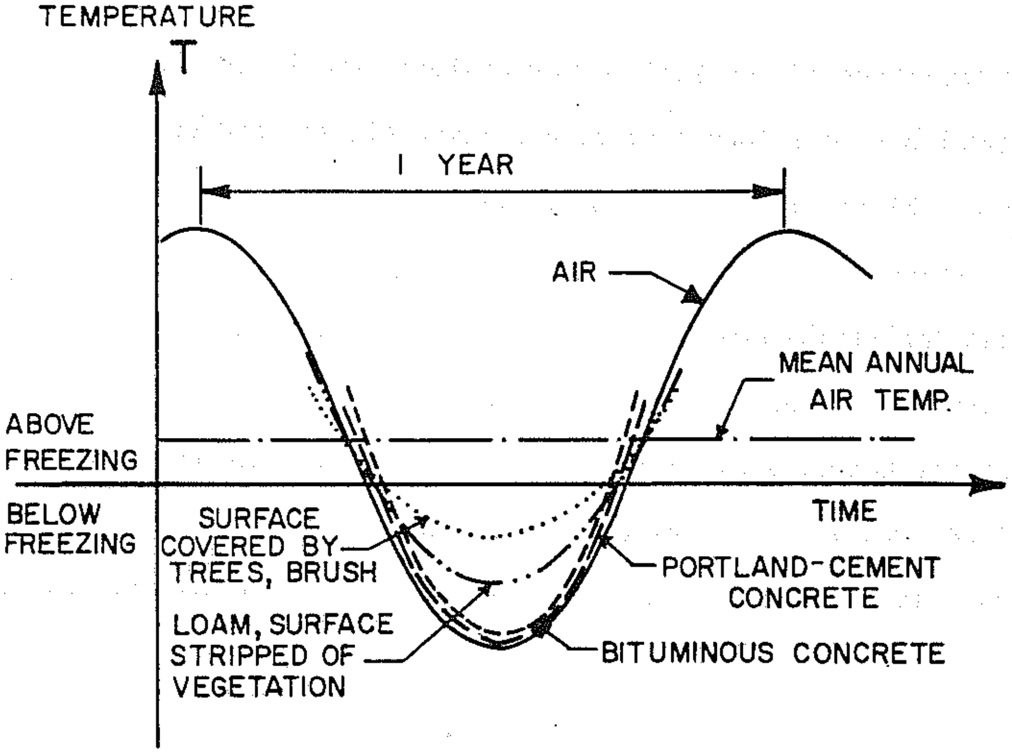


FIGURE 15

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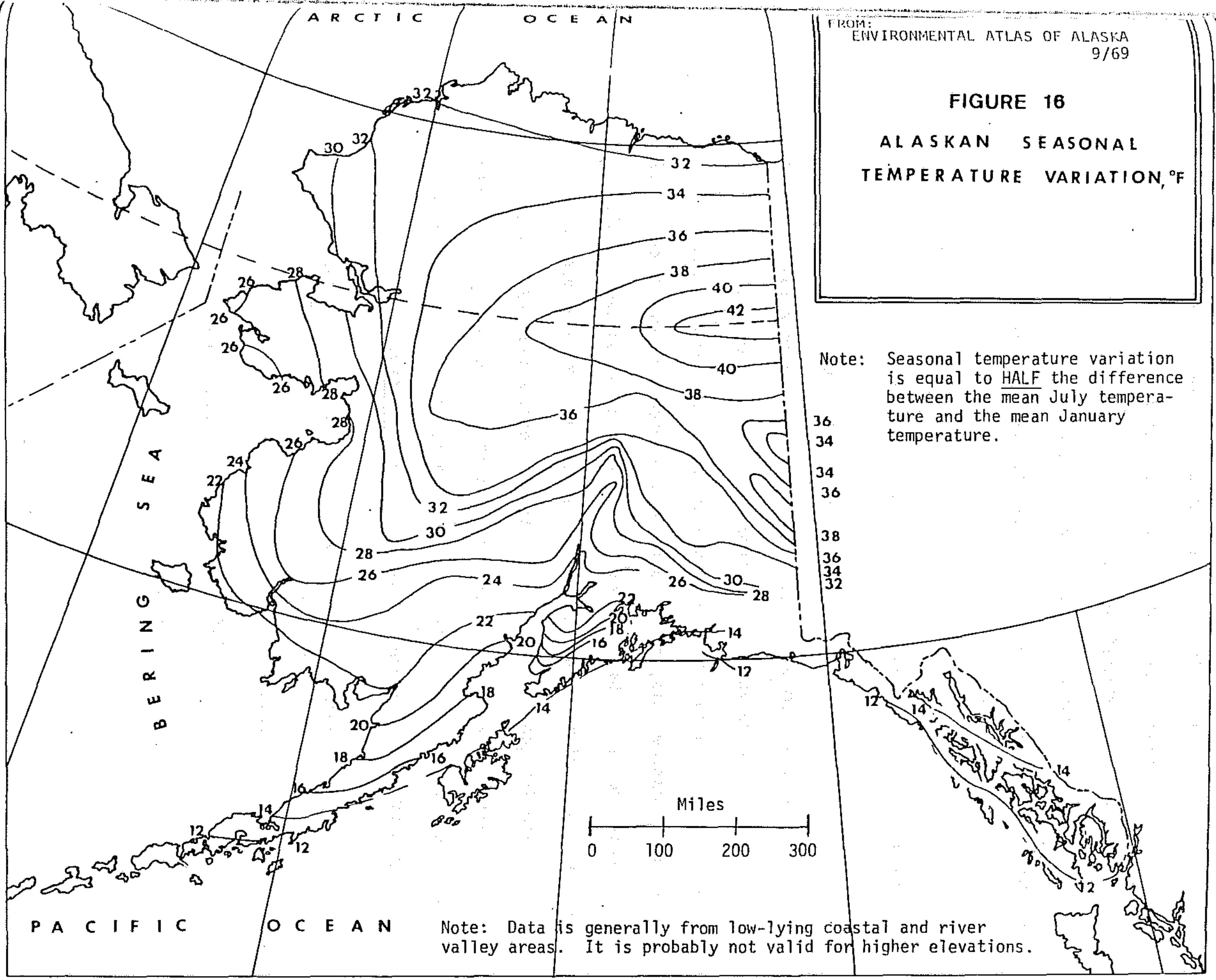
## FIGURE 16

## ALASKAN SEASONAL TEMPERATURE VARIATION, °F



Note: Seasonal temperature variation is equal to HALF the difference between the mean July temperature and the mean January temperature.

Note: Data is generally from low-lying coastal and river valley areas. It is probably not valid for higher elevations.

temperature. Figure 17 shows the mean annual air temperatures for Alaska. To obtain the lowest temperature expected at depth x, subtract $A_x$ from the mean annual surface temperature.

The amount of time that temperatures at a given depth will lag behind surface temperatures can be estimated by the following equation:

$$t_x = \frac{x}{2}\sqrt{365/\pi a} \qquad (4\text{-}5)$$

where $t_x$ = phase lag at depth x, days.

The best method for determining temperatures at pipe depth is, of course, to measure them over a period of years at the location. This is usually impossible because of the time and expense involved. If it is possible to drill a test hole and make at least one set of subsurface temperature measurements, this should be done when the soil temperatures are expected to be at their lowest. The drilling method used should be that which will disturb the natural conditions as little as possible.

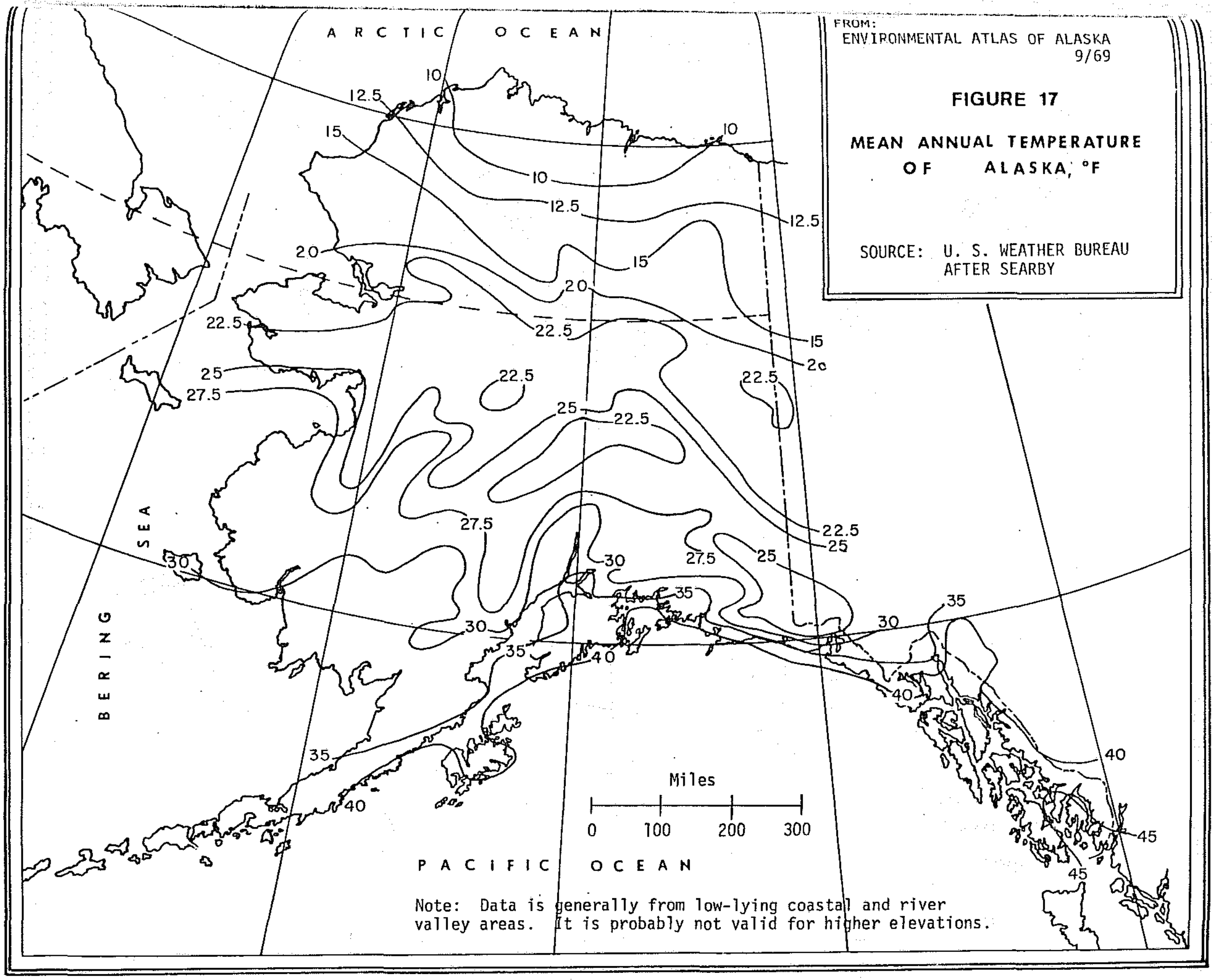
Equation 4-5 can be used to estimate the temperature lag at a given depth. However, there is an additional amount of time that must be considered because the air temperature lags behind the sun. This can be determined by use of Figure 18, <u>Seasonal Lag in Alaska</u>.

Example of Determination of the Date of Lowest
Temperatures at 5 ft. Depth in Unalakleet

Given: $a = 0.84\ ft^2/day$

$$t_x = \frac{5}{2}\sqrt{365/.84\pi} \text{ (Equation 4-5)}$$

$$t_x = 30 \text{ days}$$



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## FIGURE 17

## MEAN ANNUAL TEMPERATURE OF ALASKA, °F

SOURCE: U. S. WEATHER BUREAU
AFTER SEARBY

Note: Data is generally from low-lying coastal and river valley areas. It is probably not valid for higher elevations.

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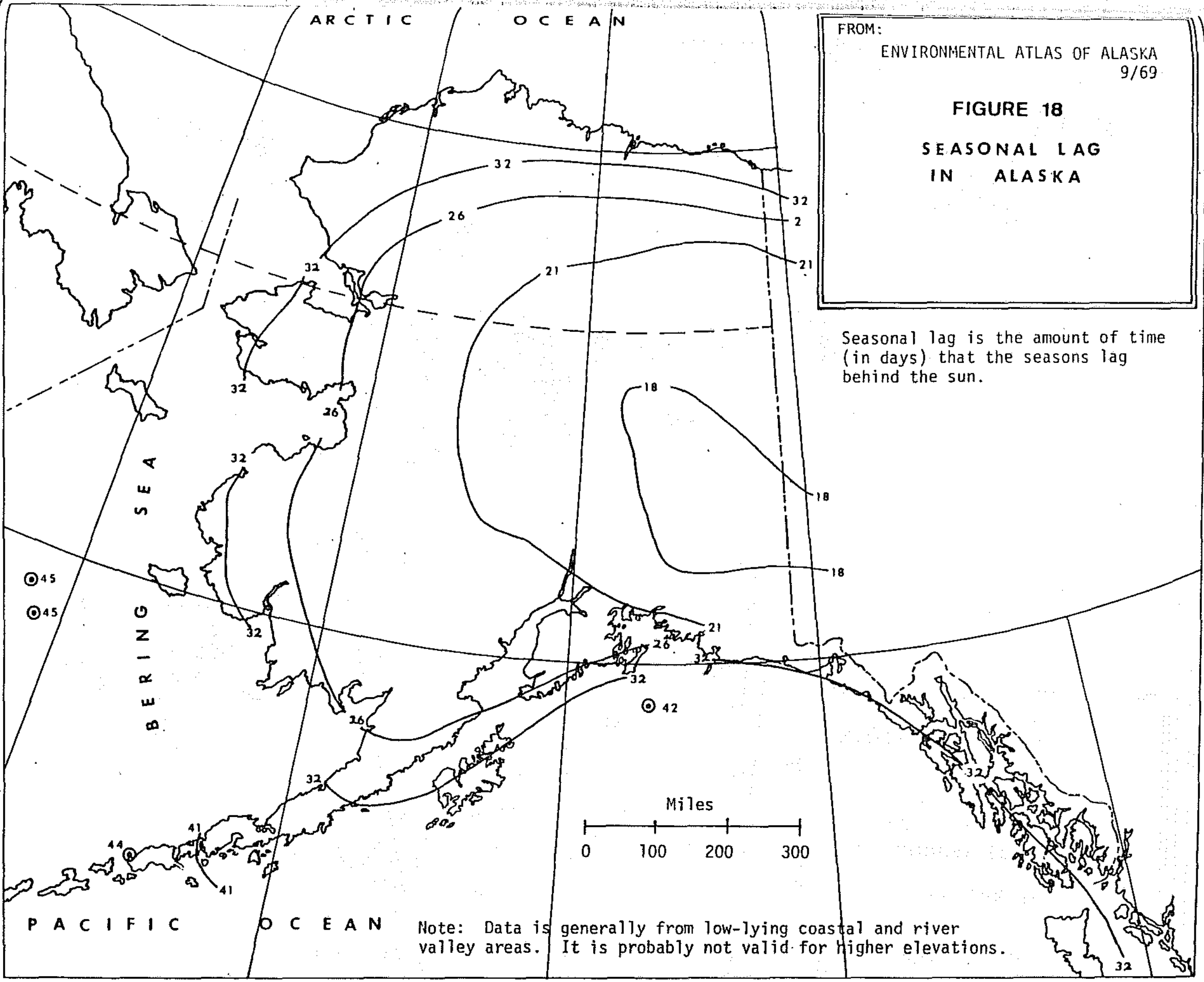
## FIGURE 18

## SEASONAL LAG IN ALASKA



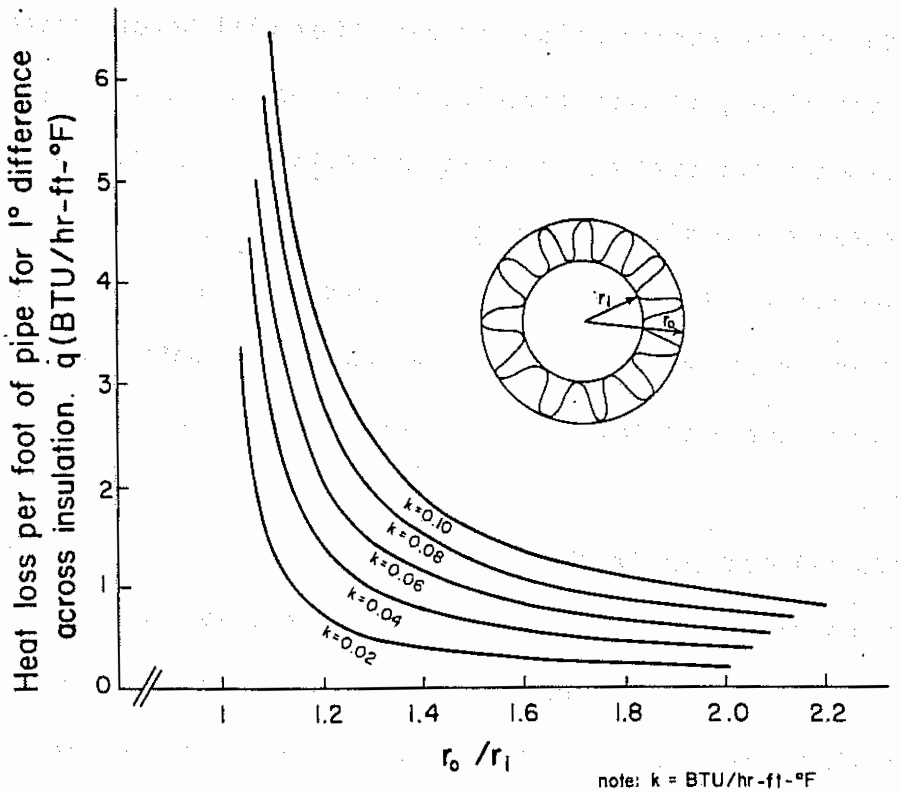
Seasonal lag is the amount of time (in days) that the seasons lag behind the sun.

Note: Data is generally from low-lying coastal and river valley areas. It is probably not valid for higher elevations.

Actually the lag time with depth would be slightly longer, since the effect of moisture in the soil is ignored in the equation above.

From Figure 18, air temperature lag time is around 26 days. Therefore, the coldest temperature at 5 ft depth would be expected around Dec. 22 + 26 = Feb. 16. Thus, the last part of February would be the best time for subsurface temperature measurements.

Figure 19 shows a series of curves which may be used to conveniently estimate heat losses from insulated pipe. To use the graph, first obtain the ratio of insulation to pipe radius. Entering the graph with this number, proceed vertically to the thermal conductivity of the insulation, and then horizontally to the left to obtain heat loss per foot of pipe for a 1°F difference across insulation. Simply multiply this by the length of pipe and the temperature gradient expected across the insulation to obtain an estimate of total heat loss.



note: k = BTU/hr-ft-°F

Figure 19

The above discussions, together with the calculations and explanations of Chapter 3, should be sufficient to determine heat loss characteristics for a single-main recirculating water system.

At the expense of stating the obvious, some comments are enumerated below for consideration during design and construction phases.

1.) Choice of Material: All pipes should be made of a material which can withstand tensile stresses due to freezing. Cast iron pipe, in our opinion, is a rather poor choice for water systems in the Far North. If a freeze-up of the mains should occur due to any reason, the cast iron pipe would be one of the first parts of the system to burst. Repair and replacement costs would be extremely high. Thin-walled steel pipe has been shown to withstand the freezing cycle better than other materials.

2.) Construction: Extreme care must be used to be certain all pipes are clean. If any foreign materials (including rodents and other animals) should get trapped during the construction process, they will become caught on the protruding pitorifices, thereby reducing flow or completely clogging the main. Unlike conventional systems, finding and alleviating the problem can be extremely expensive and time consuming.

3.) Cross-Connections: Although always a hazard in water supplies, a single cross-connection in a recirculating system has the potential of contaminating the water supply of the entire village faster than in more conventional systems.

4.) Grades: As pointed out in the main body of this report, all mains and service connections should be laid to a grade designed so that <u>all</u> water can be pumped from the system if the need should arise due to a complete shutdown during the winter months. The Unalakleet system utilized the hydrants for this purpose.

5.) Thaw Cables: The thaw cable coming to the surface above the pitorifice connection works fine as long as it can be found when needed. Good design, at extra cost, would provide for this cable to be extended to the house where it could be positively located at any time.

6.) Interior Loop Plumbing: Also mentioned elsewhere in this report was the problem of people tampering with the loop valving on the house interior (children are not always the culprits). By far the safest method of solving this problem would be to construct a tamperproof box or cage around this plumbing which would allow only water works personnel access.

7.) Boiler Selection: Two boilers should be installed at any remote facility. Any failure of one should automatically start and place the second on line.

When sizing the boilers ample capacity should be provided to handle the necessary heating of the water and the heating of the interior of the water plant-pumping station.

8.) Pumphouse Piping: Any system which incorporates more than one loop will have involved piping and valving arrangements. It is not within the scope of this report to go into details since every system will be different, but it is justified to mention a few points:

a) All exit and entrance mains should have individual meters.

b) All pumps should be installed with the necessary valving so they can be used in series or parallel, or for any chosen loop.

c) Valves to isolate any section of the plumbing should not be spared.

9.) Alarms: Alarms should be arranged to notify personnel when the water velocity drops below a predetermined minimum, the water temperature drops too low, or the electrical power fails. In small installations which are not monitored 24 hours per day, these alarms should be transmitted to a police station, operator's home, etc.

The authors feel that if a system is designed by the heat loss calculations discussed in this chapter and using sound engineering principles (and common sense), a reliable facility will be produced.

# Appendix I

## Theory

Heat losses from a buried pipe through which water is flowing vary with time. Parameters which are not constant include the following: The temperature of the ground surrounding the pipe, the soil characteristics, the pipe depth, and the flow through the pipe. However, since the effect of the above can only be approximately determined, steady state equations are used to predict heat losses. Only conductive heat flow equations will be used, since radiation and convection are considered negligible as heat dissipation mechanisms in the ground. Surface effects are also ignored, since they are of minor nature.

The basic relationship for heat conduction is given by the Fourier's equation,

$$\dot{q} = kA \frac{\delta T}{\delta x} \qquad (I-1)$$

where

$\dot{q}$ = heat transfer rate

$k$ = thermal conductivity of the material

$\frac{\delta T}{\delta x}$ = temperature gradient

If a long cylinder of length L is exposed to a temperature differential of $T_i - T_o$, the heat flow out of the cylinder may be obtained by inserting the proper area relationship for the above equation.

For a long cylinder,

$$A_r = 2\pi rL \qquad (I-2)$$

Substituting into Fourier's Law,

$$\dot{q}_r = -2\pi krL \frac{dt}{dr} \qquad (I-3)$$

With boundary conditions:

$$T = T_i \text{ at } r = r_i$$

$$T = T_o \text{ at } r = r_o$$

Rearranging the above equation and integrating,

$$\dot{q}_r \int_{r_i}^{r_o} \frac{dr}{r} = -2\pi kL \int_{T_i}^{T_o} dT \quad \text{or,} \quad \dot{q}_r \ln \frac{r_o}{r_i} = 2\pi kL(T_i - T_o)$$

Rearranging again,

$$\dot{q}_r = \frac{2\pi kL(T_i - T_o)}{\ln(r_o/r_i)} \tag{1-4}$$

For a multilayered cylinder of cross section shown in Figure 1-1, the heat loss is given as

$$\dot{q}_r = \frac{2\ L(T_i - T_o)}{\ln(r_2/r_1)/k_1 + \ln(r_3/r_2)/k_2 + \ln(r_4/r_3)/k_3} \tag{1-5}$$

where $T = T_i$ at $r = r_1$, and $T = T_o$ at $r = r_4$.

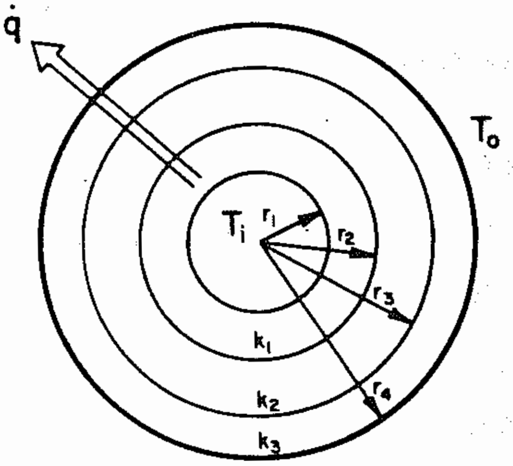


FIGURE I-1

In order to determine the temperature drop of water flowing through the pipe once the heat losses are known, the following equation may be used:

$$\Delta T = \frac{\dot{q}}{Q_m c} \qquad (I\text{-}6)$$

where $\Delta T$ = change in temperature of the water over the length of pipe for which $\dot{q}$ was computed.

$Q_m$ = mass flow rate of liquid in the pipe

$c$ = specific heat of liquid in the pipe

When a liquid flows through a pipe, $T_i$ continually decreases due to heat loss. Because of this, the driving force for heat flow from the pipe continually decreases also. By dividing the pipe into short lengths and using an iterative procedure, this change in heat flow may be taken into consideration. In this procedure, $\dot{q}_r$ is determined for a short length: T is computed from the heat loss and subtracted from the original $T_i$ to produce a smaller driving force for heat flow. This type of iterative procedure is very amenable to computer solution. However, if the temperature decrease is small compared to the temperature difference producing heat flow, the error introduced by not using an iterative procedure is very small.

# Appendix II

## Determination of Soil Properties

The determination of heat transfer properties of the soil is extremely important in predicting possible heat losses in a proposed system. Three parameters are of interest: thermal conductivity (k), specific heat (c), and thermal diffusivity (a).

Thermal Conductivity: The thermal conductivity of a soil can generally be determined to within 25 percent if soil type, dry density, and moisture content of the soil are known. Miles Kersten (7) gives equations for the determination of k for various soils both in the frozen and unfrozen state. Figures II-1, II-2, II-3, and II-4 are graphical representations for the equations. For purposes of the diagrams, "silt and clay soils" are defined as containing more than 50 percent silt and clay, while "sandy soils" consist mainly of gravel and sand of normal composition. For soils that contain 20-50 percent clay and silt, and for sandy loam soils, a combination of the charts should be used. It should be emphasized that the charts should be used with caution. Soils have been tested whose conductivity varied more than 100 percent from that predicted by Kersten's curves.

Another, more accurate, method of determining the thermal conductivity of a soil is to use a thermal conductivity probe such as that described by Arthur C. Lachenbruch in Transactions, Geophysical Union (8). The probe essentially consists of a tube about 20" long, an axial heater filament, and a thermistor placed about midway on the long axis of the tube. In order to determine the conductivity of the soil, a hole is dug to the depth that measurements are desired, and the tube is inserted horizontally into the ground.

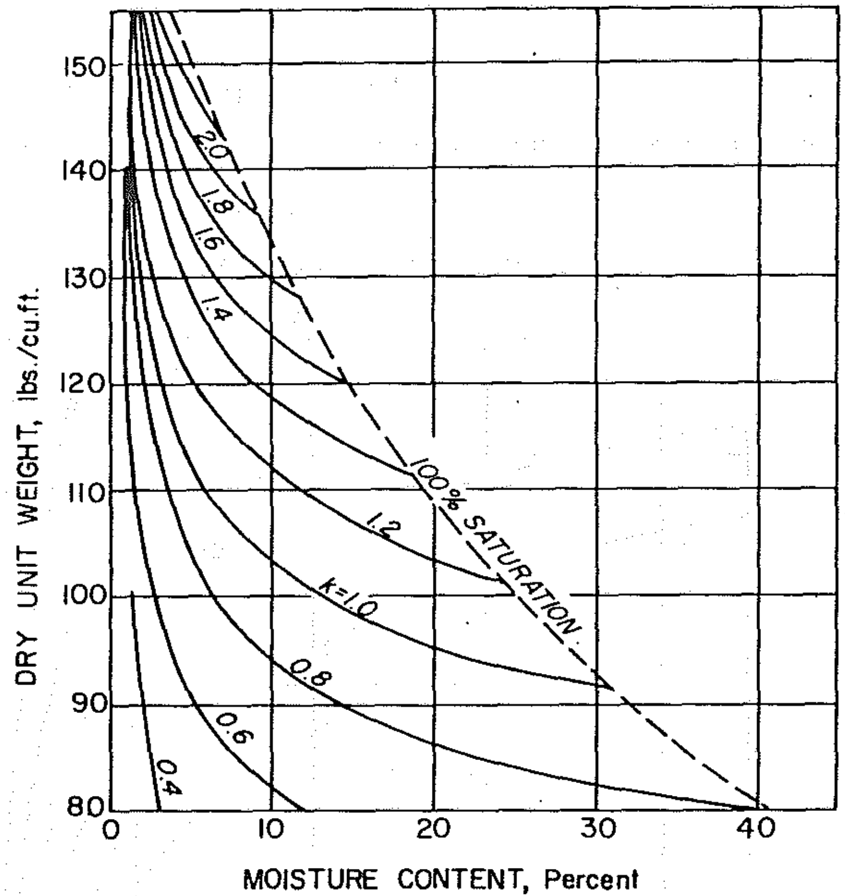


FIGURE II-1

Average Thermal Conductivity for Unfrozen Sandy Soils
After Kersten (Ref. 7)

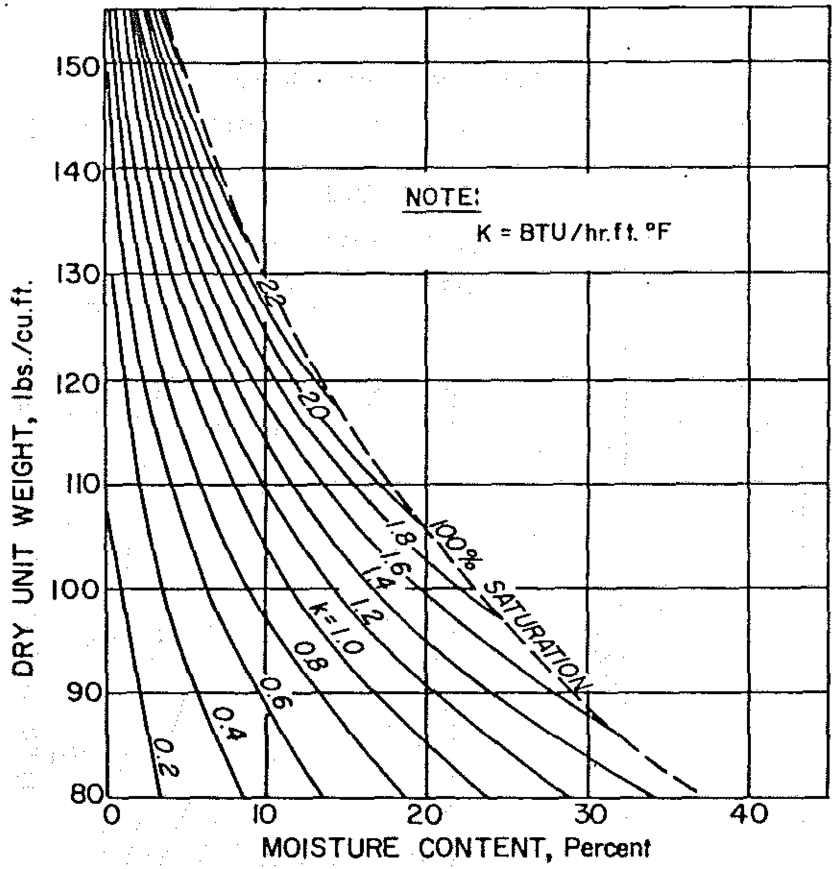


FIGURE II-2

Average Thermal Conductivity for Frozen Sandy Soils
After Kersten (Ref. 7)

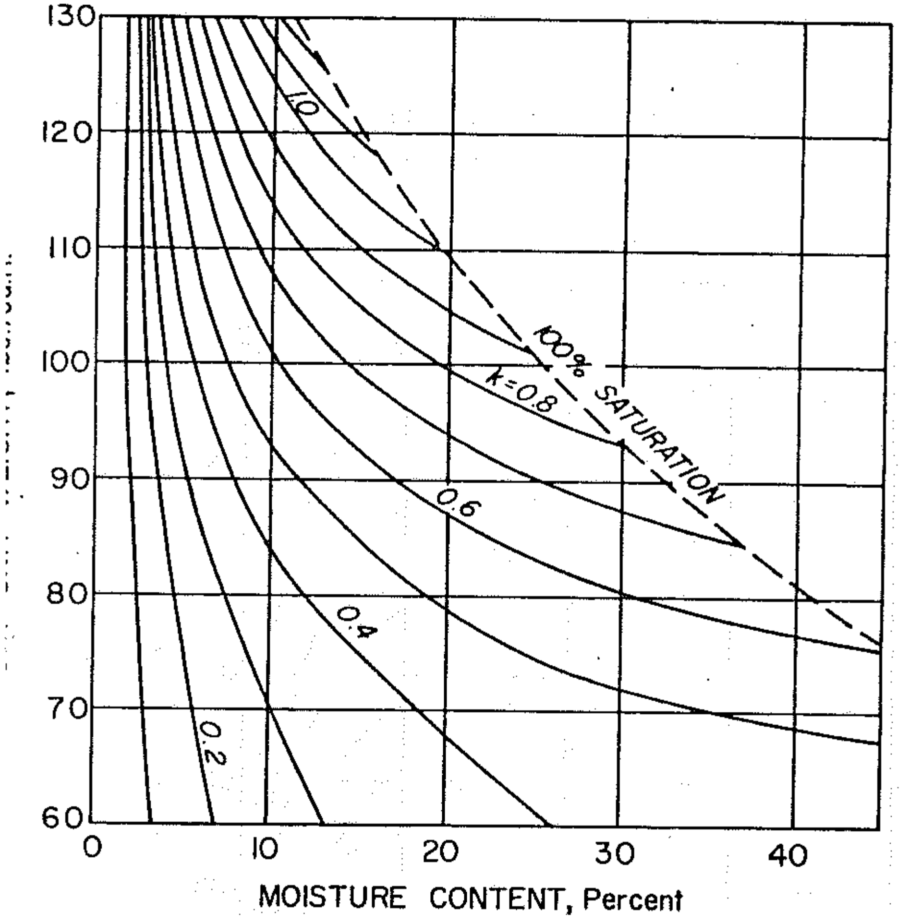
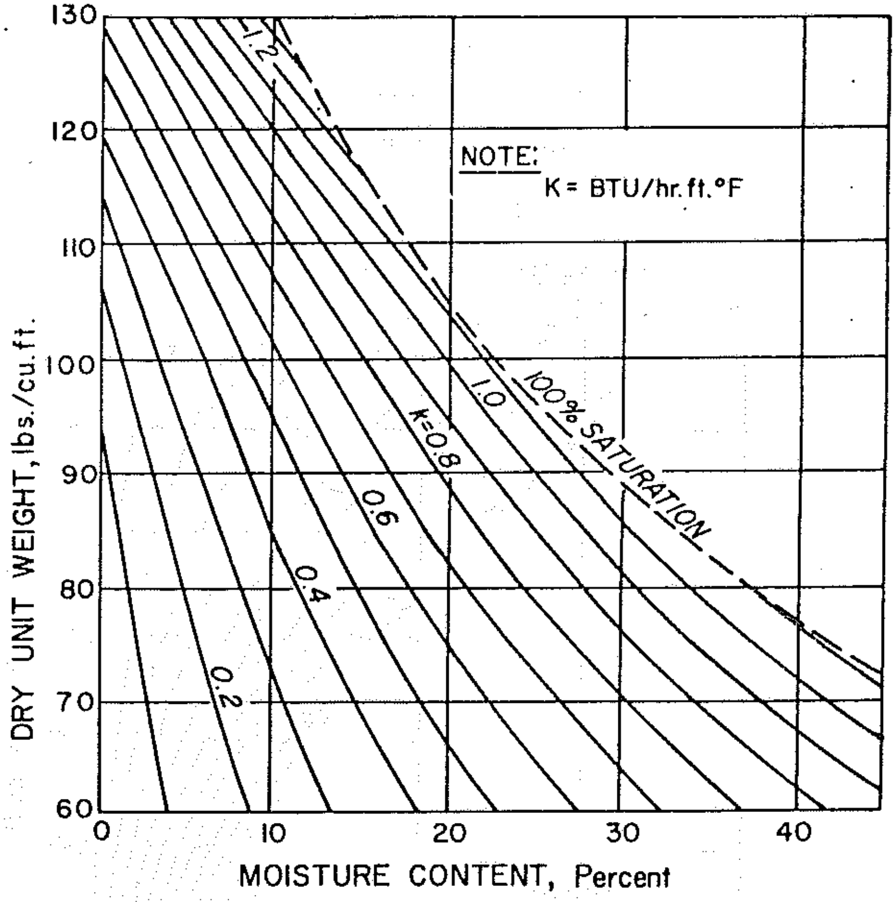


FIGURE II-3

Average Thermal Conductivity for Unfrozen Silt and Clay Soils
After Kersten (Ref. 7)



NOTE:
K = BTU/hr.ft.°F

FIGURE II-4

Average Thermal Conductivity for Frozen Silt and Clay Soils
After Kersten (Ref. 7)

A constant amount of current is passed through the filament, and the temperature increase is measured as a function of time. After a certain amount of time, the current is cut off and temperature-time observations may be continued while cooling takes place. To analyze the data, the temperatures are plotted against the logarithm of time. With certain corrections, a straight line is obtained. From the slope of the line, k may easily be derived. The probe gives reproducible results to about 2 percent, according to Lachenbruch. This is less than the variability of most soils from place to place. It is important, however, that the probe be placed horizontally, like the pipe will be placed, since thermal conductivity varies in different directions in the ground.

The importance of the thermal conductivity of the soil decreases rapidly when insulation is to be used on the pipes. If the insulative effect of the ground becomes very small in relation to that of the insulation surrounding the pipe, it can be ignored completely. The small error introduced by doing this makes heat losses appear higher than they would actually be, so it would be on the side of safety.

Specific Heat: Specific heat, the heat absorbed by a unit weight of substance when its temperature is increased by one degree, does not vary greatly in most soils. In dry soils near the freezing point it can be taken to be 0.17 BTU/lb°F. According to Kersten the average variation in specific heat of dry soils is from 0.16 at 0°F to 0.19 at 140°F, or an increase of 11 percent per 100°F temperature rise.

The specific heat of a moist soil can be obtained if the moisture content is known, by proportion of soil and water, and their respective specific heats. For the case of a moist unfrozen soil without excess moisture, the following equation applies:

$$c_u = 0.17 + 1\frac{(\text{\% by weight of } H_2O)}{100}$$

where

$c_u$ = specific heat of unfrozen soil (BTU/lb°F)

Since the specific heat of ice is about half that of water, the following equation applies when the wet soil is in the frozen condition:

$$c_f = 0.17 + 0.5\ \frac{(\text{\% by weight of } H_2O)}{100}$$

where

$c_f$ = specific heat of frozen soil (BTU/lb°F)

Thermal Diffusivity: In all problems concerning steady heat flow, thermal diffusivity is involved. The following equation may be used to determine the thermal diffusivity of a dry soil:

$$a = \frac{k}{c\gamma}$$

where

$a$ = thermal diffusivity ($ft^2/hr$)

$k$ = thermal conductivity (BTU/lb°F)

$c$ = specific heat (BTU/lb°F)

$\gamma$ = specific weight ($lb/ft^3$)

For moist, unfrozen soils, the following equation applies:

$$a = \frac{k}{\gamma_{dry}\ (c_{dry} + \frac{\text{\% by weight of } H_2O)}{100}}$$

For moist, frozen soil, the pertinent equation is:

$$a = \frac{k}{\gamma_{dry}\ (c_{dry} + \frac{.5 \times \text{\% by weight of } H_2O)}{100}}$$

The rate of temperature change of a soil with change in time is dependent on thermal diffusivity. A soil having a high value of "a" will heat faster than a body with a low value of "a". Thus over a year's temperature cycle, a soil with a low "a" will freeze to a shallower depth than one in which "a" is higher.

# Appendix III

## Symbol Table

$a$ = thermal diffusivity ($ft^2/hr$)

$A_x$ = amplitude of temperature wave at depth x(°F)

$A_o$ = amplitude of surface temperature wave above or below the mean annual surface temperature (°F)

$\alpha$ = thermal ratio (dimensionless)

$\gamma$ = specific weight ($lb/ft^3$)

$c$ = specific heat (BTU/lb°F)

$C$ = volumetric specific heat ($BTU/ft^3$°F)

$F$ = air freezing index (°F-day)

$k$ = thermal conductivity (BTU/hrft°F)

$L$ = volumetric latent heat of fusion ($BTU/ft^3$)

$\lambda$ = coefficient in modified Berggren equation (dimensionless)

$\mu$ = fusion parameter (dimensionless)

$n$ = conversion factor for air freezing index to surface freezing index (dimensionless)

$p$ = period of sine wave of annual march of temperatures (365 days)

$\dot{q}$ = heat transfer rate (BTU/hr)

$Q_m$ = mass flow rate (lb/hr)

$r$ = radius (length)

$t$ = time (days)

$T$ = temperature (°F)

$v_m$ = velocity of water in main (ft/sec)

$v_s$ = velocity of water in the service line (ft/sec)

$V_o$ = mean annual site temperature minus 32°F (°F)

$V_s$ = surface freezing index divided by length of freezing season (°F)

$W$ = percent by weight of water (%)

$X$ = depth (ft)

# Appendix IV

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# Appendix V

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