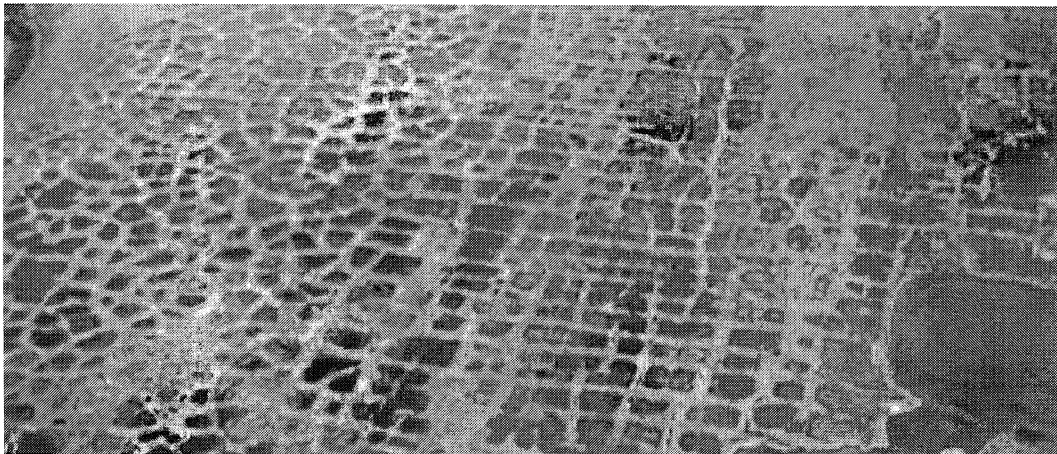# Permafrost Technology Foundation

Design Manual
for
Stabilizing Foundations
on
Permafrost

Permafrost Technology Foundation

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for
Stabilizing Foundations
on
Permafrost

By

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July 2001

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ACKNOWLEDGEMENTS

Preface

This manual is one of two companion volumes intended to present the considerations that should be part of a foundation design in permafrost regions. The first manual is for new construction on a permafrost site where things can be done correctly at the beginning to avoid all of the problems permafrost can cause later on. This manual addresses the stabilization of foundations that are in distress because of thawing permafrost under them. These foundations were not built correctly to survive the rigors of a permafrost site and need to be stabilized to avoid total failure. They are not meant to be engineering design guides or to provide design specifications. The engineering calculations required for safe and sound foundations require a qualified engineer and they are not addressed in this manual.

The manuals are intended to provide a background for homeowners, contractors, builders, Realtors, bankers, and engineers who are not acquainted with permafrost and its traps for the unwary. For the uninitiated, the first two chapters of both manuals present a background in permafrost and in construction on permafrost sites. Since the two manuals address different (and somewhat mutually exclusive) aspects of the problem, it is likely that the reader may have only one of the manuals. Therefore these two background chapters are the same in each manual. If you have both manuals you need not read the first two chapters twice. However, the information in the remaining chapters of each manual relies heavily on the understanding of the problems that are set out in the first two chapters, so read them at least once.

The stabilization of existing foundations, especially ones that are already undergoing settlement distress from thawing permafrost is a very difficult and often expensive process. The manual on stabilization of foundations summarizes ten years of research by the Permafrost Technology Foundation on various stabilization techniques and their performance under actual conditions. The foundation hopes that this information will be useful for building in the far north where these problems can be devastating if not properly addressed.

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Design Manual for Stabilizing Foundations on Permafrost

CHAPTER 1 - PERMAFROST

1.1 INTRODUCTION

Building in permafrost regions requires an understanding of the nature of permafrost and the problems that its presence presents. This chapter will provide a brief discussion of what permafrost is and is not, where it is to be found, when it must be carefully protected and when it can be ignored. The chapter will give a general knowledge of the material and its characteristics. Armed with this information the builder can attack the problems from a position of knowledge and strength.

This manual is intended as a guide for stabilizing foundations that have already been built in permafrost terrain and are experiencing distress. The high-latitude regions of both the north and south hemispheres are laced with regions where permafrost soil is found. When a building must be sited on this type of soil, proper permafrost-related design must be used. To ignore the permafrost invites the inevitable catastrophe that has so often resulted when construction proceeded without regard to the soil conditions of the site. Stabilizing such a foundation is the topic of this manual. Considerations for new construction will be found in the companion manual: *Design guide for New Construction on Permafrost*. This is not intended to be an engineering design text. Engineers experienced in this field have numerous other references that are technically more detailed and advanced. It is intended for the individual who is constructing his own home, the contractor who has a building project in a permafrost area, the inspector who is

responsible for ensuring the integrity of the final product, or the engineer who has not yet had the training and experience required to be competent in this field of expertise. Technical "jargon" cannot be completely avoided, however. When it must be used, it will be defined in terms that everyone can understand.

This manual will provide a short permafrost primer (Chapter 1) and an introduction to permafrost foundation problems (Chapter 2). The remaining chapters will present the various types of foundation stabilization methods available for different types of buildings and the various permafrost problems encountered in northern construction. A bibliography of other reference material for all types of building problems encountered in northern latitudes is included in the appendix at the end of the manual. Periodic references will be given for specific topics throughout the manual as appropriate.

1.2 What is Permafrost?

If you measure the temperature of the surface of the ground for several years, the data will eventually establish a mean maximum temperature and a mean minimum temperature. If the temperature were also monitored at a depth of say 12 inches (0.3 m), a mean high and low temperature could also be found for that depth. However, the mean high temperature at the 12-inch (0.3 m) depth would be cooler than that on the surface, and the mean low temperature would be warmer than the surface temperature.

Carrying this example a little further and referring to Fig. 1.1, assume the temperatures were measured every foot (0.33m) to a depth of approximately 50 ft (15m), the mean low temperature will be found to be a little warmer at each successive depth. Near the surface, the mean high temperature will also decrease at each depth, but the incremental amount that it decreases will be less each time until finally, at a depth of
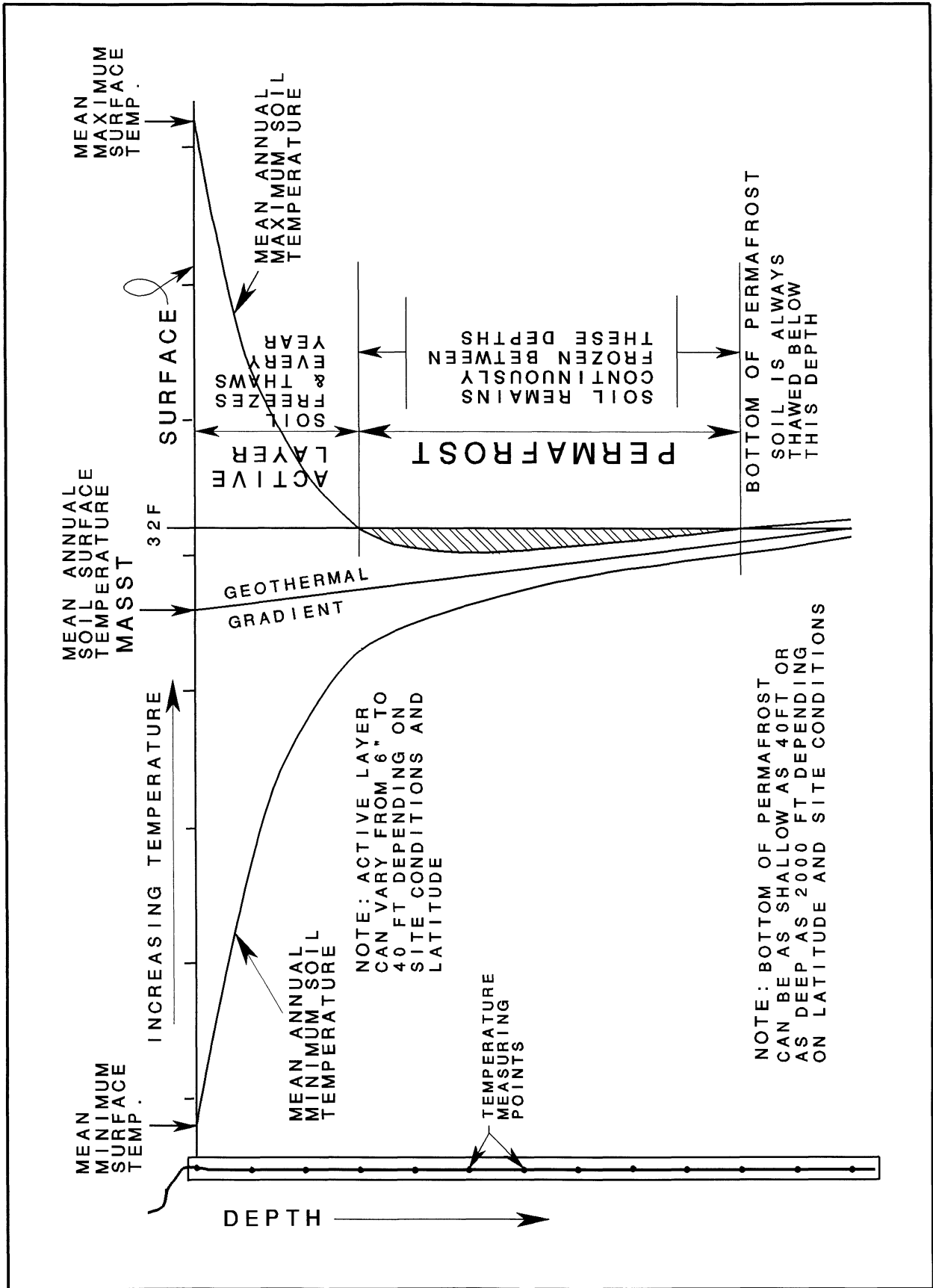
FIGURE 1.1 TRUMPET CURVE-Typical mean high and low temperature extremes vs. depth at a permafrost site.

several tens of feet, it will remain nearly constant for some depth and then finally start increasing slowly once again. The two curves make up what is known as a *Trumpet Curve* because of their shape. Since these curves were established by many years of temperature measurements, they represent the extreme mean temperatures that will be found at any depth. Excursions outside these two trumpet curves can and do happen, especially close to the surface, but if they persist, the position of the curve gradually will be modified as the data base is continually updated and the mean annual temperature gradually changes.

The difference between the high and low temperatures curves continually decreases until, at a depth of between 50 and 100 ft (~15-30 m), it becomes too small to measure. The temperature at each depth below remains essentially constant all year long.

Notice in Fig. 1.1 that as the mean high temperature decreases with depth from the surface, it falls below 32 F (0°C) at a depth of just a few feet. It remains below freezing until eventually, at a much lower depth, it begins to rise until it is above 32°F (0°C) once again. The deeper crossing of the 32 F (0°C) isotherm occurs at various depths, from several feet near the southern boundary of permafrost to as much as 2000 ft (610 m) along the north coast of Alaska. Between the two depths where the mean maximum temperature falls below 32°F (0°C) the soil remains frozen all year long. This area on the chart and in the ground represents "permafrost".

The mean <u>annual</u> soil temperature (MAST) falls midway between the high and low extremes. Below the depth where the surface effects dominate, the MAST increases with increasing depth. The line connecting these mean <u>annual</u> temperatures is known as the *Geothermal Gradient*. The slope of the gradient varies at locations around the world, but it is typically considered to be ~1.7 °F per 100 ft (~3°C per 100 m).

Permafrost can only exist if the amount of heat flowing into the soil (from all sources) is less than the amount of cooling (or more accurately the amount of heat leaving the soil). In some parts of the permafrost zone, the heat balance is tipped in favor of permafrost only in specific areas such as north-facing slopes, sheltered valleys or heavily vegetated sites. In these specific areas, heat from the sun is intercepted either partially or completely so that the cooling effect of winter is greater and permafrost can survive. When the protective cover is disrupted or removed, more heat reaches the surface of the ground, and the permafrost begins to thaw until a new thermal balance between heat input and cooling is established. Figure 1.2. shows the result of a higher surface temperature on the trumpet curve. Notice that the top of the permafrost (the "permafrost table") is deeper, and the bottom of the permafrost is shallower. Permafrost thaws on both the top and the bottom when the mean annual temperature rises because it receives heat not only from the surface, but also from geothermal heat flowing from the center of the earth.

When the surface temperature changes to a warmer value, the result is that the amount of permafrost is reduced or, in many cases, it completely disappears. The reestablishment of the thermal balance can take several years, during which time thawing and settlement gradually compromise the support for the foundation of any structure.

Up to this point our discussion has concerned only *mean* soil temperatures. At any instant in time, the temperature we measure at any particular depth will usually lie somewhere between the two mean annual extremes (i.e. inside the trumpet curve). For example, in November the surface temperature will be near point "A" (Fig. 1.3.) well below
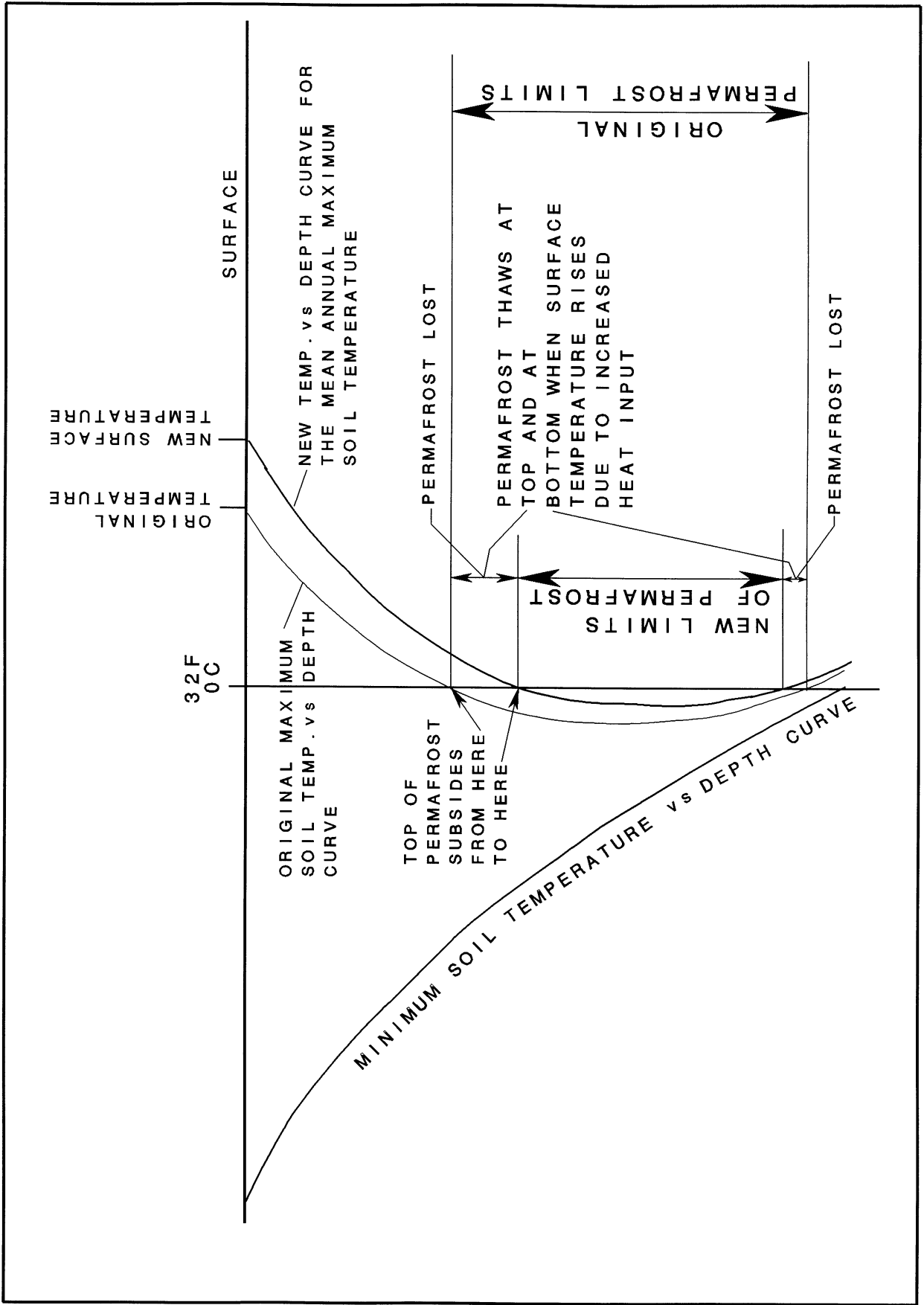
FIGURE 1.2 The effect of increased surface heat input. Note that the permafrost thaws at both the top and the bottom.

MAXIMUM
SURFACE
TEMP.

MEAN
ANNUAL
MAXIMUM
SOIL
TEMP vs
DEPTH

MEAN ANNUAL
SOIL SURFACE
TEMPERATURE

MASST 0C
        32F

LATE MAY
TEMPERATURE
WHIPLASH
CURVE

SURFACE

C

B

A

INCREASING TEMPERATURE

NOVEMBER
TEMPERATURE
WHIPLASH CURVE

MEAN ANNUAL
MINIMUM SOIL
TEMP vs DEPTH

MINIMUM
SURFACE
TEMP.

TOP OF PERMAFROST

PERMAFROST

BOTTOM OF PERMAFROST

NOTE: TEMPERATURE PROFILES
(WHIPLASH CURVES) REPRESENT
THE TEMPERATURE vs DEPTH AT
A SPECIFIC TIME (NOVEMBER AND
MAY ARE SHOWN HERE) THEY ARE
CONTINUOUSLY CHANGING IN
RESPONSE TO THE EVER CHANGING
CONDITIONS AT THE SURFACE.

THESE PROFILES ARE DERIVED
FROM TEMPERATURE DATA TAKEN
OVER MANY YEARS AND ARE THUS
THE MEAN VALUES. THEIR SHAPE
WILL CHANGE VERY SLOWLY IN
RESPONSE TO LONG TERM CLIMATIC
CHANGES SUCH AS GLOBAL WARMING

DEPTH ⟶

FIGURE 1.3 Whiplash Curves - Note that a whiplash curve must always
remain between the two sides of the trumpet curve as it
descends into the soil. The whiplash curve is an actively
changing temperature vs depth curve that reflects surface
heat descending into the soil. Therefore at each instant
in time the curve will be different.

the mean annual soil surface temperature (MASST). At the first depth below the surface (point B) the temperature will be warmer, and at the next depth it will be warmer still.

These temperatures reflect the previous summer weather whose effect is just reaching this depth. There is a time lag involved between the surface temperatures and those below the surface. The cooling effects of the autumn weather are not felt below the surface until the heat has had a time to diffuse through the surface. The deeper soils will be even warmer because they are removed farther from the surface and will not feel the surface cooling until a little later. This trend of higher temperatures with depth continues until the high temperature extreme is reached at point "C" on the chart. This particular point represents the high temperature for the year at this depth and is a function of the hottest day of the previous summer and the type of soil present at the site. (Note that at this depth the highest temperature is not reached until late autumn, much later than at the surface.) The curve then reverses itself and starts to decrease in temperature, reflecting the temperatures from the previous spring that precede the annual high summer temperature.

The curve that is made up of these "instantaneous" temperatures is named a *Whiplash Curve* because of its undulating shape. If this curve were plotted at frequent time intervals, it would be seen that the whiplash curve is a "traveling wave" that moves into the ground with time. The surface temperature changes influence the temperature at each depth, and the influence arrives at each succeeding depth at progressively later times.

This idealized and simplified example assumes constant soil properties with depth and a uniformly varying surface temperature. This, of course, is not nature's way. In reality, at any time, the curves would not be as smooth and uniform as shown, but they would begin to look like this if many years of measurements were averaged into the plot.

The word "Permafrost" was coined to take the place of the longer more awkward phrase "permanently frozen ground". After it came into common usage, it was determined that a

precise definition of the word and the material was needed. The definition that was adopted was very broad. It includes all types of soil, rock, or organic material that is part of the ground.

Permafrost, by definition then, is "any soil that has remained continuously frozen for at least two consecutive years." According to this definition, we can find permafrost in every state of the United States, all the provinces of Canada, and most of the industrialized nations of the world. Anywhere there is a freezer plant for cold storage (or, for example, a frozen orange juice manufacturing facility) there will be frozen ground below it, and if that plant has been continuously operating for more than two years, the frozen ground beneath it, by definition, will be permafrost.

This is appropriate, since many of the problems faced by contractors building in the permafrost regions of the far north are found on a smaller, but no less serious, scale in these isolated pockets of "permafrost". However, the "natural" permafrost of the cold regions is much older than the 2-year minimum. Most of it is a relic of the past ice age and is in excess of several thousand years in age. It is also much more extensive in the far north, as we shall see in the next section.

1.3 TYPES OF PERMAFROST

Such a broad definition requires that we categorize the different types of permafrost that are found. The two most important distinctions are whether the permafrost soil is stable or non-stable when it thaws. The terms "thaw-stable" and "thaw-unstable" have been adopted to describe the two groups[1]. Thaw stability is dependent on the amount of water contained within the frozen soil.

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[1] Previously the terms nondetrimental and detrimental were used for this distinction, but these two terms have fallen out of use in favor of the more descriptive thaw-stable and thaw-unstable.

When the volume of <u>frozen water</u> exactly fills the spaces between the grains of soil that are still in contact with one another, the soil is said to be "saturated." Upon thawing, soil whose water content is at saturation or below will not change its volume or "subside" since the soil grains are in contact. This soil is said to be "thaw-stable" or "non-detrimental." Soils that are truly thaw-stable are safe to build on without taking elaborate measures to protect either the structure or the permafrost since the thawing process will not affect the stability of the building's foundation. Obviously there are many occasions when permafrost is encountered and conventional construction techniques and designs can safely be used. The trick of course is in knowing when this is the case. If the soil's moisture content is greater than saturation, additional space is required for the excess water. That space is generated by separation of the soil grains to form a greater pore volume. When this soil thaws, the soil grains that are no longer separated by ice sink until they are touching each other. This overall settlement results in an unstable situation termed "thaw instability."

1.3.1 Moisture Content in Soils

If the <u>unfrozen water</u> content of the soil equals or exceeds saturation, then upon freezing, the individual grains of soil (whether silt, sand, or gravel) will be separated by the expansion of the water as it crystallizes into ice. If that soil ever thaws, there will be some subsidence as the soil particles settle until they rest on each other. Subsidence is directly related to water content of the frozen soil; as the water content increases, the subsidence upon thawing also increases. Later we will see how some soils that are unsaturated at the beginning of freezing can become super-saturated during the freezing process. These soils are referred to as "frost susceptible" soils.

In soils terminology it is customary to express the water content in percent by weight of the dry soil. It is possible, therefore, to have a soil sample with a water content that

exceeds 100% of saturation. Saturation (the maximum amount of water that a sample can hold in the pores between the <u>contacting</u> soil particles) is found to be a different percentage for each soil type. In coarse-grained soils, such as gravel, the pores between particles make up a smaller volume than in finer-grained soils, and saturation can be near 5% of the dry weight, whereas in fine-grained silts, that are frequently found in cold regions, saturation is closer to 17% of the dry weight of the soil. In soils containing a lot of peat or in muskeg, saturation can be higher still. When saturation is exceeded in a frozen soil, soil particles have been separated to provide more room for the ice. When this soil thaws, the particles will consolidate until they are in contact, pushing the melt water out of the way and in general will cause shrinking of the volume. When fine-grained soils with moisture contents in excess of saturation thaw, not only do they shrink in volume, but also they result in a "soupy" consistency, and it is very poor at supporting any type of loading. Foundations on this type of soil simply sink into the soil compounding the damage to the structure.

1.3.2 Ice Masses in Permafrost

Large accumulations of ice are often found in permafrost. These are classified according to their method of formation and their general shape. These accumulations are generally referred to as "massive ice" and are divided into three categories; "ice wedges", "ice lenses", and "clear ice".

1.3.3 Ice Wedges

This type of ice mass, named for its shape, is wide at the top and tapers to a point at the bottom. Ice wedges are formed when the soil cracks due to contraction. As the surface is cooled to a much colder temperature than the soil below, the resulting contraction of the colder soil results in a vertical crack. The crack relieves the stress that builds up between the cold surface soil and the relatively warmer lower layers. The cracks in the soil are

generally random and eventually intersect other cracks formed by the same process. The result is a network of cracks that when viewed from above form an irregular network of polygons. During spring breakup, melt water on the surface drains into the cracks and fills them. The portion of the crack that extends into the permafrost is continually frozen, so the melt water freezes and a thin wedge of clear ice becomes part of the permafrost. This process repeats each freezing season, and the crack grows a little wider each time. A very thin layer of silt is usually carried into the crack each time, and it forms a thin vertical striation of silt between the older ice from previous seasons and the newly formed ice. These striations, like the rings in a tree, give a general indication of the age of the ice wedge in "freezing season". The number of freezing seasons is not necessarily always one per year, so one cannot count striations to get an accurate age of the wedge in years. However, a large number of striations generally indicate an older ice wedge age in terms of freezing seasons.

As the ice wedge grows in width, the soil that was in the space that the ice wedge now occupies is displaced, often forming a ridge on each side of the crack at the surface. This forms a very distinctive pattern on the surface called "polygonal ground" or patterned ground." Figure 1.4 shows an artist's conception of an area of polygonal ground.

1.3.4 Ice Lenses

As fine-grained soil freezes, the freezing front (the soil level that is actively freezing) continually moves deeper into the soil. The freezing front attracts water from surrounding soil beneath it by osmosis (often called a "wicking action" because it is the same as the action of fuel moving up the wick to the flame in an old-fashioned lantern). As the freezing front moves progressively deeper into the soil, water continues to move (by osmosis) from deeper in the soil to the freezing front where it freezes to form an *Ice Lens*.
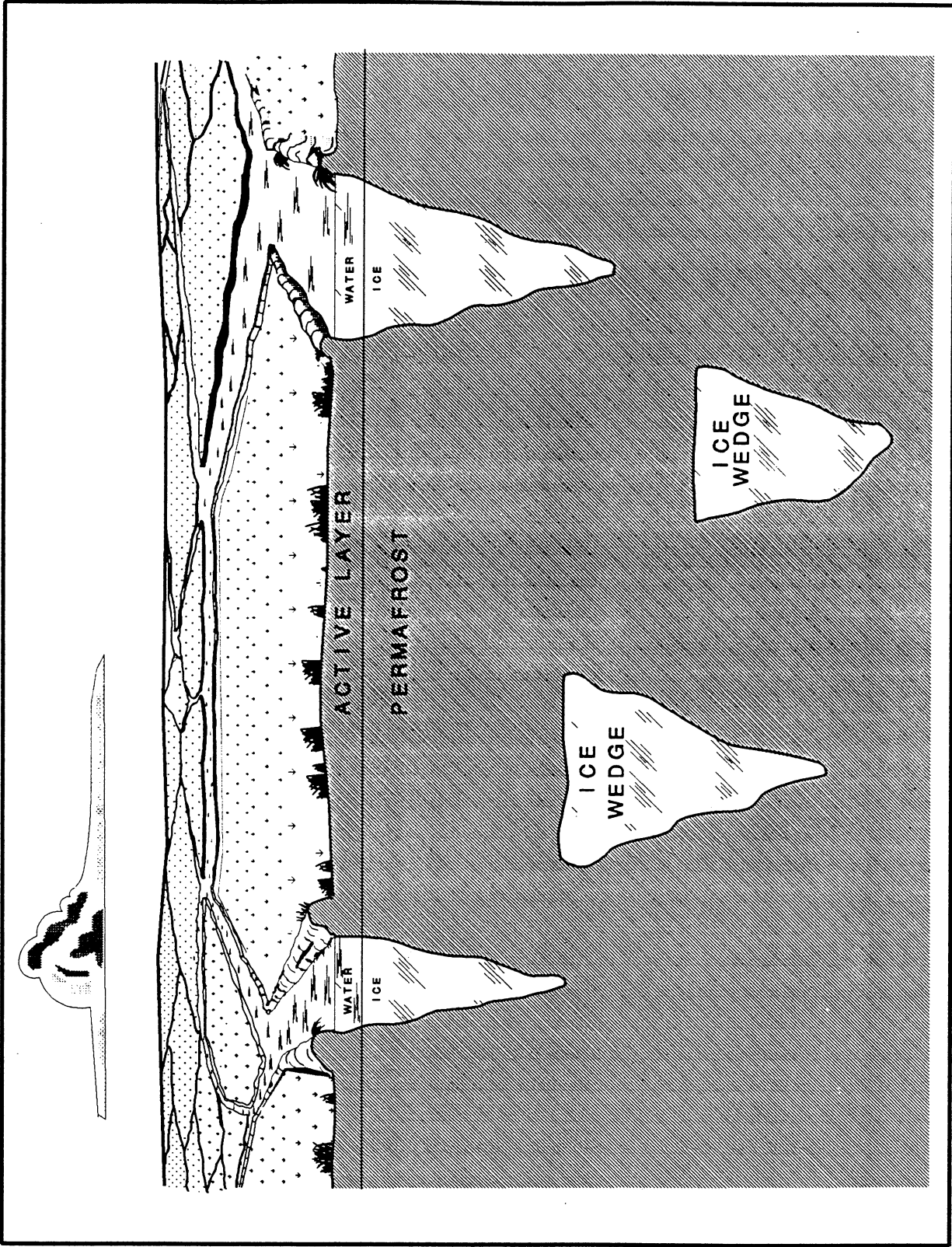
FIGURE 1.4 Artist's conception of an area of polygonal ground. Note the relic ice wedges buried at depth. They are remnants of an earlier time when they were at the surface and actively growing each year.

An ice lens grows by adding ice along its horizontal underside. In the process, silt is frequently incorporated into the ice layer as it freezes, but since the added ice layer is generally horizontal, the silt striation is also generally horizontal. The resulting ice mass that is formed in this manner is generally a long horizontal shape and is often thicker in the center, much like a convex lens, thus the name "ice lens".

Ice lenses form in the active layer every year if moisture is available from lower layers of soil, if soil conditions are fine grained enough to support osmosis or "wicking," and if freezing conditions are present. All three of these conditions are required to form an ice lens and are often referred to as the three "Ws", water, wicking and winter. If any one of these conditions can be eliminated, then the resulting ice formation and its associated heaving will be eliminated.

When ice lenses are found in permafrost, it is because they have become incorporated into the permafrost after their formation. Their method of formation is different than that of wedges, and they often cover a much larger horizontal area than does a wedge. An ice wedge by contrast usually is much larger vertically and generally (but not always) is more massive than an ice lens. The type of a massive ice form encountered in an excavation can usually (but not always) be determined by the orientation of its silt striations. Frequently wedges and lenses coexist in the same area and even intersect each other. In these situations it is often impossible (and unnecessary) to differentiate between them.

1.3.5 Clear Ice

The third type of massive ice is clear ice. This form is created when a pond or lake that has been frozen in the winter is incorporated into the permafrost before the following

thaw. There are several possible scenarios by which this might happen, for example, an event such as a landslide or dust storm could cover a frozen pond to a depth that is greater than the active layer. A clear ice mass will not have the silt striations found in wedges and lenses, but it often contains water plants and grasses that were growing in the water the summer before it was buried.

When thawing finally comes to the soil, all three types of ice provide excess water to the soil, and of course, cause extensive settling. Frost heaving results when soils that are not perfectly dry freeze. However, it is the formation of the large massive ice forms that makes frost heaving problematic. The settlement caused by soils that do not have massive ice forms is usually very small and of little concern. It is the massive ice forms that allow settlements so large that they can destroy an entire building.

When the route of a stream takes it through permafrost soil containing massive ice forms, heat from the water of the stream is sufficient to thaw the ice wedges and lenses that the stream comes in contact with. These thawed areas subside and become wide spots in the stream and are very noticeable from above. A stream with such conditions is known as a "beaded stream". It is very distinctive and can serve to warn the alert observer of an area with massive ice. Figure 1.6 shows a beaded stream in northern Alaska. There are reports of sites in the Fairbanks, Alaska area of very unstable foundation conditions. These conditions are created when high-moisture-content soils thaw (usually organic silts or even slightly organic silts). The thawed material can retain a moisture content of up to 30 to 35% and the nature of the thawed material is a gelatinous ooze. Several cases where that material seems to support a small house-size structure for a while, until the house foundation is mechanically shaken, e.g. by nearby road construction (vibratory rollers, heavy truck traffic etc.), then the structure will start to severely rack and settle.
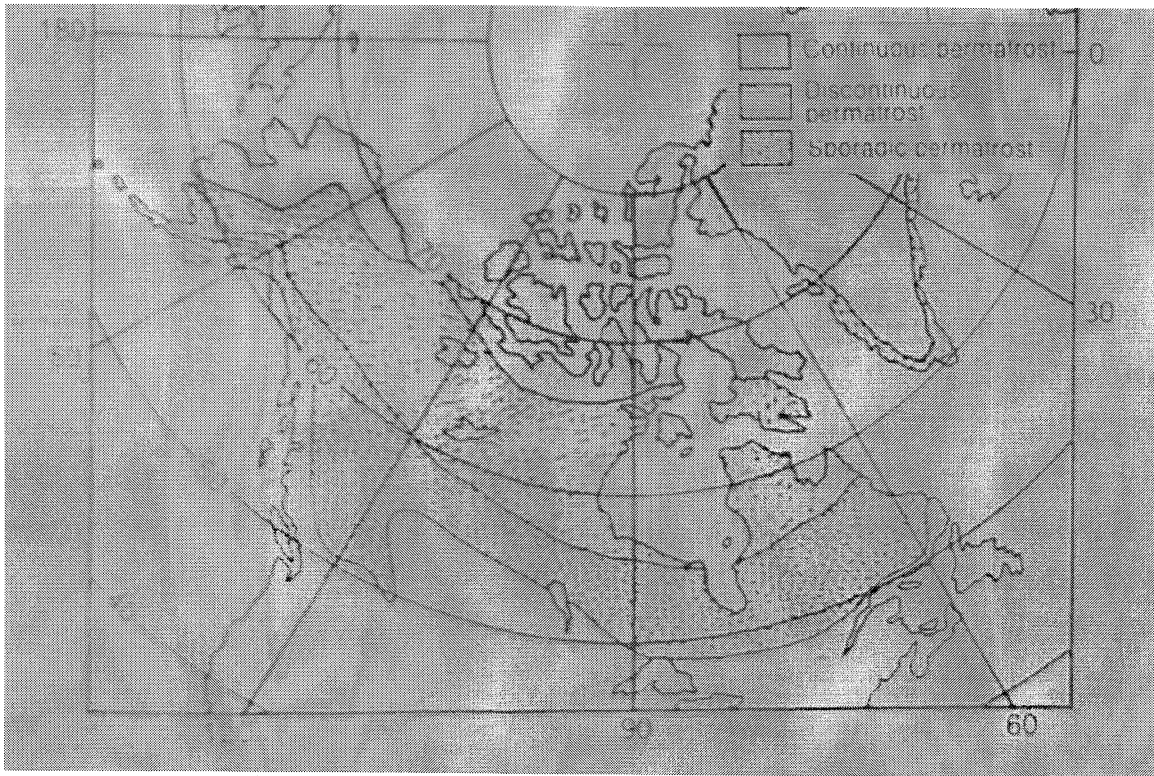
Figure 1.5. Approximate Distribution of Permafrost in the Northern Hemisphere.
Data from several sources
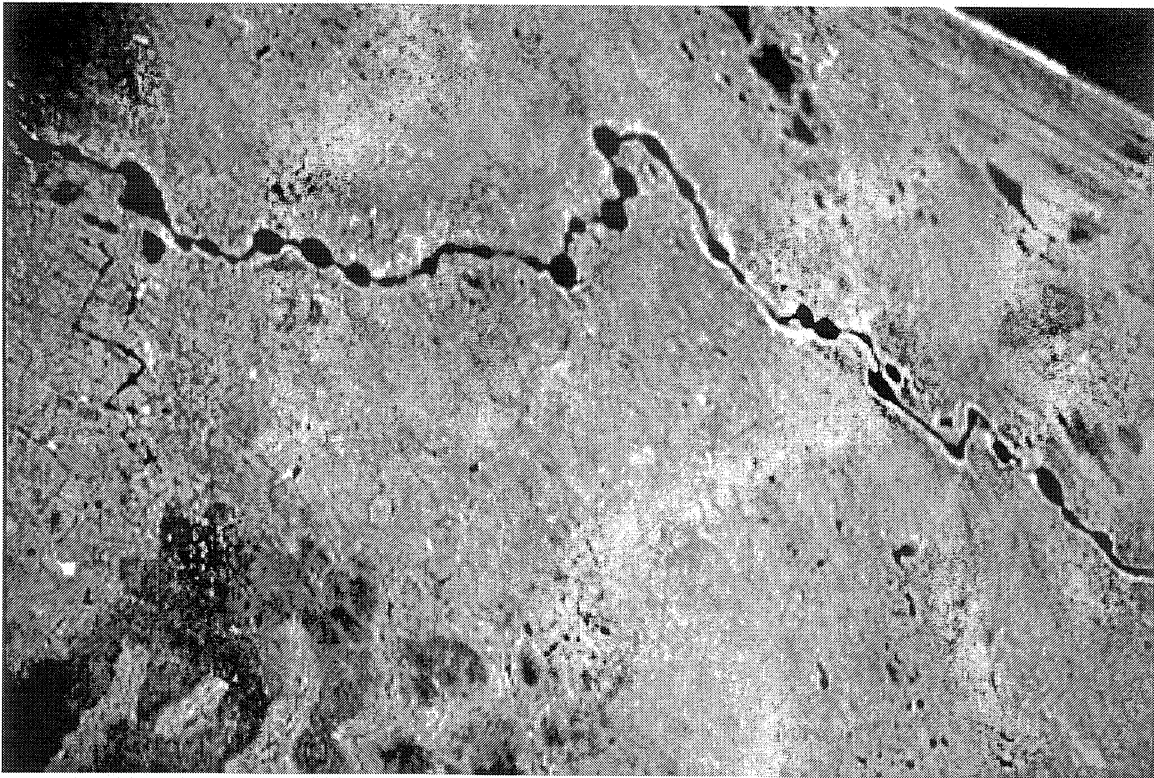
Figure 1.6. Beaded Stream in a permafrost locale

1.4 GLOBAL EXTENT OF PERMAFROST

In the Arctic, permafrost is found everywhere. Consequently, the most useful definition of the Arctic region is (for engineering and construction purposes): "that area where the permafrost is continuous". There is no question about the presence of permafrost in this region; it is virtually everywhere. It is absent only under very large lakes and rivers, or in areas of geothermal anomaly such as where hot springs come to the surface. This is known as the region of *continuous permafrost*. South of the continuous permafrost lies an extensive region where the permafrost is only found in certain spots such as the north sides of hills or mountains or in valleys where trees and moss protect the soil surface from the summer heat. This region is termed the *discontinuous permafrost* region. Figure 1.5. shows the approximate southern boundaries of continuous and discontinuous permafrost regions in North America. A region of scattered or *sporadic permafrost* lies south of the boundary of discontinuous permafrost. The boundary for this area is not accurately known. Isolated pockets of permafrost, from a few feet to several acres in size, exist hundreds of miles south of the discontinuous permafrost zone. These pockets are found at higher elevations in localities where cool conditions prevail such as muskeg, sheltered northern exposures, bogs, and swamps. The extent of permafrost is currently decreasing slowly. This may be the result of global warming due to what is called the "greenhouse effect," or it may be a centuries-long cycle that has been continuing since the last ice age ended. Whatever the cause, the net result is that there are vast areas in the discontinuous and sporadic zones that are very close to thawing. Indeed the discontinuous zone was probably part of the continuous region a few hundred years ago. Permafrost in the discontinuous and sporadic regions is very fragile and, in many cases, cannot withstand an increase in the mean annual temperature of even 0.5°F (0.28°C). These are very difficult areas in which to work. Because of the current trend of global warming, the southern boundaries of the regions of discontinuous and sporadic permafrost are moving northward, incorporating more of what is currently thought to be continuous permafrost.

There is not enough data to be conclusive, but if this trend continues, permafrost will continue to disappear, and any structure whose foundation depends on the soil remaining naturally frozen will be facing disaster.

1.5 CONSTRUCTION IN PERMAFROST

The best advice to an owner or contractor who is thinking of building on permafrost is "don't". If possible, it is almost always better to find a new site than to face the extra expense and the additional maintenance involved in construction on permafrost. The advice is seldom heeded, however.

When working in a continuous permafrost region such as the North Slope of Alaska, there is no option. In these regions, permafrost is the controlling design parameter. It must be either preserved and prevented from thawing or completely removed. Except at the southern fringe of the continuous zone, it is seldom economically feasible or even possible to completely remove the permafrost. In these circumstances, you must design and build to preserve the permafrost, and the welfare of your structure depends on how well you do this.

The discontinuous permafrost zone provides the greatest engineering challenge. It is extremely difficult to be sure that a site is free of permafrost. Current exploration capabilities are expensive and are not able to determine with absolute surety that permafrost does or does not exist in the soil beneath the site. (Chapter 2 discusses permafrost investigation in more detail.) If a site is not underlain with thaw-unstable permafrost, then less expensive conventional construction can be used. It would be foolish to go to the expense of preserving permafrost that will not subside when it thaws (thaw-stable permafrost). However, if thaw-unstable permafrost is present, a conventional foundation and the structure it supports (be it building, highway, or airstrip) will fail as the permafrost thaws. Determining whether or not the more expensive design and

construction required to protect against thaw settlement is necessary is a difficult but critical problem in this region.

Permafrost in the discontinuous and sporadic regions is very fragile because it is virtually in the process of thawing. Anything that changes the thermal conditions at the site so that the soil temperature increases will cause it to thaw. Figure 1.7 shows a house in Fairbanks, Alaska that was built on just such a site. The house was of conventional design and had a fully heated basement. It was sitting on a south-facing site with silty soils that had water contents that ranged from 22% to over 40%. At the time of this photograph the house was close to complete structural collapse. Figure 1.8 shows some of the structural damage that resulted as the permafrost thawed. The temperature conditions that exist at a site are called its "thermal regime". At a permafrost site, this means that there is not enough heat entering the soil to raise the soil temperature below the active layer to above freezing. The amount of heat from the sun that enters the soil can change dramatically as the natural vegetation on or near the site is altered. Soil temperatures at the surface are impacted by, among other things, the amount of shade provided by trees and brush, transpiration of the vegetation, and the exposure of the site. After a forest fire, for example, shade from trees and brush is reduced substantially, and the top of the permafrost (the permafrost table) is depressed. The heat of the fire has a small part in this, but the increased heat input from the sun because the shade is gone is the biggest culprit. As the brush thickens and trees return and grow, more and more of the sun's heat energy is intercepted before it reaches the ground. Soil surface temperatures gradually cool and as they do, different types of plants, such as the black spruce, which can tolerate cooler soils, begin to dominate. As the vegetation continues to grow and

Figure 1.7 A home damaged by permafrost. Note the large birch trees on the site.
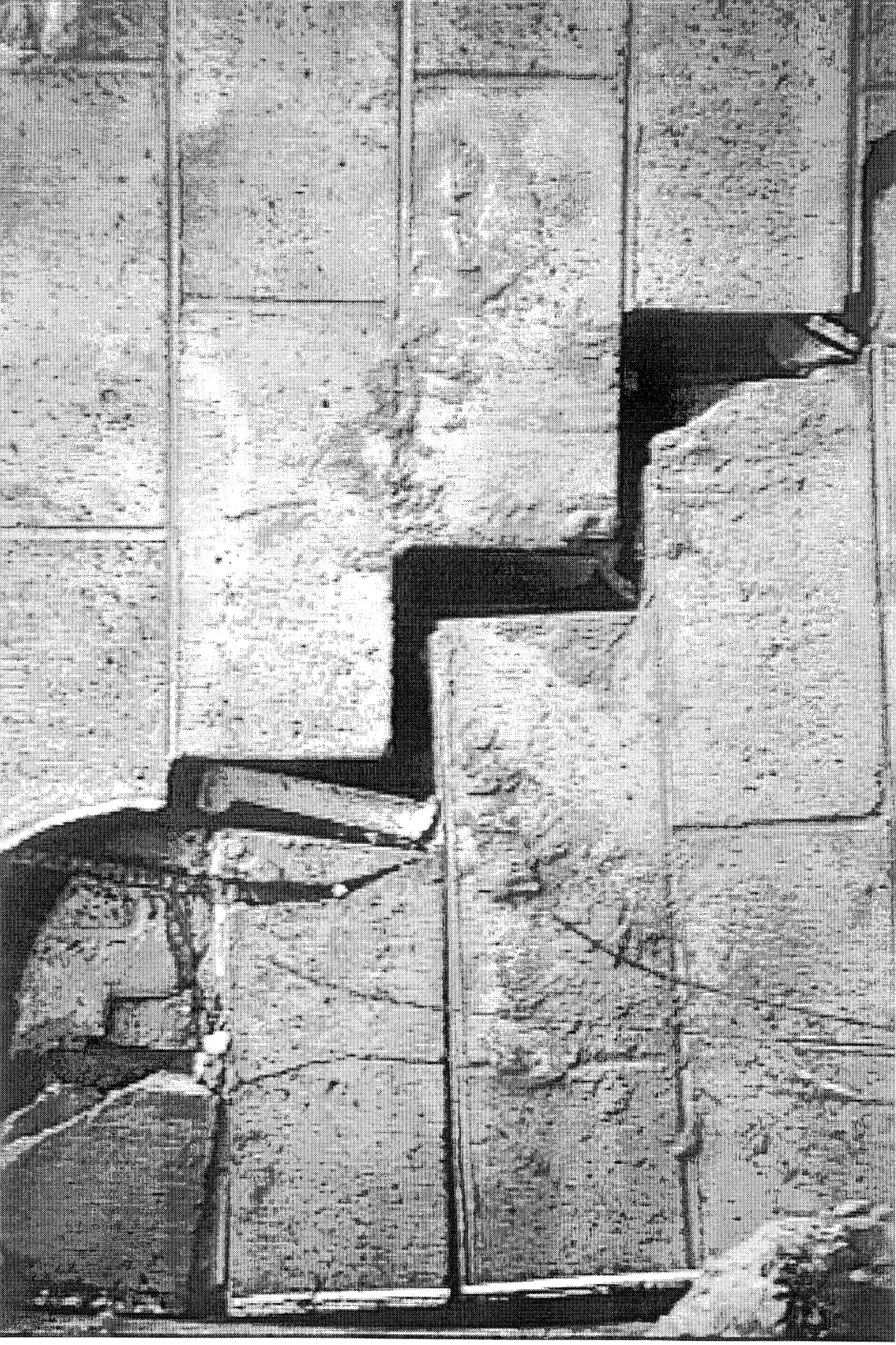
Figure 1.8 Foundation damage to the house in Fig. 1.7. Note that cracks are large enough for small animals to crawl through.

thicken, the soil receives less and less energy. Eventually the thermal regime at the site changes enough so that the summer thaw does not penetrate deep enough to remove all of the frozen soil from the winter before, and permafrost is reestablished.

If ground water was available during the freezing process, then ice lenses will develop in the frozen soil. The availability of ground water from the water table or from surrounding water sources allows lenses to continue to grow, and in the extreme they can be very large, spanning tens of feet in width and several feet in thickness.

Ice lenses are virtually 100% water, incorporating only a small amount of the silty soil surrounding them. The combined thickness of all of the ice lenses at all depths that have developed by spring is reflected in the amount of surface heaving present. As some of the seasonally frozen ground becomes permafrost, the segregated ice lenses become part of the permafrost.

Just as increasing vegetation cools the soil and makes it possible for permafrost to form and thicken, the result of removing vegetation from the site for a construction project will also change the thermal regime. More heat will reach the surface and the ground will begin to warm. The permafrost (which may be only a few degrees or even tenths of a degree below freezing) will start to thaw. The ice masses in the permafrost thaw and the soil moisture becomes supersaturated. The soil loses most of its ability to support a load. Structures on the site lose their underlying support and gradually fail.

Failure does not occur immediately. In most cases it takes several years for the change in surface thermal regime to diffuse to the depth of the permafrost. The length of time required before problems start is related to several factors; thickness of the active layer

(how deep the permafrost table is buried), the type of soil and its moisture content, and the degree that the thermal input has changed at the surface. A road or airport runway that absorbs and transfers to the soil more solar energy than arrived at the surface before construction may survive longer before developing thaw-subsidence problems because it receives heat only during warmer months. A building with a heated basement that is in contact with the soil and provides heat input throughout the entire year will begin to experience problems sooner. In any case, once the problems start, they progress at a slow rate. Sudden collapse is not likely in permafrost-related failures. Left unattended, however, the progression is relentless. Eventually the structure is no longer useable. Permafrost damage must be repaired before the structure is completely ruined. The sooner in the failure process that repair and remedial action is taken, the easier and less expensive it is. When thawing permafrost damage is left to run its course, the end result is total failure of the structure.

CHAPTER 2 - FIRST THINGS FIRST

2.1 FOUNDATIONS IN PERMAFROST

When a structure must be constructed on or across an area of known permafrost, and all alternatives[2] have been exhausted, then a proper design and careful construction is essential to the ultimate life of the structure be it house, road, or airfield. Careful construction and inspection are required to see that the foundation is properly built, since even the best design will not survive incorrect installation or construction. Careful attention to correct foundation construction will be the difference between a safe, stable structure with reasonable maintenance requirements and one with constant problems, high maintenance and a shorter lifetime.

The first step in construction on any site in the discontinuous or sporadic permafrost zones is a good preliminary investigation by a qualified and experienced engineer. The cost of the investigation is a very small amount compared to the cost of a mistake that leads to the wrong type of foundation.

2.2 THE PERMAFROST INVESTIGATION

In the zone of Continuous Permafrost such as the north slope of Alaska, permafrost is virtually everywhere and permafrost considerations are relatively simple. However, you must still determine whether or not the soil is thaw-unstable. If the soil is determined to be ice- rich, then a permafrost compatible foundation must be used if the building is to have a lifetime of more than two to three years.[3] In this region, the owner usually

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[2] Other alternatives that should be considered include excavating to remove the permafrost if it is a small isolated body, rerouting around the permafrost area (for roads) or finding a new site w/o permafrost and, finally, thawing the permafrost to eliminate it if it is a remnant that won't return.

[3] Groups involved in temporary site residency, such as exploration companies, work camps etc. will sometimes use a conventional nonfrozen-ground type of foundation on a permafrost site. They reason that the building will only be used a short time at this site and then moved to the next site. This strategy works fine if the location is truly temporary (a few months at most), however there have been numerous buildings constructed with this philosophy that have had to have a remedial permafrost-compatible foundation put in

expects the extra expense of the more costly foundation so it is more easily justified and accepted.

A permafrost investigation should include both above surface and below surface exploration. Above ground, a site survey should include interviews with residents of the area around the site in question, a detailed inspection of the site in summer weather when ground features are not obscured by snow, and a good look at the foundations and conditions of other buildings in the area. Special note should be taken of any unusual surface features such as depressions or small hummocks. These could be thermokarsts[4] and pingos[3] respectively. Both features are artifacts of permafrost either present or past. All sources of information about the site above and below ground and of the surrounding area should be considered. Well logs, however, must be viewed with a healthy dose of skepticism since the object of a good well drilling operation is to drill into the ground as fast as possible looking for water. Today's drill rigs are so powerful that they can drill completely through discontinuous permafrost without the drilling operator noticing it. These drill rigs put so much energy into the drill bit that marginally frozen ground is thawed before it reaches the surface. If a drill log from a water-well reports frozen ground, the permafrost is undoubtedly substantial, however the lack of a frozen ground report by such a well log is of no value in determining whether or not permafrost is present under the site.

The zone of discontinuous permafrost is where the most care is required. Permafrost may or may not exist on a potential construction site, or even worse is the situation where permafrost underlies only a portion of a construction site. If thaw-unstable permafrost

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later at much greater expense. The old adage "there is nothing more permanent than a temporary building" seems to have special significance in the north.

[4] Thermokarsts and Pingos are features that are found in permafrost under special conditions. A more detailed explanation of them and the problems they represent can be found in texts on permafrost such as *Permafrost* by Johnston, see the Bibliography.

does <u>not</u> exist on the site, the extra cost, higher maintenance and inconvenience of a permafrost-compatible foundation are <u>not</u> necessary. However, a conventional foundation would be a disaster if thaw-unstable permafrost did exist beneath any part of the structure. An <u>accurate permafrost investigation</u> is essential in this region.

If you are dealing with a structure with obvious settlement that you suspect is caused by thawing permafrost you must have a permafrost investigation to determine the condition of the remaining permafrost. In some cases, such as when bedrock or thaw-stable gravel[5] are close to the surface, the thaw bulb beneath the structure may have reached the bedrock or other thaw-stable material and the settlement due to thawing permafrost is complete. In this situation, further settlement will be small or nonexistent and it is no longer a problem. The appropriate action in this case is to repair the damage to the structure and forget the permafrost since the problem has run its course and the foundation is now stable. These cases are not common, and only an accurate permafrost investigation can give you the information needed for a safe rational approach to the problem.

2.2.1 Drilling

At the present, there is only one reliable means to find out what conditions exist below the surface of the ground; that is to excavate the material so that it can be examined. On a large site, this is not economically feasible. Alternatively we must rely on a sampling approach. Bore holes are drilled at specific locations on the site and samples of the soil are collected for analysis.

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[5] Thaw stability is primarily controlled by the moisture content of the soil. If the moisture content is well below its water saturation point, the soil will not settle upon thawing and it is considered to be "thaw-stable." Frozen soils that contain more moisture than they can hold at saturation are "thaw-unstable. The amount of moisture various soils can hold before they reach saturation is easily determined from soil-moisture tables found in many reference texts, e.g. Johnston, 1981 or McFadden and Bennett, 1991 both have graphs of soil-moisture relationships as do many other references.

A qualified soils laboratory then analyzes the samples taken during drilling and a borehole-log is produced. The borehole-log (usually called the "drill log") is a foot-by-foot record of the drilling operation kept by a qualified engineer and drill crew experienced in looking for permafrost. It gives specific information about the soils and conditions beneath the surface at that specific location. The permafrost drilling requires proper equipment and trained personnel who are experienced in permafrost work. Otherwise, the answers may well be meaningless or even worse, misleading. A good log will tell the soil types present, the moisture content of each different soil layer, the presence of frozen soil, its depth and condition, and the presence of segregated ice. Figure 2.1 shows a typical borehole log of a sample from a permafrost investigation. Samples taken during drilling also can be analyzed for soil grain-size gradation, which is useful in determining the frost susceptibility of the soil.

If the drilling is properly done, the drill log information is accurate, but the accuracy only applies to the soils that were actually removed from the hole. The condition of the soil between drill holes only can be inferred from the results of these tests. Nevertheless, drilling is still the most accurate and useful of all of the currently available subsurface permafrost exploration techniques for determining the site soil conditions. However, you must keep in mind what the drill log is not.

1. It does not tell you what soils conditions exist on the lot down the street or even the site next door. In fact if the lot is large it does not give a good indication of what exists over the entire lot. Multiple exploratory holes are necessary. At one location, which the author drilled in Fairbanks, Alaska, for example, it was necessary to drill seven holes on a one-acre (4047 m^2) lot to determine the location of the permafrost boundary, which finally was found to run diagonally across the lot.

GRAPHICAL DEPICTION OF EACH SOIL LAYER

LOCATION OF SAMPLE AND SAMPLE NO.

SOIL DESCRIPTION	GRAPHIC LOG	DEPTH	SAMPLE	GROUND WATER	DEPTH	PENETRATION RESISTANCE (300 LB WEIGHT, 30 IN. DROP) WATER CONTENT (PERCENT) ▲ BLOWS PER FOOT

SURFACE ELEVATION:

BROWN SILT W ORGANICS.
CLAYEY IN PLACES.
DARKER BROWN WITH DEPTH

DESCRIPTION OF SOIL LAYERS AND THICKNESS OF EACH LAYER

COLUMN INDICATES FROZEN GROUND. HERE IT STARTS AT 16.5 FT AND CONTINUES TO THE BOTTOM OF THE LOG. THIS HOLE WAS DRILLED IN AUGUST, THE FROZEN GROUND IS PROBABLY ALL PERMAFROST SINCE SEASONAL FROST WOULD BE THAWED.

GRAY BROWN SILT Nbn

5½ FOOT THICK LAYER OF CLEAR ICE

CLEAR ICE

SILT AND ICE

ICE

BROWN SILT W/ ICE LENSES

BROWN SILT AND ICE

BOH @ 35 FT.

NUMBER OF BLOWS REQUIRED TO DRIVE SAMPLE SPOON INTO SOIL

PERCENT WATER CONTENT IN THE SAMPLE

NOTE: BLOW COUNTS ARE NOT COUNTED IN PERMAFROST SOILS

NOTE: THE SOLID SAMPLE LINE INDICATES THAT A CONTINUOUS CORE SAMPLE WAS TAKEN OF THE FROZEN SOIL.

LEGEND

KEY TO SYMBOLS AND FIGURES USED ON THE LOG

SILT
GRAVEL
FROZEN GROUND
SAND
CLAY
PEAT
ORGANIC CONTENT

IMPERVIOUS SEAL
WATER LEVEL
SCREENED INTERVAL
THERMISTOR
3 IN O.D. SPLIT SPOON SAMPLE
GRAB SAMPLE
3 IN. O.D. THIN-WALL SAMPLE
3 IN. O.D. DRY CORE RUN

● % WATER CONTENT

BORING LOG

NAME: 2 mile PERMAFROST LN. BORE HOLE#1
LOCATION: 6'W & 6'N OF NW DOOR
PAGE: ONE OF ONE
DATE: AUGUST 1991

PERMAFROST TECHNOLOGY FOUNDATION

DRILL LOG LOCATION, POSITION ON SITE, DATE AND PAGE NO.

FIGURE 2.1 A typical bore-hole log from a permafrost investigation. Annotated explanations are in italics

2. The drill log does not show what exists below the bottom of the hole. It is very important to drill the hole deep enough to give all the information needed. The larger he structure, the deeper you must drill the hole. A rough, but conservative, rule of thumb is that the hole should be deeper than the minor dimension of the structure, but not as deep as the major dimension. (e.g. If the building is 50 by 70 ft. then the bore hole should extend to approximately 60 ft. unless the bottom of the hole contains poor soil conditions, whereupon deeper investigation may be needed.) Bedrock and stable foundation conditions or ice-rich permafrost may be only 1 ft below the bottom of the borehole, or they may be 100 ft deeper. You must know which is the case in order to make sound foundation decisions.

3. An extended period of time will negate the information found in a bore log. Even a year is enough time for the subsurface conditions to change. This is particularly true during the time just after a site has been cleared of vegetative cover or otherwise changed. The drill log must be current as well as accurate to be reliable. The foundation designer can develop a safe, permanent design only if the current conditions are known.

4. A permafrost investigation done for a small structure such as a home is not suitable to be used for a larger structure such as a multistory apartment complex. To repeat, the larger the building, the more detailed and extensive the drilling investigation needs to be.

2.2.2 Resistivity

To help fill in the picture between drill holes, a resistivity survey is sometimes used. This is a useful technique when coupled with the exact information presented by the drill log. A resistivity survey measures the impedance of the soil layers that are intersected by the electrical field lines. One device (e.g. the Geonics EM-31) measures the resistance between the ends of a 12 ft (3.6 m) long rod. Conditions approximately 10 to 20 ft (3 to 6 m) deep into the ground can be inferred by this technique. The depth that the field lines

penetrate depends on the rod length. The survey does not give exact information such as moisture content or density of the soil layers; it indicates only where discontinuities in the electrical field are present. The electrical field discontinuities may represent any number of different types of buried objects such as pipes or boulders or they may correlate to changes in soil properties, such as a change in soil type or a change from frozen to thawed soil. By comparing the discontinuities revealed by the resistivity survey with the known information from nearby bore holes, much can be inferred and positions of additional bore holes can be chosen. For this reason the resistivity survey is very useful in deciding where to drill exploratory bore holes. If the resistivity survey indicates very uniform properties, then additional drilling may be unnecessary or the distance between holes may be safely extended. If the resistivity survey indicates a location where anomalies exist, soil conditions are changing and more bore holes should then be drilled at that spot to provide the most reliable subsurface information.

The resistivity survey is usually comparatively inexpensive and can easily save its own cost by reducing the amount of drilling necessary to make a competent analysis of the subsurface conditions of the entire site.

2.2.3 Other Techniques

When the top of the permafrost is shallow and the overlying soils are reasonably soft, "frost probing" is an effective means of locating permafrost. This technique requires a rod (usually steel) approximately 1/2 in. diameter with a handle for pushing it into the ground by hand. Shallow frost can easily be found with this method and a little practice. A sliding impact handle can sometimes be used on more consolidated soils. However if care is not taken, it is easy to force the rod in to the point that it cannot be retrieved with the impact device. Frost probing is inexpensive, quick, and most useful in preliminary site investigations.

There are other remote data collection methods such as short pulse radar and gravitational anomaly measurements that have been tested experimentally but are not yet ready for field use. Most of these require very expensive instrumentation and provide data that must be analyzed by sophisticated means.

2.3 INSULATION USE IN THE PERMAFROST FOUNDATION

As discussed in section 1.2, when vegetation cover is removed, the soil surface begins to warm and thermal balance is changed. This results in thawing of the permafrost unless the cover is replaced. Insulation can play a big role in replacing the lost protection when vegetation must be removed. Insulation slows the rate at which heat arrives at the surface; it **does not** eliminate it. But that is exactly what the vegetation cover does. It slows the rate at which heat reaches the surface, both by providing insulation and by using some of the heat that arrives for plant transpiration, so there is less heat reaching the soil that must be offset by winter cooling. However, when the structure is a building in contact with the ground (as opposed to a road or airfield or building on an elevated foundation) heat input is no longer restricted to the summer season but flows incessantly into the soil all year long. Not only that, winter cooling is completely lost so the heat balance has undergone a double attack, summer heating is longer and winter cooling is lost. Here again insulation can help by reducing the amount of heat that reaches the soil, but insulation alone is purely a delaying tactic when winter cooling is lost. The ultimate failure of the building will be delayed by some time (a few to several years perhaps) but it will eventually still occur. Theoretically it is possible to add enough insulation to establish a thermal balance between heat input and winter cooling from the area around

the building, but this is almost never practical since the amount of insulation required is not economically feasible for buildings in the discontinuous zone. Heat flow from the building to the soil must be interrupted and carried away from the soil. Insulation makes this task easier by reducing the amount of heat that escapes from the building and by reducing the amount of heat that flows into the surface. Figure 2.2 shows a typical heat balance for a site with permafrost. Insulation is a powerful tool to be used in protecting permafrost but it must be used properly and with help from other techniques.

2.3.1. Types of Insulation

Thermal insulation can be any material that increases the resistance to heat flow. In the past such things as moss, sod, sawdust, old magazines, straw, and corrugated cardboard have been used to insulate buildings. Most modern buildings, however, use a combination of glass fiber batting and, in specialized areas, foamed plastics. Although there are a wide variety of different types of insulation for many different purposes, for construction purposes we will concentrate of a few of the more useful types. An insulation that is to be in contact with the soil must be able to avoid deterioration of its thermal properties and its physical shape in the presence of soil moisture, soil chemicals, physical loading, and other outside forces. An insulation that absorbs moisture, thereby compromising its thermal insulating properties, will not be as successful as one that can resist this type of deterioration. An insulation that is to be buried or placed on top of the soil must be able to withstand compression without losing its insulating properties. Finally an insulation system must be cost effective. The thermal resistance (a measure of the insulating value of the insulation) per dollar of cost must be as low as possible to justify its use. When insulation will not be subject to water intrusion, it may not have as

HEAT OUT MUST EQUAL OR
EXCEED ALL OF THE HEAT
INPUT SOURCES OR THE
PERMAFROST WILL THAW AS
IT HAS IN THE THAW
DEPRESSION UNDER THE
BUILDING

HEAT FLOWS FROM
THE SURFACE TO
THE ENVIRONMENT
IN THE WINTER

HEAT FLOWS FROM
THE ENVIRONMENT
TO THE SURFACE
IN THE SUMMER

HEAT FLOWS FROM BUILDING TO THE
ACTIVE LAYER ALL YEAR LONG. THIS
RESULTS IN A PERMANENTLY THAWED
"BULB" BENEATH THE BUILDING

ACTIVE
LAYER

HEAT FLOWS FROM THE ACTIVE LAYER TO THE PERMAFROST WHEN THE ACTIVE LAYER IS THAWED
(USUALLY IN THE LATE SUMMER AND AUTUMN - AUGUST THROUGH MID NOVEMBER)

THAW DEPRESSION CREATED BY THE
ADDED HEAT FROM THE BUILDING

HEAT FLOWS FROM THE PERMAFROST TO THE ACTIVE LAYER WHEN ACTIVE LAYER IS FROZEN
COLDER THAN THE PERMAFROST. (USUALLY MIDWINTER TO EARLY SUMMER)

PERMAFROST

GEOTHERMAL
HEAT INPUT TO
THE BOTTOM OF
THE PERMAFROST

FIGURE 2.2 A representation of the various heat
flow components at a site underlain with permafrost

many requirements. Obviously there is no perfect insulation that is best in all conditions, so we must make compromises and choose different insulations for different applications. A brief review of the more commonly used insulations will help to make these choices.

2.3.2 Fiberglass Insulation

Glass fiber batting is the most commonly used modern insulation material, primarily because it has the highest ratio of thermal resistance per unit cost combined with one of the highest thermal resistances. It is relatively inexpensive, resists mold and fungus, and is stable over a wide range of temperatures. It is also easy to install, does not require a skilled craftsman and is readily available in a wide variety of configurations to meet the needs of almost any application. Of course, even larger thermal resistance can be obtained with a thicker stud space, but when the stud space has been determined, then the thermal insulation can be increased in that space by compressing the fiberglass batts. Conversely, fiberglass batts have very little resistance to moisture accumulation, and they lose a substantial amount of their thermal resistance when moisture accumulates within the fiber batts. Thermal resistance declines by as much as 70% when moisture content (by volume) within the batts exceeds 3%. As moisture contents increase from 3% to 8%, thermal resistance continues to decline, but at a slower rate. The decreased thermal resistance causes as much as 3.8 times more heat loss. Figure 2.3 shows the relative increase in heat loss as moisture is absorbed in various types of insulations.

The thermal resistance of glass fiber batt is a function of the density of the fibers in the batt. Different manufacturers produce batts of slightly different densities, but installation procedures can create the greatest variation in density. Since the batt is easily
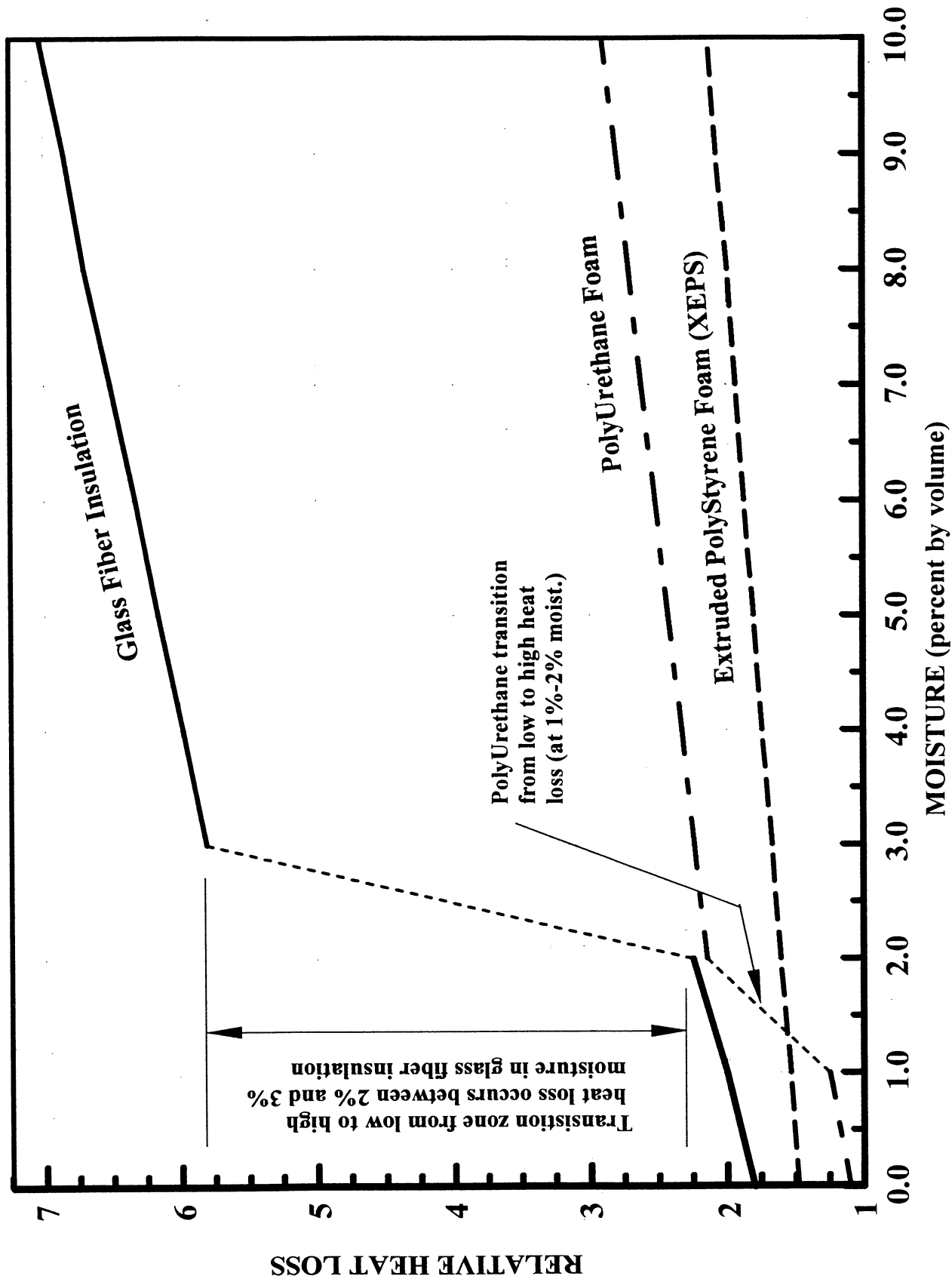
FIGURE 2.3 Relative increase in heat lost through several types of insulation due to absorption of moisture

compressed, an oversized batt (i.e. a batt that is thicker than the space between the joists into which it is being installed) can be installed and then compressed by covering the space with a rigid board such as plywood. In a given stud space, up to a 15% increase in thermal resistance, compared to an uncompressed batt, can be realized by this method. Table 2.1 shows the resultant thermal resistance achieved by compressing glass fiber insulation into a thinner stud space (Alaska Dept. of Regional Affairs, 1991).   For each specific stud space thickness, the R-value of the space increases when thicker batts are compressed into it. For example a 2x6 stud space has an installed R-value of 18 when a 6.125 in. batt is used, but when a 9.5 in. batt is compressed into the stud space, the R-value increases to 21, a 16% increase without increasing the wall thickness. Mineral fiber insulations are also available in batt form. Their thermal properties are very close to those of glass fiber, but their cost is slightly higher. Their principal advantage is a higher melting point, making them useful as high temperature insulation for furnaces etc. Like fiberglass batts, mineral fiber batts also suffer from water accumulation within the fibers.

Table 2.1 Thermal Resistance of Compressed Glass Fiber Batts

Nominal		Initial R-value and Batt Thickness					
Stud Size	Actual width	R-38 12"	R-30 $9^1/_2$"	R-22 $6^3/_4$"	R-19 $6^1/_8$"	R-13 $3^5/_8$"	R-11 $3^1/_2$"
		Installed R-value at Final Thickness					
2"x12"	$11^3/_4$"	37					
2"x10"	$9^1/_4$"	32	30				
2"x8"	$7^1/_4$"	27	26				
2"x6"	$5^1/_4$"		21	20	18		
2"x4"	$3^1/_2$"		14	13	13		
2"x3"	$2^1/_2$"					10	9
2"x2"	$1^1/_2$"					6	6

Alaska Dept. of Regional Affairs 1991

Other types of insulation are not as adversely affected by moisture.

2.3.3 Insulations for Use in the Soil

The following types of insulation are commonly used for various applications in and on the ground. Each has its own strengths and weaknesses and will be appropriate for specific applications.

2.3.4 Foamed Polystyrene

Foamed polystyrene insulations are widely used in construction and offer many advantages for specific applications. If water intrusion can be expected, then **extruded** expanded polystyrene insulation (the insulation designation is **XEPS**) should be considered. This insulation is commonly called "blue board", however it is available from several different manufacturers each using their own specific color. The important distinction is the term "extruded" for this designates an insulation that has a closed cell structure. It is one of the most water resistant insulations currently available, although under some very adverse applications it too will absorb water and lose thermal resistance. When insulation is required around a foundation wall or in other applications where the insulation is to be buried, XEPS is one of the best choices. It is a rigid board and has the ability to maintain its thickness under load, which is essential when it must be buried or loaded.

Foamed polystyrene is also available in expanded (but not extruded) board (commonly called "bead board" or "molded polystyrene board" and designated as **EPS** by insulation manufacturers). This type of insulation is manufactured by thermally expanding beads of the polystyrene plastic in a mold to form large billets. The billets are then cut into board stock of the desired thickness. The unexpanded beads are placed in the mold and treated

with steam to expand them and activate their surface. The newly expanded beads stick together to form a cohesive solid whose density can be regulated by the manufacturer. The individual polystyrene beads, even in the expanded state, are probably as moisture resistant as the XEPS insulation, but the voids between the beads provide a path for water to enter the board and they constitute a substantial volume into which water is absorbed into the insulation. A denser grade of EPS, which is claimed to be more water resistant, is also available at a somewhat higher cost.

The thermal resistance of dry, foamed-polystyrene board (either XEPS or EPS) is close to but slightly higher than that of dry glass fiber, but it resists moisture much better and its thermal resistance is reduced at a much lower rate when it does absorb water. The initial cost of both XEPS and EPS, however, is between 5 and 7 times that of fiberglass when compared on a thermal resistance per dollar basis. Because of the cost advantage, fiberglass will continue to be used, especially in areas where it offers a substantial economic advantage.

2.3.5 Foamed Polyurethane

Polyurethane foam offers some unique advantages that make it very useful for special building and construction applications. It can be foamed in the field by mixing two liquid components and pouring or spraying the mixture into the location where insulation is needed. The mixture then expands in place to form a foam layer or coating. It can be sprayed on complex surface shapes such as pipes, valves, and fittings giving a surface insulation coating that conforms to the shape of the item insulated. The ability to spray the insulation before it expands also makes it attractive for filling cracks and sealing

around openings. Before mixing, the two basic component liquids occupy a very small volume, making them easy and inexpensive to transport. This is especially important for remote sites where shipping costs are high. Polyurethane insulation can be foamed or frothed into difficult-to-access spaces, such as the annulus between two pipes to produce an insulated pipe with a protective shell. Another application is to foam the stud spaces of walls in the manufacture of pre-built wall sections. Since the foam produces considerable pressure as it expands, rigid forms to support the walls must be used to prevent the wallboard from bulging as the foam expands. Finally it has one of the lowest thermal conductivities of any insulation short of vacuum. This gives it one of the highest thermal resistances of any insulation of the same thickness. However, its initial thermal resistance immediately after foaming is substantially higher than it is after the foam has aged. But even the aged foam has one of the highest thermal resistances of commercially available building insulations. Polyurethane foam is expensive; for an equivalent thermal resistance its cost is 4 to 7 times higher than fiberglass.

One of the chief disadvantages of polyurethane foam is that it has an open-cell-structure that allows water to readily permeate throughout the foam causing a substantial gain in thermal conductivity and a corresponding loss in thermal resistance. Although there are waterproof coatings that can be sprayed on to mitigate this problem, these coatings are very expensive. The coatings are also easily damaged during construction, leaving the underlying foam vulnerable to moisture intrusion.

2.3.6 Foamed Polyisocyanurate
Polyisocyanurate is very similar both in chemical makeup and in thermal properties to Polyurethane. It is available in board stock for insulating flat surfaces.

2.3.7 Chemical Stability of Foam Insulation

One further consideration concerning the foamed insulations discussed above: hydrocarbon fuels rapidly attack poly**styrene** foam turning it into a non insulating gel. Poly**urethane** foam, however, is quite stable even when fully submerged in gasoline or diesel fuel. This is an important consideration if foam insulation is to be used where it may come into contact with any type of hydrocarbons. Buried foam insulation to be placed under the gravel fill of a refueling station, for example, should be poly**urethane** not poly**styrene**. Even though polyurethane will lose a good deal of its thermal resistance as it absorbs moisture from the ground, it is the better choice, because it will withstand contact with a hydrocarbon while a hydrocarbon spill of any magnitude will completely destroy the polystyrene foam. The loss of thermal resistance in the polyurethane foam can be up to 30% as it absorbs moisture that infiltrates the gravel. However, you can compensate for the loss by doubling its thickness. This also applies to the area around the fuel tank for a building. Fuel spills invariably happen when refilling the tank, so the insulation must be capable of withstanding them.

CHAPTER 3 – TECHNIQUES FOR STABILIZING PERMAFROST

3.1 Overview

Buildings by their very nature are flexible structures. They can deflect without failure in the face of lateral forces such as wind and they can absorb small internal movements due to shrinking of materials; even impacts such as trees falling on them or vehicles crashing into them are absorbed by the flexibility of the structure. In these cases the flexibility is an asset, and it lets high stress in one area be distributed to surrounding areas so that structural members are not overstressed. However, there is a limit to this flexibility. When external forces act on a building in such a way as to remove the support that the building receives from the ground, the limits of flexibility are easily exceeded. To serve its intended purpose for a normal lifetime, the building relies on a stable foundation that does not shift, heave, or settle. In permafrost regions, this is not always the case. Permafrost itself is a rather solid stable material that will support a substantial load if it is kept frozen. However, it permanently deforms very slowly under load. This slow deformation is termed "creep" and if unchecked, it can eventually lead to foundation failure.

When a building is in structural distress because its foundation is failing due to thawing permafrost, a program for stabilizing the building must be initiated. There are several approaches available and choosing the correct one is an exercise in engineering economics. If money were of no concern, there is no building that could not be stabilized. However, this is almost never the case, and most of the time money is the controlling factor. When the overall cost of the fix, including the initial cost, plus the

maintenance and operating costs, approaches the value of the building, then the solution is not acceptable.

This is never more clearly illustrated than in the case of a private home. In most situations the home is the largest investment that a family makes, often most of the family savings have gone into the home. Little is left for expensive repairs of a foundation problem. Unfortunately, there is usually little choice in the matter because if the problem is ignored, the damage will accumulate until the house is destroyed and the total investment is lost.[6] In this respect permafrost can be likened to cancer, since the sooner the problem is recognized and action is taken to stop its progress, the better the chance of saving the structure and the lower the overall cost will be.

Choosing the best course of action to solve the problem depends on many factors. What are the conditions of the soil under the structure? What type of structure is involved? How large is it? Can it be moved economically? Does it have a heated basement? Does it have a floor slab in contact with the soil (a slab on grade)? What soil conditions exist beneath the structure is undoubtedly the more important question and the most difficult to answer. Once again we must have an accurate subsurface investigation to determine what problems we are facing. Without this information we are capable of only blind guesses that will likely not address the problem in the most efficient and economical way.

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[6] It should be pointed out that most home owner's insurance only covers damage that occurs rapidly. This provision essentially disallows a number of damage mechanisms such as permafrost related damage.

3.2 Keeping the Permafrost Frozen

One approach to stabilizing thawing permafrost is to stop the thawing by removing or reducing the amount of heat flowing to the permafrost. Almost every construction project results in removal of the protective vegetation on the surface. The loss of this cover allows more summer heat to enter the soil, and the balance between winter cooling and summer heating is changed. Some permafrost will thaw before that balance reaches a new equilibrium. In the case of a heated building with a conventional foundation, heat input into the soil from the building is constant 24 hours per day 365 days per year. Unless measures are taken to stop it this heat input will thaw even the coldest permafrost.

3.2.1 Natural Convection

The Russians pioneered this traditional solution to the problem, and we Americans have modified and improved it. The design fix relies on eliminating or at least greatly reducing the amount of heat that reaches the permafrost. The first step is to intercept the heat from the building before it reaches the permafrost. To do this, the building is raised above the surface of the ground. This is done to break the heat transfer path by decoupling the building from the ground on which is rests. This allows cold, winter air to circulate under the building to remove any heat that escapes from the bottom of the building. In the summer, the building itself provides some protection from summer heat by shading the ground and thus reducing the solar input to the soil beneath it.

Insulation also plays an important part. By itself, insulation will not stop heat from entering the soil under a building that is in contact with the ground, but it does reduce the

amount of heat that enters the soil (or conversely the amount of heat that escapes from the inside of the building). The floor of the raised building must be well insulated to minimize the amount of heat lost from the building, to keep the floor warm and comfortable inside the building, and to provide a heated space for utilities such as water and sewer lines that must be protected from freezing. An insulated plenum under the floor structural members is usually built for this purpose.

The airspace between the bottom of the building (the insulated plenum) and the surface of the ground must be enough for unimpeded circulation of cold winter air. As a rough rule of thumb, this is usually considered to be 3 feet. However that distance is directly related to the overall size of the building and the amount of wind at the site. A small one room cabin at an unprotected site with moderate wind may get by with 1 to $1\frac{1}{2}$ foot of clearance. A small home of approximately a 30-foot width should have about 3 feet, and a larger building such as the British Petroleum building in Prudhoe Bay, Alaska has and probably needs 4 to 5 feet of clearance (see figure 3.1). If the site is well protected from wind or receives a lot of snow, then the clearance must be larger. The important point is that the circulation of air must not be restricted in any way, and the larger the building the less likely that the ground under the center of the air space will receive enough cold air circulation for adequate cooling. The aspect ratio defined by the minor dimension of the building divided by the clearance height above the ground should be less than 10. Figure 3.2 illustrates this principle.
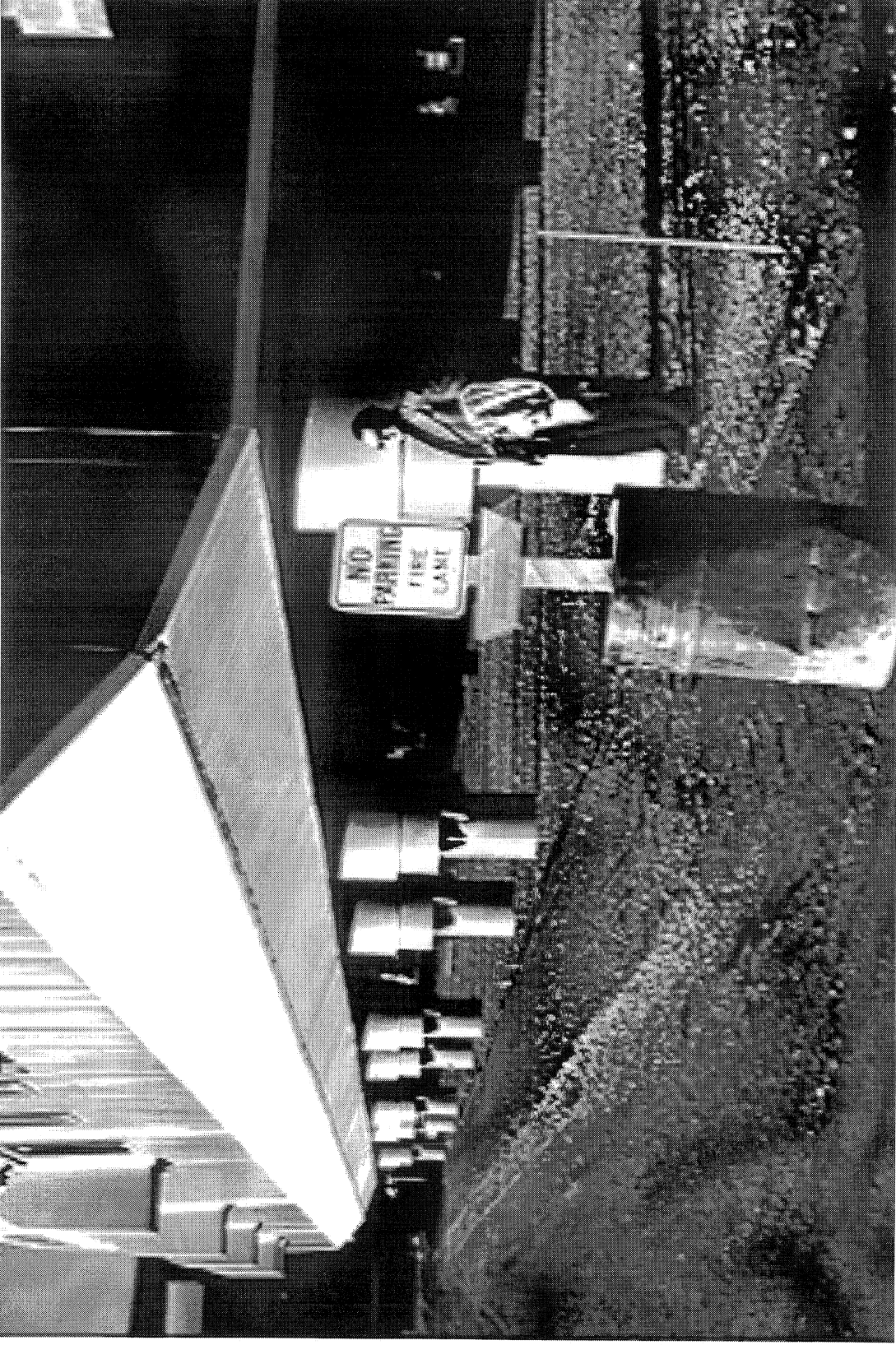
Figure 3.1 British Petroleum Building in Prudhoe Bay, Alaska. Note that the building is raised above the ground by about 8 ft.

NOTE: ASPECT RATIO a/b SHOULD
BE LESS THAN 10

BUILDING WIDTH = a

HEIGHT ABOVE GROUND = $b = a/10$

GROUND SURFACE

ACTIVE LAYER

PERMAFROST

PILES ANCHORED INTO
THE PERMAFROST AT
AT LEAST 2X THE
THICKNESS OF THE
ACTIVE LAYER
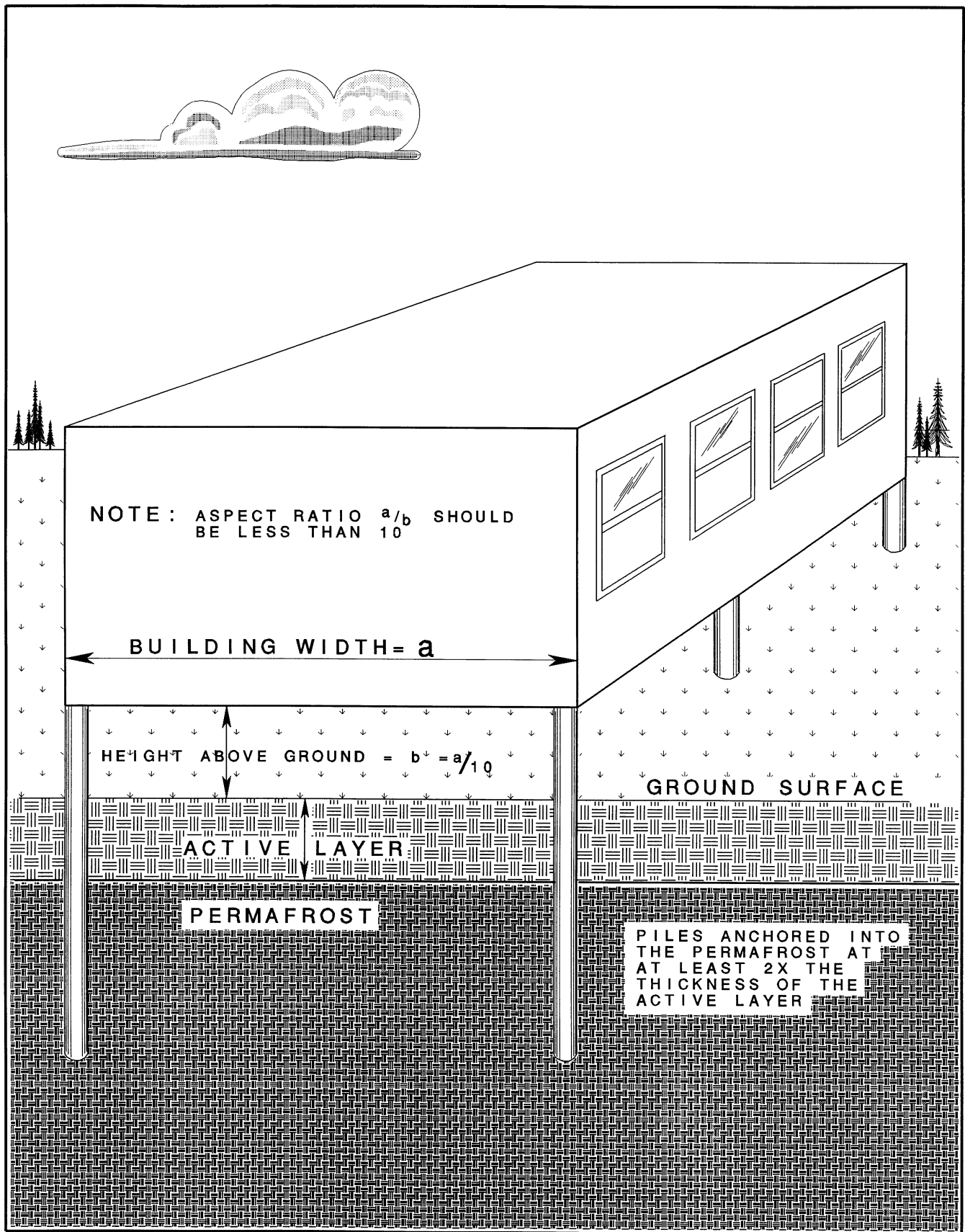
FIGURE 3.2 Aspect ratio a/b to determine
building height above ground

When an existing building must be raised above the ground, supporting the building in the elevated position becomes a primary problem. If it is possible to install pilings (either slurried type or driven type piles) to support the structure, this is usually the preferred method. Piles have several advantages; they can be anchored into the permafrost so that they do not move during the coming and going of seasonal frost, they provide a good deal of lateral support for the building to resist wind loads and earthquakes (often enough so that no further side support is needed), and some types of piles can be refrigerated if the permafrost is so fragile that it needs extra help to support the building loads that are transferred to it. Pile installation is discussed in Chapter Four.

When piles cannot be used, then a surface foundation must be considered. Post and pad or crib foundations can be used, although they are subject to the heaving and subsiding effects of seasonal frost during autumn freeze-up and again during spring thaw. Also these foundations do not provide significant lateral support, so this must be built into them. Installation of these foundation configurations is also discussed in Chapter Four.

Esthetics also enters in. The raised building is thought to look strange by many owners, and an attempt to achieve more acceptable or more pleasing appearance is often made by skirting the air space. It is sometimes reasoned that this will also keep out debris, animals, or other items. While keeping the space free of intrusion, the skirting also substantially reduces free airflow that is so critical to the health of the permafrost. Skirting or any other restriction on free airflow beneath the building must not be allowed.

Although the argument that "in the summer, skirting is desirable because it will reduce warm airflow beneath the building that can destructively warm the ground" is correct, but such seasonal skirting must be removed before the beginning of winter and reinstalled each summer. After a few winters or a change of occupants in the building, this chore is usually forgotten, and the skirting remains in place throughout the winter. The consequence of losing the winter cooling outweighs any advantage of reducing the summer airflow by several orders of magnitude. Skirting is almost always detrimental to the permafrost beneath the building and thus for the building itself.

Storage space in a home or any other building is always in short supply, and there never seems to be enough. The large space beneath the building is often an irresistible temptation for storing seasonal equipment or other currently unused items. This must be strictly avoided. Anything that is placed in the air space will disrupt the flow of air and allow heat to enter the soil that would normally be carried away. This will eventually work towards thawing the permafrost.

3.2.2 Forced Convection

When it is not possible to raise the building, or when it is sitting on a conventional concrete foundation wall, winter cooling may have to be accomplished by forced convection instead of relying on natural airflow. In the previous section "free convection" relies on typical winter weather with its associated wind to provide the cooling beneath the building. Free convection is without operating cost, and all that one must do is to ensure that nothing interferes with the free flow of air beneath the building.

Forced convection, however, comes with a built-in operating cost, although it may be minimized by careful design and installation. Fans or blowers are used to force cold outside air into and out of an enclosed crawl space under the building. The forced convection must be controlled so that it only operates when the outside air is colder than the air in the enclosure (crawl space) beneath the building.

Any building with a crawl space is a possible candidate for this type of cooling solution, and it is particularly applicable to structures that have a concrete foundation wall already in place. An insulated, heated plenum must be installed under the floor structure to provide enough room for the water and sewer lines (and any other utilities that are freeze sensitive). The crawl space below the insulated plenum must be large enough to allow for unimpeded airflow between the plenum and the ground.

Installation requires that the foundation wall be breached in at least two or more places and that fans or blowers be installed to move air through the remaining crawl space below the plenum. The number of openings will depend on the size and shape of the building and on any obstructions that might exist in the crawl space. Usually, half of the openings are used for intake of cold air, and the other half contain the fans that exhaust the air that has warmed as it moves through the crawl space.

As stated above, the fans should only run when the outside air is colder than the air in the crawl space or the soil under the building. To do this, a "smart" fan controller that

compares the temperatures of the outside air and the air in the center of the crawl space must be used (controllers that do this are commercially available, e.g. Omega Instruments Inc.). When the outside air is colder than the crawl space air by one or two degrees Celsius (1.8 to 3.5 °F), the controller turns on the fans. When the crawl space air temperature has cooled to the same temperature as the outside air, the controller turns the fans off. During the summer months, the fans will be off most of the time, and during most of the winter months they will be running almost all of the time. In Alaska, however, there are three to five months each year when the nighttime air temperature is colder than the soil, but the daytime air temperature rises until it is warmer than the soil. This is when the controller pays its way. A large amount of cooling in the crawl space is gained during these "shoulder seasons" that would be lost without a controller that is sophisticated enough to make the decisions when to turn the fans on and off, sometimes several times a day. Figure 3.3 illustrates a typical forced-air cooling system.

The openings in the foundation wall should be positioned so that airflow is established throughout the entire crawl space. Care should be taken to use enough openings to avoid stagnant air pockets. In general openings should be made in pairs, so that there are the same number of intake openings as there are exhaust openings containing fans, however the more important consideration is that the airflow is unimpeded. The cross sectional area of intake opening should be large enough so that the airflow velocity across the openings is somewhat less than the exhaust fan velocity. It is acceptable to use more air intake openings than exhaust openings if they are needed to ensure ventilation to all parts of the crawl space beneath the building. Good quality bathroom fans will generally be

INSTALL FAN CONTROLLER INSIDE HEATED PORTION OF THE BUILDING TO REDUCE ITS EXPOSURE TO WEATHER AND FOR SECURITY.

FAN CONTROLLER

AIR TEMPERATURE SENSOR

LOCATE THE AIR TEMPERATURE SENSOR ON THE INTAKE SIDE OF THE BUILDING, AT LEAST 12" AWAY FROM THE BUILDING.

FAN POWER 110V 60~

AIR INTAKE OPENINGS (SCREENED)

AIR FLOW

AIR FLOW

AIR FLOW

AIR FLOWS THROUGH THE CRAWLSPACE BELOW THE INSULATED PLENUM

CRAWL SPACE TEMPERATURE SENSOR (CENTER OF CRAWL SPACE)

INSULATED PLENUM FOR UTILITIES

AIR FLOW

EXHAUST FAN OPENINGS (SCREENED)

AIR FLOW

AIR FLOW

AIR FLOW

AIR FLOW

Figure 3.3   Forced air ventilation for a crawl space with an insulated plenum above

adequate to serve as exhaust fans in most homes and smaller buildings. On larger buildings, especially ones with unusual crawl space configurations, a larger blower and even some ductwork may be needed. The overriding consideration is to get cold airflow into all parts of the crawl space.

The specific type of controller used will dictate the type of temperature sensor that is needed. Usually the sensor will be either a thermistor or a thermocouple. These can be purchased from the controller manufacturer. The placement of the temperature sensors is important. The outside air temperature sensor should be placed so that it is shielded from the sun and removed from the surface of the building far enough so that it is not influenced by the building or any air outlets from it. It should be at least 1 meter (39 inches) above the ground (more in areas of deep snow) and on the same side of the building as the intake openings.

The crawl space air temperature probe should be placed beneath the building so that it is approximately ½ to ⅔ of the distance from the intakes to the exhaust fans. When possible it is desirable to locate the air intakes on the north side of the building and the outlets on the south side. If the north side is not practical, locate the intakes on the east side of the building with the fans on the west side.

The fan controller should be located inside the building so that it is not subject to the outside temperature extremes. It should be installed in a location where it does not tempt anyone to tamper with its settings. Since most controllers are meant for a general market,

they can be set for many configurations and it is possible to change the settings so that the fans turn on to bring in warm air instead of cold. Children or "knob twiddlers" must be thwarted if this system is to operate properly.

3.3 Cooling Devices

There are several devices that can be used to cool the soil or to intercept heat input into the soil. If the foundation of the building is in contact with the soil and cannot be elevated as discussed above, one or more of these devices may be used to protect the permafrost from thawing. Installation of the devices varies with the device, but it usually requires a major amount of work to get the device installed under an existing building. The most frequently used devices are natural-convection-devices including heat tubes, thermosyphons, convection loops, and mechanical refrigeration units.

3.3.1 Terminology for Natural-Convection Devices

Natural-convection devices can be used to increase the rate of heat transfer out of the soil and to sub-cool the vicinity around the device to produce colder and thus stronger permafrost which enhances the ability of the permafrost to survive summer or other increased heat input. If the device operates without the aid of external power, it is called a natural-convection device. There are several types of natural-convection devices, and there is no standard terminology that is universally accepted. However, Heuer et al. (1985) propose the following terminology that is logical and definitive and serves our purposes. We will adopt their suggested terminology, with slight modifications, for reference to these types of devices.

First the devices will be classified as either: 1. Open, or 2. Closed. This will refer to whether they are open to obtain their working fluid from the environment (e.g. cold air drawn in by a blower), or closed so that they have a captive working fluid (like the captive red alcohol or mercury sealed in a glass thermometer). A closed device can be further classified as either "single-phase" or "two-phase." This refers to whether its working fluid changes phase from liquid to gas during its operation. Open type devices are almost all single-phase, however there are also a few closed single-phase devices. The closed two-phase device is termed a "thermosyphon", and a closed single-phase device is referred to as a "convection tube." Open devices will be called "air convection piles" if they have openings on the same end of the device or "air ducts" if the openings are on opposite ends of the tube. Fig. 3.4 shows several natural-convection devices.

In addition, when a convection tube is constructed so that the working fluid flows around a continuous loop, it is called a "convection loop". If an internal wick is added to a thermosyphon to enhance liquid transport from one end to the other, it is called a "heat pipe".

Other names that have been used for these devices include "thermal tube" and "thermo tube." These names generally refer to closed devices. Also, if the device is designed to support a structural load, then the term "thermo-pile" is used. "Thermo-probe" is reserved for a thermosyphon that is used for cooling only and is not load bearing. The largest (and in 2001 perhaps the only) manufacturer of these devices is Arctic Foundations Inc. of Anchorage, AK.
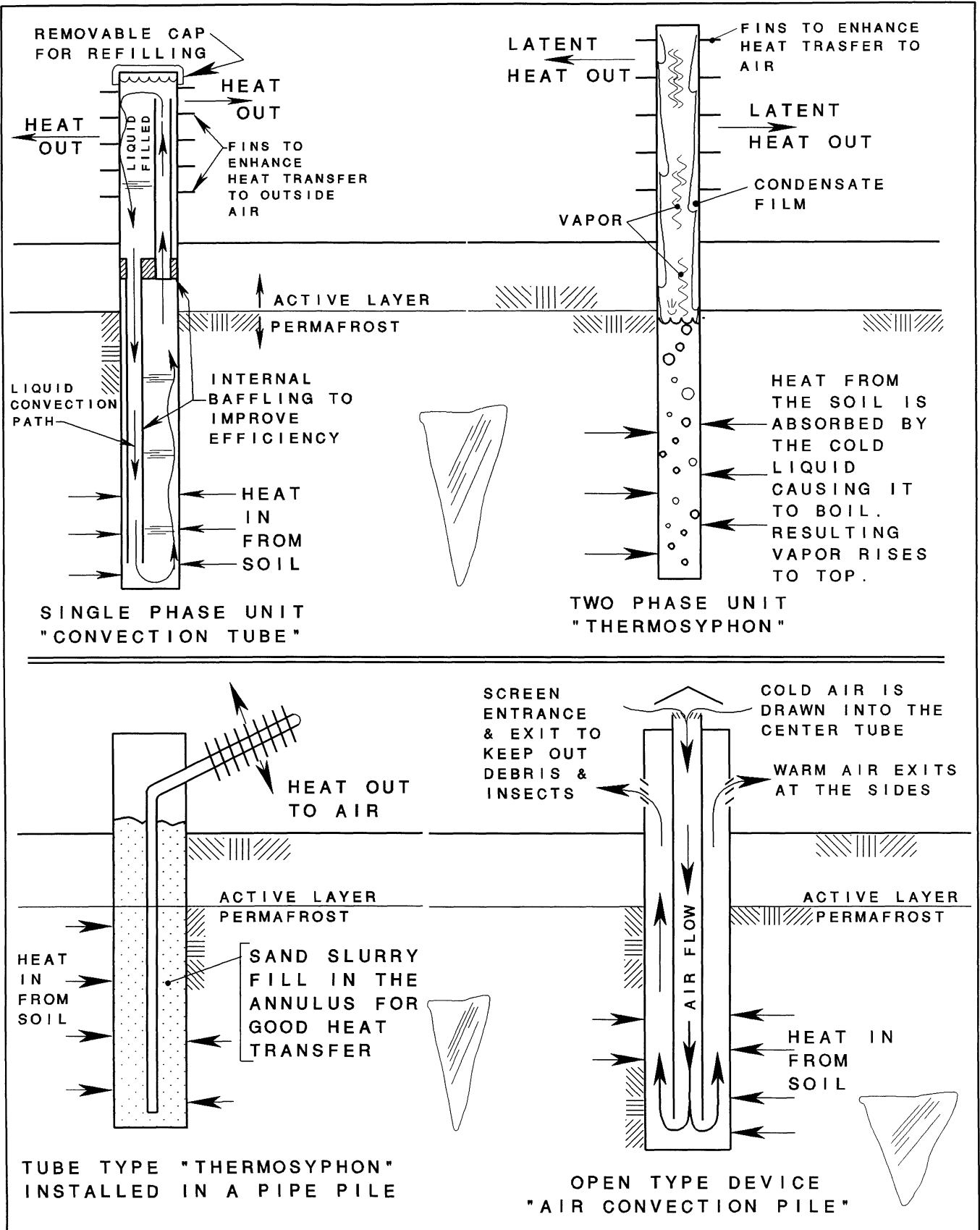
Figure 3.4 Four typical natural convection devices

The term "passive cooling devices" or "passive techniques" is sometimes used to refer to natural-convection devices in general. "Passive" refers to the fact that these devices do not use external power for their operation and have no moving parts. When they are operating, the convection activity within these devices is far from passive so the term "passive" is something of a misnomer; a better term might be "forced" or "natural" as is used in heat transfer. See Table 3.1 for a summary of these terms.

Table 3.1 Terminology for Natural-Convection Devices

Open (All Single Phase)
Air Convection Pile - has openings on the same end   **Air Duct** - has openings on opposite ends
Closed (Thermal Tube or Thermotube)

Single-Phase
     Convection Tube –working fluid moves heat out of the ground by convection w/o phase change
     Convection Loop –working fluid continuously circulates around a loop

Two-Phase
     Thermosyphon -generic term for two-phase devices
     Heat Pipe -a name referring to the presence of an internal wick to enhance condensate flow
     Thermo-probe –non-load-bearing device used for cooling only
     Thermopile –load-bearing device used for structural support as well as cooling

After *Construction in Cold Regions* by McFadden and Bennett - 1991

3.3.2 Mode of Operation of Natural-Convection-Devices

Natural-convection-devices have been used successfully to protect the underlying permafrost for many years. There are several configurations, but basically they all involve a long tube or pipe, part of which is buried in the ground with the remaining part extending out of the ground and exposed as much as possible to the weather. The pipe is filled with a working fluid that provides the means of transferring heat from the bottom of the unit to the top. The device is installed in the soil beneath a structure with one end of the tube extending vertically into the cold winter air above the surface. The buried end of the tube may be anchored into the permafrost, or if the underground portion of the tube

is installed on an angle, it will be located so that much of the buried surface will be near the interface between the active layer and the permafrost.

The working fluid in a closed single-phase device (a convection tube) is a nonfreezing liquid. During the winter, when the air temperature is colder than the soil temperature the liquid in the top of the tube (the aboveground portion of the device) is cooled by the cold outside air. This portion of the tube usually has fins on the outside to enhance the flow of heat from the liquid inside the tube to the outside air. As liquid cools it becomes denser and heavier; the colder fluid next to the wall sinks to the bottom of the tube, displacing warmer fluid and setting up a convection cell that forces the warmer fluid up the center of the tube to the top where it comes in contact with the walls of the aboveground portion of the pipe. The warm fluid is cooled by the pipe walls and begins to sink toward the bottom. After it reaches a few feet below the ground surface, the cold descending fluid comes into contact with the warmer wall of the underground portion of the pipe. Since the descending fluid is colder than the surrounding soil, heat from the soil flows into the pipe and warms the fluid, thus cooling the soil. This cycle continues until the soil is nearly the same temperature as the outside air. The fluid convection inside the tube transfers heat from the soil below the surface to the outside air above the surface much faster than the normal route where heat travels through the layers of soil, vegetation, and even snow to get to the surface. Therefore the soil near the tube (especially near the bottom of the tube) is cooled much faster and to a lower temperature than the surrounding ground.

Internal baffling is often used inside the tube or pipe to segregate the warm and cold fluids and thus improve the efficiency of the tubes operation. This convection heat cycle continues to move heat out of the soil around the pipe as long as the air temperature is a few degrees colder than the soil temperature. When the air warms to the same temperature as the soil the liquid in the top of the tube is no longer cooled; the convection flow stops and the tube becomes dormant. During the summer, therefore, the devices cease operation and are idle; they do not run in reverse.

A two-phase unit (a thermosyphon) works in exactly the same manner except that the working fluid is chosen so that it will change phase from liquid to vapor and back during the cycle's operation. The tube must be hermetically sealed to maintain the pressure required to operate at the chosen temperature (usually a few degrees below freezing). The type of working fluid is chosen so that it will evaporate at a temperature near the temperature of the soil to be cooled. When the thermosyphon is first filled, the tube contains liquid in the bottom and vapor of that liquid in the top. The liquid in the bottom of the tube (referred to as the "evaporator section") warms to the same temperature as the soil surrounding the thermosyphon. During the warming, the working fluid evaporates, generating vapor, which rises to the top and increases the pressure inside the tube. This continues until temperature-pressure equilibrium is established, at which time evaporation stops and the tube becomes dormant. When the air temperature above ground falls below the temperature of the soil, vapor in the top of the tube begins to condense, lowering the pressure within the tube. The lower pressure causes the liquid in the bottom of the tube (the evaporator section) to boil. The amount of heat needed to cause evaporation (called the "latent heat of vaporization") is very large and is drawn

from the surrounding soil. The amount of vapor that can be produced is limited by the amount of latent heat that can be drawn from the soil. The vapor is much less dense than the liquid, and it rises to the top of the tube (the condenser section) where it comes in contact with the cold wall of the tube causing it to condense back to a liquid and giving up its latent heat. The latent heat moves through the pipe wall and is carried away by the cold winter air. The condensed liquid (called "condensate") then trickles down the wall of the tube to join the liquid in the evaporator section thus completing the cycle.

Condensation at the top lowers the pressure within the thermosyphon, but boiling in the liquid in the bottom produces more vapor that raises the pressure. These opposing actions continually balance each other and determine the temperature-pressure relationship of thermodynamic equilibrium. If the air temperature gets colder, condensation increases and pressure drops. The pressure drop creates increased boiling and the production of vapor, thereby raising the pressure to restore equilibrium, all this at a higher level of fluid and vapor activity within the thermosyphon. A new dynamic state of equilibrium is achieved, and heat transfer out of the soil increases proportionately. Figure 3.5 illustrates the details of operation of natural convection devices.

3.3.3 Limitations on Operation

The speed at which heat can move through a material varies from one substance to another. Aluminum conducts heat at a very fast rate, while heat moves through fiberglass batting at a much slower rate. The property of a material that determines how fast heat can move through it is called its "thermal resistance." The larger the thermal resistance

HEAT FLOW →

VAPOR CONDENSES
ON THE TUBE WALL
WHENEVER OUTSIDE
AIR TEMPERATURE
IS COLDER THAN
SOIL TEMPERATURE

HEAT FLOW →

CONDENSER SECTION

HEAT FLOW ←

COLD AIR
CARRIES THE
HEAT AWAY
FROM THE
FINS

VAPOR

CONDENSATE FILM

CONDENSATE FILM

VAPOR FILLS THE
TOP PORTION OF
THE TUBE. THE
WARMEST VAPOR RISES
TO THE TOP.

COLD CONDENSATE TRICKLES
DOWN THE TUBE WALL TO THE
EVAPORATOR SECTION

SURFACE OF GROUND

ACTIVE LAYER

PERMAFROST

HEAT FLOW ←

HEAT FLOW →

WHEN LIQUID IN THE
BOTTOM OF THE TUBE
IS COLDER THAN THE
SOIL SURROUNDING IT,
HEAT FLOWS INTO THE
LIQUID CAUSING BOILING.

VAPOR BUBBLES FORM AND
RISE TO THE SURFACE.

SOIL AROUND THE TUBE
BECOMES VERY COLD
INCREASING ITS
STRENGTH AND ABILITY
TO SUPPORT A LOAD,
BUT ALSO LIMITING
CONTINUED HEAT FLOW
INTO THE HEAT TUBE.

HEAT FLOW ←

EVAPORATOR SECTION

SCALE EXAGGERATED TO SHOW INTERIOR DETAILS

FIGURE 3.5   Details of a two-phase heat tube operation

the slower heat moves through it. The total thermal resistance of the complete heat-transfer path includes all of the materials between the source of the heat and the cold winter air e.g., thermal resistance of the tube walls, the convection circuit inside the tube, the air films on the surfaces, and the frozen soil around the tube. All of these add together to produce the total thermal resistance, and this total is what limits the amount of heat that can be removed from the soil. Some of the resistances can be reduced, e.g. to minimize the thermal resistance between the outside air and the tube, fins are used on the outside of much of the aboveground section of the device.[7]

The thermal resistance of a two-phase system is much lower than that of a single-phase system; therefore the two-phase systems initially are more efficient at getting heat out of the soil. However, after the first few months of operation a new thermal resistance begins to develop in the form of the growing cylinder of frozen soil around the buried portion of the tube. As the soil next to the buried pipe reaches the same temperature as the pipe, the evaporation process inside must draw heat of vaporization from warmer soil that is progressively farther and farther away. This long thermal path continually grows, as the frozen cylinder around the pipe enlarges and becomes the dominant resistance to heat flow in the system. The internal thermal resistance of the device gradually becomes a minor component of the overall thermal resistance of the path from the unfrozen soil around the pipe to the outside air. Therefore, after some time (a few months to a year), the heat must move through so much frozen soil that the parameter that controls the amount of heat that can be removed from the ground becomes the thermal resistance of

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[7] The finned section is often referred to as the "radiator;" however, like an automobile radiator; only a small amount of the heat is transferred to the air by thermal radiation. Convection, particularly forced convection when wind is present, is the predominant mode of heat transfer at this point in the heat transfer path.

the frozen ground around the pipe. This limiting thermal resistance condition is the same for both devices, so that after the initial period, they both remove heat at about the same rate (Johnson 1971).

In the condenser portion of the pipe (the aboveground portion including the finned section), the fins are installed to provide a larger surface area to increase the amount of heat that can be transferred from the pipe to the air. This is the type of performance enhancement that is also needed in the belowground portion to counteract the growing thermal resistance of the frozen soil, but it is very difficult to install an extended surface area (such as fins) in the buried portion of the tube to reduce the thermal resistance. Other enhancements need to be developed for this part of the system.

3.3.4 Working Fluids

Some of the working fluids that can be used for thermosyphons include carbon dioxide, butane, propane, ammonia, and Freon. To efficiently freeze soil these devices need to begin operation between 25°F and 30°F (–4°C to -1°C) (slightly below the freezing temperature of water). Every working fluid requires a different pressure within the tube to start boiling at these temperatures. Some fluids, such as butane, operate at below atmospheric pressure while others like carbon dioxide require several hundred psi in order to operate at the desired temperature. Thermosyphons using high-pressure fluids must be manufactured to "pressure vessel standards." To meet this requirement, a certified pressure vessel welder must be on hand to do any welding required during installation. See McFadden and Bennett 1991 for more information on thermosyphon

working fluids. Thermosyphons are more efficient internally than single-phase devices; therefore, they can be smaller and lighter than convection tubes of the same capacity.

Convection Tubes (single-phase devices) on the other hand use fluids such as water and glycol or water and alcohol. Since they are not pressurized, they can be built in a moderately well-equipped home workshop. To increase their efficiency, internal baffling should be added, but the baffling can be fabricated from locally available materials. It is important to seal the tubes well since the working fluid is usually detrimental to the frozen soil if it leaks and will likely cause the permafrost to thaw. This, of course, will seriously worsen the problem the devices were installed to correct.

3.3.5 Monitoring the Operation of Convection Devices

Determining how well a convection device (either a single or two-phase type) is operating is not an easy task, but there are several methods that can be used to at least confirm that the units are still in operation. During cold weather, if the device is transferring heat, the temperature at the bottom of the fins next to the pipe wall will be a few degrees warmer than the surrounding cold air. A thermistor attached to the pipe just below the fins will measure the pipe wall temperature and show that the unit is at least operating.

A more sophisticated (and more expensive) procedure uses an infrared temperature-measuring device to confirm operation by showing that the fin/pipe area is warmer than the surrounding air. Care must be exercised to make these measurements during periods of stable, cold temperature. Night is the best time for measuring temperature with the

infrared device. The diurnal temperature variation between daytime and nighttime is often so much (especially in the spring and fall) that cooling of the soil during the night results in the evaporator region being so cold that the units will not operate during the much warmer hours during the day. Night measurements are also easier and more reliable due to the lower temperature of the surrounding air.

In the case of thermosyphons with higher working pressures (e.g. carbon dioxide filled), the internal pressure can be measured at the charging valve to determine if it is still pressurized. The internal pressure should be in the range for the working fluid as determined by the temperature of the evaporator section (See McFadden and Bennett 1991). A pressure that is considerably lower than prescribed indicates that the unit is not operating properly and that the working fluid level is low and that the unit may have a leak.

During installation of the unit, temperature probes such as thermistors or thermocouples should be installed to monitor the temperature of the soil around the buried evaporator section. These temperatures not only indicate whether or not the units are working but also give a more quantitative indication of how well the unit is performing. Place the temperature probes at various distances from the tube wall to determine if the temperature gradient is colder or warmer as the distance from the tube increases. Since convection devices are dynamic during times of rapid temperature change, measurements should be made only when the temperature has been relatively stable for a day or two previously. A continuous record of soil and air temperatures collected on a regular

schedule is the best way to monitor convection tube operation when using soil temperatures.

3.3.6 Installation Requirements

Thermosyphons must be installed so that their entire length from the bottom to the top is set to a positive slope. This is necessary to allow the normal buoyancy process of convection to work. The slope can be shallow, even approaching level and they will still work, but as the slope decreases from vertical toward horizontal, the performance of the device also decreases. The units continue to operate as long at the vapor has access to the colder condenser section and the condensed working fluid can return to the evaporator section. Slopes should be no less than 15 horizontal units to one vertical unit. Steeper slopes are recommended for the buried portion of the pipe. This is to give some protection against development of a negative slope caused by settlement or frost heaving. For new buildings, thermosyphons should be installed beneath the site prior to initial construction. The evaporator sections can be laid in trenches in the fill or active layer with the condenser sections protected from construction damage. They should be placed so that the design slope is assured and supported along the entire length of the evaporator section. The lower end of the evaporator section should be at the top of the permafrost while the upper end is embedded in the fill. A layer of clean compacted sand 6 to 8 in. thick (150 to 200 mm) should be placed for bedding beneath the tubes. When the units are in place on the bedding, they must be checked to be sure that they have support along their entire length and that they don't "bridge" any holes or voids. Once this is done, sand should be compacted around the tubes in 3 to 4 in. (75 to 100 mm) layers until the tubes are covered to a depth of about 6 in. (150 mm). This will allow good heat transfer

between the soil and the pipe. The pipe trench should be backfilled to near the level of the surface, and then a two to four inch layer (50 to 100mm) of extruded polystyrene foam insulation (XEPS foam) should be placed over the area beneath the structure to reduce the heat flow into the frozen soil. The insulation should then be covered with a 4 to 6 inch (100 to 150 mm) layer of clean gravel to protect it. Note: If there is any possibility of a hydrocarbon spill such as heating fuel or gasoline, then refer to section 2.3.7 Chemical Stability of Foam Insulation, to choose the best type of insulation for this case.

Insulation is very effective in this type of installation because it reduces the amount of heat flowing into the permafrost while the thermosyphons effectively bypass the insulation to maintain winter freeze-back that is so essential to permafrost survival.

When natural-convection devices are used to stabilize existing buildings, special drilling techniques must be used to install the bottom of the unit (the evaporator section in thermosyphons or the heat collection section in single-phase units) into the thawed zone under the foundation (see section 5.6 and 5.7 for installation details).

3.3.7 Mechanical Refrigeration

Sometimes more cooling is required to protect the permafrost than can be economically supplied by convection methods. In these cases mechanical refrigeration of the foundation may be the only solution. There are some advantages and several disadvantages to this solution. The advantages include:

1. The ability to supply cooling at any location with precise control

2. The ability to supply cooling continuously throughout the year without

dependence on the vagaries of seasonal weather or outside air temperature.

3. The ability to supply and control large amounts of cooling power when needed.

The disadvantages of this approach include:

1. Relatively high operating cost

2. High installation cost

3. High equipment cost

4. The need for power at the site to run the refrigeration equipment

5. Noise from the operating refrigeration equipment

6. Mechanical equipment that has a limited lifetime and requires more

   maintenance than other solutions.

Although many of these disadvantages can be minimized with proper design, they cannot

all be completely eliminated.

Commercial refrigeration units are available in a wide variety of sizes that will provide

the amount of cooling needed for any requirement from air conditioning to freezing

probes. For instance, the units have been used to rapidly refreeze pile installations so that

the piles could be loaded earlier to preserve the construction schedule. In another

application, Rangeview Construction Inc. used large rental refrigeration units to quickly

remove heat from the thawed soil beneath a building to stop subsidence and preserve the

permafrost while waiting for winter weather to activate a convection cooling system that

took over once cold weather arrived. Since the refrigeration unit can easily be controlled, the precise amount of cooling can be supplied to the specific location where it is needed.

A specialized refrigeration system called a "Heat-Pump" is designed for heating buildings in localities where there is an adequate source of environmental heat. These units are widely used for home heating systems where there is a supply of warm ground water or in warmer climates where the normal ground temperatures are warm enough to supply the source of heat. The units are set up to:

1. Collect heat by cooling the ground water or soil around the building,

2. Concentrate the heat by raising the temperature to the point that it is useful for heating the building

3. Distribute the heat to the building or home.

Systems such as this have been used to protect the permafrost beneath buildings and to use the heat removed from the soil above the permafrost to supplement the heating system inside the building.

3.3.8 Heat Pump Operation

The heat pump consists of a compressor, an expansion valve, and two heat exchangers. The compressor in the heat pump compresses the working gas (called a refrigerant) until it is a hot, high-pressure fluid. When a gas is compressed, its temperature rises so that much of the heat that it contains can be removed from the hot fluid by circulating it through a heat exchanger called a "condenser coil" (much like the radiator of a car) where fan-forced air removes the excess heat, cooling the hot, compressed fluid to near room temperature (see figure 3.6). The high-pressure fluid leaves the condenser coil and

travels through a short pipe to an expansion valve where its high pressure is released. As the fluid expands it enters into another heat exchanger called the "expansion coil." When a high-pressure refrigerant expands, its temperature drops in direct proportion to the pressure drop, and it becomes very cold. As the very cold gas passes through the expansion coil, it absorbs heat from a heat transfer liquid (HT liquid) that is also passing through an adjacent passage in the expansion coil. The HT liquid is cooled until its temperature is well below the soil temperature beneath the building. The HT liquid is then pumped into a grid of tubes that is embedded in the soil under the building. The cold HT liquid flowing through the tube grid in the soil absorbs heat from the soil, cooling the soil that the HT liquid re-warmed. Thus the HT liquid captures heat that has passed through the floor of the house and heat that has entered the soil from outside during warm weather and carries the heat back to the expansion coil of the heat pump. Meanwhile the warmed refrigerant in the expansion coil of the heat pump leaves the expansion coil and flows back to the compressor where the cycle begins again. In this manner, heat is absorbed from the soil, transferred to the refrigerant in the expansion coil, concentrated to a much higher temperature in the compressor and then discharged into the building at a high enough temperature to supplement the heating system for the building. This system requires a heat pump and a grid of pipes or tubes buried under the building where heat can be absorbed from the soil. Most heat pump units operate at a coefficient of performance (COP) from about three to five. The COP is a measure of how much heat is captured by operating the heat pump. For a COP of three, every Watt of electricity that is used to run the heat pump results in three Watts of heat energy being discharged into the house. Obviously to offset the high cost of electricity used to run the

FAN

COOL AIR

COMPRESSED
REFRIGERANT
(VERY HOT)

COMPRESSOR

(WHEN A REFRIGERANT
IS COMPRESSED IT
GETS VERY HOT)

REFRIGERANT IS
WARMED WHEN IT LEAVES
THE EXPANSION COIL

COLD COOLING
FLUID

HEAT FROM THE SOIL
WARMS THE COLD COOLING
FLUID

CONDENSER COIL

EXPANSION COIL
(HEAT FROM COOLING FLUID
TRANSFERS TO THE COLD
REFRIGERANT)

HEAT IS TRANSFERRED
FROM THE HOT REFRIGERANT
TO THE AIR IN THE CONDENSER

WARMED AIR
TO HEAT
THE
HOUSE

COOLED COMPRESSED
REFRIGERANT
(ROOM TEMP.)

EXPANSION VALVE
(AS THE REFRIGERANT EXPANDS
ITS TEMPERATURE FALLS)

EXPANDED REFRIGERANT
(VERY COLD)

WARM COOLING
FLUID

COOLING TUBE GRID

FIGURE 3.6 Details of the Heat Pump and Soil Cooling Grid

heat pump, a high coefficient of performance is desirable. As the temperature of the heat source (in this example the soil under the building) drops, so does the COP. When temperatures are as cold as the average soil temperatures in Alaska, the COP is usually well below 3. This coupled with the high cost of electricity discourages their use unless an abundant source of inexpensive heat, such as a hot spring, is available. The soil temperatures below a house, however, are considerably warmer than typical outdoor soils in Alaska. These warmer soils would result in a higher COP in this case.

Commercial heat pump units are usually designed to heat an entire home or building and the smallest of these units is usually larger than is needed for the purpose of cooling the soil beneath a house. However, a few manufacturers specialize in small, high-performance units that lend themselves to this application.

Protecting the permafrost under a house with a heated basement is difficult. There are only a few options available that are practical. One possible option is to abandon the basement, to insulate the floor above it, and to cool it as much as possible using winter air. Although this is an extreme measure, it will save the rest of the house from ultimate destruction as the permafrost thaws. A heated basement, however, usually represents a substantial investment and an important part of the home. Owners are usually very reluctant to give up their basement. (If the basement can be sacrificed, then the problem can be nicely solved using the forced-air-cooled crawl space solution that is described in section 3.2.2 above.

Thermosyphons are still another approach that can be used, but installing them under an existing house is difficult and requires specialized equipment with trained operators. Also, thermosyphons do not operate during the summer. (See Permafrost Technology Foundation report on a thermosyphon-stabilized foundation).

The third option is to collect the heat entering the soil under the house with mechanical refrigeration such as the heat pump discussed above. Using the heat recovered from the soil to supplement the heating system in the house and in this manner reclaiming much of the energy used to run the heat pump helps to make this type of system somewhat more economically viable, however it is not the optimum solution and can be very expensive to install. Unlike most other systems discussed above, this system also has continual operating and maintenance expenses. On the plus side, however, it allows cooling of the underlying permafrost throughout the entire year, not just in the winter.

3.3.9 Minimizing the Disadvantages of Mechanical Refrigeration

The operating cost of a refrigeration system specifically dedicated to protecting the permafrost is high and would normally make this type of system economically prohibitive. However, when the heat pump approach is used so that much of the energy used to run the system is reclaimed to help heat the house and lower the heating fuel cost, it can be more attractive.

Another tactic is to install an accessory to the heat pump system that is commonly referred to as an "economizer." This can be used to lower the overall operating cost even

more. The heat pump compressor is really not needed during the winter when outside air temperatures are low enough to cool the heat transfer fluid (HT fluid) to the required temperature. A valve can be used to divert the HT fluid from the expansion coil to a liquid-to-air heat exchanger located outside the house. The outside heat exchanger then can supply the required cooling of the HT fluid using cold winter air, and the heat pump can be turned off during a substantial period of the winter in Alaska. When the HT fluid is diverted, the cost of operating the heat pump compressor will be saved. However, there are still the operating costs of a fan to blow cold winter air across the outside heat exchanger and of the HT fluid pump. This type of system has not been studied by the Permafrost Technology Foundation to determine initial capital costs or operational savings.

Finally, insulating the basement walls in addition to the floor will help reduce energy loss and allow the air temperature in the basement to be maintained at a lower temperature while still being comfortable. Insulation around the outside perimeter of the house will also help by reducing the amount of heat that flows into the soil from the outside during the summer. Keeping snow removed from around the perimeter will also help by enforcing the winter cooling of the soil around the house.

The cost of installing the heat pump system can be reduced if the basement has enough ceiling space to allow the cooling tube grid, insulation, and flooring to be installed on top of the existing basement floor.

3.4 Thaw Bulb Equilibrium

The thawed soil beneath a building gradually increases in depth and widens slightly until a volume of thawed soil called the "thaw bulb" exists (see figure 2.2). The thaw bulb grows deeper due to the continual input of heat from the house above. As the thaw bulb grows into the permafrost, the potential for thaw subsidence becomes a concern. If the permafrost contains a greater amount of water, in the form of ice, than the saturation limit for the type of soil present, settlement will take place and the building will settle. As the amount of water increases above saturation, the amount of settlement also increases proportionately. However, if the amount of water produced by the thawing of the accumulated ice in the permafrost is less than the saturation limit for that soil, no settlement will take place. Certain permafrost soils are notable for being "dry." Clean sand and gravel soils are often dry or more accurately "thaw stable". Even silt, in some locations, is dry enough that there is little or no settlement upon thawing.

The thaw bulb will not enlarge forever. The amount of heat entering the soil from both the house and from the environment is generally nearly constant with time and can only thaw so much permafrost. Unless the amount of heat entering the soil is increased (by additions to the house or by a series of warm years) the thaw bulb will eventually stop growing. At this time it is said to have "reached maturity." If the mature thaw bulb has penetrated only a small amount of thaw-unstable, high-moisture-content permafrost, then there will be very little settlement. The problem arises in determining what the conditions of the permafrost are below the entire structure. A borehole exploration by an experienced drill team can give an indication, however, the borehole only reveals the

conditions at that specific site. Permafrost is so variable that conditions 10 to 20 feet away from the borehole may be entirely different. If there is thaw-unstable permafrost under just one corner of the house, there will be substantial damage to the structure when that permafrost thaws.

The Permafrost Technology Foundation reported on studies of an older home that had existed at its present site for over 25 years before the study started. (See PTF report on Cordwood drive 1999). Boreholes showed that the permafrost beneath the structure was marginally thaw-unstable, with a frozen sand layer at about 25 feet. The settlement damage consisted of the following:

1. The garage floor slab contained several large cracks and was uneven

2. The garage door had a wedge shaped crack beneath it where the uneven slab had settled.

3. Some of the piers in the crawl space that supported the floor had settled and needed to be shimmed to restore their support.

The settlement damage was repaired, and the house was studied for seven years. No further settlement was noted. The report's conclusion was that the thaw bulb had reached maturity and the house was not likely to suffer any further settlement damage.

When permafrost is marginally thaw stable to a greater depth than the frost bulb can be expected to achieve, settlement may not be disastrous as the permafrost thaws, and the

most economical course of action may be to repair the minor settlement damage as it occurs and to allow the thaw bulb to reach maturity.

A note of caution is needed here. The only way to access the conditions of the permafrost is to drill several boreholes into it, collect undisturbed samples of the soil at appropriate intervals, and have the moisture content of the samples measured. Even with boreholes at all four corners of the house, the soil conditions beneath the house can only be inferred. Boreholes may have missed a large massive ice wedge or ice lens beneath the structure. Therefore the approach of letting the thaw bulb reach maturity should only be considered when the structure has existed for at least 10 years or more and the thaw bulb is already nearing maturity. This should be confirmed by a permafrost exploration conducted by a qualified engineering firm experienced in this area.

This situation is fraught with uncertainty, however. For example a person selling a house with some obvious settlement problems may contend that the damage occurred some years earlier and the settlement has not reoccurred, indicating that the thaw bulb has reached maturity. It would be difficult for an engineer evaluating the situation to contradict this contention by examining or even drilling the site at one point in time. In this situation, repeated settlement measurements on the foundation of the structure over a period of time (several months to a few years) may be the only way to resolve the question one way or the other. The buyer must be very cautious.

CHAPTER 4 - PILES

4.1 Overview

In construction terms, a pile is a long slender column that is placed into the ground to support a vertical load. They are usually steel, wood, or concrete. Because the below-ground portion is supported laterally and the aboveground portion is relatively short, they are generally much more slender than architectural columns which must be designed to resist buckling under load. Steel piles for small buildings can be as small as six inches in diameter while wooden piles are generally trees that have been debarked and treated to prevent wood rot and are therefore usually larger in diameter than steel piles when supporting the same vertical load.

All types of wooden piles must be protected from wood rot because they are usually exposed to water for a great deal of the time. Steel piles should be protected from corrosion because soils in the far north are generally quite corrosive.

Concrete piles (which are used more extensively by the Russians than the Americans) have their own problems. If they are precast, they are very heavy and it is difficult to install them without damage. Heavy equipment capable of supporting and lifting the pile is needed. If they are cast on site in a prepared hole, then care must be taken to ensure that the pile is not so massive that the heat of hydration given up by the concrete curing process does not thaw the permafrost. At the same time, the pile must be massive enough and the surface protected well enough to keep the frozen soil into which the concrete is poured from damaging the uncured concrete. Enough time after casting the pile must be allowed for complete curing of the concrete and for complete permafrost freeze-back and

formation of an adequate frozen bond (called the "adfreeze bond") between the soil and the pile.

4.2 Pile Installation

Pile foundations have been the "conventional foundation" used in new construction on permafrost sites since the Russians first developed it decades ago. Although the American and Russian approach to pile foundation design has diverged widely over the years, pile foundations are still used extensively in the northern regions of both countries. The foundation consists of piles embedded through the active layer into the permafrost to anchor them. They extend above the surface to raise the building off the ground far enough to allow free air circulation between the bottom of the building and the surface of the ground.

Years of experience in permafrost construction has taught that for a building to be thermally de-coupled from the surface it must be raised at least 2 ft (0.6 m) above the ground (see discussion in chapter 3.2.1). The overriding consideration is that the space beneath the building must have free circulation of winter air to carry away any heat that escapes through the floor. Since the building presents an obstacle to air flow, larger buildings require a higher air space beneath them. Buildings such as warehouses or dormitories for working crews have traditionally been raised 3 ft (~1 m) or more. In Prudhoe Bay, Alaska the British Petroleum Co. built their main operations building on piles that elevated the building over 5 ft above the surface, and to further encourage air

flow beneath the structure the bottom of the building was contoured to give a more aerodynamic shape and less wind resistance (see figure 3.1).

Free air circulation beneath the structure is essential. Without it, the permafrost is not adequately protected from the heat of the building. All too often the area beneath the building is allowed to become a convenient covered storage place where everything from bicycles to old furniture is placed. When the space is even partially filled the airflow is compromised and winter cooling cannot do all that is needed to protect the permafrost. The practice of applying skirting around the bottom of the structure to "dress it up" is even worse. This defeats the purpose of raising the building off the surface, traps enough heat from the building to warm the ground and ultimately thaws some of the permafrost beneath the building causing the piles to lose their support and the foundation to fail.

It is also essential that the pilings be embedded deeply enough into the permafrost to provide support for the structure and also to resist the heaving effects that take place in the active layer. The "adfreeze" bond that develops between the permafrost and the pile provides the required support for the pile. This bond comes from the moisture in the soil and is absent in perfectly dry soil (of course perfectly dry soil almost never exists in the northern environment). The strength of the bond is temperature dependent, the colder the soil the higher the adfreeze bond strength. Since the active layer gets much colder each winter than the permafrost (see figures 1.1 and 1.3), the adfreeze bond in the active layer is much stronger than in the relatively warmer permafrost below. As the active layer freezes each winter, frost heaving often develops, creating an upward force on the

embedded piling.   The adfreeze bond between the pile and the permafrost plus the

structural load on the pile must be large enough to resist the active-layer heaving force.

In order for the weaker permafrost adfreeze bond to overcome the heaving force, the

depth of embedment into the permafrost must be much greater than the thickness of the

active layer. In addition, most piling designs attempt to weaken or eliminate the adfreeze

bond in the active layer by use of sleeves or coatings on the pile (see section 4.2.8).

4.2.1 Slurried Piles

For many years the "slurried pile" has been the most commonly used design.   This

design uses a drilled hole that is 4 to 6 inches larger in diameter than the largest diameter

of the pile to be placed in it. The name is derived from the slurry that is compacted into

the annulus between the pile and the hole. Figure 4.1 shows a typical slurried pile

installation.

When a drilled and slurried pile is placed, the portion of the pile that will be in the active

layer is typically wrapped with three layers of black polyethylene film. In Alaska this has

been found to be an effective way to reduce the active layer's adfreeze grip and thus to

reduce frost heaving forces on the pile.   Black polyethylene is preferred due to its better

resistance to ultraviolet degradation. Since the portion of the film that is buried in the

active layer is not exposed to sunlight, clear polyethylene could be used if the above-

ground deterioration of the film was acceptable. Figure 4.2 shows a typical polyethylene

film installation in the active layer. Other practices use viscous films of wax or grease to

coat the pile in the active layer, and some new epoxy coatings that were developed to

PILE EXTENDS
ABOVE THE SURFACE
AT LEAST 3 FEET
AND UP TO 5 FEET AT
A SITE THAT HAS
LITTLE WIND

ICE LENS

OUTER CASING
IS SET IN THE
ACTIVE LAYER TO
BREAK THE BOND
BETWEEN THE
SOIL AND THE
PILE

ANNULUS BETWEEN PILE
AND ACTIVE LAYER IS
FILLED WITH WAX AND
SAND OR OTHER NON-
FREEZING, VISCOUS
SLURRY

ACTIVE LAYER

TOP OF PERMAFROST

TOP OF PERMAFROST

ANNULUS BETWEEN PILE
AND PERMAFROST IS
FILLED WITH CLEAN
SATURATED SLURRY

PERMAFROST

ICE WEDGE

WHEN A WOOD POLE
PILE IS USED, THE
LARGE END IS PLACED
IN THE BOTTOM OF
THE HOLE TO ENHANCE
THE PERMAFROST'S
DOWNWARD HOLDING
FORCE

MINIMUM DEPTH THAT THE PILE
IS EMBEDDED INTO THE
PERMAFROST IS 2x THE DEPTH
OF THE ACTIVE LAYER

ICE
WEDGE

FIGURE 4.1 Typical slurried pile installation at a permafrost site. Note that the ice lenses in the active layer are only present when the active layer is frozen.
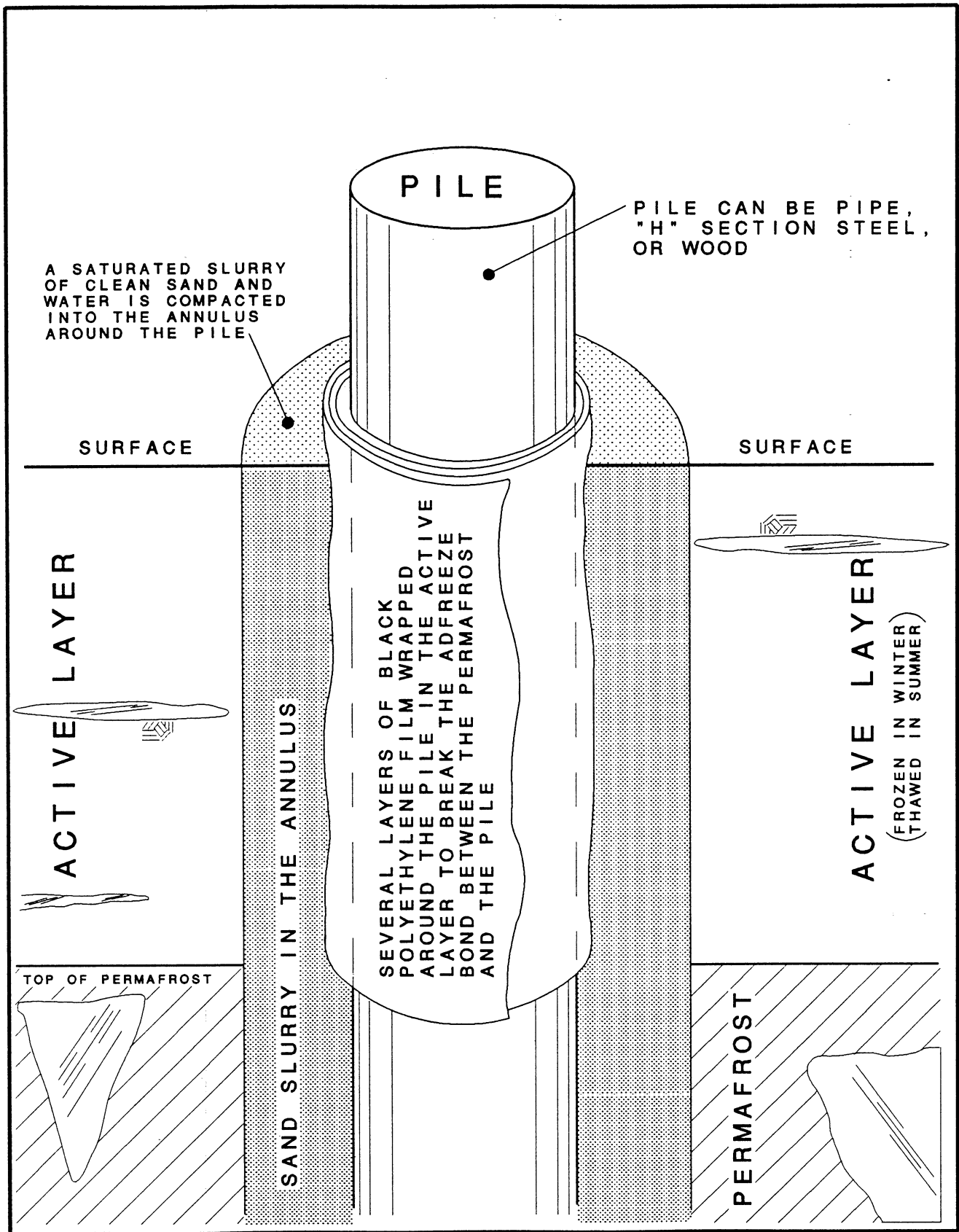
FIGURE 4.2 Polyethylene film used to break the adfreeze
bond in the active layer on a slurried pile

resist ice adherence show a good deal of promise for the future. Environmental concerns also must be considered in the choice of materials that are placed in the ground. A "slip sleeve" has also been used with some success, however, the adfreeze bond on the outside of the sleeve causes it to heave. It can eventually frost jack (the process of repeatedly heaving a little each year) completely out of the ground leaving the pile unprotected in the active zone. Care must also be taken to ensure that the sleeve is not long enough to contact the structure being supported by the pile thus transferring the heaving forces on the sleeve to the structure. Figure 4.3 shows a gate that has been frost heaved successively over several years. This successive heaving is termed frost jacking and can completely expel buried objects such as fence posts, power poles, and gate stanchions from the ground. The gate in this example has heaved differentially, with the right-hand side heaving much more than the left.

When wooden poles are used, the pile is placed with its larger end at the bottom of the hole. This increases the permafrost's ability to hold the pile while the tapered surface reduces the active layer's adfreeze grip on the pile and thus reduces the heaving force.

Since the hole is larger than the pile, the open space (the annulus) around the pile is filled and compacted with sand slurry. Vibratory compactors are preferred, but if unavailable, long rods and careful tamping has been used. Originally the slurry used in the permafrost zone was made from the material removed from the hole during drilling. A sand-slurry was used where the pile passed through the active layer. However, more recent practice has found that clean sand-water slurry for the entire annulus gives the best results and the
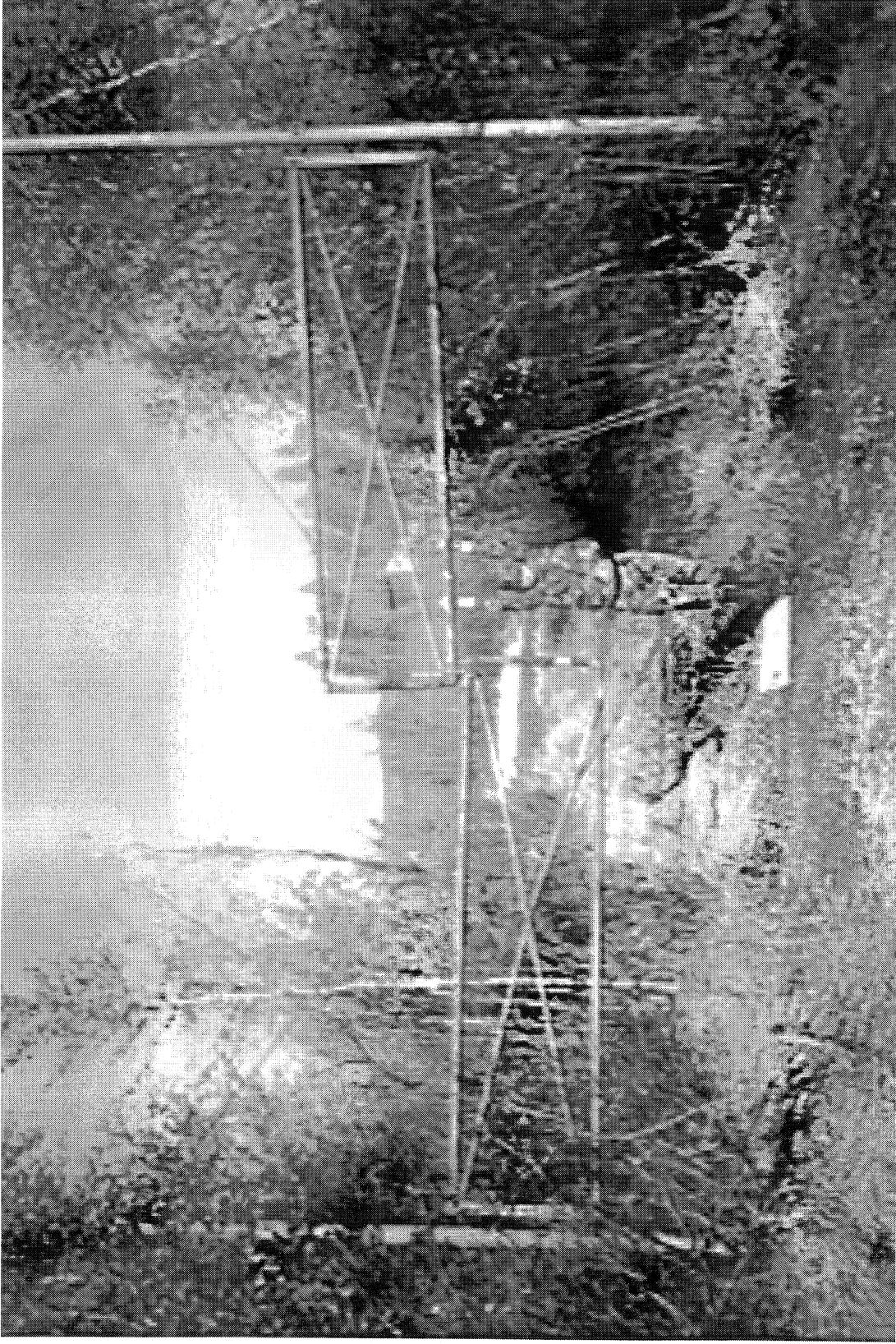
Figure 4.3 A frost jacked gate at the CRREL site in Fairbanks, AK. Note how much more one side has jacked than the other.

fewest installation problems. Make the slurry by mixing clean sand[8] with water until a consistency is achieved that gives about a 6 in. "slump." This slurry consistency is easier to work with, gives more uniform results, and develops just as strong an adfreeze bond to the pile (Kinney 1986) as the original material. When clean sand is not available, and the auger cuttings that are removed from the hole must be used for slurry, they must be sorted to make sure that they are free of wood, peat, or other organic materials, and they must not have any residual ice pieces. A concrete mixer works well to prepare slurry. Excess water should be avoided and water should not be allowed to enter the hole.

When ground water is present, a casing may have to be used, at least in the active layer, to prevent water from flooding the hole. Both adfreeze strength and the time required for the slurry to freeze (freeze-back time) will be affected adversely when excess water enters the hole. As stated above, the slurry must be well compacted to eliminate voids or air pockets and to enhance soil-to-pile contact for a strong adfreeze bond in the permafrost zone. An adfreeze-bond breaker should be used in the active layer.

Wooden piles (and pipe piles with capped bottoms) often try to "float" out of the hole while the slurry is being placed. When this happens, the pile must be held in place until enough slurry freezes to hold the pile in place. When floating is anticipated, it is advisable to fill only the bottom few feet of the annulus with slurry. Then allow slurry freeze-back to anchor the pile in place before the rest of the slurry is placed. When this is done, water must not be allowed to enter the hole during the freeze-back period, as it will

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[8] Clean sand is defined as having less than about 6% (by weight) of silt or finer materials, i.e. 6% passing a #200 sieve.

add detrimental heat to the permafrost, delay the freeze-back, and may still float the pile out of the hole.

4.2.2. Pile Freeze-back Time

For slurried piles, freeze-back time depends on the amount of slurry that must be frozen. It is therefore desirable to keep the size of the annular volume around the pile as small as practical. Placing and compacting the slurry, however, argue for as large an annulus as practical. Usually standard size augers allow the hole to be between 4 and 8 inches (50 to 200 mm) larger than the pile. This leaves an annular space of 2 to 4 in. (50 to 100 mm) around the pile. When the thickness of the annulus exceeds about 4 inches (100mm) the amount of expensive slurry required is excessive. Even more important, too much freeze-back time is required before the pile can be loaded and also too much heat is added to the permafrost. On the other hand, when the annulus is less than about 2 in. (50 mm) wide, placement and compacting of the slurry gets to be very difficult, and slurry voids in the annulus often result.

Loading the piles before freeze-back is complete can destroy the adfreeze bond, cause the pile to "float out of the hole, and otherwise destroy the load-carrying capacity of the pile. Enough time must be allowed for the heat that is introduced into the hole by the slurry and the pile to be dissipated and for the adfreeze bonds between the soil and the pile to be fully developed. The amount of heat that must be removed to freeze the slurry consists of three parts:

1. The "sensible heat" required to lower the temperature of the slurry and pile to the freezing point, then

2. The "latent heat of fusion" that must be removed to cause the water in the slurry to freeze, and finally

3. The "sensible heat" to lower the slurry and pile from the freezing point to the desired temperature that will provide an adequate adfreeze bond strength.

The total heat to be removed is:

$$Q_{Total} = Q_{sensible} + Q_{Latent} \quad \text{(BTU or kJ)} \tag{4.1}$$

The magnitudes of both Q_S and Q_L are a function of the annular volume (V_a).

$$V_a = \frac{\pi}{4}(D_h^2 - D_p^2) \tag{4.2}$$

Where:

V_a is annular volume per unit length of hole (ft^3/ft or m^3/m)

D_h is the hole diameter (ft or m)

D_p is the average pile diameter (ft or m)

The sensible heat (Q_s) is:

$$Q_s = V_a \gamma_{ds} \left\{ \left[\left(\frac{m.c.}{100} \right)(c_w) + c_{ds} \right] \left(T_{sl} - T_f \right) + \left[\left(\frac{m.c.}{100} \right)(c_i) + c_{ds} \right] \left(T_f - T_{pf} \right) \right\} \tag{4.3}$$

and the latent heat (Q_L) is:

$$Q_L = V_a \gamma_{ds} (m.c.) L \tag{4.4}$$

Where:

γ_{ds} is the density of the slurry material when it is dry (lb$_m$/ft^3 or kg/m^3)

$m.c.$ is the moisture content of the slurry in percent of the soil's dry weight (%)

c_w is the specific heat (heat capacity) of water (*1 BTU/lb$_m$ °F or 4.2 kJ/kg °C*)

c_{ds} is the specific heat of the dry slurry material (0.17 *BTU/lb$_m$ °F or 0.71 kJ/kg °C*)

c_i is the specific heat of ice (0.49 BTU/lb$_m$ °F or 2.0 kJ/kg °C)

T_{sl} is the temperature of the slurry when placed (°F or °C)

T_f is the freezing temperature (32 °F or 0 °C)

T_{pf} is the temperature of the surrounding permafrost or the temperature at which

the adfreeze strength is considered to be adequate (°F or °C).

L is the latent heat of fusion for water (143.3 BTU/lb$_m$ or 333 kJ/kg)

Except in very dry soil, the value of the latent heat Q_L is much larger than the sensible

heat Q_S, so the sensible heat term often can be omitted without a large error.

Crory (1966) gives the following approximate relationship for determining the freeze-

back time (t) in hours.

$$t = \frac{(D_h)^2}{12.1\alpha} \left[\frac{Q_T}{C_{vpf}(D_h)^2 (T_f - T_{pf})} \right]^{1.33} \tag{4.5}$$

Where:

C_{vpf} is the volumetric specific heat of permafrost at the site (BTU/ft^3 °F or kJ/m^3 °C)

α is the thermal diffusivity of the permafrost (ft^2/hr or m^2/hr)

Average typical values for volumetric specific heat (C_{vpf}) for permafrost is 28 BTU/ft^3 °F

and for the thermal diffusivity α is 0.048 ft^2/hr.   Other values of C_{vpf} and the value of α

for a specific site can be found in *Construction in Cold Regions* by McFadden and

Bennett, 1991 (see the bibliography at the end of this manual). These calculations are not

trivial and must be done with care. Be sure to use the same type of units throughout each

equation; do not mix English and Metric units such as lbs/in.^{3} and kg/m^3.   When in doubt

a qualified permafrost engineer should be consulted to check results before loading the

piles.

Fig. 4.4 from the US Army manual number TM 5-852-6 gives a graphic, approximate

solution to the freeze-back problem that is usually accurate enough for most construction

purposes.

The required load divided by the load capacity of each pile will determine the number of

piles that are needed. However, when slurried piles are used, the spacing between piles

must also be considered, since the heat added to the permafrost during the freeze-back of

the slurry can be sufficient to raise the temperature of the permafrost enough to cause

thawing problems. The amount of heat added to the permafrost during slurry freeze-back

(Q_{fb}) can be calculated from equation 4.6.

$$Q_{fb} = (Q_T)(l)N_p \qquad\qquad (4.6)$$

Where:

Q_T = the total heat added by the slurry of the pile (eq. 4.2 plus eq. 4.3)

(BTU/ft or kJ/m)

l = the average length that each pile extends into permafrost (ft or m)

N_p = number of piles in the foundation

The detrimental effect of raising the permafrost temperature can be found as follows:

1. The effective length and width of the site are found by adding the distance of

one space between the piles (s) to the overall length and to the overall width

Definition of terms:

t = freezeback time - hours

K = Thermal conductivity of permafrost - BTU/ft hr F

C = Volumetric heat capacity of permafrost - BTU/cu. ft F

a = Diffusivity of permafrost - sq ft per hour (= K/C)

Q = volumetric latent heat of slurry per foot of pile - BTU/ft

ΔT = initial temperature of permafrost in number of degrees
below freezing - (32-T)

r = Radius of pile hole - ft

$$\frac{Q}{Cr^2 \Delta T}$$

$$\frac{a\,t}{r^2}$$
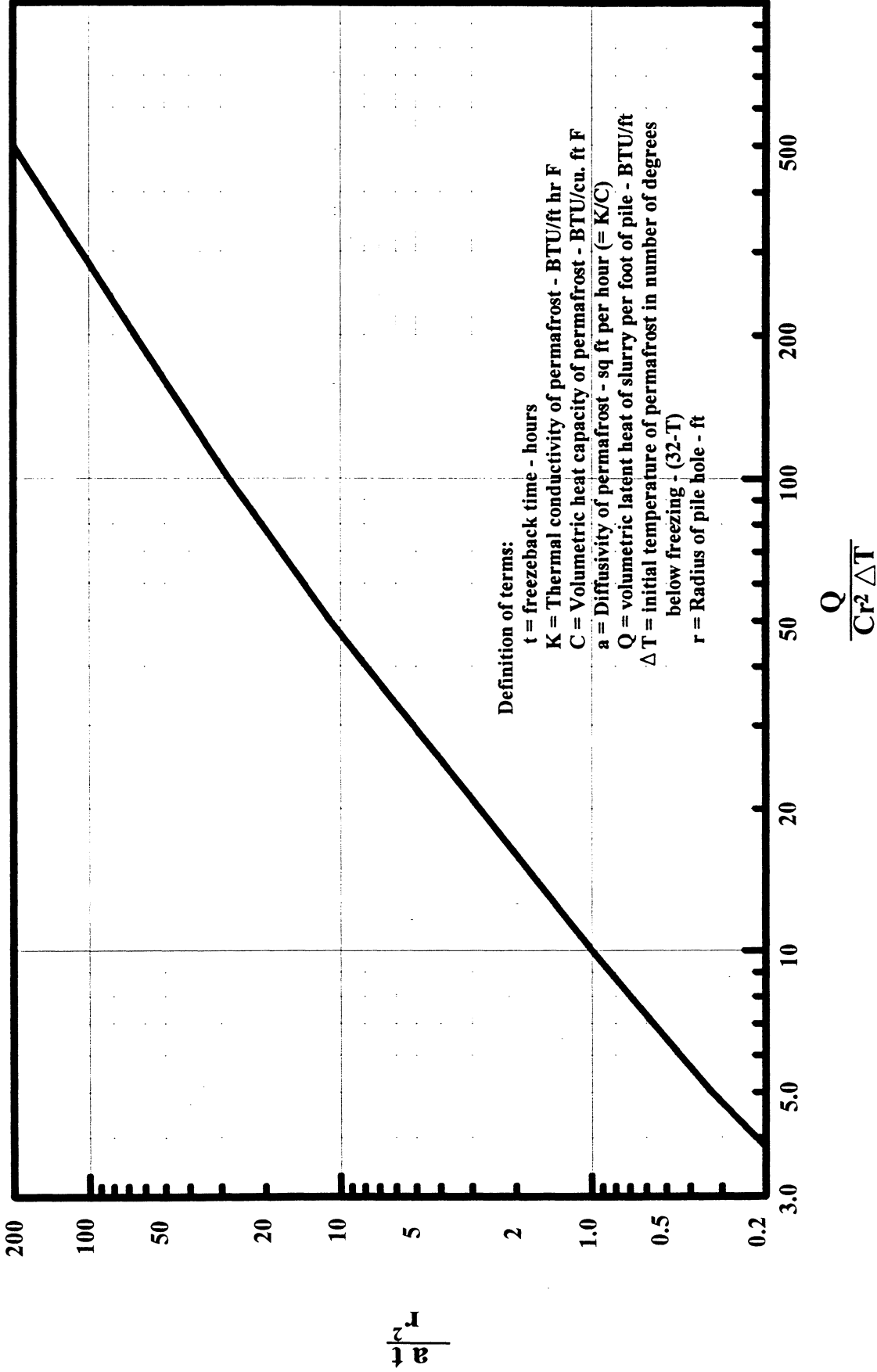
Figure 4.4 General solution of slurry freezeback around piles. From Dept. of Army Technical Manual 5-852-6

of the foundation. Then the revised area is length+one space x width + one space.

$$\text{revised area } A_r = (L+s)x(W+s)$$

2. Multiply the revised area by the average depth (d_p) that each pile extends into the permafrost to obtain the volume of permafrost affected (V_{pf}).

$$V_{pf} = A_r \, d_p$$

If we assume that the heat will be evenly distributed throughout that permafrost volume, the rise in the permafrost temperature is approximated by:

$$T_{final} = T_{initial} + \frac{Q_{fb}}{V_{pf} C_{vpf}} \tag{4.7}$$

Where:

V_{pf} = the volume of permafrost affected

C_{vpf} = the volumetric specific heat of permafrost (~28 BTU/ft^3°F, See above)

The amount of temperature rise that the permafrost can absorb without adverse effects depends on its initial condition. If the average permafrost temperature is below 20°F (-7°C), a temperature rise of 4°F or 5°F (2 or 3 °C) is probably acceptable. This would be the case for say the North Slope of Alaska. On the other hand, if the site is near the southern border of continuous permafrost, average permafrost temperature will be closer to 28°F to 30°F (-2°C to –1°C). In this region a temperature rise of a single degree may be too much. Between these extremes, the problem becomes a judgment call and is best made by an experienced engineer. As a reference to just how much the adfreeze bond depends on temperature, fig. 4.5 shows the adfreeze bond strength with respect to
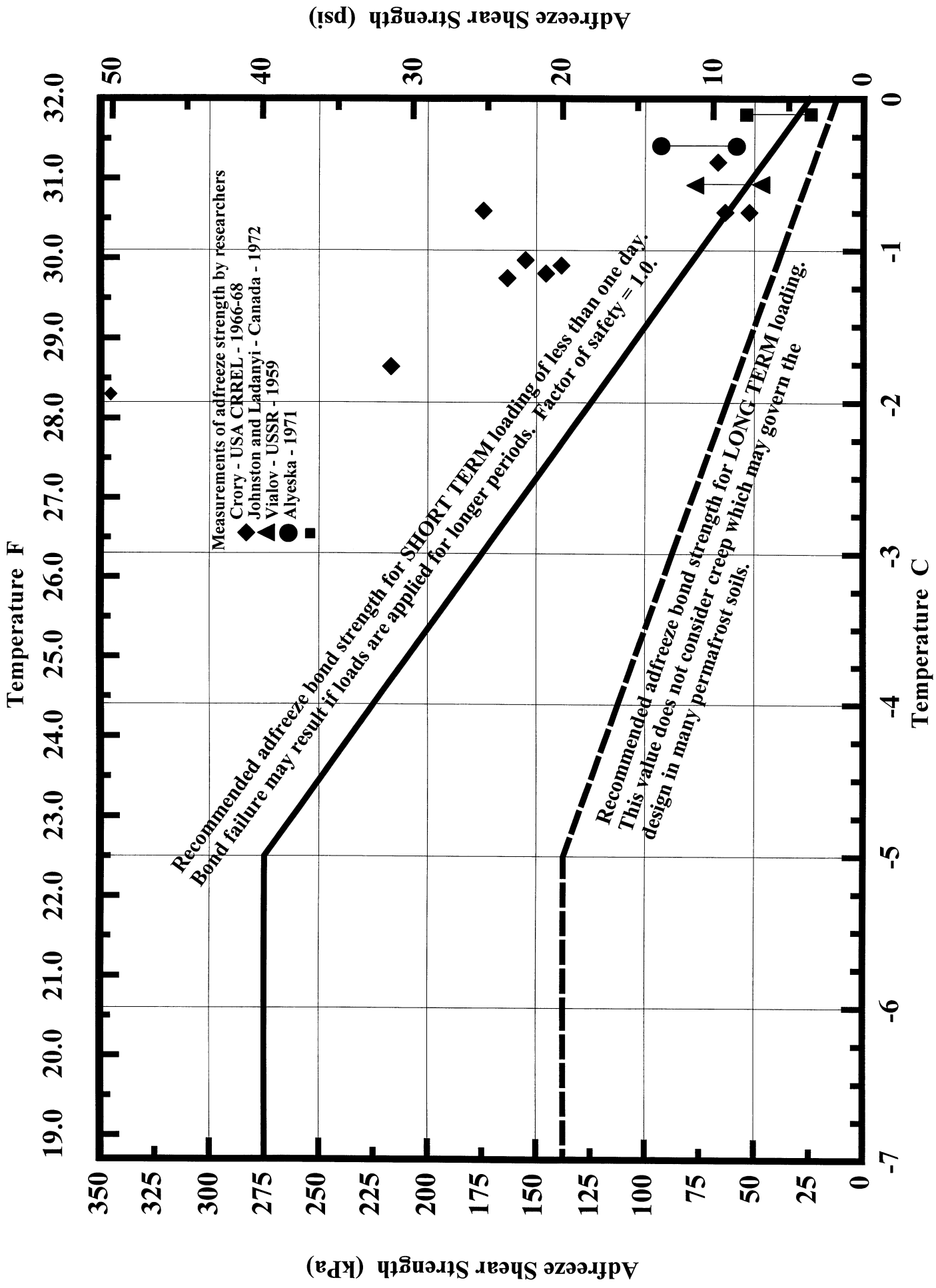
Figure 4.5 Adfreeze Bond Strength vs. Permafrost Temperature (after Johnston 1981)

temperature as reported by several permafrost researcher studies (Johnston 1981).

4.2.3 Driven Piles

Steel pipe piles can be driven into frozen soil without pretreating the permafrost when the soils are relatively dry, uniform, fine-grained materials that are free of cobbles or boulders. Marginally frozen silt, for example, allows piles to be driven without much difficulty. At sites where the soil is colder and therefore stronger, pile-driving difficulty increases rapidly with decreasing soil temperatures. Higher moisture content and saturated, coarse-grained materials also increase the difficulty of successful pile driving. Driving into hard frozen gravels is, for all practical purposes, impossible without prethawing a pilot hole, or pre-boring a hole of nearly the same diameter and depth as the pile to be driven. Piles that are driven into cold, hard-frozen gravel have been found to collapse "accordion style" rather than to penetrate the frozen gravel. Prethawed pilot holes have been used with some success when driving piles into frozen soils. Prethawing is discussed below.

Piles that are driven into frozen silt without thermal pretreating generally do not introduce very much heat into the permafrost. However, if a heated pilot hole was used to prepare for pile driving, then the calculations discussed in section 4.2.2 (above) for slurried pile freeze-back can be used to determine freeze-back time and to estimate pile spacing. When a preheated hole is used to prepare the soil for driving a pile, the diameter of the freezing isotherm around the pile (after the pile has been driven) is used instead of the outside hole diameter (D_h) in equation 4.2. Also, in place of the slurry properties,

the soil properties and moisture content of the on-site material must be used. When driving a structural shape such as an "H" pile or an open pipe, then the term for the diameter of the pile (D_p) in equation 4.2 is considered to be zero.

Used oil-field drill steel, when available, can be driven into frozen soils more readily than can pipe piles. Oil field drill steel is a very thick-walled pipe of relatively small diameter, and its rigidity helps transfer impact forces to the driving tip. It can be very cost effective under the right circumstances.

Placing piles by driving them into the permafrost has both advantages and disadvantages compared to the drilled and slurried method. If driving equipment is available, and soil conditions are favorable, placing driven piles is often faster and less expensive. Driven piles freeze back more quickly and can be loaded sooner. Placing piles by driving also is very attractive when ground water is present in the active layer. Water in the active layer makes it difficult to keep a hole drilled for a slurried pile from sloughing unless it is cased. Although placing piles by driving does not have sloughing problems, the equipment needed is expensive and not always available, especially in more remote sites. Also when driving into frozen gravel, silt with cobbles, or very hard frozen soil, pre-preparation of the soil is necessary, and this raises the cost of driving significantly. Another disadvantage to placing piles by driving involves the accuracy with which they can be placed. Driven piles cannot be consistently placed as accurately as drilled and slurried piles. When using impact hammers to drive piles, centerline tolerances of ±2 in. (50 mm) and vertical plumb within 2% are about the limit of accuracy that can be

maintained. Vibratory hammers do somewhat better, and centerline tolerances of ±0.5 in. (13 mm) and plumb can be achieved with experienced operating crews. The pile in a thawed driven hole can be vibrated until these tolerances are achieved. However, placement tolerances of drilled and slurried piles are limited only by the time and patience of the crew.

To prepare hard-frozen permafrost or frozen gravel prior to driving piling, drill a smaller diameter pilot hole at the point where the center of the pile is to be located. Fill the pilot hole with hot water 60°F to 212°F (10°C to 100°C) several hours prior to driving the pile. Prewarming the frozen soil to near the thawing point reduces its strength and makes driving into difficult soils possible. For more detail on prethawing see reference texts such as *Construction in Cold Regions* by McFadden and Bennett 1991.

Although steam seems like the logical choice for prethawing, experience has shown that hot water is a more practical choice. It has been reported that steam thawing frequently causes overheating of the hole and surrounding permafrost and that "larger than necessary thaw zones and huge voids" result from steam thawing. Hot water gives more control over the thaw diameter in the soil around the hole and less warming of the surrounding permafrost; this will result in shorter freeze-back time. Water will also fill small cracks or voids in the frozen soil and help achieve stronger adfreeze bonds between the piles and the permafrost (Nottingham et al. 1983).

Make the diameter of the pilot hole about ½ the diameter of the pile. You will have to determine the water temperature by trial experiments. Water temperature will primarily

depend on the amount of latent heat required to thaw the permafrost, however, if the initial temperature of the permafrost is very cold, the sensible heat needed to raise the temperature of the frozen soil to the freezing point will add to the heat requirement. The desired final preheating condition is achieved when a column of soil is thawed whose diameter at the interface between the active layer and the permafrost is the same as the diameter of the pile to be driven (see figure 4.6). Successful thawing has been reported using water-temperature ranges that vary from 60°F to 212°F (15°C to 100°C) depending on the initial conditions of the permafrost at the site (Nottingham et al. 1983). Although the type of driving hammer is important, impact, vibratory, and sonic hammers all have been used to drive piles successfully. Sonic hammers, however, have not performed as well in frozen coarse-grained soils or in very cold weather. Impact hammers, which can produce very high driving forces, are preferred for extremely hard driving conditions. They have been found to perform well when they are used for driving into all types of permafrost, and if thermally pre-prepared pilot holes are used, impact hammers can produce driving rates up to 5 ft/min (1.5 m/min). In warm, fine-grained permafrost that has not been prethawed, driving rates for impact hammers can be up to 12 in./min (300 mm/min) (Nottingham et al. 1983).

Vibratory hammers perform well in soft frozen soils or in fine-grained soils. Vibratory hammers are very efficient when used with prethawed pilot holes, and they can drive a pile at rates up to 20 ft/min (6 m/min).

TEMPERATURE
SENSING DEVICE

PILOT
HOLE

32°F

INSERT TEMPERATURE
PROBE TO THE TOP OF
THE PERMAFROST.
WHEN TEMPERATURE AT
THIS POINT GETS TO
32°F, HOLE IS READY
FOR PILE DRIVING

DIAMETER OF THE THAW
CYLINDER TO BE THE
SAME AS THE PILE TO
BE DRIVEN

THAWED ACTIVE LAYER
PERMAFROST

PILE
DIAMETER

PILE
DEPTH

FILL PILOT HOLE
WITH HOT WATER
AT A TEMPERATURE
OF 60 °F TO 212 °F

CYLINDER OF
THAWED SOIL
AROUND PREHEAT
HOLE

DEPTH OF PILOT HOLE
BELOW PILE TO BE
ONLY AS MUCH AS NEEDED
FOR SEATING PILE

FIGURE 4.6 Preheating a pilot hole in preparation for
driving a pile into permafrost

Brittle fracture of steel parts begins to be a concern as temperatures drop below 10°F (-12°C), and when the temperature falls below –15°F (-26°C), brittle fracture is a significant problem. When temperatures fall below –30°F (-34°C), high impact driving should probably be stopped until warmer weather returns (Bennett 1986).

4.2.4 Driven Piles vs. Slurried Piles

The choice of pile type will largely be decided by the availability of equipment. If pile-driving equipment is available and the soil conditions are favorable, then driving may be the most economical method. Consideration must be given to the affects of the driving disturbance on the building and the conditions around the site. On the other hand if the cost of mobilizing the driving equipment is prohibitive, the soil is frozen gravel, or there are neighboring buildings nearby, then slurried piles may be preferred and possibly less expensive. Availability of piles must also be considered. At remote sites, for example, timber piles that can be obtained locally may be more economical that shipping in metal piles. Timber piles must, of course be installed in bored and slurried holes while steel-pipe piles can be either driven or slurried.

4.2.5 Pile Load Capacity

The load to be placed on each pile must be determined. The weight of the structure must be estimated and distributed over the total number of piles. The number of piles will be selected to ensure that the load on each pile will not exceed its carrying capability. The load carried by each pile will be transferred to the soil through the adfreeze bond between the pile and the permafrost. Ice and frozen soil are essentially visco-plastic materials, so

the loaded pile will gradually settle as the ice in the adfreeze bond deforms. The deformation of the ice in the adfreeze bond is called "creep." The long-term settlement of the pile is referred to as "pile creep" or just "creep".

There are three categories of creep. At first loading, the pile creep will be relatively high but will decrease with time. This type of decreasing creep is referred to as "primary creep". After the initial primary creep is over, the creep will stabilize at a constant rate, neither increasing nor decreasing with time. Constant creep rate is termed "secondary creep". After a long period of secondary creep, if the load is too high, the rate of creep will again begin to increase. This period of increasing creep rate is known as "tertiary creep". Tertiary creep must be avoided because it invariably leads to adfreeze bond failure. The three stages of creep are shown in Fig. 4.7.

The pile must be designed to keep the secondary creep rate low enough that the accumulated creep will not exceed the maximum deformation criteria for the structure during its lifetime. To keep the loads low enough to stay in secondary creep, more piles can be added, the pile's depth into the permafrost can be lengthened, or the load otherwise lowered. If a structure has areas of higher loading, such as a building containing heavy machinery in one location, that must be considered in the placement and selection of the number of piles. Creep calculations are a very difficult advanced engineering subject and beyond the scope of this manual. A qualified engineer should be consulted if creep criteria are of concern in any foundation.

SOIL
FAILURE

TERTIARY CREEP ZONE
WHERE THE CREEP RATE
INCREASES WITH TIME
ULTIMATELY ENDING
IN ADFREEZE BOND
FAILURE

INFLECTION POINT WHERE THE
CURVE CHANGES FROM SECONDARY
TO PRIMARY CREEP

SECONDARY CREEP
RATE ZONE - WHERE
CREEP RATE IS
CONSTANT, NEITHER
INCREASING NOR
DECREASING WITH
TIME

PRIMARY CREEP ZONE
WHERE THE CREEP RATE
DECREASES WITH TIME

STRAIN (SETTLEMENT PER UNIT DEPTH)

TIME ⟶

FIGURE 4.7 The three stages of soil creep.

When a pile is very heavily loaded it may go into tertiary creep without exhibiting noticeable primary or secondary creep stages. When this happens, the adfreeze bond supporting the pile will usually fail in a short period of time (Phukan 1985). However, tertiary creep is of little interest since it must be strictly avoided because once a pile has reached this stage it will fail relatively soon.

4.2.6 Pile Length

When a pile is to be supported by the adfreeze bond to the permafrost, the load to which it will be exposed over the life of the structure will determine its length. The pile must be long enough to support the structure above the ground surface, to pass through the active layer, and then be embedded far enough into the permafrost to support the load. The depth into the permafrost must be enough that the adfreeze bond strength between the permafrost and the pile is stronger than any frost heaving force imposed in the active layer. The required depth to accomplish this should be calculated to be accurate, but a rough rule of thumb is that it should not be less than twice the thickness of the active layer.

4.2.7 Adfreeze Bond Strength Calculation

As discussed above, the strength of adfreeze bonds is temperature dependent. As seen on figures 1.1 and 1.3, in midwinter and early spring the frozen active layer is colder than the permafrost. Since colder temperatures result in stronger adfreeze bonds, the adfreeze bond in the active layer, per foot of embedment, is stronger than the bond in the permafrost. The magnitude of the force that can be applied to the pile is the product of

the adfreeze bond strength times the overall area over which the bond grips the pile. To

resist heaving transferred to the pile through the stronger active-layer bond, the pile must

be embedded into the permafrost deep enough so there is a larger surface area to provide

a permafrost bond that is stronger than the active-layer heaving force.

Fig. 4.5 shows the strength of the adfreeze bond between frozen soil and wood or steel

piles as a function of temperature (after Johnston 1981). Note that the adfreeze strength

in the active layer at 21°F (-6°C) is approximately four times as great as it is in

permafrost at 30 °F (-1 °C). The surface area of permafrost bond would therefore need to

be four times as great to overcome the heaving force. Experience has shown, fortunately,

that the entire active layer rarely gets this cold except perhaps in the extreme north where

the active layer is as thin as six inches.   In experiments to measure forces in the active

layer, Buska and Johnson (1988) report heave forces on "H-section" piles of 180,000 lbs

and on pipe piles of 251,000 lbs. (802 and 1118 kN). The largest heave forces occurred

when the depth of frost into the soil was 7.2 ft (2.2 m) on the "H" pile and 4.6 ft (1.4 m)

on the pipe pile. To resist a heaving force this large could require that the pile be

embedded in the permafrost to a depth in excess of 20 ft. The pile length needed to

extend through the active layer and this deep into the permafrost with enough pile left to

elevate the structure the required amount aboveground results in piles that are in excess

of 30 feet long, which are very expensive to install.

The material used for the pile must have sufficient strength to resist the tensile stresses

resulting from the opposing forces of heaving and permafrost anchoring that are acting on

it. In their study, Buska and Johnson measured internal stresses of 7500 psi (51.7 MPa) in their "H" pile and 17,170 psi (118.4 MPa) in their pipe pile. Most mild steels have tensile strengths in excess of 60,000 psi, but wood has tensile strengths in the range of 1500 to 2500 psi. Wooden piles are solid, so that they have a much greater cross sectional area over which the stress is distributed, but they clearly need to be larger in diameter to keep stresses below failure limits.

4.2.8 Reducing the Bond Strength in the Active Layer

To reduce the heaving force acting on the pile in the active layer, treat this portion of the pile with some means to reduce the ability of the moisture in the soil to form a bond or to "grip" the pile. In Alaska, materials that do not form a strong bond to ice have been found to effectively reduce or eliminate the gripping action of the active layer. Three layers of 6 mil-thick, black polyethylene film wrapped around the pile are commonly used when placing slurried piles. Black polyethylene is preferred since it is more resistant to ultraviolet degradation than clear film. The use of grease and sand slurry in the active layer was common practice before the advent of environmental concerns.

For driven piles, augur a hole through the active layer to the permafrost. Then place a pipe sleeve in the active layer and drive the pile inside the sleeve. Fill the annulus between the sleeve and the pile with environmentally acceptable, nonfreezing, slurry such as wax and sand as mentioned above. When this is done, the adfreeze bond in the active layer will form on the sleeve, and it will heave without transmitting the heaving force to the pile inside. Note the caution in section 4.2.2 (above) about the length of the heaving

sleeve. Dry, clean sand can be used in the annulus if it can be assured that it will not become saturated with water. This is difficult unless wax or some other substance is used to keep the sand from becoming frost-heave-susceptible. Clean, dry sand will not frost heave, but if it becomes very wet it can freeze into a solid mass and form an adfreeze bond with the pile. The combined sand/pile combination can be heaved as a unit by the surrounding soil.

4.2.9 Lateral Loads

Piles have little resistance to lateral loads in that part of the pile that extends from the bottom of the structure to the top of the permafrost. If the active layer at the site is very deep or the building is set very high above the ground, lateral stability becomes a concern. Larger piles, cross bracing, or closer spacing may be required to obtain the required lateral load stability. This is particularly important where earthquakes are a concern or where wind loads are high. Wind loads at sites throughout Alaska are available from various sources such as *The Environmental Atlas of Alaska* by Hartman and Johnson 1978.

4.2.10 Shallow Pile Foundations

When neither drilling nor driving equipment is available for pile placement (e.g. in remote areas) a shallow pile foundation that anchors shorter piles in the active layer may have to be used as somewhat of a last resort. This foundation is very labor intensive and is not as reliable as the deep pile foundation discussed above but may suffice when other methods are not feasible. The foundation depends primarily on "end-bearing" of the

footing on the permafrost to support the load. The footing, therefore, must be capable of accepting the pile's load and must be large enough to distributing that load to the permafrost without overloading the frozen soil.   See again figure 4.5, which shows that the frozen soil strengths are dependant on the temperature of the permafrost. If the foundation is in warm permafrost near the southern boundary of the continuous permafrost region or is in the discontinuous permafrost region, the permafrost strength will be low and will require a larger footing than if it is in cold permafrost such as that on the north slope of the Brooks Range.

To construct this type of foundation, footings or piers are placed in pits that have been excavated as deeply as possible into the permafrost (Fig. 4.8). A nonfrost-susceptible fill[9] approximately 8 to 12 in. (200 to 305mm) thick should be placed and compacted in the bottom of the pit. The footing (concrete pad or treated wood pad) is placed on the fill. The footing must be sized to provide adequate long-term bearing capacity. The pile, post, or pier that is to support the building is secured to the footing, and the pit is backfilled as soon as possible. Minimum disturbance of the permafrost and of the surface ground cover during construction should be a primary concern.

Since this type of foundation is not anchored into the permafrost, there is nothing to counteract the heaving forces that can be generated in the active layer.   For this reason, it is critically important that the adfreeze bond in the active layer be eliminated.

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[9] To be classified as a nonfrost-susceptible fill, the material must have less than 6% by weight of the soil grains passing a #200 sieve. Even if the fill passes this requirement at the time of placing, it can be contaminated by intrusion of fines so that it no longer qualifies therefore it is prudent to guard against this circumstance by providing adequate drainage for silty runoff etc.

SHIMS ADDED OR REMOVED AS NEEDED TO MAINTAIN LEVEL OF STRUCTURE

CROSS BRACING AS NEEDED FOR LATERAL STABILITY

36" CLEARANCE (24" MINIMUM)

POST OR PIPE PILE

PROTECT INSULATION WITH 2"-3" OF CLEAN GRANULAR FILL.

2" EXTRUDED POLYURETHANE FOAM INSULATION 1.5 x HOLE DIAMETER

CLEAN, SANDY GRAVEL (N.F.S) BACKFILL

POLYETHYLENE SHEET TO BREAK ADFREEZE BOND IN THE ACTIVE LAYER

ACTIVE LAYER
PERMAFROST

EXCAVATE INTO THE PERMAFROST APPROX. 18" THEN BACKFILL WITH 8" CLEAN, COMPACTED GRAVEL. PLACE FOOTING AND COMPACT GRAVEL AROUND FOOTING.

FOOTING

18"

8"

ICE WEDGE

ICE

Figure 4.8 Shallow foundation not anchored in the permafrost.

This can be done with one or more of the above techniques (i.e. polyethylene wrapping, slip sleeves with wax and sand between the sleeve and the pile etc.) One other means that will help reduce possibilities of frost heave is to backfill the pit that was excavated for the pile/footing with a nonfrost-susceptible material such as clean, coarse gravel. Adequate time must be allowed for the permafrost to freeze back beneath the newly placed footing and pile or pier before loading the foundation.

4.2.11 Minimum Pile Foundation Specifications

Adequate piles have been made of pipes, steel "H" columns, treated wood poles or timbers, and even concrete. Any material that will support the load of the building and remain stable is probably acceptable. However, to be successful, all pile-type foundation designs have to encompass the following minimum specifications:

1. The foundation must raise the building above the surface high enough to promote uninhibited air circulation beneath the building (for example: 1-2 ft (0.3 - 0.7 m) for very small buildings, 2-3 ft (0.7 – 1 m) for garage size buildings, 3 ft (1 m) for a home and 4-5 ft (1.2 – 1.6 m) for larger buildings).

2. Heavy insulation must be placed in the floor of the structure so that heat loss through the bottom of the building will be minimized. This will not only protect the permafrost but also it will help to keep the floor inside the building reasonably comfortable.

3. Air flow between the bottom of the building and the surface must be unimpeded. Nothing must be allowed to be stored in that space. Anything, even bicycles

and toys, will interfere with free air circulation during the winter months and compromise the foundation.

4. In the active layer, the adfreeze bond must be eliminated or reduced between the supporting pilings, posts or piers by one or more of the means discussed above.

5. The pile must be stabilized against lateral loads to safely withstand wind and/or earthquake loads. Cross bracing between piles is usually used for this purpose, however, this must be used with careful thought as the cross bracing will impede air circulation beneath the structure. Use the minimum amount of cross bracing needed.

6. The pile must not provide a heat path from either the building or the outside environment into the permafrost. Thermal breaks must be used when there is a possibility of heat flow through the pile into the permafrost. A thermal break is simply an interruption of the low thermal resistance path (i.e. the steel pipe) between a heat source such as the building and a cold area such as the permafrost. Reflective metal wrapping or insulation on the aboveground portion of the pipe may be needed for pipe and H section piles if they are exposed to the sun.

The Trans-Alaska pipeline uses multiple thermal breaks in their vertical support members (VSMs) to interrupt possible heat flow from the hot oil to the permafrost. The thermal breaks are in the form of joints with very small contact areas, air spaces between warm and cold surfaces, and high thermal resistance layers between contacting surfaces.

Wood is a high thermal resistance material so that a wooden pile provides a good thermal break. Steel or concrete piles, on the other hand, are relatively high thermal conductivity materials and may require insulated breaks such as a layer of wood or other high-thermal

resistance material at the joint between the building and the pile to stop heat flow into the

pile and on into the permafrost.

CHAPTER 5 – STABILIZATION OF FOUNDATIONS

5.1 Overview

We are now ready to look at the types of foundation systems that can be used to stabilize an existing building on a site underlain by thaw-unstable permafrost. The needs of the structure will dictate the choice of the foundation type. Large buildings require different foundations than small buildings. Roads and driveways present different problems than buildings. Heavy floor loads also have their individual requirements. Fragile, warm permafrost poses different problems than stable, cold permafrost. The list of differences is extensive, and each site must be evaluated individually taking into consideration all of the variables to decide which type of foundation will be the best overall choice.

Basically the problem resolves to one of protecting the building from further damage due to thawing of underlying permafrost. A foundation design for new construction usually tries to de-couple the structure from the permafrost so that heat escaping through the bottom of the building can be carried away from the surface by the cold winter air. This approach has been very successful in protecting permafrost from heat introduced by buildings, oil pipelines and other structures. An existing structure, however, presents several complications. The problem is still one of stopping the further thawing of the underlying permafrost, but with the building in place, several options used by new construction are no longer available. Some designs still rely on cold winter weather to not only carry away the heat that escapes the building but also to reinforce the permafrost by refreezing the active layer each year. This strategy cannot be used for all foundations,

however. Structures where the foundation must be in contact with the ground surface such as roads and runways or buildings with very high floor loads such as aircraft hangars or heavy equipment maintenance buildings cannot be economically raised above the surface to take advantage of the presence of winter. Protecting the permafrost in these cases requires different approaches.

The scope of this manual will limit itself to stabilizing foundations of existing buildings at sites underlain with thaw-unstable permafrost. Up to this point, we have discussed the basic tools and techniques that are available to us to use in permafrost foundation systems. In this final chapter we will look at the practical aspects for stabilizing a structure that is on thaw-unstable permafrost. We discuss the various means for stabilizing different types of foundations and the considerations involved in choosing the most appropriate method.

Each foundation must be assessed individually. Conditions affecting each site are so diverse that no one standard approach will be appropriate for all cases. Fortunately, as we have seen in previous chapters, we have an array of tools and techniques available. Factors influencing the type of stabilization system to be used include, but are not limited to, the soil conditions at the site, the building's structural needs, the owners desires, economics involved, the environmental and weather conditions at the site, and future construction in the area. This chapter will focus on each foundation type and discuss its strengths and weaknesses so that the best system for each specific case may be chosen. The aim, of course, is to stabilize the foundation at the least possible cost. However, all

parameters must be analyzed and prioritized so that in the end the building's owner can choose the system that best fits his needs.

5.2 Pile Foundations

Pile foundations are an excellent choice for new construction at a site with thaw-unstable permafrost. This type of foundation is time proven and if the piles are properly designed to take into account the long-term effects of creep, this can be a maintenance free solution that will last the life of the building. However, it is difficult to place piles of any type under an existing building unless it is small enough to be temporarily moved off of the site while the piles are being installed. If equipment is available to move the building, a better site (if one is available) may be a more economical solution than trying to cope with conditions at the present one. However, situations arise where it is best to move the building temporarily, install a pile foundation as discussed in Chapter 4 above, and then move the building back onto the new foundation. If the thaw bulb is very deep, the pile's load carrying capability may not rely on an ad freeze bond where it passes through thawed soil and, therefore, the pile may have to be very long. In this case, it must be determined if a pile foundation is economically viable or if another approach would be better.

If the building cannot be moved, then piles can be installed around the perimeter of the building to support beams or trusses that run under the building to support it. This technique is limited to buildings small enough that the span of the beam or truss is not too large, as the size and thus the cost of structural members long enough to span between

widely separated piles rises very quickly. Since several beams will be needed to provide the necessary support, this is somewhat of a last resort with respect to pile foundations.

A pile foundation is, in general, a controversial choice for an existing building. However, if you can solve the difficulties of the installation, then a pile foundation is a reliable time-tested solution that should be considered along with the other alternatives available.

5.3 Releveling an Existing Foundation

When an existing foundation needs to be releveled it is usually best to relevel from below the footing. When this is done, the distress on the foundation wall can be neutralized as well as relieving structural problems above the foundation.

5.3.1 Preparation

Dig a trench to the bottom of the footing around the perimeter of the building to expose the entire footing. Be careful not to break any utilities, like sewer or water lines, which enter the building under ground. Once the footing is uncovered, excavate spaces beneath the footing that are just large enough to accommodate a hydraulic pillow jack[10]. Excavate and place hydraulic pillow jacks at frequent intervals under entire footing. The jacks should be spaced approximately four to five feet apart and on both sides of any open cracks to avoid further damage or overstressing of the footing and foundation wall.

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[10] Any type of jack that has adequate lifting force can be used, but pillow jacks are particularly suited to this operation since they require less excavation below the footing, and a single individual can control and raise them at the same time to minimize stress to the footing and foundation wall during the operation.

Connect each of the pillow jacks to a 3-way valve with hydraulic pressure hose to control the flow of fluid to and from each jack. A central control board containing the 3-valves from all of the jacks is a convenient way to control the overall raising of the building.

The 3-way valve can be set to send fluid from the pump to the jack for raising or from the jack back to the reservoir for lowering. A high-pressure, low-volume pump capable of producing at least 500 psi will be sufficient to raise the building. A high-pressure car wash pump is usually adequate since the low-volume flow of the pump results in a very slow gentle raising of the building. Clean water is the ideal hydraulic fluid to use, as it is non-polluting if a spill occurs, and it is readily available. A 55-gallon drum will act as a reservoir for the pump to draw from. Each jack can be drained through the 3-way valve back to the 55-gallon reservoir.

Next, prepare a small plastic cup with a tube fitting in the bottom (figure 5.1) for each jacking position. Install the cup on the side of the house approximately three inches above the top of the foundation wall. Connect a plastic tube to the fitting on the bottom of the cup and route it to the central location where the pump and control valves are to be located. Mount the plastic tubes from each cup on a board so that the level of each jacking point can be monitored. Fill the all of the cups with water (add propylene glycol if this is a winter operation to avoid freezing) until the water level in the cup is exactly the same distance above the top of the foundation wall in each cup. The top of the liquid in the tube at the central monitoring and control location will be at the same elevation as the liquid in its cup (Figure 5.1). During releveling, as the foundation moves up or down, the level of the water in each tube will track the movement of the foundation at its

PILLOW JACK

PILLOW JACK

HYDRAULIC HOSES

PRESSURE PUMP

WATER SUPPLY

ATTACH A CUP TO THE FOUNDATION WALL ABOVE EACH JACK

CLEAR VINYL TUBING

PILLOW JACK

CENTRAL CONTROL BOARD

SEPARATE VALVE TO EACH PILLOW JACK

WATER LEVEL IN THE TUBES SHOWS THE ELEVATION OF EACH CUP

ELEVATION MONITORING BOARD

EXCAVATE TO EXPOSE THE FOOTING AND PLACE PILLOW JACKS UNDER THE FOOTING AT INTERVALS OF A FEW FEET.

NOTE: ATTACH A CUP TO THE FOUNDATION WALL ABOVE EACH JACK. ATTACH CLEAR VINYL TUBING TO FITTING ON THE BOTTOM OF EACH CUP AND ROUTE THE TUBING TO THE MONITORING BOARD. FILL THE CUPS AND THE TUBING WITH WATER. MARK THE INITIAL WATER LEVEL IN THE TUBING ON THE MONITORING BOARD. AS THE FOUNDATION IS RAISED THE WATER LEVEL IN THE TUBE WILL RISE ABOVE THE MARK TO SHOW THE ELEVATION OF THE CUP AT THAT POINT.

FIGURE 5.1 JACKING AND ELEVATION MONITORING SYSTEM FOR RELEVELING A BUILDING FOUNDATION

position. Before starting to relevel, place a horizontal reference line on the board behind the tubes so that the fluid level can be easily monitored. This mark should be approximately 3 inches above the water level in the highest tube. When the top of the liquid in every tube has reached this mark, the house will be level and the footing will be at least three inches (75 mm) off the ground and much of the footing may have been raised much more. This clearance between the footing and the ground provides enough space below the footing for granular fill to be placed and compacted to support the building in the newly leveled condition.

5.3.2 Releveling the Foundation

When preparations are complete, turn on the high-pressure pump and open the 3-way valves to fill each pillow jack. Carefully watch the water level in the elevation monitoring tubes and close the 3-way valve to stop raising the building when the liquid level inside each tube reaches the level mark. Also take care not to over-inflate the pillow jacks, as they will rupture if this is allowed to happen.

As each pillow jack reaches its limit (about 10 to 14 in. (250 to 350 mm)), place blocks to support the footing in its elevated position and then drain the jack to deflate it. Remove the jack and place compacted gravel fill to support the jack at a higher elevation. Then replace the jack and re-inflate it to continue to raise the building. Continue this operation until all jacking points are level. Once the building is raised and a level position is attained, compact pea gravel under the footing to support the foundation at the higher position. The jacks are then deflated lowering the building onto the compacted gravel

fill. If the gravel has been carefully compacted the building will remain level. When a satisfactory level position has been attained, you can remove the jacks and backfill the trenches around the footings. Since it is always possible that a building on permafrost will need leveling again, the excavations under the footing where the jacks were placed can be framed to keep them from filling with soil so that the jacks can be easily replaced for a future releveling operation. Cosmetic and/or structural damage to the building that was caused by the thaw subsidence can now be repaired and a method to stabilize the permafrost can be installed.

5.3.3 Measuring the Performance of the Stabilizing System

Regardless of the system used, when the stabilizing system is installed it is very important to install a means of monitoring its performance. Two types of measurements are important, temperatures and elevations (often referred to as "levels").

Temperature measurements beneath the building give information about the level of cooling taking place. They will alert you to conditions of too rapid cooling, refreezing of thawed permafrost, or of freezing around the cooling devices that can lead to heaving of the foundation. Also should the system break down or the performance deteriorate, temperature measurements will provide the first indication of the problem. Without temperature information, there is almost no way to determine whether or not the system is working properly. If a problem does arise, early warning and timely response to fix it will result in less cost and possibly no damage to the structure. If the system is operating properly, temperature measurements will give the peace of mind that all is well, a very

comforting sensation when living with permafrost. Temperature measurements are most easily done with either thermistors or thermocouples. These are small "beads" of materials that are temperature sensitive. They are connected to an instrument that is designed to convert the electrical signal that returns from the beads to a temperature. Thermocouples and thermistors operate by different principles, and each requires a different type of monitoring instrument, however, either will produce acceptable results. Temperature should be monitored at several positions and depths beneath the building, but the connecting wires from the monitoring beads can be routed to a central location where all of the temperatures can be read by the monitoring instrument. A rotary switch that connects each temperature bead to the monitoring instrument is convenient and reduces the chore of taking a full set of temperature measurements. Figure 5.2 shows details of a temperature monitoring system. Temperatures should be taken frequently at first (weekly) then as the trends are determined the monitoring frequency can be changed to a schedule that is appropriate. It is important to observe the temperatures to determine if soil temperatures are rising under the building which would indicate danger to the underlying permafrost.

Elevations of the foundation are also very important. As with temperatures, they will also alert you to potential problems of continued subsidence or of heaving. It is usually best to make the elevation or "level" measurements on the footing. This requires that access directly to the footing be established at several points around the perimeter of the building. A cylinder of solid material (such as concrete or a large bolt) attached rigidly to the footing and extending up to a few millimeters above the floor provides a reliable and
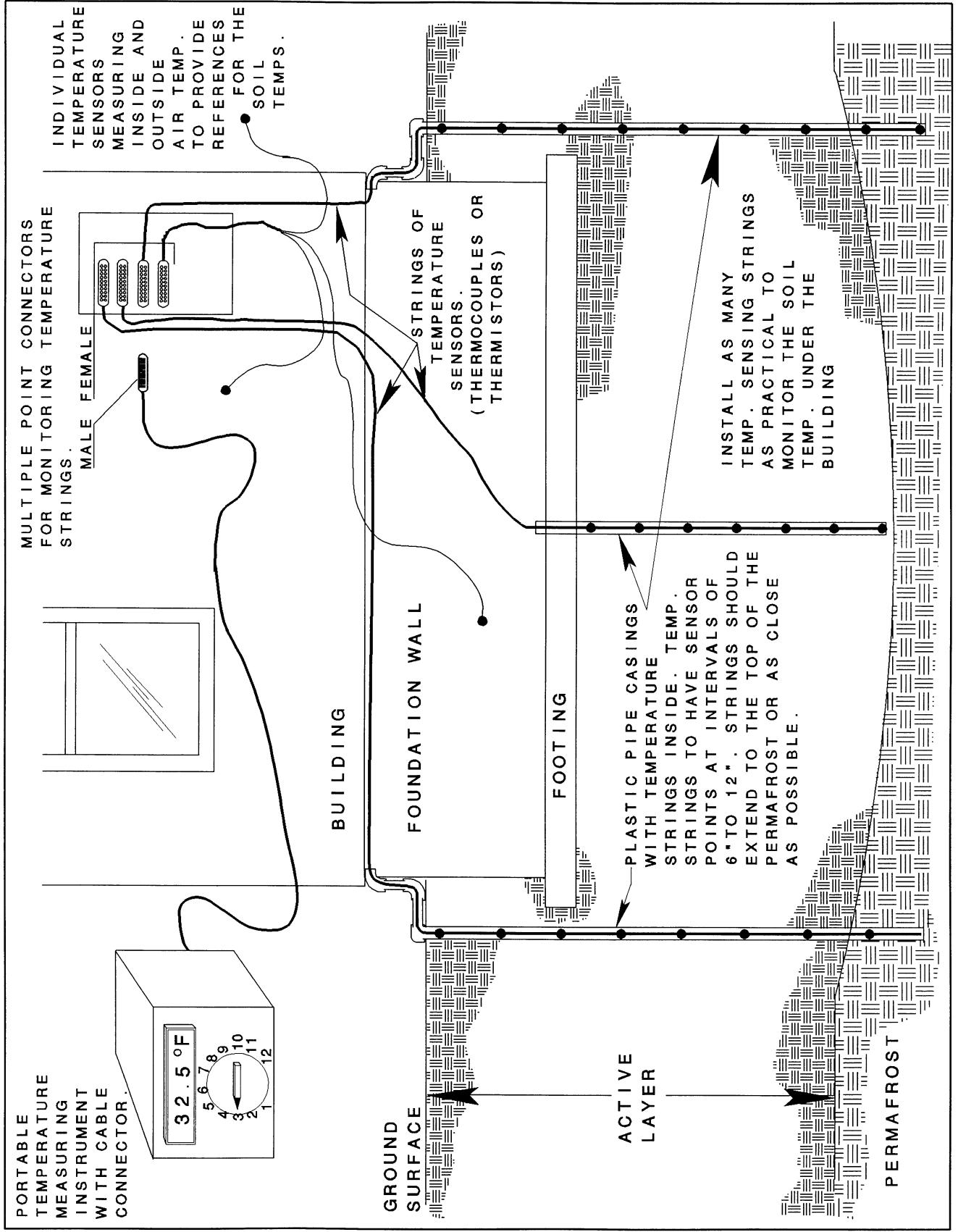
FIGURE 5.2 Details of a typical Temperature Monitoring System.

easily found point for elevation measurements to determine the level of the foundation. As an expedient alternative these measurements are sometime made on a concrete basement floor that is in contact with the footing. When this is done the location of the rod should be permanently marked on the floor so that exactly the same spot can be monitored each time.

The procedure used to monitor the elevations is to use a telescopic surveyor's level to measure the relative elevation of each of the footing positions (level points) to determine if the foundation has moved. A "rod" (a homemade rod made from a 6 ft (2 m) long 2x4 with a rounded bottom works well) with an easily read scale (graduated in $1/8$ inch or in 1 millimeter increments) firmly attached is placed on each of the level points and the telescopic level is used to read the elevation of the rod. The rod is then moved to another of the "level points" and the elevation of that point is recorded. When all of the points have been measured they can be compared with each other and with previous readings to determine if any differential settlement is occurring. It is also important to know if there is any overall movement of the structure with respect to the surrounding terrain. To do this, establish a benchmark well outside of the building that is visible to the telescopic level when it is set up to measure the footing positions. See that the benchmark is firmly embedded into the permafrost as shown in figure 5.3. This may require using a drill rig to bore a hole well into the permafrost. The benchmark rod should also have a sleeve of plastic in the part that passes through the active layer to eliminate frost heaving (see section 4.2.8). If you are not thoroughly familiar with the proper procedures for level

SURVEYOR'S ROD

NOTE: IF THE FLOOR IS
NOT STABLE OR IS
FLOATING, THEN BOLTS
CAN BE ATTACHED TO
THE FOUNDATION WALL
AND THE ROD PLACED ON
THEM FOR THE ELEVA-
TION MEASUREMENTS.

BARS
ANCHORED
INTO THE
FOOTING
AND
MEASURED
FROM THE
OUTSIDE
ARE THE
BEST
LEVEL
REFERENCE
FOR THE
FOOTING

THE ROD IS PLACED ON EACH MARK
AND THE ELEVATION OF THAT
POINT IS MEASURED BY THE
LEVEL. THE ELEVATION OF EACH
POINT IS COMPARED TO THE
ELEVATION OF THE PERMANENT
BENCHMARK OUTSIDE THE
BUILDING. ELEVATIONS SHOULD
BE MEASURED ON A REGULAR
PERIOD OF A FEW WEEKS DURATION.

FOR FLOOR SLAB LEVELS
PLACE PERMANENT MARKS
ON THE FLOOR TO
ENSURE THAT EXACTLY
THE SAME POINT IS
MEASURED EACH TIME
LEVEL MEASUREMENTS
ARE MADE

A SURVEYOR'S LEVEL
IS USED TO SIGHT
THE ELEVATION OF
EACH POINT AND
THE PERMANENT
BASEMARK.

ESTABLISH A STABLE EXTERIOR
BENCHMARK FOR LEVEL
REFERENCE TO THE SURROUNDING
ENVIRONMENT. ANCHOR IT INTO
THE PERMAFROST AND PROVIDE
AN ADFREEZE BOND RELIEF
SLEEVE IN THE ACTIVE
LAYER. (e.g. THE
WELLHEAD PIPE IS USUALLY
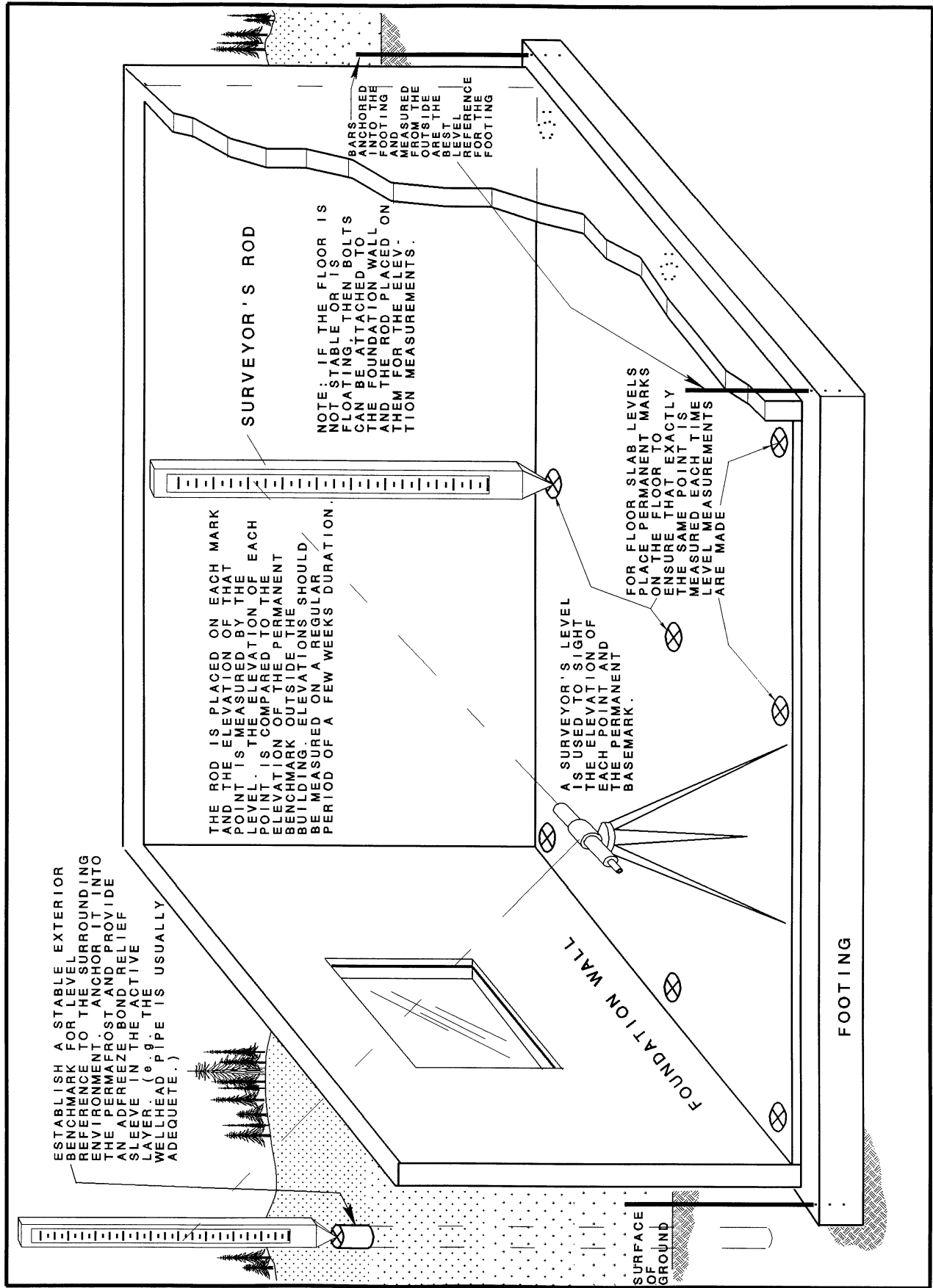ADEQUETE.)

FOUNDATION WALL

FOOTING

SURFACE
OF
GROUND

FIGURE 5.3 Foundation Elevation Measurements

measurement, a local Surveyor or Civil Engineer can set up and perform the first set of level measurements and train you how to do it correctly in the future.

5.4 Post and Pad Foundations

In new construction, the 'post and pad' foundation is the most commonly used of the surface foundation options. A drawing of the details of a post and pad foundation is shown in figure 5.4. Since the foundation can be installed one point at a time, it is a viable option for stabilizing small existing buildings that are in distress. The building should be raised enough to provide working room beneath it, the existing failed foundation removed and the posts and pads installed such that the top of the posts are in a level plane. The building is then lowered onto its new level foundation.

5.4.1 Traditional Post and Pad Foundation Details

The post and pad foundation rests on top of the surface (or at least rests on the soil under the top layers of vegetation). Post materials can include pressure-treated "all weather" wood, steel pipe, or concrete piers. The posts support the building a few feet above the surface to provide space for winter air to cool the ground and reinforce the permafrost. As discussed above, wood provides much higher resistance to heat flow into the soil than does either steel or concrete. This is an important consideration when marginal permafrost is present. If the permafrost is close to thawing, then steel and concrete are less desirable than wood for this application.

The footing for this foundation is a pad of concrete or wood that has been pressure-treated with a preservative to eliminate rot. The pad is used distribute the load from each

EXCAVATE
PITS THRU
ORGANIC
LAYER TO
UNDISTURBED
MINERAL SOIL
BACKFILL W/
COMPACTED
NFS SOIL

SHIMS

POST

CROSS BRACING FOR
LATERAL STABILITY

ANCHOR
BOLTS

POST

PAD

PAD

PEATY ORGANIC LAYER

NFS
FILL

NFS
FILL

UNDISTURBED MINERAL SOIL

ACTIVE LAYER

PERMAFROST

TYPE A-THIS TYPE IS PRACTICAL FOR SITES WITH A LIMITED
SOURCE OF NONFROST-SUSCEPTIBLE FILL   (CLEAN GRAVEL)

EXCAVATE TO
PERMAFROST
AND BACKFILL
W/ COMPACTED
NFS FILL TO
CREATE A PAD
UNDER THE
STRUCTURE

SHIMS

CROSS BRACING FOR
LATERAL STABILITY

POST

COMPACTED
NFS PAD

PAD

ORIGINAL
GROUND
SURFACE

NEW PERMAFROST
TABLE

ORIGINAL PERMAFROST TABLE

TYPE B-A NON FROST SUSCEPTIBLE PAD UNDER THE STRUCTURE
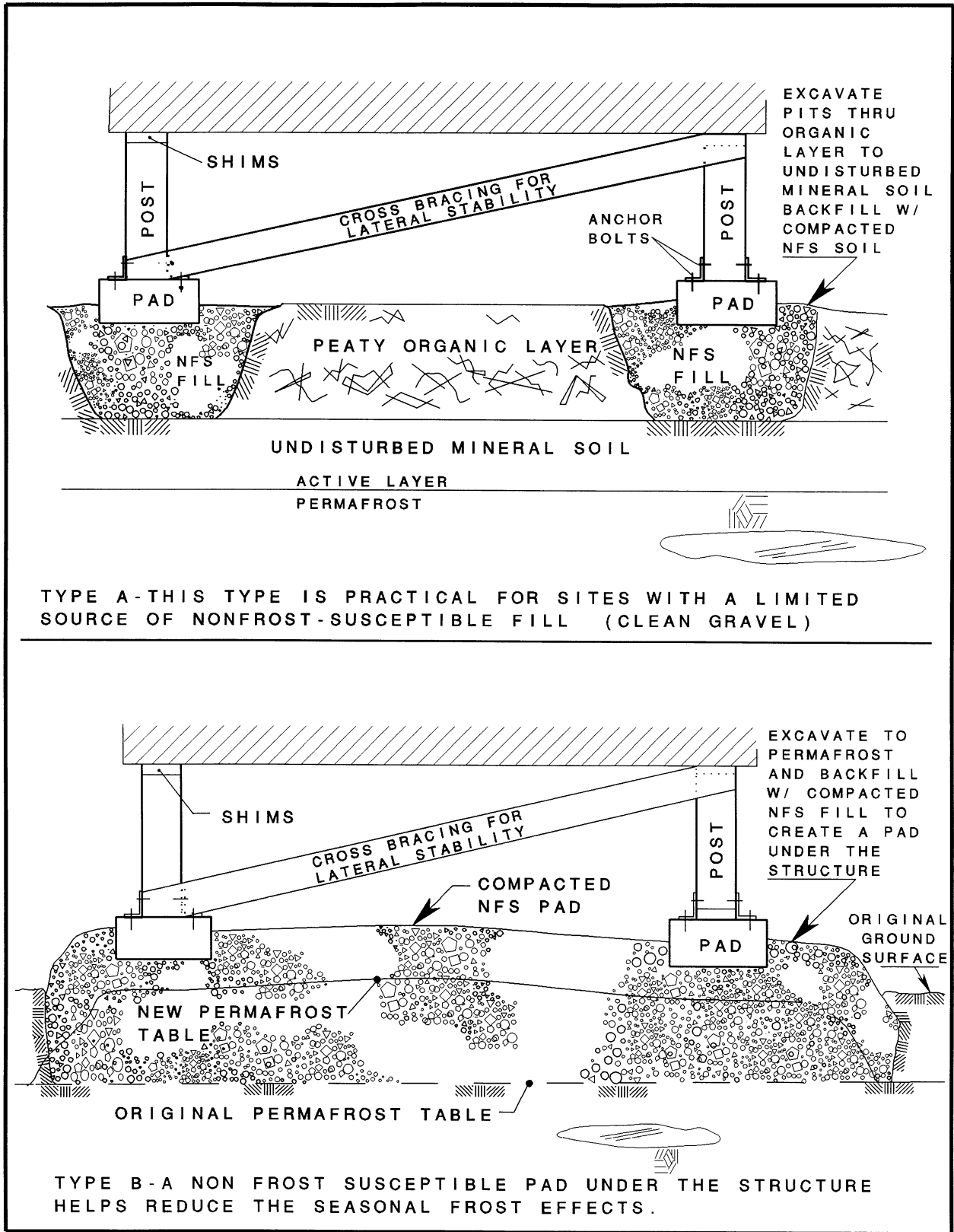HELPS REDUCE THE SEASONAL FROST EFFECTS.

Figure 5.4   Post and pad foundation details.   In type
B the permafrost will rise into the gravel pad as
thermal equilibrium is reestablished and will help
reduce seasonal frost movement.

individual post over a larger area of soil to keep the stress on the soil low enough so that the foundation will not sink into the active layer during summer weather. Since soil conditions and building weight at any given site can vary widely, the size of the pads required to prevent sinking will also vary. For dry active-layer soils, keep the soil stress beneath the pad at 10-lb/square inch (psi) or below (The soil stress is the post load in pounds divided by the pad area in square inches). For example if the post load is 1000 lb., then the pad area must be 100 square inches (a 10"x10" pad) since 1000/100 = 10 psi. A rough "rule of thumb" is to keep the stress on the soil beneath the pad as low as possible. This translates into using the largest pad that is practical. The load that the post applies to the pad comes from the weight of the building divided by the number of posts supporting that weight. As the building weight increases and/or the softness of the soil increases the pad area in contact with the ground must also increase. If the soil is relatively dry granular soil, then the load to pad area can be increased somewhat.

Table 5.1 gives a rough guide to maximum soil stresses for sizing the footing pads in various types of soil.

Table 5.1 Suggested Soil Stress Levels Beneath Footing Pads

Type of Soil	Soil Stress in psi	Soil Stress in psf
Dry Silt (well consolidated)	7 to 14	1000 to 2000
Moist Silt	3.5 to 7	500 to 1000
Dry granular soil	10 to 28	1500 to 4000
Wet granular soil	7 to 14	1000 to 2000

psi = lbs/square inch, psf = lbs /square foot, 1 psf = 144 psi. Granular soil includes gravel, sand, sandy gravel etc.

Remember you must calculate an accurate weight for the building including its contents and its occupants. This requires some thought and a foreknowledge of what the building is to be used for. Storage buildings can accumulate very large loads from the materials placed in them. Homes are easier, but don't forget the furniture and all of the occupants

including guests.   Calculate the stress using the maximum load and the worst soil conditions encountered during the year.   Then because of all the uncertainties over the life of the structure, use a safety factor of at least two to one by doubling the overall weight that you calculated.

An approximate way of determining allowable soil stress under a footing in the field is to have, for example, a 180 lb (~ 90 kg) person stand on a 3½" by 5¼" (133 mm) board (a piece of 4x4 cut 5¼" long will do).   This will apply 9.8 psi (1411 psf) to the soil.   If the board sinks into the soil, then use a larger board until you find one that doesn't leave a significant indentation and back-calculate to find the stress that the soil can support.   The following example explains the concept further.

A 4 x 10 wood plank (the actual dimensions of a 4 by 10 are 3½ x 9¼" (89 x 235 mm)) is to be cut into squares 9¼" x 9¼" (235 x 235 mm) to be used for the pads in a post and bad foundation.   Each pad has a surface area of 85½ square inches (0.055 m^2) and should be able to support 300 - 600 lb. (136 – 272 kg) on soft soil or 600 – 1200 lb. (272 – 544 kg) on hard dry soil.   Choose the pad size for the worst soil conditions that will prevail at the site over the course of the year. These conditions may occur during spring breakup or during heavy autumn rains.   If the building weighs 15,000 lbs (6800 kg) and the contents including occupants are expected to weigh a maximum of 10,000 lbs (4500 kg) then the 25,000 lbs (11,300 kg) load must be divided between the supporting foundation posts.   If the building has 12 posts, each post will transfer a load of 25,000/12 = 2083 lbs (940 kg) to its respective pad.   The proposed 9¼" x 9¼" pads will not support this load even in the

best soils. Larger pads or more posts are needed. A 16" x 16" (0.4 x 0.4 m) pad will support a load of :

Dry very hard soil (14 psi from table 5.1) will support:

$(14 psi)(16 \times 16) in^2 = 3,584$ lbs. (1620 kg) Or including a safety factor of two it will support $3584/2 \cong 1,800$ lbs (810 kg).

The number of posts that are required to distribute this load is then:

$25,000 / 1,800 = 13.8$ or 14 posts ($11,300/810 = 13.9$ or 14 posts).

We must increase the pad size and/or the number of posts to meet these specifications.

On the other extreme, if the soil at the site is wet silt (soil stress limit =3.5 psi from table 5.1), the pad size will have to be even larger (lets try 24" x 24"). The 24" x 24" (0.61 x 0.61 m) pad has an area of 576 square inches (in^2 or 0.37 m^2), and this pad in very wet silt will support $3.5 psi \times 576 in^2 = 2,016$ lbs (913 kg) or with the safety factor of 2 only 1,008 lbs (504 kg). The required number of posts becomes: $25,000/1,008 = 24.8$ or 25 posts. This is a lot of posts for a small building, but the only alternative in this type of soil is to increase the pad size even larger or to move to a site with better soil conditions.

Whenever a wood pad is in contact with soil it must be treated to avoid decay (In accordance with the American Wood Preservers Association's standards, treated wood will be stamped "AWPA."). If the site is damp or if it is frequently exposed to moisture, the joint between the post and the pad will likely collect enough moisture to sustain decay organisms, so if the post is wood, it also must be treated wood.

The crushing strength parallel to the grain of most construction grade softwoods (pine, fir and spruce) is about 1000 psi, the size of the post must be chosen so that its crushing strength is not exceeded. For example, if a building transfers a load of 2500 lbs to each post, the compression load on a four x four wood post (whose actual cross section dimensions is 3½" x 3½") will be 2500/ 3½ x 3½ = 204 psi. This is well below the crushing strength and provides a nice safety factor for the post. However, a wood pad under that post would be loaded perpendicular to the grain where wood has a compression strength of only 220 psi for spruce and white pine and up to 385 psi for Douglas fir. This is still below the ultimate crushing strength but provides little safety factor. A six by six post (actual dimension = 5¼" x 5¼" = 27.6 in²) would lower the stress between the post and the pad to 90 psi. This would be a much better choice and would provide a safety factor of slightly over two.

Finally the stress on dry granulated soil (10 psi from table 5.1) would require a pad of 2500/10 = 250 in². A 16" x 16" pad provides 256 in². It is possible to consider reducing the load by using more posts or compacting the gravel fill under the building so that it will carry a larger stress (up to 20 psi, table 5.1).

A gravel fill transfers the load to the soil on which it lies and that stress is still limited to the values in table 5.1. However, the gravel pad increases the effective bearing surface of the pad by up to the thickness of the gravel on all sides[11]. For example a 4 inch thick

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[11] This assumes the standard load angle of 45°. Conservative calculations use a load angle of 60° reducing the amount of load spread at the bottom of the fill considerably. In situations where the underlying soil has potential for becoming very wet it would be well to use the conservative approach. A four inch fill would

gravel fill would spread the bearing surface of a 10" x 10" pad making it effectively 18" x 18". With a 2,500 lb load applied, the soil stress at the bottom of the gravel fill would be 2500/18x18 = 7.7 psi well within our limits of dry silt. For wet silt the gravel fill may need to be 6 to 8 inches thick, thereby distributing the stress under the 10" x 10" pad to effective areas of 22" x 22" or 26" x 26" respectfully. Even at 26" x 26" the soil stress under the gravel fill will be 3.7 psi. Remember to include the weight of the gravel in calculating the load on the soil. Gravel has a dry unit weight of approximately 120 lbs per cubic ft. The volume of gravel applies a load of: (26/12 x 26/12 x 8/12) x 120 = 376 lbs. to the soil in addition to the building load. If an 8" fill is used and the building is applying 2,500 lbs load, the total stress on the soil at the bottom of the fill is: (2,500 + 376)/26 x 26 = 4.25 which is too high for very wet silt. Clearly cutting down the 2500 lb load from the building by distributing its load over more posts should be considered for this case.

To best prepare the site, place and compact a nonfrost-susceptible granular fill that extends at least 6 ft (1.8 m) beyond the perimeter of the building on all sides. However, in remote sites where gravel is very expensive, the individual post pads often are placed directly on the original ground surface. When this is done, the ground surface at each post and pad position is prepared by removing all vegetation until the undisturbed mineral soil is exposed. Where the organic soil layer (peat etc.) is more than two or three inches thick, it is prudent to backfill the resulting surface excavations with nonfrost-susceptible (NFS) material such as clean, well-graded gravel to maintain the level of the

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spread the bearing surface of a 10" x 10" pad to only 14.6" x 14.6" in this case and it would require an 8" fill to increase the load bearing surface to 18" x 18".

surface and to avoid pits around the pads that can collect water. The pad or any other footing, for that matter, should never be placed directly on a segregated ice layer. If this situation occurs, the ice should be entirely excavated. If that is not practical, it must be excavated enough to allow a layer of compacted sand at least 12 in. (300 mm) thick to be placed between the footing and the ice.

Posts (e.g. 6x6's, 8x8's, pipes, or other suitable materials of appropriate length) are used to elevate the structure to the required height above the surface to protect the permafrost from heat loss from the building. Except in the very smallest of buildings (e.g. small one room storage shacks) the height of the foundation should raise the bottom of the building a minimum of 2 ft (610 mm) above the site's ground vegetation. The object is to provide an unimpeded airway for winter air circulation between the building and the ground. Since any vegetation under the structure will die and become a fire hazard it should all be removed, leaving bare ground beneath the structure.

As stated above, the floors in all elevated foundation designs need to be well insulated to reduce heat loss and to make the interior more comfortable for the inhabitants. In areas of marginal permafrost, you may also have to place insulation on the ground over the bare soil under the building to further protect the permafrost. If a gravel fill has been placed under the building the insulation should be buried 2 to 4 inches (50 to 100 mm) in the gravel to protect the insulation from damage. However, remember that insulation will also reduce the amount of winter cooling that the site receives and that cooling is needed to sustain the permafrost. So insulation must be used with care in this case. Thermal

modeling by an engineer experienced in this area might be needed to make this determination.   The ideal situation is to provide ground insulation when the air temperature is above freezing and to remove it in the winter just before the air temperature drops below freezing. This, however, creates the logistics problem of where to store the insulation in the winter season and a maintenance chore of installing it each spring and removing each fall that is difficult to sustain over the life of the building.

In earthquake zones or in high wind areas, cross bracing between posts is needed to stabilize the structure against horizontal loads. Many parts of the cold regions are subject to high winds and/or earthquakes. In these regions, cross bracing is essential and ground anchors are advisable for the lighter-weight construction often found in prebuilt or "mobile" homes. "Duck Bill" anchors and cables are often used for anchoring smaller structures on permafrost soils.

Since this type of foundation is supported on the surface rather than beneath it, the foundation and the structure will rise and fall as the active layer heaves each fall and thaws each spring. This requires that the building be releveled to compensate for uneven frost heaving. As winter approaches and frost heaving starts, raise the building with a jack at each post and add or remove shims between the top of the post and the building to restore the structure to a level condition. This must be done whenever differential movement of the foundation becomes noticeable, which is usually during the fall freeze-up or the spring thaw but can occur at any time during the year. If anchor bolts are used between the structure and the post or the ground, they must be long enough to

accommodate the raising and shimming operation. A sticking door or a window that no longer opens freely often will be the announcement that this maintenance chore is needed. Normally, the releveling exercise will be required at least twice yearly. At sites where frost action is severe, it may be necessary to relevel several times during each seasonal transition between freezing and thawing.

Surface foundations are best for sites in which heaving potential is low, but if the required maintenance is performed as needed, the foundation will withstand most differential heave situations. The use of a surface foundation design should be limited to situations where the owner or occupant is capable and willing to accomplish the continual maintenance chore whenever it is needed. It can be a suitable foundation stabilization solution for smaller, lightweight, temporary buildings. It is most popular in remote, undeveloped areas of the north where large equipment is not available, since one or two persons with minimal tools can install it. When properly installed and continually maintained, the post and pad foundation provides a low cost stabilizing solution under normal conditions. It will not accommodate large-scale permafrost subsidence that is found where the permafrost is thawing over a large area around or near the structure due to unusual outside heat input.

5.4.2 Adjustable Post and Pad Foundation

To make the releveling chore easier and quicker, mechanical jacks can be substituted for the posts. Then whenever an adjustment is needed, it is a quick and simple task to insert the adjusting bar into the jack supporting a position that is out of level and raise or lower

that position in the foundation.   To further simplify the procedure a water level (see section 5.4.3 below) is usually installed all around the structure to show the elevation of the building at each jack position in the system.   Differential settlement is then easily noted in each standpipe of the water level.   When one part of the building moves downward (as in settlement) the liquid level in the standpipe will rise above the permanent marker.   When part of the building moves up (as in heaving), the liquid level in the standpipe will show the differential movement, this time by sinking below the permanent level mark on the tube.   Use the adjustable jack support at that location to raise or lower the building as needed to keep it in perfect level.   Design specifications must ensure that the jacks are adequate to support the load of the building at each point and that they have enough travel to accommodate the maximum heaving expected at the site.   Obviously this method is only applicable to smaller buildings that can be raised by mechanical jacks and individual labor.   When this type of support is installed it is a short simple chore to relevel the building.

5.4.3 Water-level Monitoring System

Water levels are very useful for long term monitoring of the level condition of a building, and they are easy to make and install using a 3/8" diameter clear plastic tubing.   Use the tubing to make a loop that encircles the building.   Attach the loop to the outside wall a few inches above the top of the foundation wall[12].   Cut the tubing loop and insert tees at each jack location and connect vertical sections of tubing that will form "standpipes."

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[12] This example uses the top of the foundation wall as a reference for establishing the building's level position. If the foundation wall was originally level and flat then if it is brought back to a level position the building also will be level. If the top of the foundation wall cannot be relied upon for level reference, then

Attach the standpipe tubes to the building's wall so that they run vertically upward to an elevation where the liquid in them can easily be seen. Leave the top of each standpipe open and connect the bottom into the loop. Mount a small reservoir (approximately a pint to a quart in volume) in a position so that it is above the level of the main loop but several inches below the level of the top of the standpipes. The reservoir should be close to the highest point on the foundation wall. The reservoir provides a reserve of liquid to fill the loop and the standpipes. When the building is raised or lowered to its level position, the top of all of the standpipes must be above the final position of the reservoir. Figure 5.5 shows the details of a water level installation. For cold weather operation, fill the reservoir with a nonfreezing liquid such as a mix of water and propylene glycol. Choose a liquid that does not easily evaporate.

The reservoir will, in turn, fill the encircling loop and every standpipe. After the filling is complete and all air bubbles have been worked out of the lines, mark the level of the fluid in the reservoir. Measure precise distance above the foundation wall or whatever reference line is used at each standpipe and make another permanent mark on each. These marks will then represent the plane of the foundation wall. When a jack is used to raise or lower any portion of the building, the top of the fluid in the nearest standpipe will show the amount of differential vertical movement at that point. The top of the liquid in the reservoir and in each standpipe defines a level plane. Since the standpipes are attached to the building, when the building moves, marks on the standpipes move accordingly. When each of these marks coincides with the top of the water in the

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some other reference must be established, e.g. a line on the outside of the building that represents the position of the inside floor may be used.

ATTACH TUBING TO THE OUTSIDE OF THE
HOUSE. INSTALL VERTICAL RISERS WHEREVER
A LEVEL MEASURE IS DESIRED. LEVEL THE
HOUSE USING A SURVEROR'S LEVEL AND THEN
MARK THE LEVEL OF THE LIQUID AT EACH
VERTICAL RISER. WHEN THE LIQUID LEVEL
RISES ABOVE THE INITIAL MARK, THAT POINT
ON THE HOUSE HAS SETTLED, WHEN THE LIQUID
LEVEL MOVES BELOW THE MARK THEN THAT
POINT ON THE HOUSE HAS RISEN

OPEN END VERTICAL
RISER TUBES OF
CLEAR PLASTIC ARE
PLACED AT CORNERS
AND AS NEEDED
ALONG SIDES

LIQUID
LEVEL

SUPPLY RESERVOIR
FILL WITH NON-
FREEZING LIQUID

LIQUID LEVEL IN
THE SUPPLY
RESERVOIR MUST
BE AT ABOUT THE
MIDPOINT OF THE
VERTICAL RISERS

LIQUID TO BE A NONFREEZING
FLUID SUCH AS WATER AND
ETHYLENE GLYCOL

CLEAR PLASTIC TUBING WITH
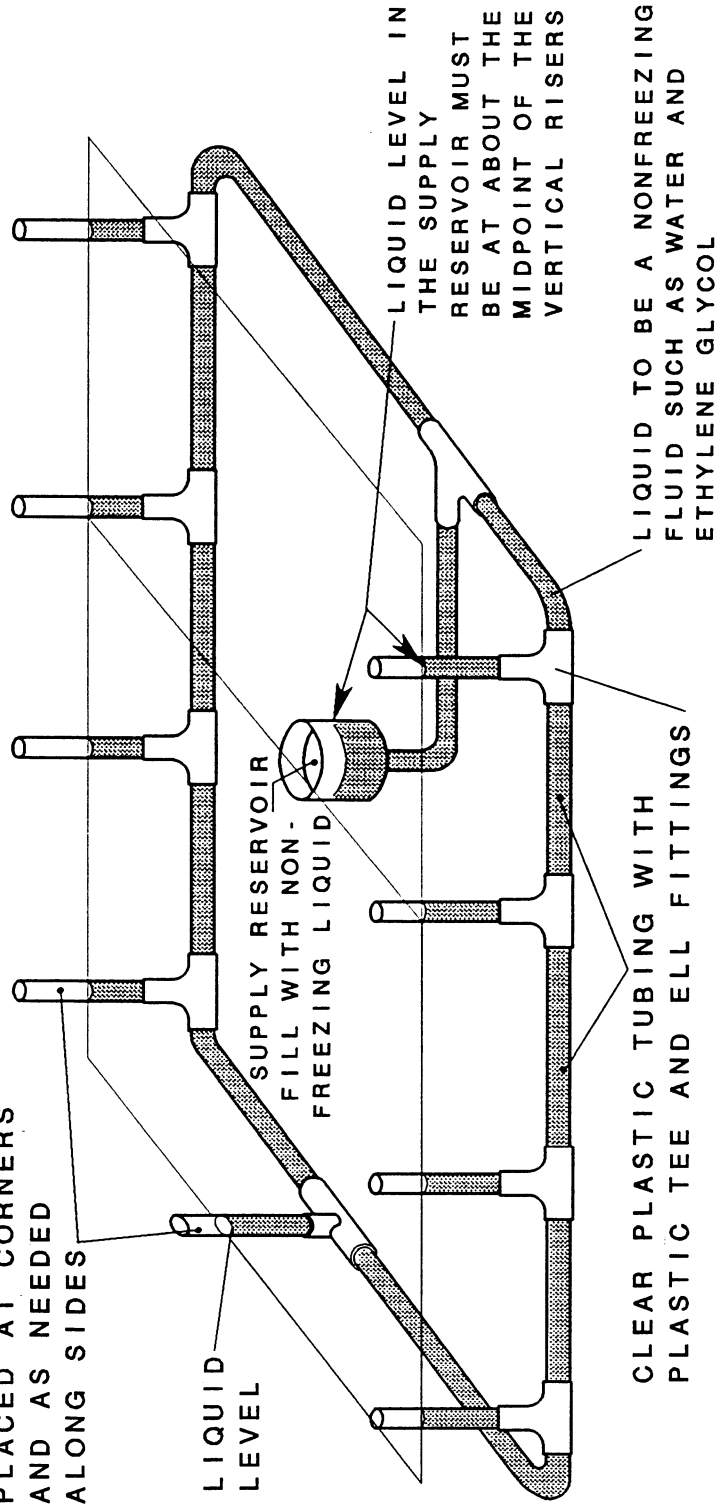PLASTIC TEE AND ELL FITTINGS

FIGURE 5.5 Water Level Details

standpipes then the marks are all at the same plane and the building is level. With the water level for reference it is easy to use a jacking system to raise or lower the building until all parts of it are level.

5.5 Buildings with a Crawl Space

Buildings with a crawlspace that are suffering distress from permafrost thawing beneath them are usually one of the easier situations to stabilize. The crawlspace generally doesn't represent a large plus to the building's value or usefulness and can be sacrificed without loss to the overall utility of the structure. Utilities such as water and sewer lines that are protected from freezing by the crawlspace must be protected by other means, and the bottom of the building must be insulated to stop excess heat loss and an uncomfortably cold floor. In each situation, the most economical stabilization solution will depend on the type of foundation and the degree of distress that is already present.

5.5.1 Collapsing Foundation Wall

If the foundation is in extreme distress it may not be possible to save it, and the building must be supported by a new foundation. A post and pad foundation (described above in section 5.3) may be the easiest and most economical solution. The first step is to level the building with jacks to relieve any structural distress caused by the old collapsing foundation. Support the building in its level position with temporary piers that are at least three feet wide (figure 5.6) to provide adequate stability to the building in its elevated position while working under it. After the building is stably supported on the piers, remove the old collapsing foundation wall and install the post and pad foundation as outlined in section 5.4. Be sure to make the posts long enough to provide an adequate

clear air space below the building. After all of the foundation posts and pads are in place and their tops are at a level plane, the building can be lowered onto them. At sites where lateral loads can be high, it may be desirable to replace the posts and pads with permanent ballast filled piers as shown in figure 5.6

Install a plenum under the building that is insulated from the cold and that will provide both protection for the water and sewer lines and the needed insulation for the floor. This will keep the floor comfortable and reduce the amount of heat that escapes through the bottom of the building. Be sure to provide a means of access to the plenum so that the water and sewer lines can be repaired if that ever becomes necessary. It is very important to be absolutely sure that the building is secure on very stable supports before anyone is allowed to go beneath it for any reason. When installing the post and pad foundation, the length of the posts must be enough to provide a space that will allow winter air to flow freely between the bottom of the insulated plenum and the ground (figure 5.6). The cold air will carry away any heat that escapes from the building before it can enter the soil and will promote winter cooling to reinforce the permafrost. In the summer, shade from the building will offer some protection from the sun's heat input. In windy regions, during the winter, the area under building will be scoured free of snow thus eliminating the insulating effect of the snow. However, if nearby buildings or vegetation disrupt the scouring effect and snow collects under the building, it must be removed so that the permafrost can receive the full benefit of the cold.

BUILDING INTERIOR

FLOOR

FLOOR JOIST

NO INSULATION HERE

SEWER LINE

INSULATED PLENUM

INSULATE EXTERIOR WALLS AND BOTTOM.
SEAL ALL CORNERS AND CRACKS TO STOP
DRAFTS. DO NOT INSULATE BETWEEN THE
BUILDING INTERIOR AND THE PLENUM SO
THAT BUILDING HEAT CAN KEEP PLENUM WARM

WATER PIPES

INSULATE WATER AND SEWER LINES WHERE THEY EXIT THE PLENUM

WATER LINES

4" RIGID FOAM INSULATION

PLYWOOD SHELL AROUND THE OUTSIDE OF THE PLENUM

CRAWL SPACE

ROCKFILLED PIERS SUPPORT THE BUILDING AND ALLOW FREE AIR FLOW THROUGH THE OPEN CRAWL SPACE
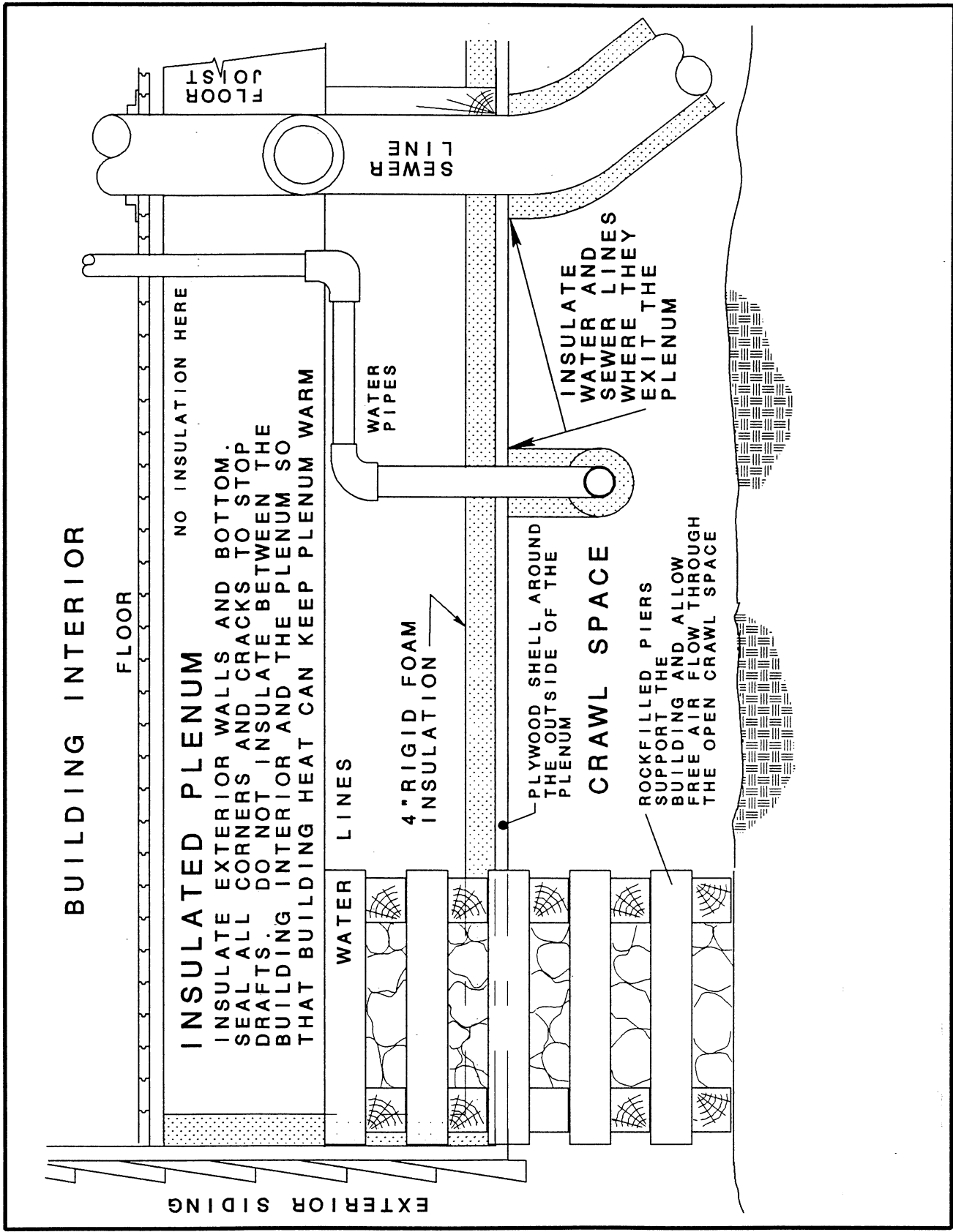
WATER LINES

EXTERIOR SIDING

FIGURE 5.6 Building on Piers with an Insulated Plenum

5.5.2 Structurally Sound Foundation Wall

If the degree of distress is mild so that the footing and foundation wall are still structurally intact, it may be possible to relevel the foundation and continue to use it. A building that is caught in the early stages of permafrost thawing can often be stabilized before the damage has compromised the integrity of the structure. When this is the case, a forced-air cooling system in the crawl space can be one of the least expensive and at the same time one of the most effective means of stabilizing the building (see section 3.2.2 for details). The Permafrost Technology Foundation developed this technique in 1991 and tested it on a two-story home sited on ice-rich permafrost in Fairbanks, Alaska. The final report on this research was published by the Permafrost Technology Foundation in 1998 and is available on request to anyone who has an interest.

If the building is suffering differential settlement that has progressed to the point where it is out of level by more than a couple of inches, then it must be releveled as described in section 5.3 before further damage takes place.

If, however, settlement has not progressed to the point that structural damage has occurred, the level of the floor is still satisfactory, and the building is otherwise still functional, then the forced-air cooling system can be installed and set in operation at the beginning of cold weather. As described in section 3.2.2 an insulated enclosure (plenum) must be installed at the top of the crawl space to house and protect the water and sewer lines that run under the floor. The remaining crawl space must be at least 2 ft (preferable 3 ft or more) high so that the fans can make the air circulate throughout the entire crawl

space. If there is not enough room under the plenum after it is installed, steps must be taken to increase the height of the crawl space. This is easily done during the releveling process. Otherwise the insulated plenum must be made smaller, or the utilities must be rerouted so that they do not run under the floor, or the building must be raised until the crawl space is adequate. In any case, the floor must be insulated to keep it comfortable while the cold air is being drawn through the crawl space.

When correctly installed and maintained, this system has been shown to not only stop further permafrost thawing, but also to cause previously thawed permafrost to refreeze. There is a possibility of frost heaving during the refreezing process, and this must be monitored and if it occurs it must be corrected. A water level as described in section 5.4.3 is an inexpensive and convenient means to do the monitoring.

If frost jacking is detected, adjust the controls on the fans to reduce the amount of cold air drawn into the crawl space until an equilibrium setting is found that stops permafrost thawing but does not induce frost heaving. It may not be possible to totally eliminate differential heaving, and another releveling of the foundation wall may be necessary after the permafrost has stabilized.

In the house that the Permafrost Technology Foundation used to test this stabilization system, the permafrost refroze from a depth of 15 ft to a depth of approximately 8 ft without significant frost heaving. The original concrete foundation wall was 14" out of level prior to installing the forced-air cooling system. After an initial releveling and the

installation of the forced-air cooling system, the house maintained its new level position within an inch for the entire seven years that the house was monitored.

5.6 Buildings with Heated Basements

Basements are usually a substantial portion of the overall investment and utility of the building. Owners are very reluctant to give them up unless it is the only alternative to losing the building. If the basement can be sacrificed, it can be treated like a large crawl space and an inexpensive forced-air cooling system can be installed as described in the previous section. This is often the best solution since stabilizing buildings with basements is both difficult and expensive.

5.6.1 Releveling the Basement

A building that has settled differentially to the point that it must be releveled compounds the problem. Releveling this type of foundation is more expensive than shallower foundations since the footings and foundation wall are buried deeper in the soil and the floor slab will often have to be removed. Releveling a basement foundation adds considerably to the mounting cost of stabilizing. In some cases it may be better to sever the connection between the building and the foundation wall, raise the building off the foundation and relevel the top of the foundation wall. The building can then be lowered onto the foundation wall and reattached. Of course, the foundation wall must still be structurally sound and able to support the building for this to be considered. Otherwise an expensive releveling at the bottom of the footings will be required.

Once releveled, the foundation must be protected from further thaw settlement. To do this the heat entering the soil from the basement must be intercepted and carried to the surface before it can reach the permafrost. Natural-convection devices (thermosyphons and convection tubes) are one method of collecting the heat. To effectively intercept heat from entering the soil through the floor of the basement, the natural-convection devices must be installed so that the heat collection portion of the device passes under the building. See section 3.3 for details on operation and installation. The natural-convection devices are not inexpensive and installation under an existing building is difficult and requires specialized drilling equipment. If, as is very often the case, the soil under the building is so wet that a drilled hole will not stay open, the installation is even more expensive since very specialized directional drilling equipment and trained operators are needed.

5.6.2 Installation of Natural-Convection Devices Under Existing Buildings

For the best effect, the natural-convection device should be installed with its heat collecting section (the evaporator section in a thermosyphon) under the floor of the basement as shown in figure 5.7. This requires drilling an inclined hole under the building from the surface on one side to a location below the footing on the far side of the building. The natural-convection device is inserted into the hole and a slurry of drill or auger cuttings is compacted into the annulus around the pipe. It is important that the hole be larger than the natural-convection device so that the annulus remaining after insertion of the natural-convection device is large enough to get slurry all the way to the bottom of

THERMOSYPHONS PLACED
EVERY 6 TO 10 FT. AS
NEEDED

FINNED CONDENSER
SECTION--VAPOR
FILLED-GIVES
UP HEAT TO AIR

GROUND SURFACE

ACTIVE
LAYER

PERMAFROST
SOIL

EVAPORATOR PORTION OF THERMOSYPHON
LIQUID FILLED-ABSORBS HEAT FROM SOIL

APPROXIMATE BOUNDARY
OF PERMAFROST BENEATH
THE HOUSE

FINISHED
DAYLIGHT
BASEMENT

THAWED SOIL BENEATH THE HOUSE

THERMOSYPHON EXTENDS TO A
POINT UNDER THE FOOTING
OF THE OPPOSITE WALL
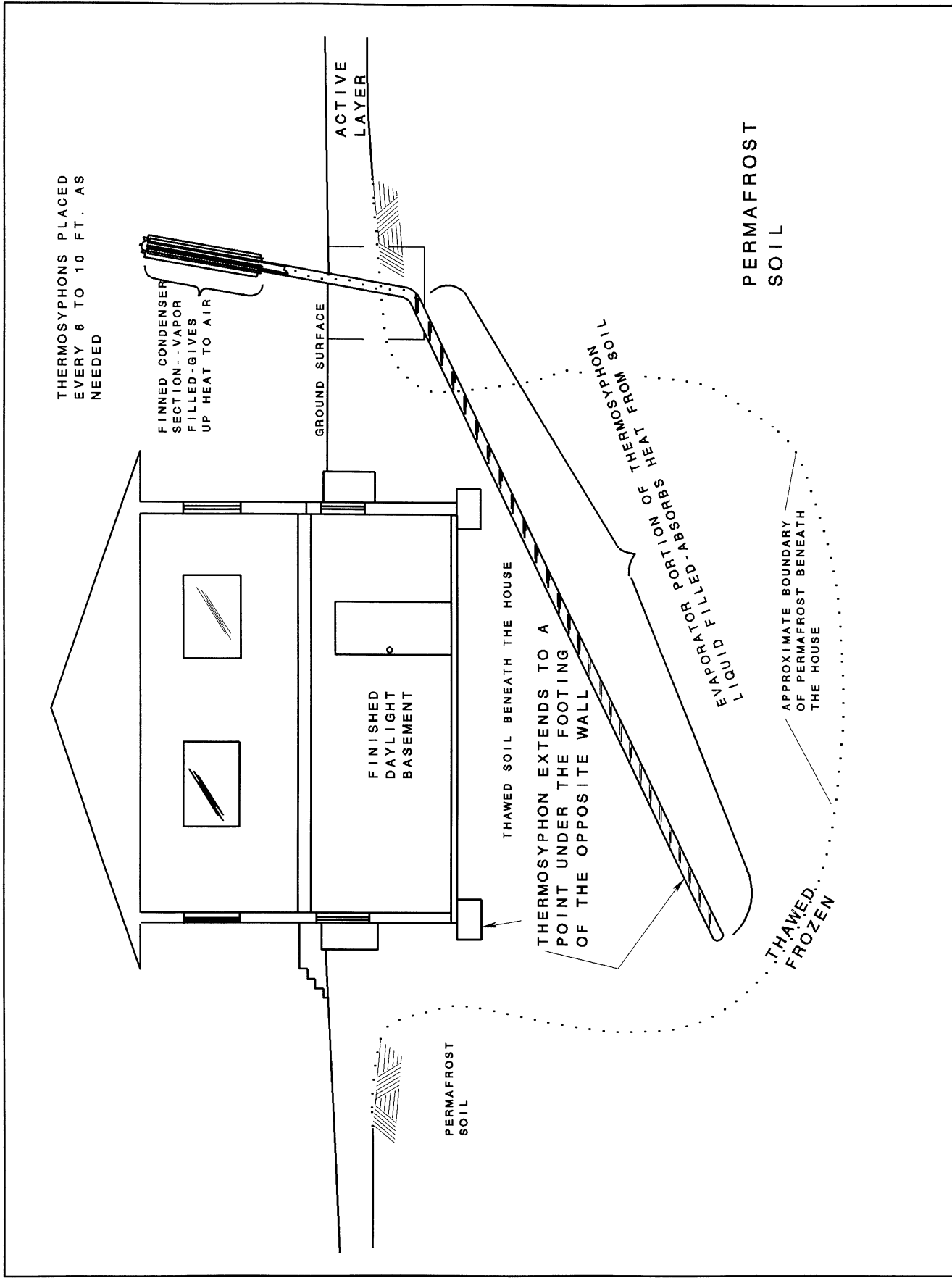
THAWED
FROZEN

PERMAFROST
SOIL

FIGURE 5.7 Location of a natural convection tube under a building

the hole without leaving any voids around the pipe. Voids act as insulation and greatly reduce the heat flow from the soil into the pipe.

The thawed soil under a building built on permafrost will often be so saturated with water that the soil becomes thixotropic[13]. The problem is that as soon as the drill is removed, the thixotropic soil slurry flows into it and the hole closes. The refilled hole will not allow a convection tube or thermosyphon to be inserted. Forcing the pipe into the ground requires high-thrust equipment such as a drill rig and often ends up damaging the natural-convection device. In addition, forcing the natural-convection device pipe into the ground where the hole was drilled cannot be relied upon to get the heat collecting section of the device into the proper location under the building.

Permafrost Technology Foundation developed a means of installing thermosyphons in soil that is too soft to maintain an open hole. The technique uses a directional drilling system that can change the direction of the drill's bit to cause it to drill (or auger) a hole that forms an arc that passes under the building and resurfaces on the far side of the building. The drill operator can control the direction that the drill advances by applying the appropriate force to the drill stem as it progresses into the ground to direct it to the desired depth and position under the building and then back up to the surface on the far side of the building. While the drill's bit is in the soil, its lateral location can be monitored from the surface, and the operator makes necessary corrections at the drill rig

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[13] "thixotropic" is a big word with the very mundane meaning of "catsup-like" A thixotropic solid is about as close to being a liquid as is possible without actually being a liquid. Such a material will flow under the slightest pressure or force much as catsup flows. A hole in such a material will not stand open but like a liquid the soil will flow and close the hole as soon as the drill or auger is removed.

to "steer" the drill bit. Once the drill has resurfaced on the far side of the building, the auger or bit is removed, the empty thermosyphon pipe without its evaporator section is attached to the drill stem and the pipe is pulled back through the hole as the drill stem is withdrawn. Once the drill stem is completely back out of the hole, it is detached from the thermosyphon pipe that is now positioned properly under the building. Trained and skilled operators are required to be sure that the hole is drilled to the proper depth and that its deepest point is under the far foundation of the building so that when the thermosyphon is drawn into the hole it is positioned where it needs to be for proper cooling. Figures 5.8 through 5.11 show details of the thermosyphon placement using this method.

Once the thermosyphon pipe is positioned correctly, the evaporator section containing the cooling fins is welded onto the pipe and the completed unit is ready to be filled with its working fluid. If carbon dioxide (CO_2) is used for the working fluid, the pressure inside the pipe after charging with CO_2 will be in excess of 400 psi. (McFadden 1991). This requires that a welder who is certified for pressure vessel welding make all the pipe welds. Charging the empty thermosyphon is done by first pumping out the air inside using a vacuum pump and then refilling the thermosyphon with the working fluid. The manufacturer[14] provides a 3-way valve to facilitate this operation.

The strategy for use of the natural-convection device is to intercept and carry away heat that flows into the soil from the house or from the surface. If the proper amount of heat is

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[14] At the time of this writing in February, 2001 there is only one manufacturer of thermosyphons known to the author. That is Arctic Foundations in Anchorage, AK. Balch Engineering in Fairbanks, AK periodically manufactures single phase natural-convection devices.
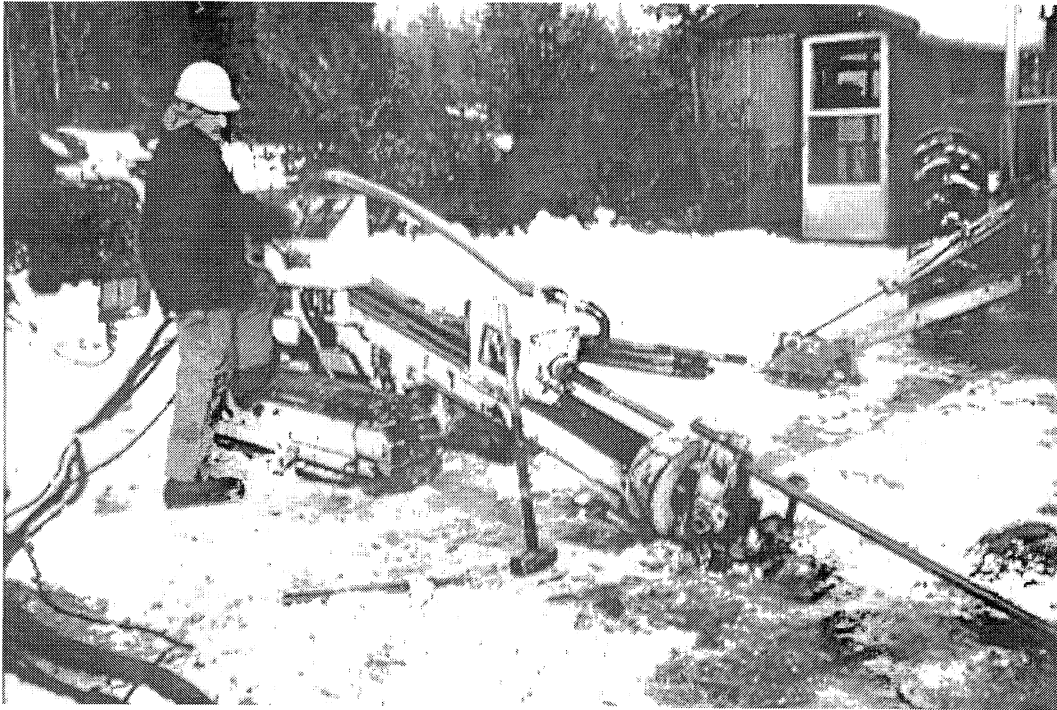
Figure 5.8 Directional drilling rig boring a pilot hole in an arc that extends under the house and exits on the opposite side.

Figure 5.9 Feeding the thermosyphon pipe back into the hole attached to the drill stem as the drill stem is withdrawn.
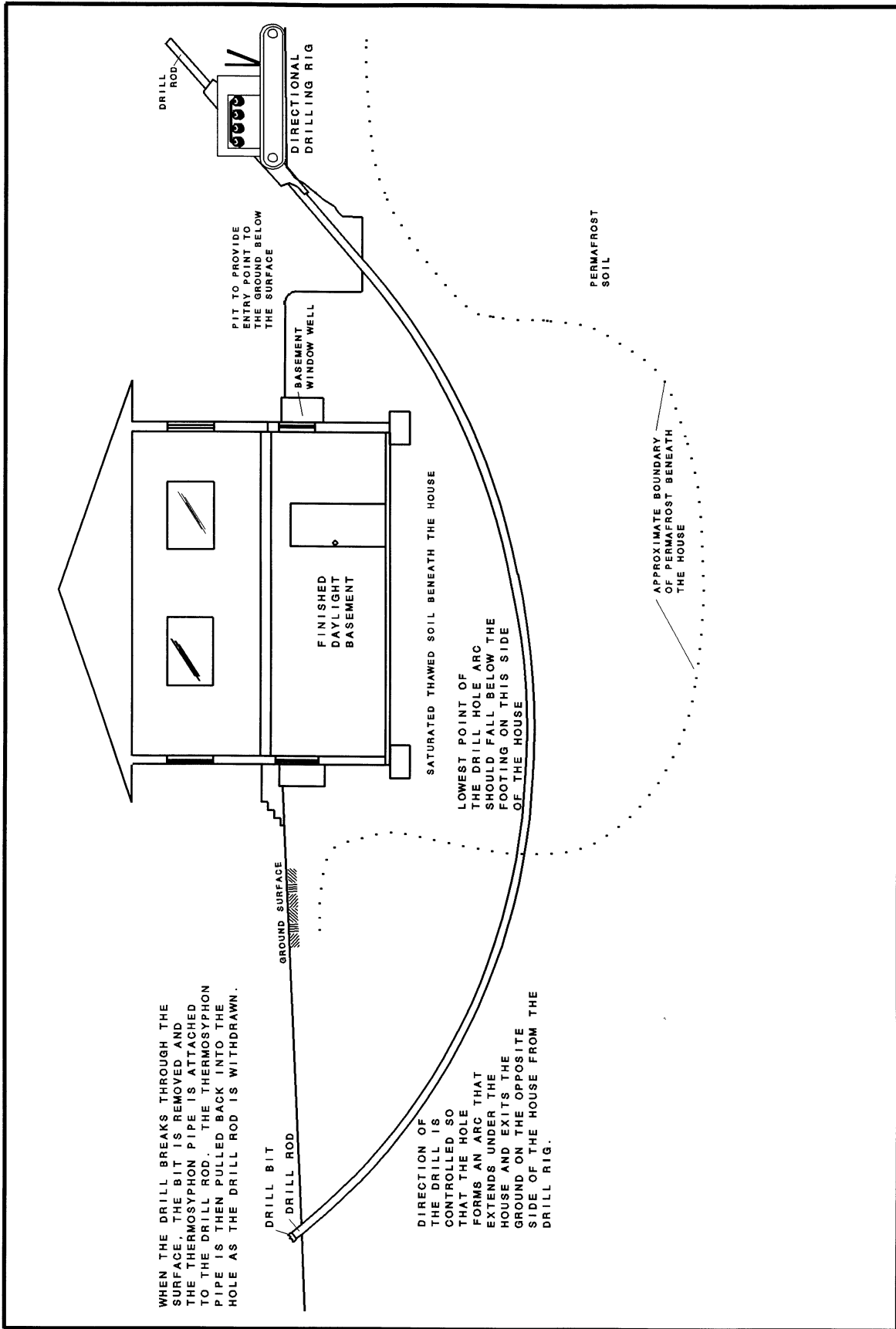
FIGURE 5.10 Directional drilling beneath a structure for thermo-syphon placement when soils are too soft to support the hole.

THERMOSYPHONS PLACED
AS NEEDED TO INTERCEPT
HEAT ENTERING THE SOIL
BEFORE IT REACHES THE
PERMAFROST

FINNED CONDENSER
SECTION--VAPOR
FILLED-GIVES
UP HEAT TO AIR

ACCESS PIT FOR
THE DIRECTIONAL
DRILL

FINNED CONDENSER
SECTION IS WELDED
ON AFTER DRILL ROD
IS DETACHED HERE.

GROUND SURFACE

BASEMENT
WINDOW WELL

PERMAFROST
SOIL

THAWED SATURATED SOIL BENEATH THE HOUSE

BASEMENT

EVAPORATOR PORTION OF THERMOSYPHON
LIQUID FILLED-ABSORBS HEAT FROM SOIL

APPROXIMATE BOUNDARY
OF PERMAFROST BENEATH
THE HOUSE

THERMOSYPHON EXTENDS TO
BENEATH THE OPPOSITE
WALL

THAWED
FROZEN

PERMAFROST
SOIL

THERMOSYPHON PIPE
IS PULLED INTO THE
HOLE AS THE DRILL
ROD IS WITHDRAWN.
SATURATED THAWED
SOIL IN THE THAW
BULB COLLAPSES AROUND
THE THERMOSYPHON PIPE
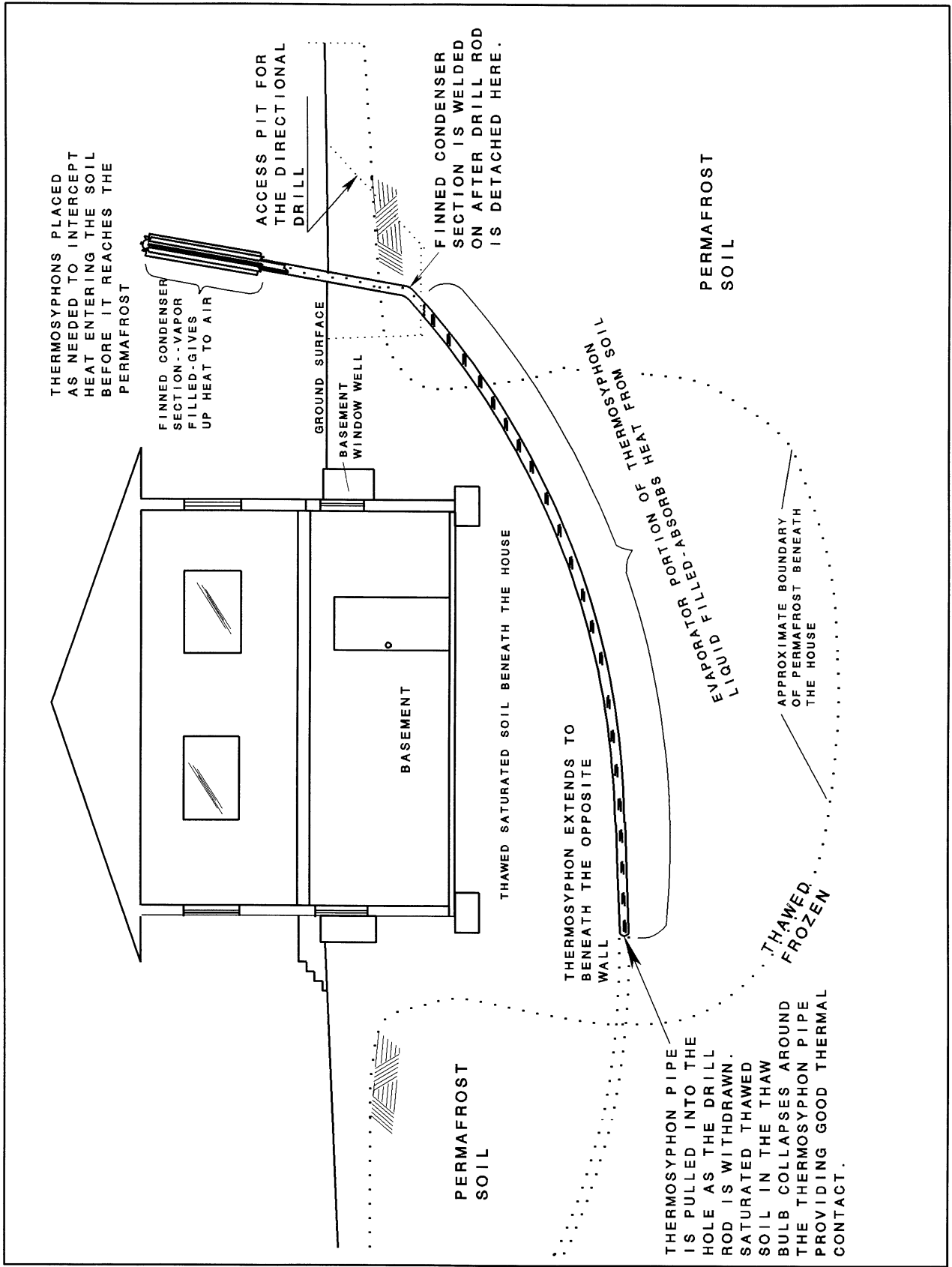PROVIDING GOOD THERMAL
CONTACT.

FIGURE 5.11 Final position of the thermosyphon using
the directional drilling method of installation

intercepted and removed before it reaches the permafrost, then thawing and subsidence will be stopped and the foundation will become stable. Removing the correct amount of heat is an elusive balance. Soil in the immediate vicinity of the natural-convection device will freeze, but if too much heat is removed, the thawed permafrost under the house will refreeze also and frost heaving may become a serious problem. On the other hand, if too little heat is removed, then the permafrost will continue to thaw, albeit more slowly, and subsidence will continue. The design of a stabilization system using natural-convection devices is a sensitive heat transfer problem and is best left to a qualified engineer. To reduce the high cost of the installation it is important not to install too many natural-convection devices. But if not enough are installed, then additional units may have to be added later and all of the initial mobilization and demobilization costs will have to be paid again. Some control of the cooling power of the natural-convection device is possible after it is installed by covering a portion of the fins so that cold air cannot circulate across them. However, it is a narrow range of control, and the installed cooling power, which is determined by the number and size of the units, must be within that range.

5.6.3 Insulation in the Heated Basement

To reduce the amount of heat that flows into the soil, install insulation on the inside of the foundation walls and on the floor. Use a sub-floor over the floor insulation to protect it and to allow the basement to be used for normal purposes. Install wood paneling or wallboard over the insulation on the walls to protect that insulation from damage. An engineer experienced in heat tranfer should calculate the type and thickness of the

insulation. However, if that is not practical, then use at least 2" to 4" of fiberglass or rigid foam insulation in the walls and 4" to 6" of rigid foam on the floor.

A properly sized insulation system will quickly pay for itself over the short term by reducing the number of natural-convection devices needed, and will, over the long term, reduce the amount of heat needed to keep the basement at the desired temperature.

5.6.4 Refrigeration Cooling of the Foundation

Another approach to removing heat from the soil beneath a heated basement foundation was discussed in sections 3.3.7 through 3.3.9. Mechanical refrigeration has several advantages and also several disadvantages. Because of its high maintenance and operating costs and the other disadvantages listed in the sections above, it is considered a less desirable choice. In addition, it is a difficult and expensive system to install in an existing building that is already undergoing some permafrost-thawing distress.

The installation starts with removal of the basement floor (this usually requires breaking the concrete slab with a jackhammer). Next relevel the foundation. Releveling is usually easier once the floor slab has been removed and the footings are exposed on the inside of the building. Excavate spaces under the footings to place pillow jacks and relevel the house as described in section 5.3.

After the house is level, install a grid of cooling pipes in the soil beneath the house as described in section 3.3.7. At this stage of the project, while the ground beneath the floor

is still accessible, install an array of temperature measuring points in the soil under the cooling grid so that the cooling process can be monitored (see section 5.3.3 for details). This is very important since there is no other way to determine if the soil is being cooled at the proper rate. At least one string of temperature measuring points should be installed vertically from the soil surface down to the top of the permafrost or at least as deep as possible. The string should have temperature points at intervals of 2 feet or less. Temperature measuring strings are available commercially, or most professional engineering firms can direct you to a source.

The next step is to place four inches of extruded polystyrene insulation over the cooling grid and install a new floor. The new floor should be removable if possible to give access to the cooling grid system to accommodate repairs or adjustments to it or the temperature strings.

Because of the operating noise, it is often desirable to install the refrigeration system outside the house in an outbuilding of its own. However, if a heat pump is used as described in section 3.3.8, it will probably be better to dedicate a portion of the basement to the unit. A small room or enclosure that is well soundproofed is recommended to isolate the rest of the building from the noise of the compressor.

Although a mechanical refrigeration system is attractive in theory, in practical application it is not found to be as desirable or economical as systems that use passive-cooling natural-convection devices.

5.7 Buildings with a Slab-on-Grade Foundation

Slab-on-grade foundations are often used for homes and for buildings with large floor loads such as heavy equipment garages and aircraft hangars. Unfortunately, when a slab-on-grade foundation is used a site where the permafrost is thaw unstable, it frequently goes into distress relatively quickly. This is a difficult foundation to relevel without first removing the floor, so like the heated basement, releveling is an expensive operation. Removing the floor is usually a labor-intensive operation using jackhammers. Once the foundation is releveled, the permafrost can then be stabilized by a variety of means.

5.7.1 Passive Cooling with Natural-Convection Devices

After removal of the floor slab, natural-convection devices can be installed relatively easily and without drilling equipment. Once the ground under the floor slab is exposed, dig a trench with the proper grade (as described in section 3.3.6) under the footing and across the floor to span the width of the building. One trench is needed for each natural-convection device. The number of devices needed for a building is a complex heat transfer problem and should be determined by a qualified engineer. Slip the natural-convection devices of choice (thermosyphons or single phase heat pipes) under the footing and into place in the trenches. The outside of the foundation will need to be exposed along the length of one side to allow the natural-convection devices to be placed. Once the devices are installed, fill the trenches with clean sand and compact it around the pipes for good thermal contact. As in the basement installation discussed above (section 5.6.3), a temperature-monitoring array of thermistors or thermocouples should be installed (see section 5.3.3 for details).

Once the instrumentation is in place, spread insulation over the entire floor area and install a new floor. The insulation thickness will depend on the inside temperature of the building. A person experienced in heat transfer in buildings should calculate the thickness of the insulation required. If such a qualified person is not available to determine the required insulation thickness, use four to six inches of extruded polystyrene insulation for a home or maintenance garage and six to eight inches for a building with higher temperatures inside. Note the caution in section 2.3.7 on the use of polystyrene insulation if there is any possibility of a hydrocarbon spill.

5.7.2 Cooling with a Forced-Convection Crawl Space

Small buildings and homes that don't have to support large floor loads can establish a crawl space beneath the floor. Once the floor has been removed and the building is being releveled, it is easy to raise the building to provide a crawl space beneath. Then a forced-convection crawl space cooling system (as described in sections 5.5.2 and 3.2.2) can be installed. This is one of the most economical and reliable stabilization systems for small buildings and homes, but it relies on enough cold winter air to cool and stabilize the permafrost. In locations near the southern boundary of permafrost or near the coast, this type of system may not be able to provide the necessary cooling power. In marginal regions where the permafrost is close to thawing, check with a qualified engineer to determine if this type of system will work.

5.8 Three Dimensional Truss Foundation

When the typical concrete or block foundation under a structure looses the support of the soil on which it rests, it usually fails due to the loads place on it by the building. Most foundations distribute the load of a building and its contents over a large enough area so

that the load does not exceed the strength of the soil on which it stands. As permafrost thaws its strength drops dramatically, and it no longer is able to support the loads imposed by the foundation. When this happens, the foundation is left without support in some spots, and the foundation becomes subject to different types of loads that it was not designed or expected to withstand. Most foundations are very strong in compression, but relatively weak in bending and tension. As soil support is lost over portions of the foundation, loads that were previously strictly compression are converted to bending and even tension. Most foundations cannot support these loads and so the foundation fails. The structure of the building is then left without continuous support and wracking occurs.

If a foundation could be built that was perfectly rigid and equally strong in resisting compression, bending and tension loads, it would protect the building from wracking even if it lost support from the soil on which it rests. If soil support is lost, the foundation may tilt or even sink, but if it is perfectly rigid, it will continue to support the building structure above without allowing any wracking. When the foundation is releveled, the building will also be level without suffering any wracking which would damage its structure. It is practically impossible to build a foundation that is perfectly rigid; however, since the building itself is slightly flexible, it can absorb a small amount of wracking without failure. Therefore, what is needed is a foundation that is just rigid enough to support the building, even when soil support is lost, while only transferring a small "acceptable" amount of distress that will not cause wracking to the building. By applying standard engineering techniques, it is possible to build a foundation that is strong enough to meet the required load criteria without allowing undue wracking of the

building.   The problem of course is cost.   With enough money, we can design a foundation that will float in space with no soil support whatsoever.   The problem is to build a foundation that is both strong enough and economical enough to meet the needs of buildings on permafrost.

Trusses are generally found to be one of the most economical means of constructing a very rigid structure, and a three dimensional truss that is rigid in all three dimensions would provide a foundation that should protect a building resting on it from wracking in spite of what happens to the soil beneath it. Figure 5.11 shows a commercially available three-dimensional-truss foundation made by Triodetics Inc. The manufacturer states that this type of foundation will support a structure while allowing a negligible amount of wracking even when the soil subsides under only one corner. Since the foundation is a combination of trusses using members that have a finite strength, it must be sized appropriately for the weight of the building it supports. This type of foundation is generally used only on single story buildings, however, theoretically at least, it could be designed for any size building. The foundation is shipped from the factory in pieces for assembly at the site, and it can be assembled under a building that is in permafrost distress if it can be raised a few inches to provide working room for assembly. Once assembled the building can be lowered onto its new foundation.

Since the weight of the building (including the foundation) is transferred to the soil at several points beneath the foundation, when subsidence (or heaving for that matter) causes support to be lost under one of these points, the load of the other points increases
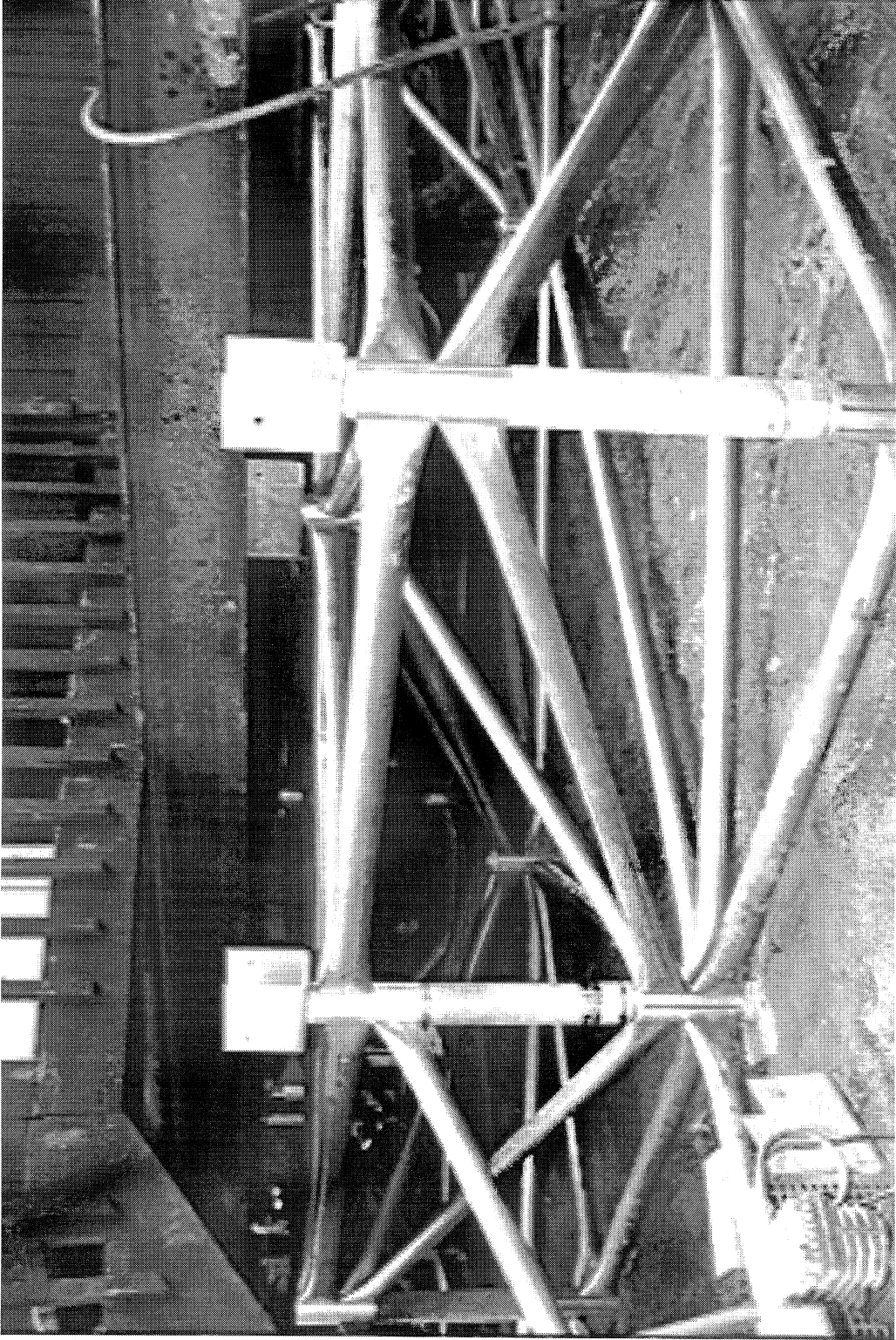
FIGURE 5.12 The Triodetic "space frame" type of foundation.

to support the total weight. This may result in both the foundation and building tilting or settling into the soil, but if the truss foundation is rigid enough, the top of the foundation changes very little in size or shape. Therefore only a minimal amount of wracking forces are transferred to the building. If the building's weight changes (due to an addition of very heavy equipment inside, for example) the truss members distribute the increased load so that several of the members share the load and no one member is overloaded. However, even this type of foundation can be overloaded and fail. When it does fail, the failure may be sudden and catastrophic much the same as when a truss-type roof collapses from overloading by heavy snow.

5.9 Final Considerations

Several basic rules are common to all permafrost stabilizing systems. The overall aim is to stop further thawing of the permafrost and further damage to the structure while at the same time avoiding any frost heaving of the foundation. Few, if any, buildings can survive the loss of their foundation support, and foundations in turn rely on the support of the ground on which they rest. When the ground becomes unstable, regardless of the cause, from permafrost thawing to earthquake to frost heaving, the foundation will move and, unless it is rigid, it will cause wracking of the building's structure.

Permafrost is slowly retreating in the far north; the southern boundary of continuous-permafrost is moving farther north. The discontinuous and sporadic permafrost regions are also changing. This is another indication of a current global warming trend that is

now affecting our planet.   If the climate continues to warm, more permafrost will thaw and more foundation stability problems will emerge.

A stabilization system for a building that is in distress must be designed to protect the building over its entire useful life. This requires forethought when selecting and sizing the system to be used. The condition of the building as well as the surrounding area must be considered. In addition, any foreseeable future changes that will affect the thermal regime in which the building exists must also be considered. This is difficult at best and perhaps impossible in some cases, so generous safety factors should be used for whatever design you select. Make it easy to add supplementary cooling to the foundation should that become necessary in order to maintain the permafrost.

When possible make your foundation "thaw proof." Removing the frozen soil from interaction with the system can do this. An example is to extend pilings until they rest on stable bedrock, thus removing the frozen soil problems from the system. This is not often possible, but when it is, it should be considered as it eliminates the problem of future thawing and makes the foundation "thaw proof." Another example is to remove the permafrost by excavation or by thawing and then to backfill with thaw-stable soil and to compact it to create a stable site. This is applicable when only a small amount of permafrost exists at the site, but when it is possible; it removes the frozen soil problems permanently.

5.9.1 Air Flow Beneath the Elevated Foundation

When the foundation relies on winter airflow to freeze and reinforce the permafrost, you must make sure that that airflow is never interrupted. Many examples exist of perfectly good permafrost-stabilized foundations failing because the airflow beneath the building was compromised. Examples include using a snowplow to push snow against the building to "help insulate it," but in doing this, all airflow beneath the building was blocked. Snowdrifts caused by nearby obstructions also have grown until they block airflow below the building. In another case a new building maintenance manager was not informed that the covers over the air ducts that carried winter air beneath a maintenance shop had to be removed before winter set in. After 3 years, the concrete floor of the shop was more than a foot lower in the center than around the perimeter. Storage of summer equipment beneath the building is another frequent violation that reduces or eliminates the required airflow below the structure.

The examples seem to be endless, but the message to the persons who design and construct the foundation stabilization system is clear. If the system relies on airflow beneath the structure, the system that supplies that airflow must be as foolproof as possible. It must not rely on the memory of any individual or group to initiate but must be self sustaining in every way possible.

5.9.2 The Surrounding Site

The mess hall at a mine in western Alaska was built on permafrost and performed satisfactorily for the first winter at the site. The wind at the site kept the snow scoured

clean beneath the building. During the second summer, however, several new buildings were built for expanded operations. Since the site was very windy, it was decided that the buildings should be positioned as closely as possible to minimize the exposure of the workers when they moved from building to building. The new arrangement of buildings changed the air movement at the site, and during the following winter snow drifted into areas between the closely packed buildings so rapidly that a crew of men had to be detailed to continually shovel walkways between the buildings so that movement between them was possible. In addition, airflow beneath the buildings was no longer present and the permafrost began to thaw. Although the original design was adequate and performed satisfactorily the first year, changes in the surrounding site compromised the permafrost foundation.

More subtle, but just as devastating in the long run, are things such as regrowth of brush and trees that had been cleared around a building causing site conditions to change such that the permafrost foundation no longer received enough winter cooling and was no longer stable.

Although it is difficult to predict the future events around a site, some effort must be made to consider possible events that would adversely affect the site. Is the site in an area of future growth? Will the current thermal conditions exist indefinitely? Are the boundaries of the site sufficiently protected to keep future growth from becoming a problem? All of these questions need to be considered and planned for.

5.9.3 Access to the Site

Finally, access to the site must be incorporated into the permafrost stabilization design. Roads, driveways, and parking lots all change the thermal regime of the site. The system must be adequate to maintain stability even with the increased heat input from these necessary thermal changes. After the system is installed, the design parameters must be maintained or the design may fail.

Although not a permafrost example, a somewhat similar example comes from the design of a septic system for a hangar at an Alaskan airport. The site parameters called for an area to be set aside for the septic tank and the drain-field. The designer was assured that he could be certain that the snow on this area would be undisturbed. In order to keep the costs down, the designer used the insulating value of the average snowfall of the area to supplement the installed insulation to keep the septic system from freezing. The first winter after the system was installed, a new manager was assigned to the area, and he decided that more parking was needed. Without considering the consequences, he opened the area over the septic system to parking. The snow was removed and it proved to be a very adequate parking lot. However the septic system froze every winter and was unusable until midsummer each year.

Access to the site is an important part of the usability of the structure. It must be planned for during the initial stages of the stabilization design, and any restrictions on access must be maintained to protect the integrity of the stabilization system. Plan for all possible increases in usage. Make the design as fool proof as possible.

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APPENDIX

A Photo Collection of Permafrost Problems

FIGURE A-1 Aerial and ground views of polygonal ground on the North Slope of Alaska
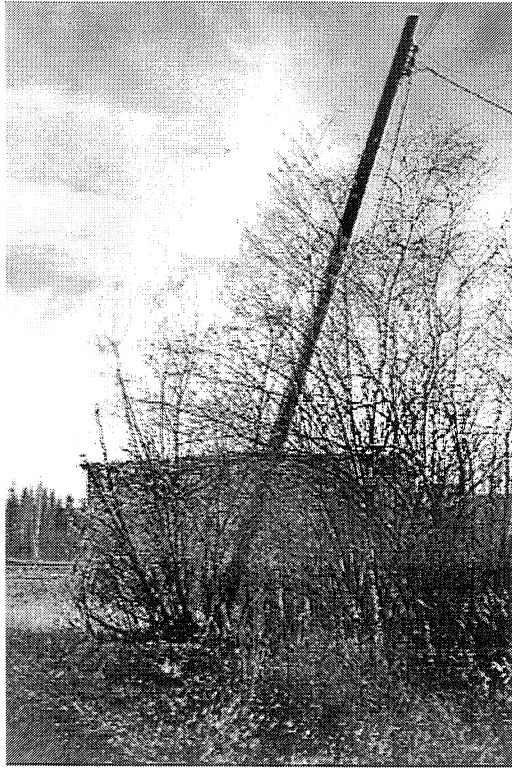
FIGURE A-2 Frost jacking in action, power pole (top) and fence (bottom)

Figure A-3 Thermokarst (top) that developed from the thawing of a massive ice form such as the ice lens exposed in a road cut (bottom). The thermokarst swallowed the small shed sitting on the surface.

Figure A-4 Road traversing a permafrost area. Notice the "drunken" power poles along the road, as well as the undulating surface.
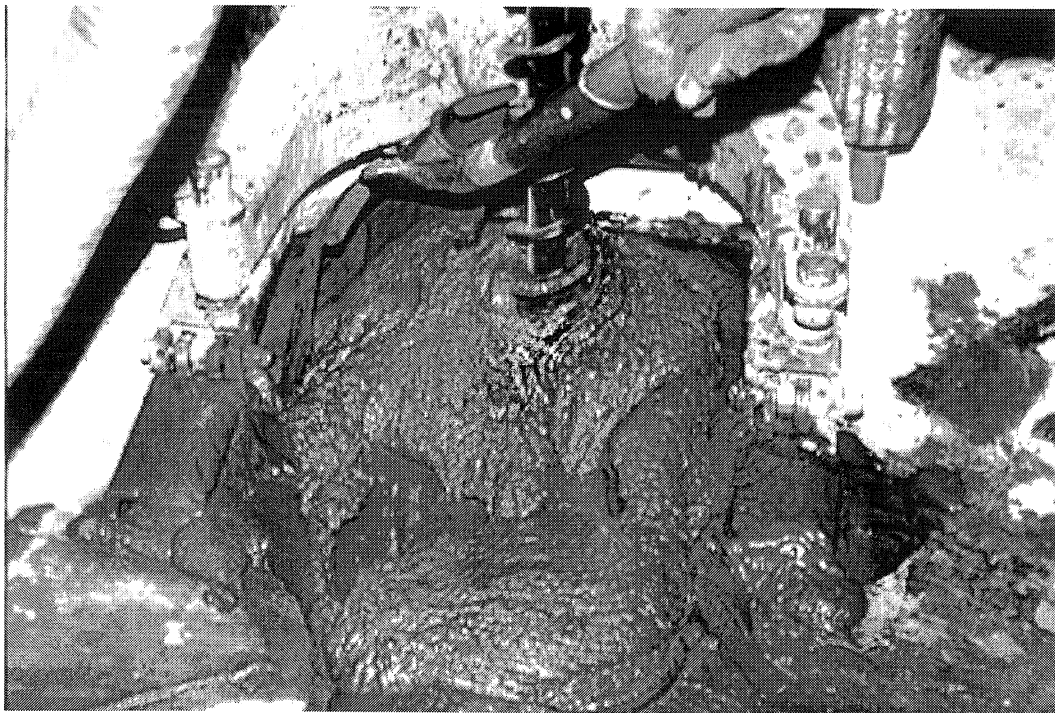

Fibure A-5 Thawed permafrost "muck" augured out of a hole beneath a house during drilling for a permafrost investigation.