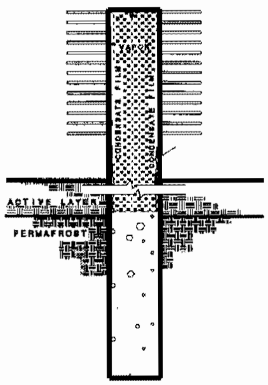

PERMAFROST TECHNOLOGY FOUNDATION

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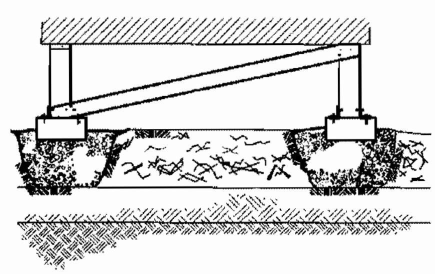
DESIGN MANUAL
FOR
NEW FOUNDATIONS
ON
PERMAFROST

SEPTEMBER 2000



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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. One 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. The other manual addresses the retrofit stabilization of foundations that were built incorrectly for a permafrost site and need to be stabilized to avoid 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 nine 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.

ACKNOWLEDGEMENTS

The **Permafrost Technology Foundation,** Fairbanks, Alaska produced this manual. Distribution is free to Libraries and educational organizations upon written request. It is available to others for a $10 printing, shipping, and handling fee. It is also available on Permafrost Technology Foundation's Internet site at www.permafrost.org.

The research and development work that led to the manual was initially funded by a grant from the **Alaska Housing Finance Corporation (AHFC).** The grant included 10 houses that were built on permafrost and that were suffering damage from the thawing of the permafrost. In addition to the houses, AHFC made a repayable cash grant to repair the houses and start the research. Without this help, the project would never have been possible. The cash grant has now been repaid to AHFC's and their foresight in supporting this research is yielding dividends such as these manuals.

This manual was written by Dr. Terry McFadden Ph.D., P.E. Dr. McFadden has practiced engineering and conducted engineering research in Alaska for 32 years. He has authored two books and over 60 reports, manuals, and papers on the subject of cold weather engineering. Dr McFadden is a Professor Emeritus of the University of Alaska Fairbanks School of Engineering and is a past director of the Alaska section of the U.S. Army Cold Regions Research and Development Laboratory.

The fundamentals presented herein are a combined result of the research and experience of many engineers, student engineers, and consultants who have worked in the field of cold regions engineering for many years. The late Dr. E.F. Rice of UAF and Dr. Thomas Kinney of Shannon and Wilson Inc. both contributed substantially to the manual with their research, teaching and, in Dr. Kinney's case, his active involvement in the project.

Mr. Robert McHattie and Mr. Allen Vezey reviewed the manual for technical content. They both spent a great deal of time and effort in this endeavor and their detailed review along with their comments and suggestions was invaluable. They deserve sincere thanks; the author greatly appreciates their input.

Robert L. McHattie MCE, P.E. holds degrees in Geology and in Civil Engineering from the University of Alaska Fairbanks. His work experience includes more than 26 years with the Alaska Department of Transportation's Northern Region. His first hand knowledge of permafrost was gained from 10 years of permafrost research and 15 years as the Northern Region Geotechnical Engineer dealing with many combinations of permafrost and foundation types.

Allen Vezey holds a degree in Civil Engineering from Georgia Institute of Technology, 1972. He has 28 years of construction experience working on Alaskan projects, including six years work on the Trans Alaska Pipeline project. He is a former Alaska State Legislator, the past president of the Associated General Contractors of Alaska, and he owns Lakloey, Inc. a general contracting firm in Fairbanks, Alaska

In addition the Board of Directors of the Permafrost Technology Foundation must be thanked for their insight, their time, and their support over the life of the project.

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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 designer/builder can attack the problems from a position of knowledge and strength.

This manual is intended as a guide for design and construction of foundations that must be built in permafrost terrain. The high latitude regions of both the northern and southern hemispheres are laced with permafrost. When a building must be placed on permafrost, proper 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. This manual is one of a set of two and deals specifically with new construction. Stabilizing buildings that have already been built on permafrost is covered in the companion volume: *Stabilization of Foundations on Permafrost.* This manual is not an engineering design text. 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 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, and it will outline the various types of foundation problems and their solutions for different types of buildings and requirements encountered in northern building. A short bibliography of other reference

material for all types of building problems encountered in northern latitudes is included at the end of the manual, and references will be given for specific topics throughout the manual as appropriate.

1.2 PERMAFROST

If you measure the temperature of the surface of the ground for several years, the data can be used to establish an average or "mean" high temperature and an average or "mean" low 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 meter) 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 12 inches (0.3 m) to a depth of approximately 50 ft (15 m). As the depth increases, the mean low temperature will be found to be a little warmer at each successive depth. The mean high temperature will decrease at each depth, but the amount that it decreases will be less as depth increases until finally, at a depth of several tens of feet, it will remain nearly constant for some depth and then start slowly increasing once again. If the high and low temperatures are plotted with respect to depth, the two lines make up what is known as a *Trumpet Curve* because of its shape. Since these curves were established by many years of temperature measurement, 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 surface temperature gradually changes. These changes occur naturally in many cases, but man-caused changes are common and often more abrupt.

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 essentially remains constant all year.

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 discontinuous permafrost to as much as 2000 ft (610 m) along the north coast of Alaska. Between the two depths where the mean 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 annual 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 annual 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 or equal to the amount of cooling (or more accurately the amount of heat leaving the soil). This balance between the two heat fluxes is known as the *Heat Balance*. In the discontinuous 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 areas heat from the sun is intercepted either partially or completely so that the cooling effect of winter is greater than summer warming and permafrost can survive. (Cooling due to the transpiration by the plants can also be substantial) 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

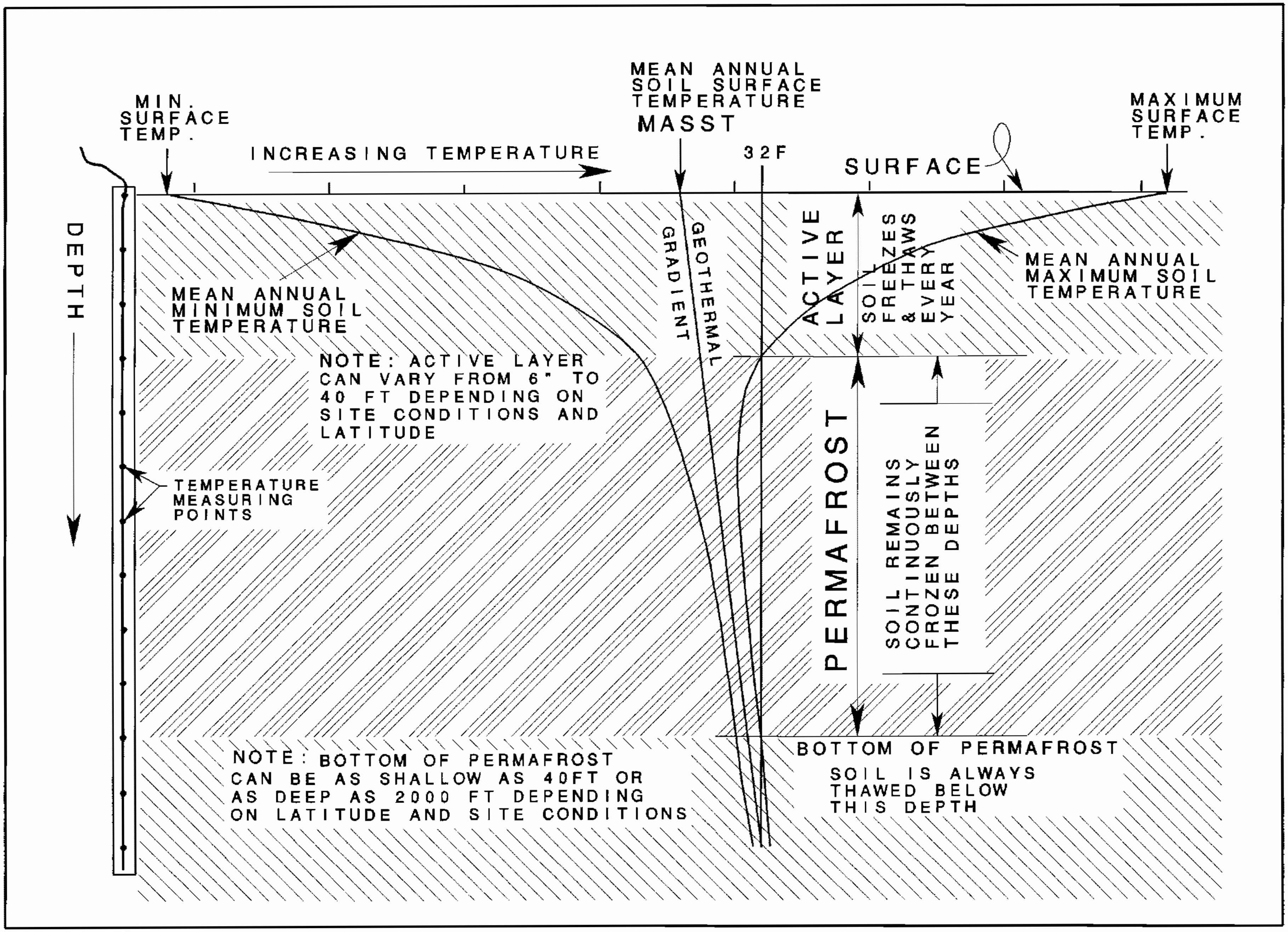

FIGURE 1.1 Trumpet curve. Typical mean high and low soil temperatures with respect to depth at a permafrost site.

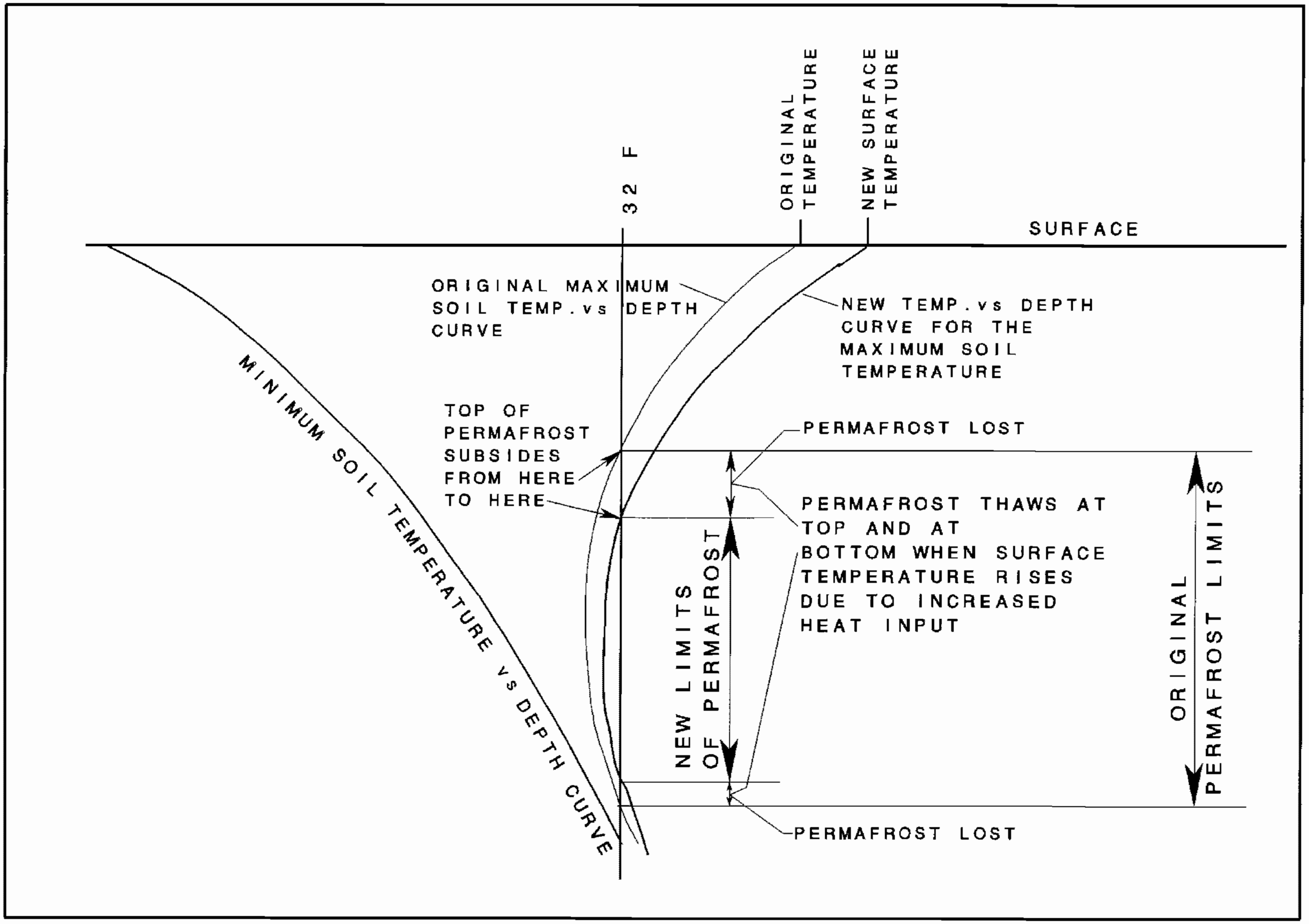

FIGURE 1.2 The effect of increased surface heat input. When construction, forest fire or other circumstance changes the thermal balance so that more heat enters the surface a new mean maximum temperature is gradually established. Note that the permafrost thaws at both the top and the bottom.

curve. Notice that the top of the permafrost (the "permafrost table") is deeper, and the bottom of the permafrost is shallower. When the surface temperature increases, permafrost melts from both top and bottom because it receives heat not only from the surface, but also from the geothermal heat flowing from the center of the earth.

As a result the amount of permafrost is smaller or in many cases completely disappears. The reestablishment of a thermal balance that allows permafrost to exist can take several years, or may never occur. During this time, thawing and settlement (if the soil settles upon thawing it is said to be *Thaw-Unstable*) 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 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. This reflects the heat gain from previous summer weather whose effect is just reaching these depths. There is a time lag involved between the surface temperatures and those below the surface. The cooling effect of autumn weather is 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 (Fig.1.3). 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.

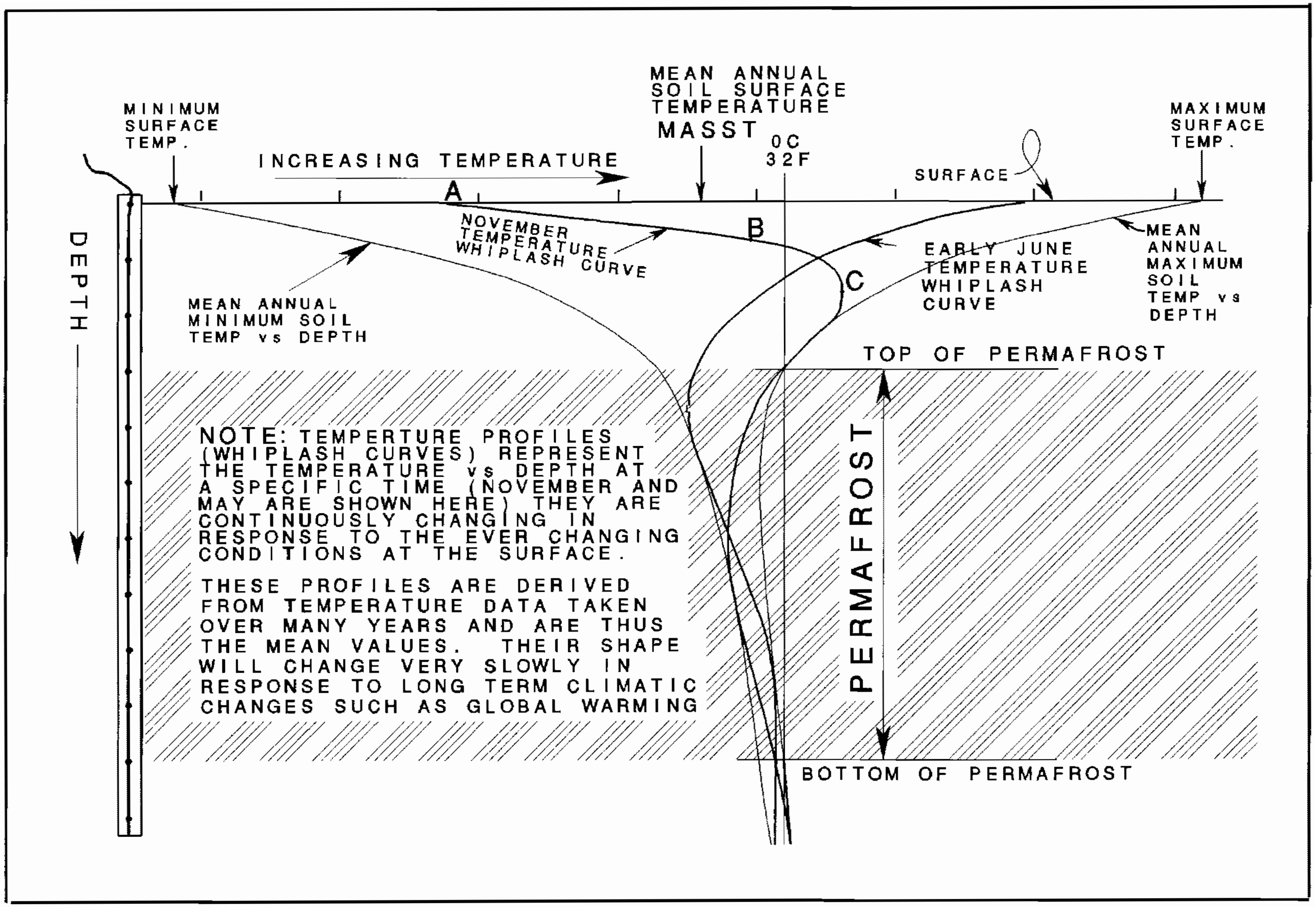

FIGURE 1.3 Whiplash curves. Note that a whiplash curve must always remain between the two sides of the trumpet curve at it descends into the soil. The whiplasn curve is an actively changing, temperature vs depth curve that reflects surface heat moving into and out of the soil, therefore at each instant in time the curve will be different.

A plot of these "instantaneous" temperatures forms an line called a *Whiplash Curve* because of its undulating shape (Fig. 1.3). 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 changes in surface heat input influence the temperature at each depth and the effect arrives at each succeeding depth at progressively later times. This 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 after 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 man made 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

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.

When the volume of frozen water exactly fills the spaces between the grains of soil that are still in contact with one another, the soil is said to be "saturated." Soil that has more water than needed to fill the voids is also considered saturated, but is said to have excess water or excess ice. Upon thawing, a soil whose water content is at saturation or less will not change its volume or "subside" since the soil grains are always in contact with one another. This soil is said to be "thaw-stable." Permafrost 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 result in compaction (a process where water is expelled as the soil volume decreases and subsides until the soil grains are all in contact). Obviously there are many occasions when permafrost is encountered when conventional construction techniques and designs can safely be used. The trick, of course, is in knowing when this is the case. If a frozen soil's moisture content is greater than saturation, additional space is required for the excess ice (water when it thaws). That space was generated by separation of the soil grains to form a greater pore volume during the freezing process by formation of ice lenses etc or later by the formation of ice wedges. When this soil thaws, soil grains sink until they are resting against each other since they are no longer separated by ice. This overall consolidation of the soil grains is termed "thaw instability" and results in settlement of the surface and foundation failures. Even a soil that has less than the amount of water needed for saturation can be dangerous if a source of water becomes available during the seasonal freezing cycle. In this case frost-

[1] Previously the terms non-detrimental 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.

heaving resulting from moisture migration to the seasonal freezing front can cause frost heaving and severe damage (more on this later).

1.3.1 Moisture Content in soils

If the unfrozen water 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 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 of an already saturated soil increases, the subsidence upon thawing also increases. Later we will see how some soils that are unsaturated at the beginning of freezing can attain large excess void content 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 voids between 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 20% 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 causing a 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. That portion of the crack that extends into the permafrost is in a continually frozen environment, 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.

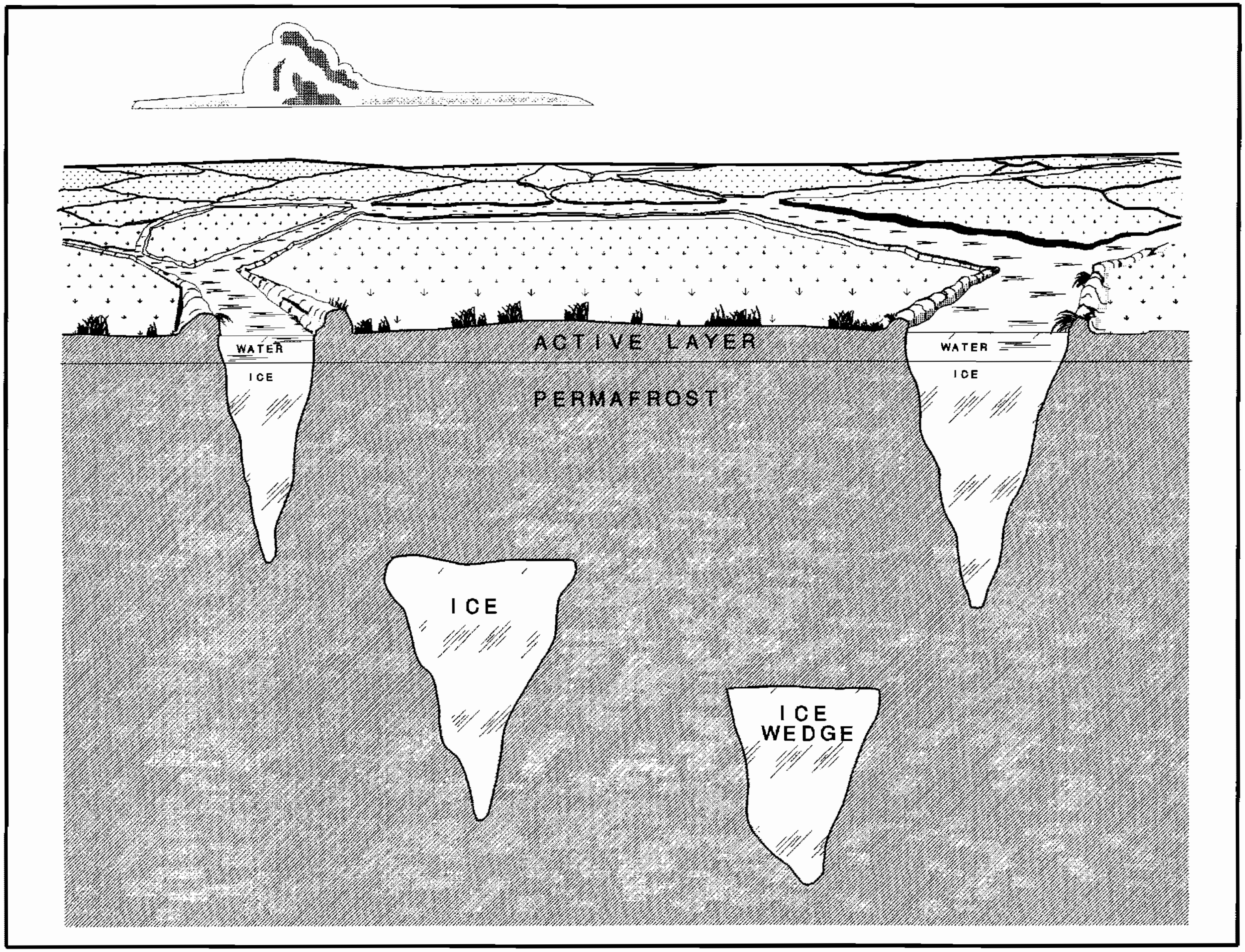

FIGURE 1.4 Artist's conception of an area of polygonal ground. Note the relic ice wedges buried at depth. They are remnants of an earlier time when they were at the surface and actively growing each year.

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*.

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, therefore, 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 or in some areas of the north, old buried glacial ice can become part of the permafrost. A clear ice mass will not have the silt striations found in wedges and lenses, but 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. A small amount of frost heaving results when soils that are not perfectly dry freeze (about 9% of the volume of the soil's moisture). 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 except when repeated heaving creates a jacking action that continues for several years. 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 in the stream is sufficient to melt the ice wedges and lenses that the stream comes in contact with in the banks and streambed. These melted 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 containing massive ice.

1.4 GLOBAL EXTENT OF PERMAFROST

In the Arctic, permafrost is found everywhere. Consequently, the most useful definition of the Arctic region (for engineering and construction purposes) is: "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, sheltered areas on the south side of hills or mountains or in valleys that are protected from the summer heat etc. It is often found in locations where it is not expected, but it is in discrete local areas, not everywhere as in the continuous zone. 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 melting. 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 frozen will be facing disaster.

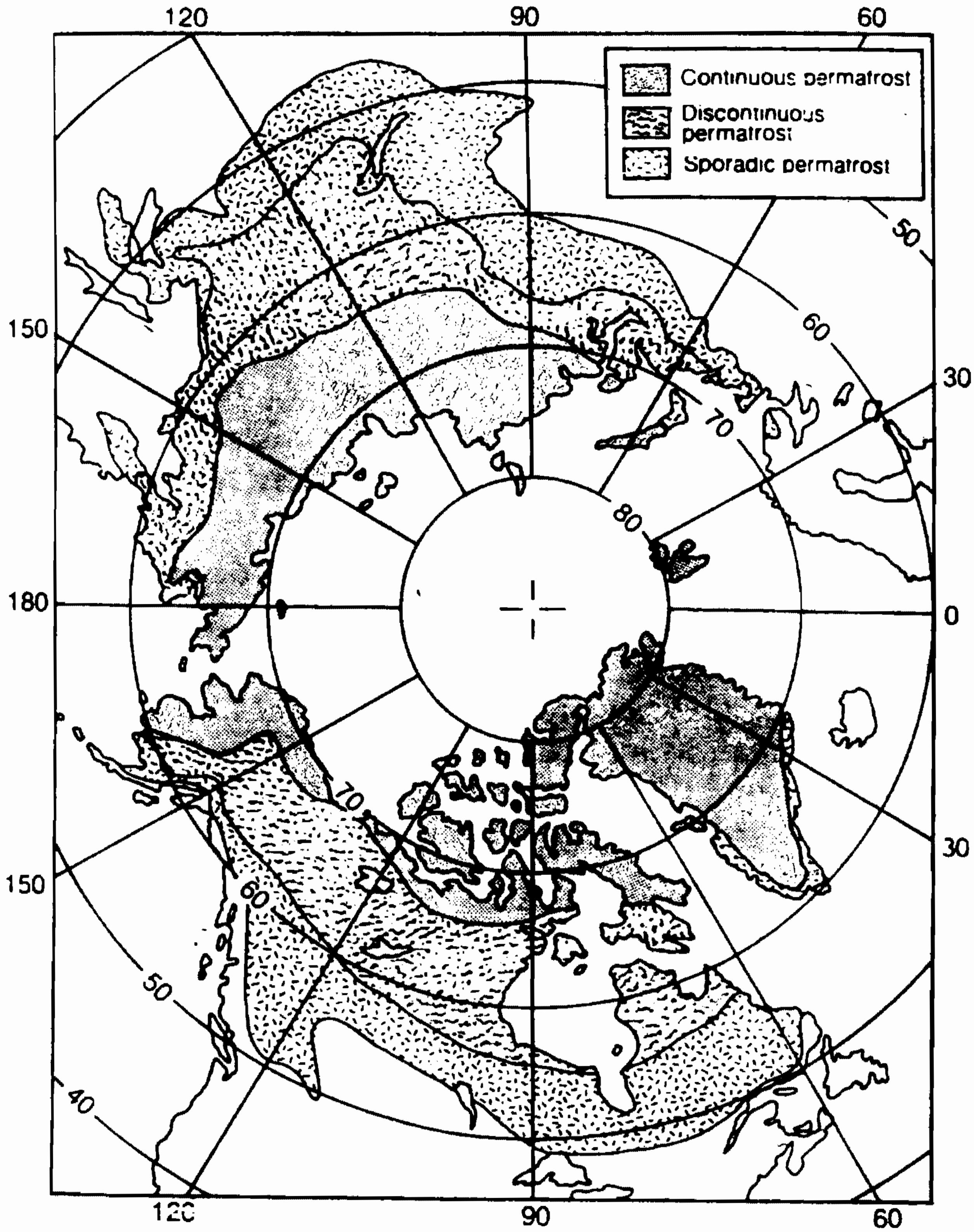

FIGURE 1.5 Approximate distribution of continuous, discontinuous and sporadic permafrost in the northern hemisphere. (Data from several sources)

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 the continuous permafrost region such as the North Slope of Alaska, there is no option. In these regions, permafrost is the controlling design parameter. If the permafrost is thaw-unstable, it must be either preserved and prevented from thawing or completely removed by either excavation or by completely thawing it before construction. 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 melts (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 melts. 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 melting. Anything that changes the thermal conditions at the site so that

the soil temperature increases will cause it to thaw. Fig. 1.6 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 1.7 shows some of the structural damage that resulted as the permafrost melted.

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 then 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 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.

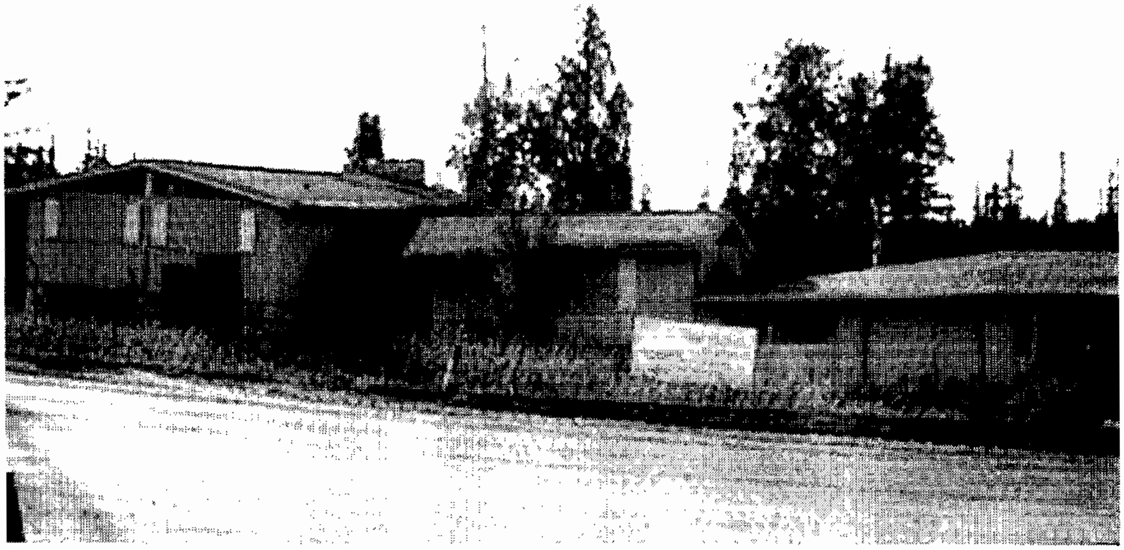

Figure 1.6 A house built in Fairbanks, AK on thaw unstable permafrost. This house with its heated basement eventually deteriorated until it was uninhabitable. It was finally burned because it had become a safety hazard to the community.

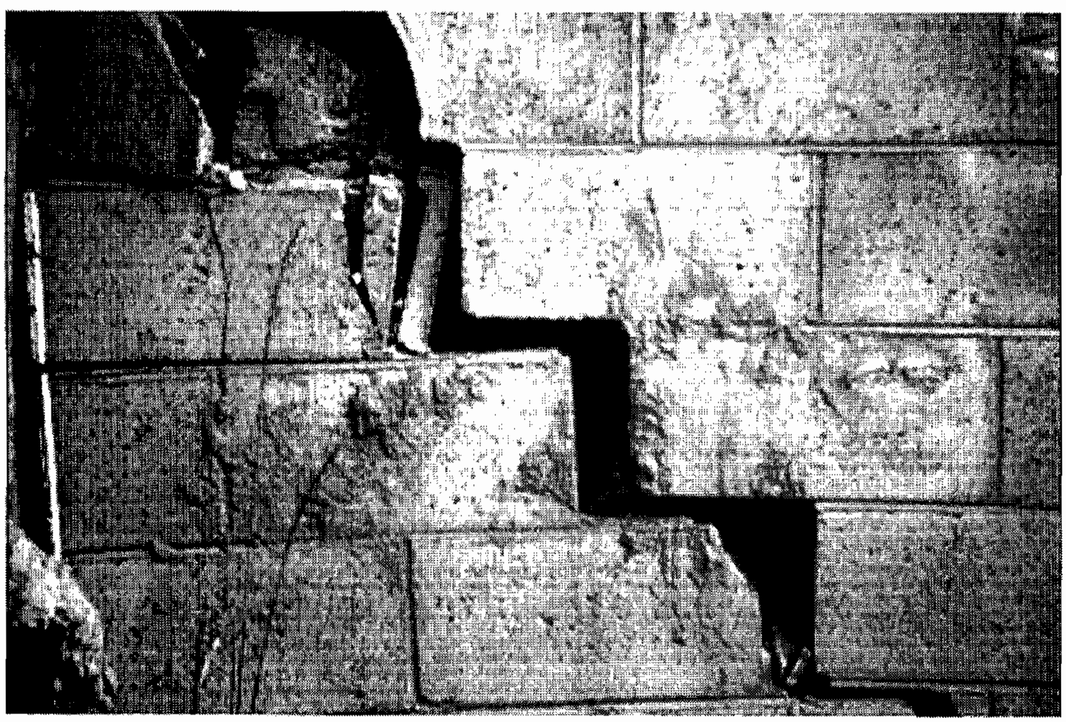

Figure 1.7 this is some of the foundation damage that thawing permafrost caused to the house above. Note that the cracks are wide enough for small animals to crawl through.

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 a 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 close to or right at the freezing point) will start to thaw. The ice masses in the permafrost melt and the soil moisture becomes wet and incapable of supporting much load. 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 usable. 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, for even the best design will not survive improper installation or construction. Proper 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 thaw-unstable, 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 extra expense of

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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 permafrost site with a conventional non-frozen ground type of foundation. They reason that the building will only be used a short time and then moved to the next site. This strategy works fine if the location is truly temporary, however there have been numerous buildings constructed with this philosophy that have had to have a remedial permafrost compatible foundation put in later at much greater expense. The old adage "there is nothing more permanent than a temporary building" has special significance in the north.

the more costly foundation usually is expected by the owner 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 including 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. Some areas have known permafrost maps and aerial photos can often show permafrost features. 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 right 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 melted 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. Well logs can show the presence of permafrost but they cannot be relied on to show the absence of it.

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

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. A qualified soils laboratory then analyzes the samples taken during drilling and a bore-hole-log is produced. The bore-hole-log (usually called the "drill log") is a foot-by-foot record of the drilling operation kept by an 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 trained personnel with proper equipment 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 substantial amounts of ice. Fig. 2.1 shows a typical bore hole 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 subsurface permafrost exploration techniques for determining the site soil conditions currently available. However, you must keep in mind what the drill log's limitation are.

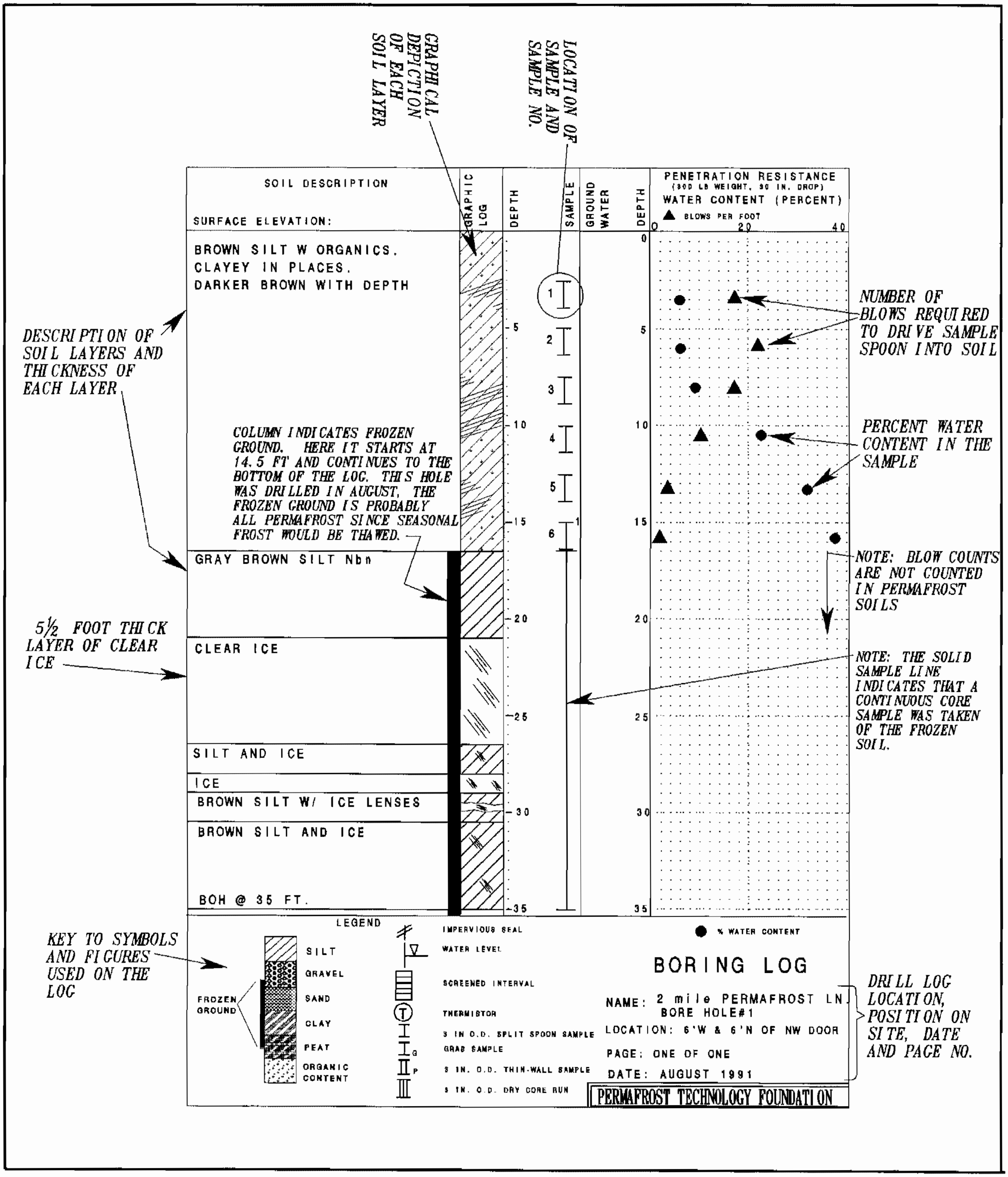

FIGURE 2.1 A typical bore-hole log from a permafrost investigation. Annotated explanations are in italics

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.

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.) 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 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 between the ends of a long rod (a typical rod is 2 ft (3.6 m) long, but

other types of resistivity devices are available). Typically soil conditions approximately 10 to 20 ft (3 to 6 m) deep into the ground can be inferred by this technique although some devices are now available that measure very deep. 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 reasonthe 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 additional bore hole(s) can then be drilled in that area to provide maximum 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 permafrost 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 to be useful.

2.3 INSULATION AND 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 vegetation cover does this very effectively since it provides both shade and transpiration cooling. Vegitation slows the rate at which heat reaches the surface so that less heat enters the soil that must be balanced 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 as 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.

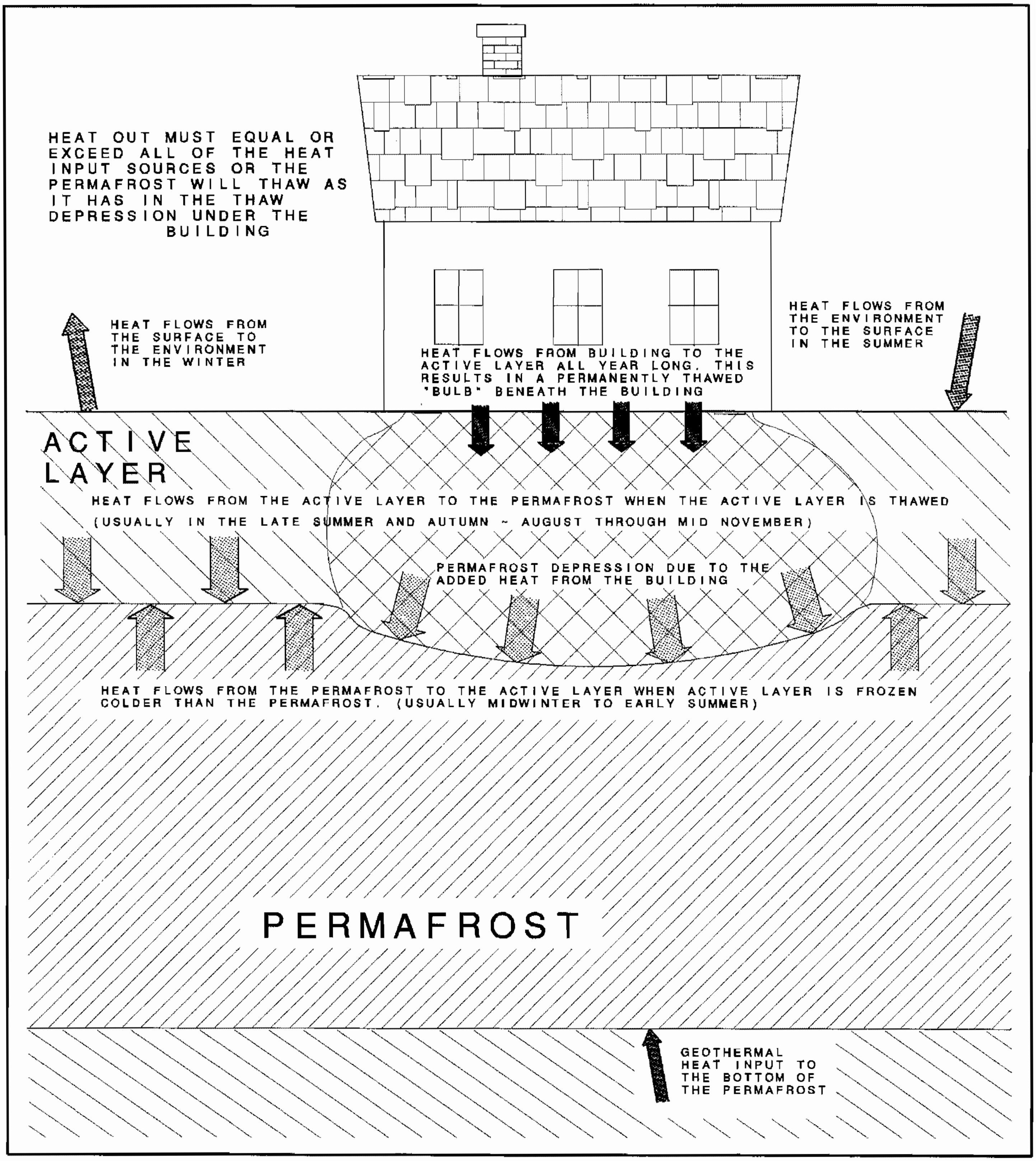

FIGURE 2.2 A representation of the various heat flow components at a site underlain with permafrost

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 water absorption. 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 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. 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 due to moisture accumulation in the glass fiber batts. 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 size and number of the dead air spaces trapped within the batt. Installation procedures can create a considerable variation in the size and number of the air spaces. Since the batt is easily compressed, oversized batt (i.e. batt that is thicker than the stud space thickness into which it is being installed) can be placed in the stud space and then compressed by covering the space with rigid wall boards on each side. 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 glass fiber batts, mineral fiber batts also suffer from water accumulation within the fibers. Other types of insulation are not as adversely affected by moisture.

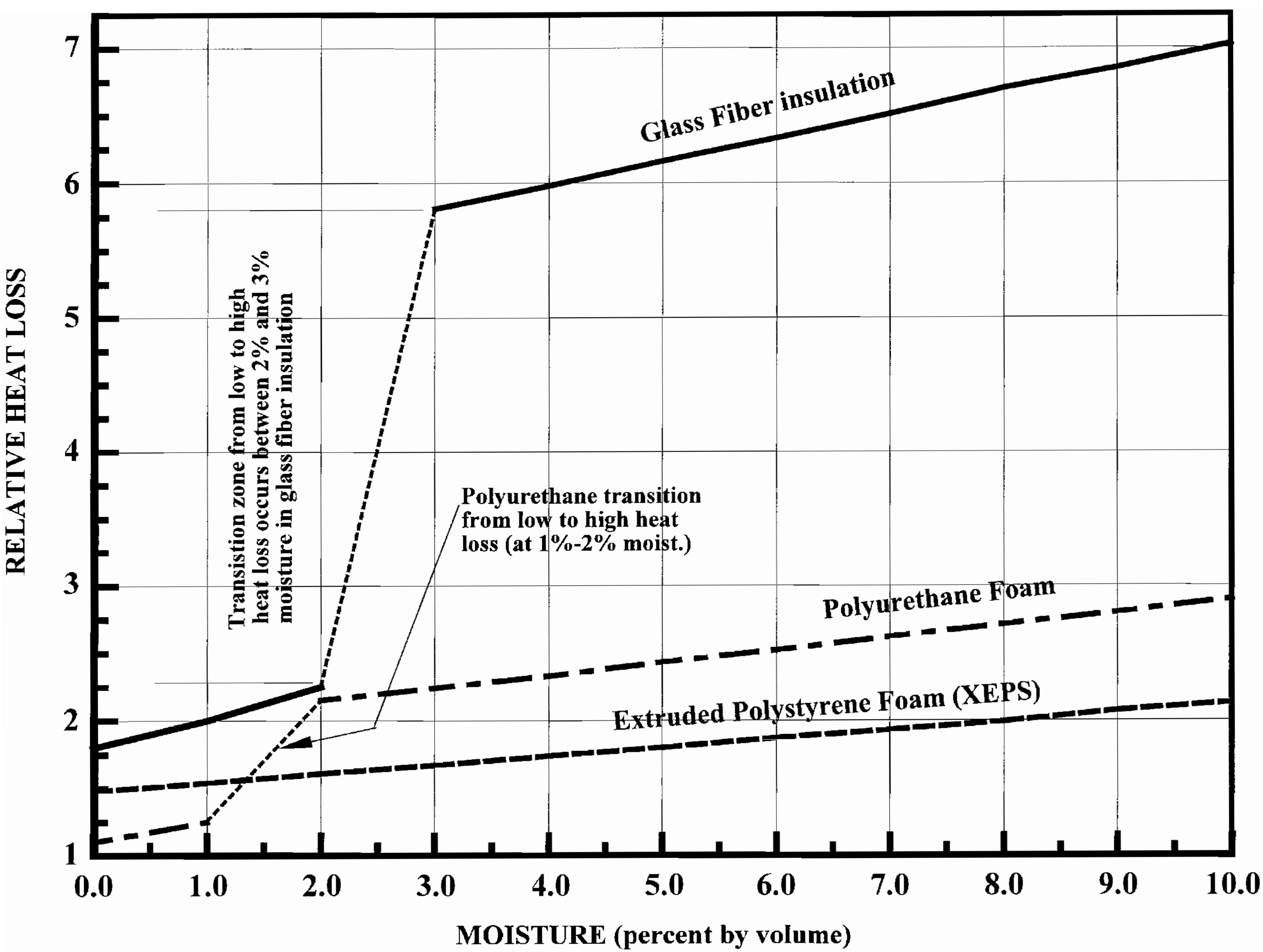

FIGURE 2.3 Relative increas in heat lost through several types of insulation due to absorption of moisture

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

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 Foam 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" or "high density polystyrene", 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. It should also be noted that foamed insulations are manufactured in different grades to support different loads. The higher load carrying capacity usually has a lower thermal resistance so attention to detail in this regard is important. Also, unlike glass fiber insulation, rigid insulation cannot be compacted into a thinner stud space to achieve better insulating performance.

The thermal resistance of dry, foamed-polystyrene board (either XEPS and 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.

2.2.5 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 conductivity immediately after foaming is substantially lower than it is after the foam has aged. But even aged foam has one of the highest thermal resistances of commercially available building insulations. Polyurethane foam is expensive; its equivalent insulation 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.

2.2.6 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.

When disposing of left over or unwanted foamed polyurethane and Polyisocyanurate insulation do not allow it to be burned. When burned the foam can form a very toxic cyanide based gas.

2.2.7 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 - FOUNDATION TYPES

3.1 OVERVIEW

Armed with the information of chapters 1 and 2, we are ready to look at the types of foundations that are available for use at 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 permafrost from thawing due to the change in the thermal regime of the site caused by the construction process (clearing and traffic on the surface) and the presence of a new structure (which increases the heat input to the soil). Most foundations try to de-couple the structure from the permafrost so that heat can be carried away from the surface by the normal winter weather. This approach has been very successful in protecting permafrost from the heat of buildings and oil pipelines. This approach relies on the presence of sufficiently 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 approach cannot be used for structures such as roads or buildings with high floor loads such as aircraft hangars where the foundation must be in contact with the surface.

We will not consider conventional foundations used in areas where there is no permafrost nor will we cover construction of roads or airfields in permafrost terrain. The scope of this manual will limit itself to foundations for buildings at sites underlain with thaw-unstable permafrost.

3.2 Slurried Pile Foundations

This type of foundation has been the "conventional foundation" used at permafrost sites for decades since the Russians first developed it. Although the American and Russian approach has diverged widely over the years, it is still used extensively in both countries. The foundation consists of piles embedded into the permafrost and extending 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. (.6 m) above the ground. The overriding consideration is that the space beneath the building must have free circulation of winter air. Since the building presents an obstacle to air flow, larger buildings require a wider air space beneath. Buildings such as warehouses or dormitories for working crews have traditionally been raised 3ft (~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. Even worse, is the practice of applying skirting around the bottom of the structure to "dress it up." 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.

The pilings must be embedded into the permafrost deeply enough to provide support for the structure and to resist the heaving effects that take place in the active layer between the permafrost and the ground surface.

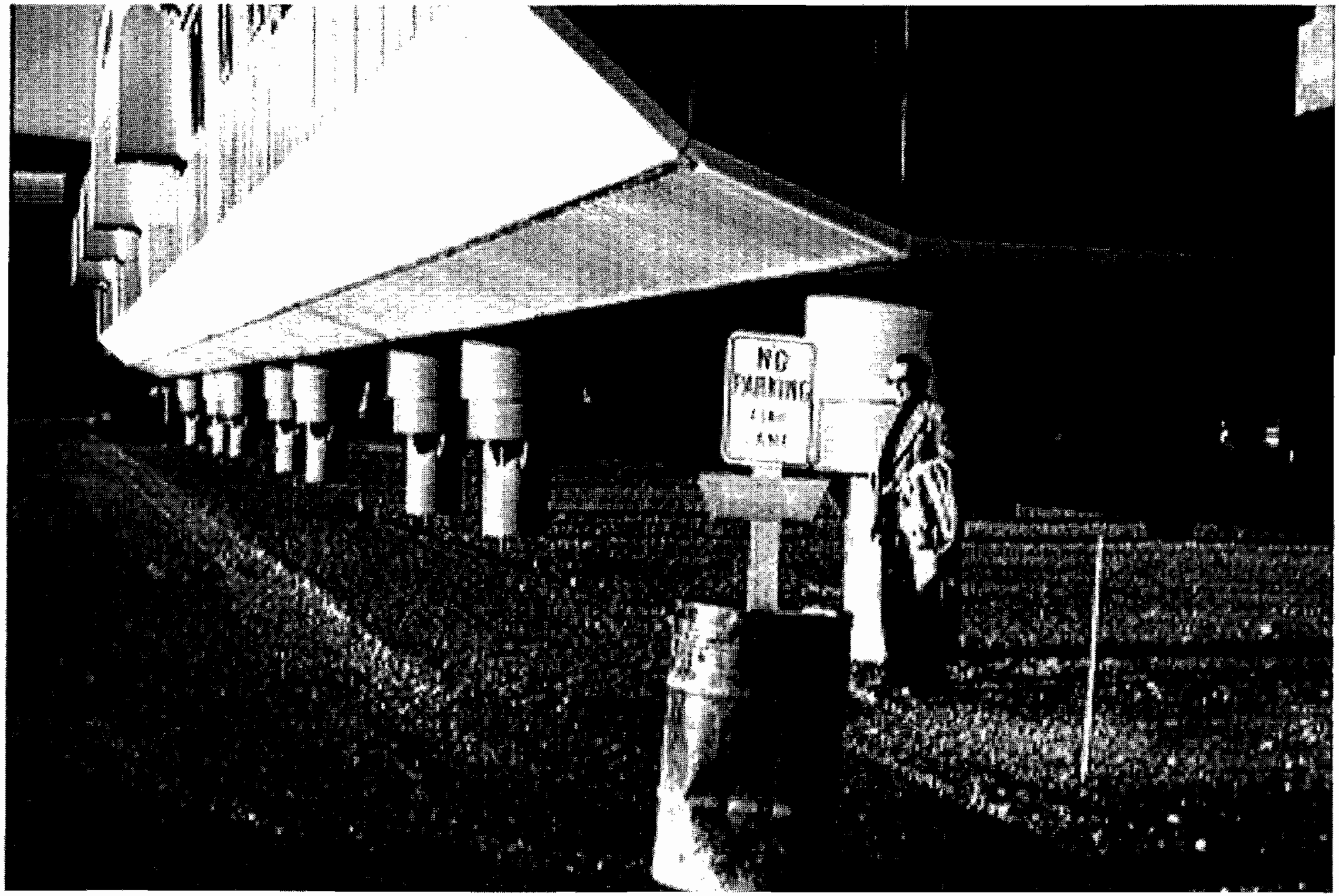

Figure 3.1 British Petroleum Building in Prudhoe Bay, Alaska. Note how the leading edge of the bottom of the building is contoured to give more aerodynamic flow of air under the building.

The "adfreeze" bond between the soil 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 (although 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 resist this heaving force. In order for the weaker permafrost adfreeze bond to overcome the heaving force in the active layer, 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 3.2.7 below). It should be noted that a slurried pile foundation typically costs from \$20 to \$40 per square foot of structure, and even more in very large structures. Although this is expensive, it is far less than the cost of any remedial action that will result when an inappropriate foundation type is used.

3.2.1 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 3.2 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 a very 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

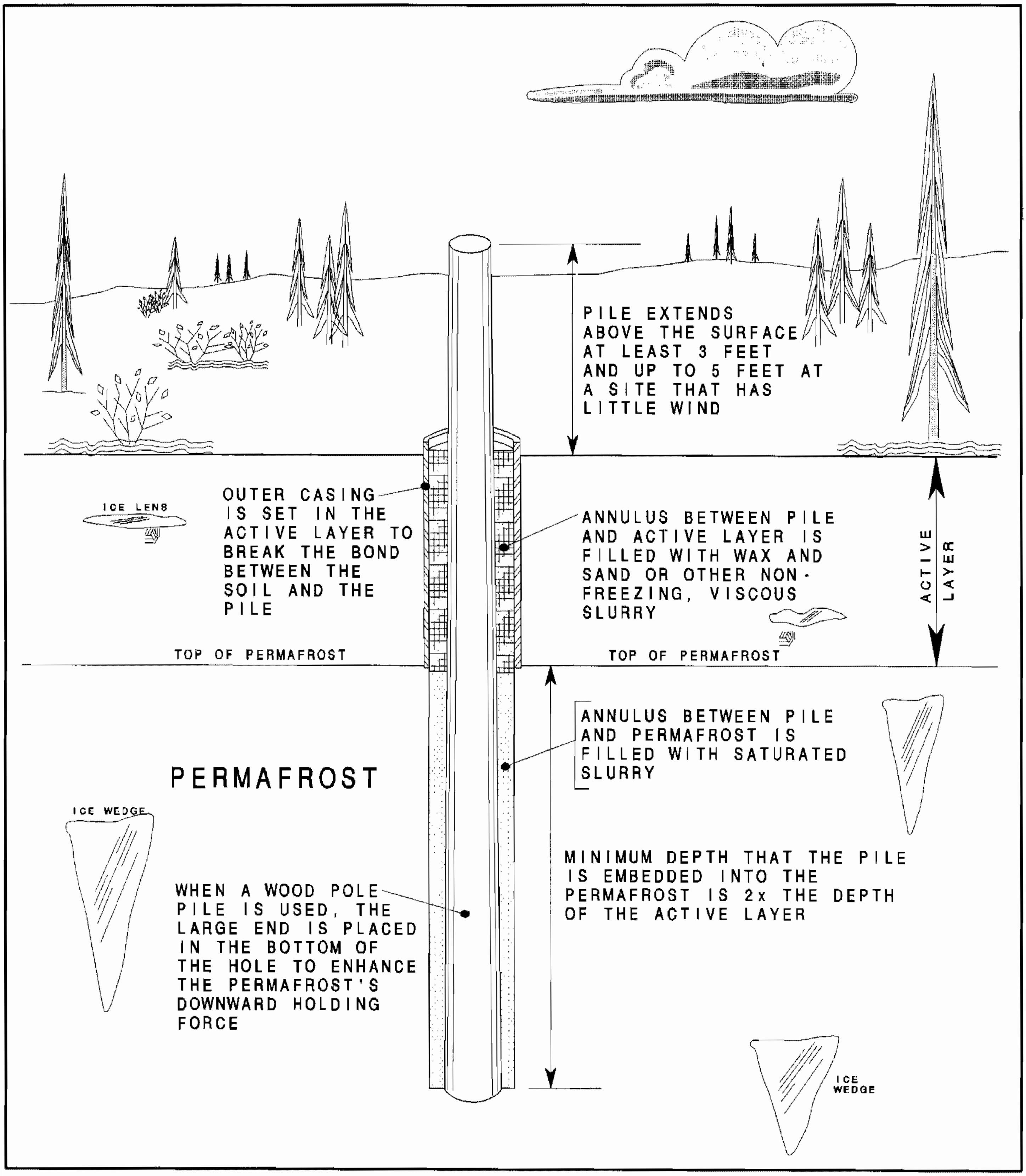

FIGURE 3.2 Typical slurried pile installation at a permafrost site. Note that the ice lenses in the active layer are only present when the active layer is frozen.

the active layer is not exposed to sunlight, clear polyethylene could be used if the aboveground deterioration of the film was acceptable. Figure 3.3 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 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 3.4 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 the larger end at the bottom of the hole. This increases the permafrost's ability to hold the pile while reducing the active layers heaving force.

The annulus around the pile is filled with sand slurry, which is compacted around the pile. Vibratory compactors are preferred, but if unavailable, long rods and careful tamping can be used. One approach argues that the slurry used in the permafrost zone should be made from the material removed from the hole during drilling, and a sand-slurry should be used where the pile passes 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 fewest installation problems. Make the slurry by mixing clean sand[5] with

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

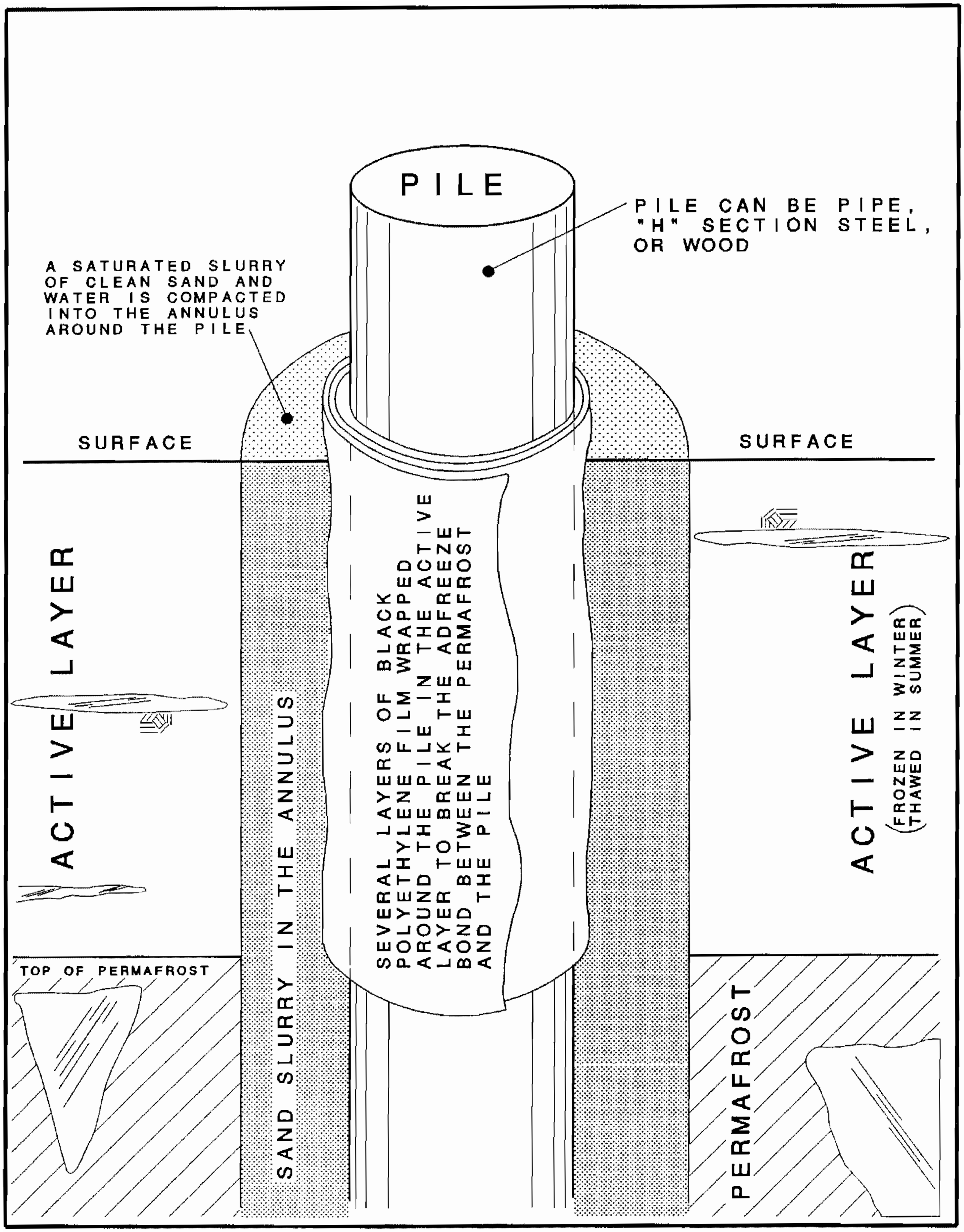

FIGURE 3.3 Polyethylene film used to break the adfreeze bond in the active layer on a slurried pile

FIGURE 3.4 Frost heaving in action. This gate has frost jacked several feet over a period of several years. The right hand stanchion has heaved more than the left stanchion, but even the left side has heaved nearly three feet.

water until a consistency is achieved that gives about a 6 in. (150 mm) "slump." This slurry is easier to work with, gives more uniform results, and develops just as strong an adfreeze bond to the pile (Kinney 1986). When 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 or 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 not be allowed nor should water 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. The slurry must be compacted as stated above to eliminate voids or air pockets and to enhance soil-to-pile contact for a strong adfreeze bond in the permafrost zone.

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

3.2.2. 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 are difficult to avoid.

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 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:

$$Q_{Total} = Q_{sensible} + Q_{Latent} \quad \text{(BTU or kJ)} \tag{3.1}$$

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

$$V_a = \frac{\pi}{4}(D_h^2 - D_p^2) \tag{3.2}$$

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:

$$Q_s = V_a \gamma_{ds} \left\{ \left[\left(\frac{m.c.}{100} \right) (c_w) + c_{ds} \right] (T_{sl} - T_f) + \left[\left(\frac{m.c.}{100} \right) (c_i) + c_{ds} \right] (T_f - T_{pf}) \right\} \qquad (3.3)$$

and the latent heat (Q_L) is:

$$Q_L = V_a \gamma_{ds} (m.c.) L \qquad (3.4)$$

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 F*)

c_{ds} is the specific heat of the dry slurry material (0.17 *BTU/lb*$_m$ *° or0.71 kJ/kg °C F*)

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.

$$t = \frac{(D_h)^2}{12.1\alpha} \left[\frac{Q_T}{C_{vpf} (D_h)^2 (T_f - T_{pf})} \right]^{1.33} \qquad (3.5)$$

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. 3.5 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 3.6.

$$Q_{fb} = (Q_T)(l)N_p \tag{3.6}$$

Where:

Q_T = the total heat added by the slurry of the pile (eq. 3.2 plus eq. 3.3) (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

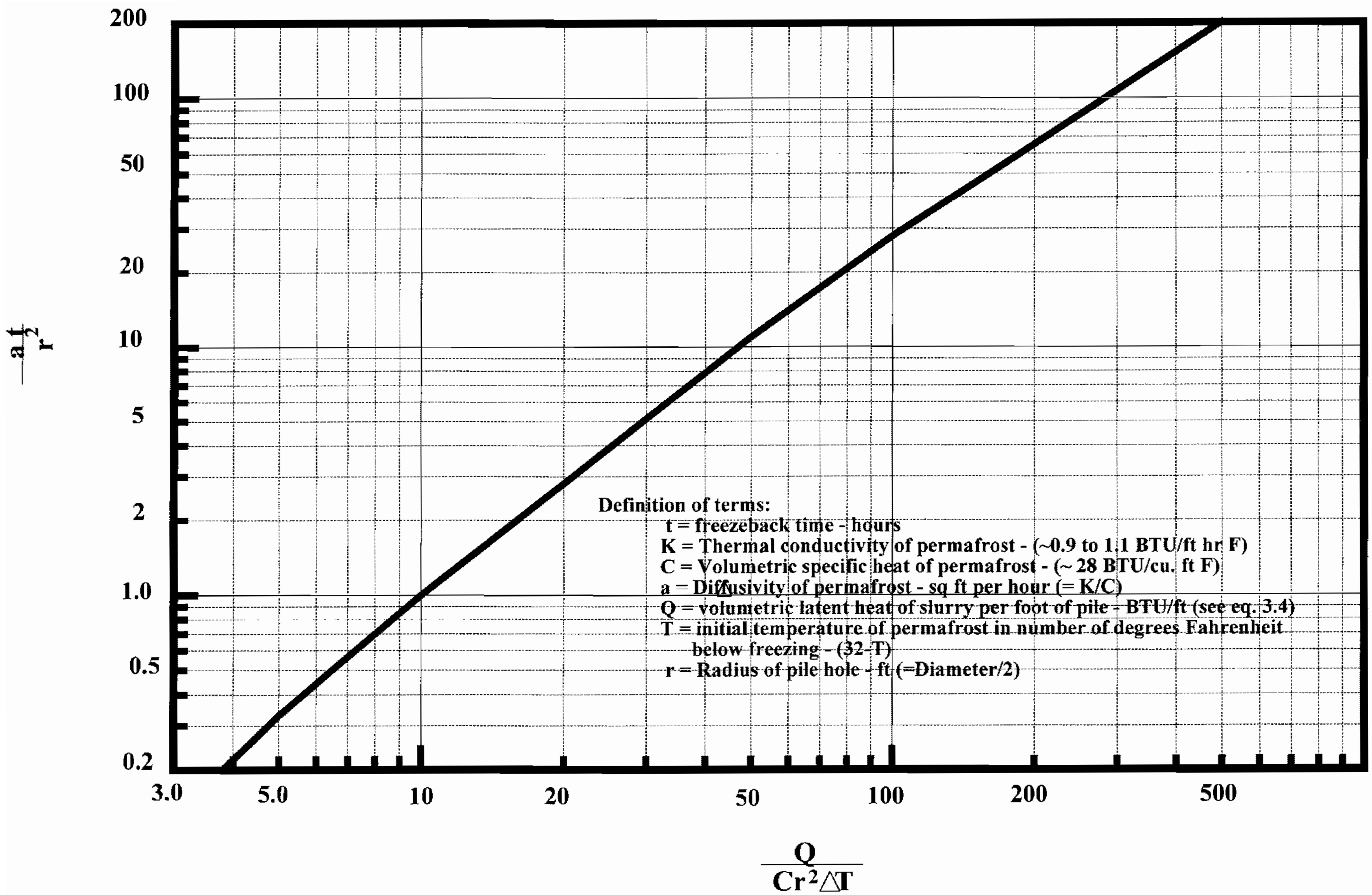

Figure 3.5 General solution of slurry freezeback around piles. From Dept. of Army Technical Manual 5-852-6

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

1. Determine the volume of permafrost involved. Add the spacing distance between piles to the overall length and width of the foundation.

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

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

$$T_{final} = T_{initial} + \frac{Q_{fb}}{V_{pf} C_{vpf}} \tag{3.7}$$

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). A temperature rise of a single degree will be too great. In 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. 3.6 shows the adfreeze bond strength with respect to temperature as reported by several permafrost researcher studies (Johnston 1981).

3.2.3 Driven piles

Steel pipe piles can be driven into frozen soil without pretreating the permafrost when the soils are relatively dry, uniform, fine-grained material that is free of cobbles or boulders.

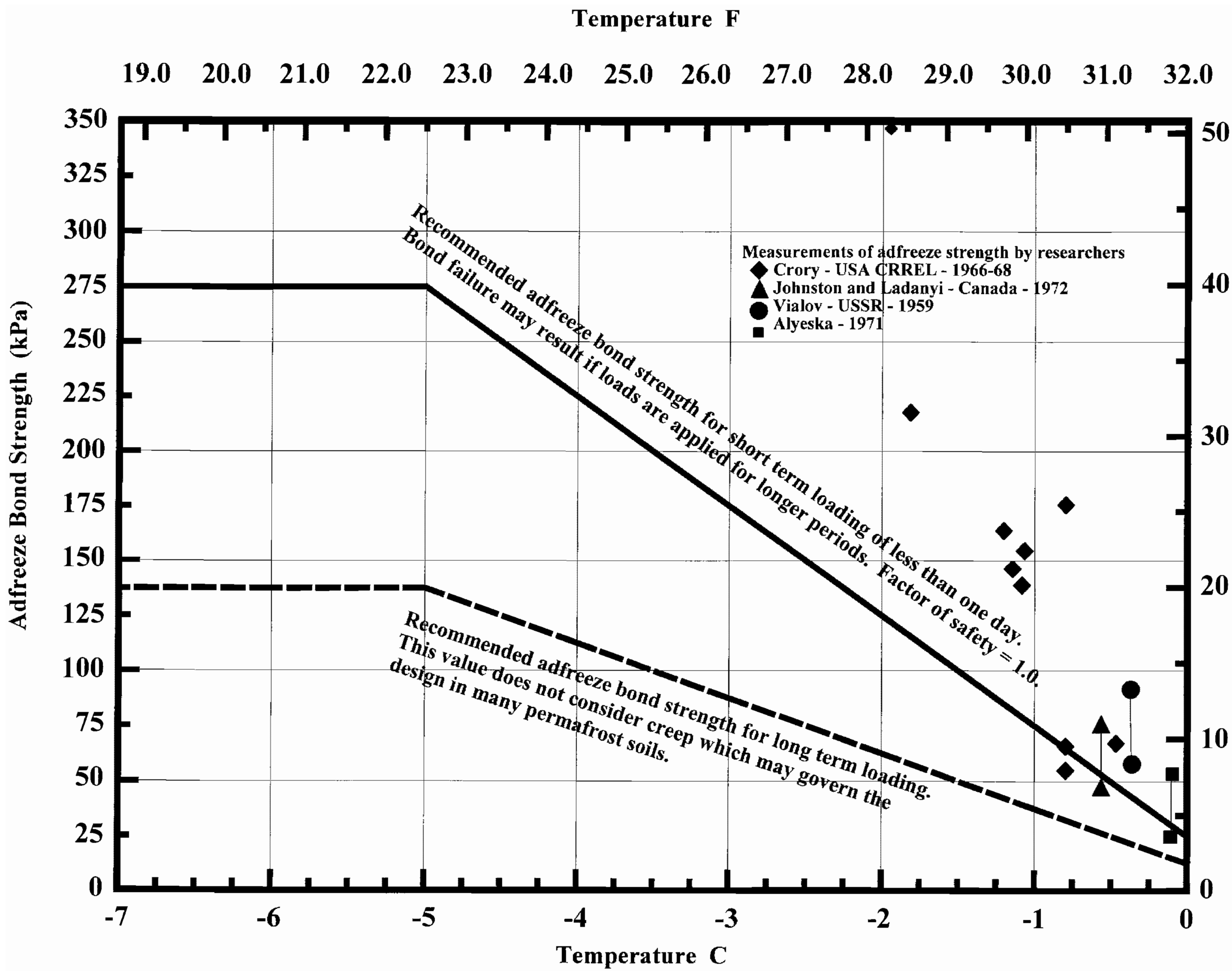

Figure 3.6 Adfreeze bond strength vs. permafrost temperature (after Johnston 1981)

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 preboring 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 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 has been used before driving, then the calculations discussed for slurried pile freeze-back can be used to determine freeze-back time and to estimate pile spacing. When working with preheated holes for driven piles, 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 3.2 In place of those 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) is considered to be zero in equation 3.2.

Used oilfield drill steel, when available, can be driven into frozen soils more readily than can pipe piles. Oil field drill steel is, in essence, very thick walled pipes of relatively small diameter. They can be very cost effective under the right circumstances.

3.2.4 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 assure 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 high enough, 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. 3.7.

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 may be added, the piles may 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 very difficult, and beyond the scope of this paper. A qualified engineer should be consulted if creep criteria are of concern in any foundation.

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.

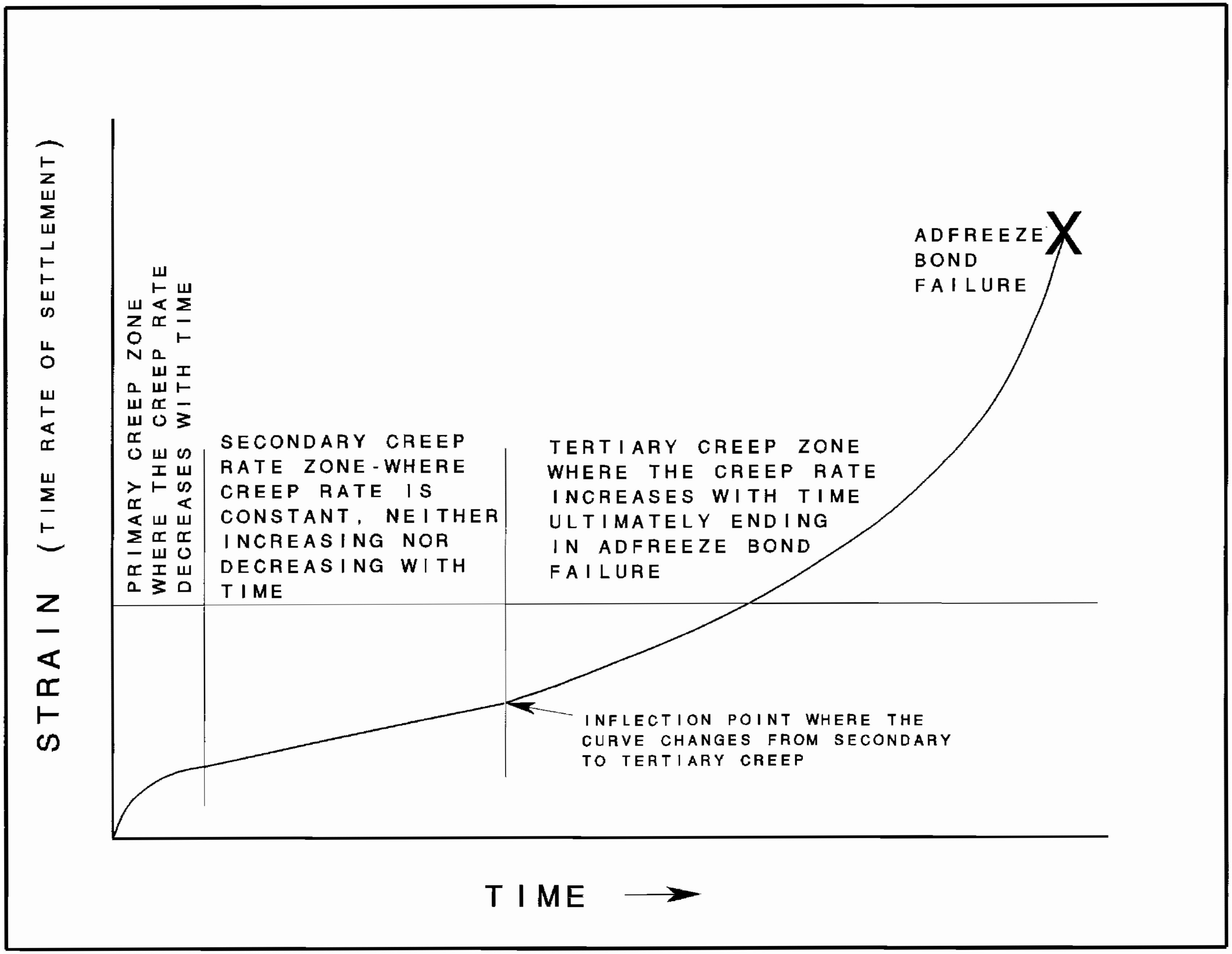

FIGURE 3.7 The three stages of soil creep.

3.2.5 Pile length

When a pile is to be supported by the adfreeze bond between it and 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 so that it can be embedded far enough into the permafrost, to pass through the active layer and support the structure at the proper height above the surface. 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.

3.2.6 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 spring the frozen active layer is colder than the permafrost. Since colder temperatures result in stronger adfreeze bonds, the active layer bonds per foot of embedment are stronger than those in the permafrost. The strength of the force 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 the stronger active-layer bonds the pile must be embedded into the permafrost deep enough to provide a larger area to create a stronger overall bond that will resist the active-layer heaving force.

Fig. 3.6 shows the strength of the adfreeze bond between frozen soil and wood or steel piles as a function of temperature (Johnston 1981). Note that the difference in surface area of adfreeze strength in permafrost at 30 °F (-1 °C) needed to overcome the force from an active layer at 21°F (-6°C) is approximately four to one. Experience has shown, fortunately, that the entire active layer rarely gets this cold except perhaps in the far north. In experiments to measure forces in the active layer, Buska and Johnson (1988) report heave forces on "H-section" piles and on pipe piles of 180,000 and 251,000 lbs. (802 and 1118 kN) respectively. 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.

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. Clearly wooden piles need to be larger diameter to keep stresses below failure limits.

3.2.7 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 black polyethylene film wrapped around the pile are commonly used. Black polyethylene is preferred since it is more resistant to ultraviolet degradation than clear film. The use of grease and sand slurry or wax and sand slurry in the active layer was common practice before the advent of environmental concerns. On driven piles auger 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 3.2.2 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 will 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.

3.2.8 Lateral Loads

Piles have little resistance to lateral loads in that part of the pile that extends from the bottom of the structure to top of the permafrost. If the active layer at the site is very deep, larger piles 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 are available from various sources such as *The Environmental Atlas of Alaska* by Hartman and Johnson 1978.

3.2.9 Driven Piles

Piles can be driven into permafrost without pre-preparation if the soil is a uniform, fine-grained material that is not too hard. Placing piles by driving them into the permafrost has some advantages and some disadvantages over the drilled and slurried method. If driving equipment is available, placing driven piles is often faster and less expensive. Driven piles freeze back more quickly and can be loaded sooner. Placing piles by driving is very attractive when ground water is present in the active layer where it may be difficult to keep the hole drilled for a slurried pile from sloughing without being cased. Although placing piles by driving does not have these 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.

Pre-preparation of hard frozen permafrost or frozen gravel prior to driving piling, involves drilling 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. Pre-warming the frozen soil to near the melting 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 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 less freeze-back time. Water will fill small cracks or voids in the frozen soil and helps 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, sensible heat to raise the temperature to the freezing point will add smaller extra 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 3.8). Successful thawing using water-temperature ranges that vary from 60°F to 212°F (15°C to 100°C) has been reported 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 successfully drive piles. Sonic hammers, however, have not performed as well in frozen coarse-grained soils or in very cold weather.

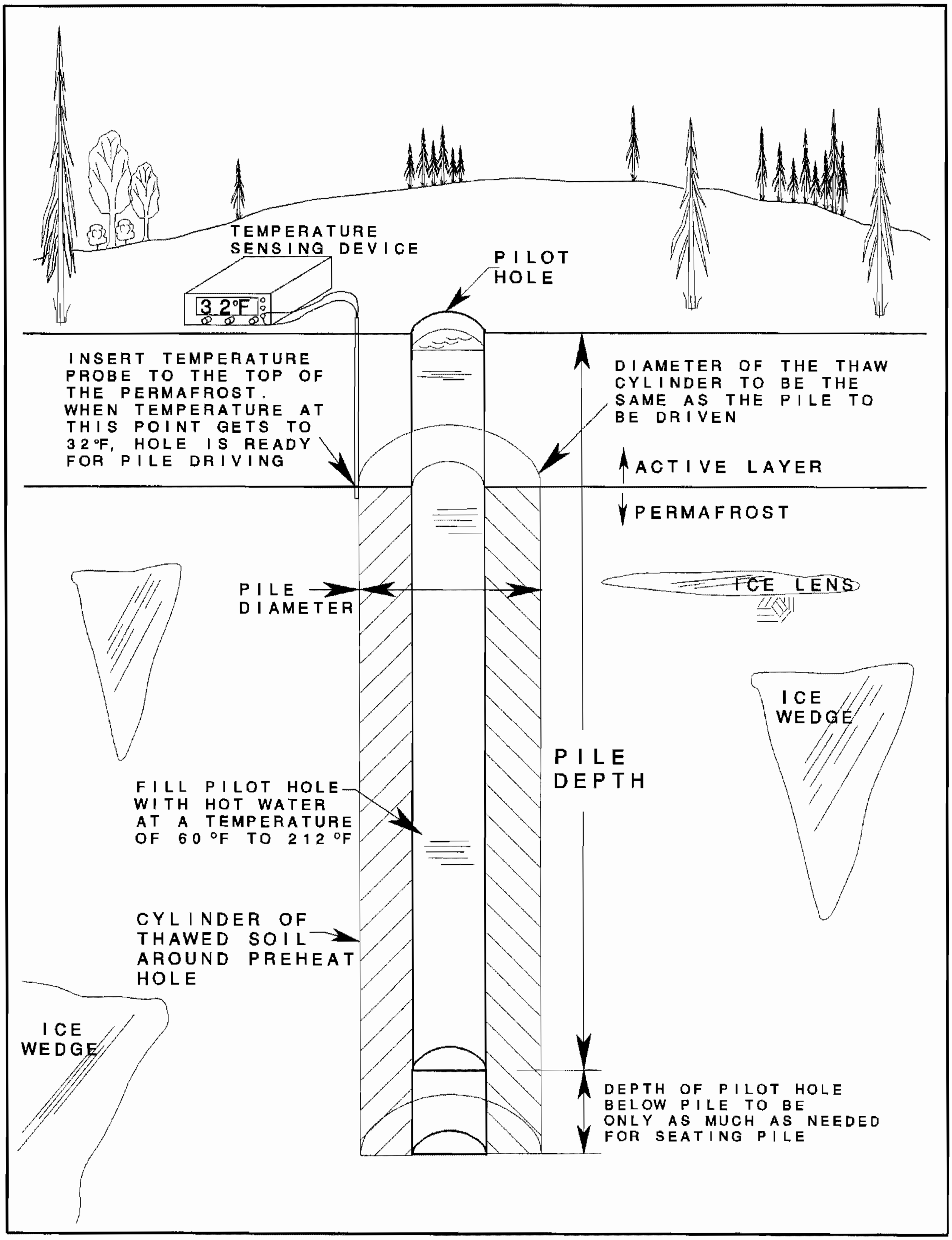

FIGURE 3.8 Preheating a pilot hole in preparation for driving a pile into permafrost

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 driven 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, impact hammer driving rates 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 up to 20 ft/min (6 m/min).

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).

3.2.10 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 permafrost 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 will 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 3.6; 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 soil 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. 3.9). A non-frost-susceptible fill approximately 8" to 12 in. (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. 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 non-frost-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.

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 (1-2 ft for very small buildings, 2-3 ft for garage size buildings, 3 ft for a home and 4-5 ft for large buildings).

2. Heavy insulation must be placed under the floor of the structure so that heat loss from the bottom of the building will be minimized. This will not only protect the

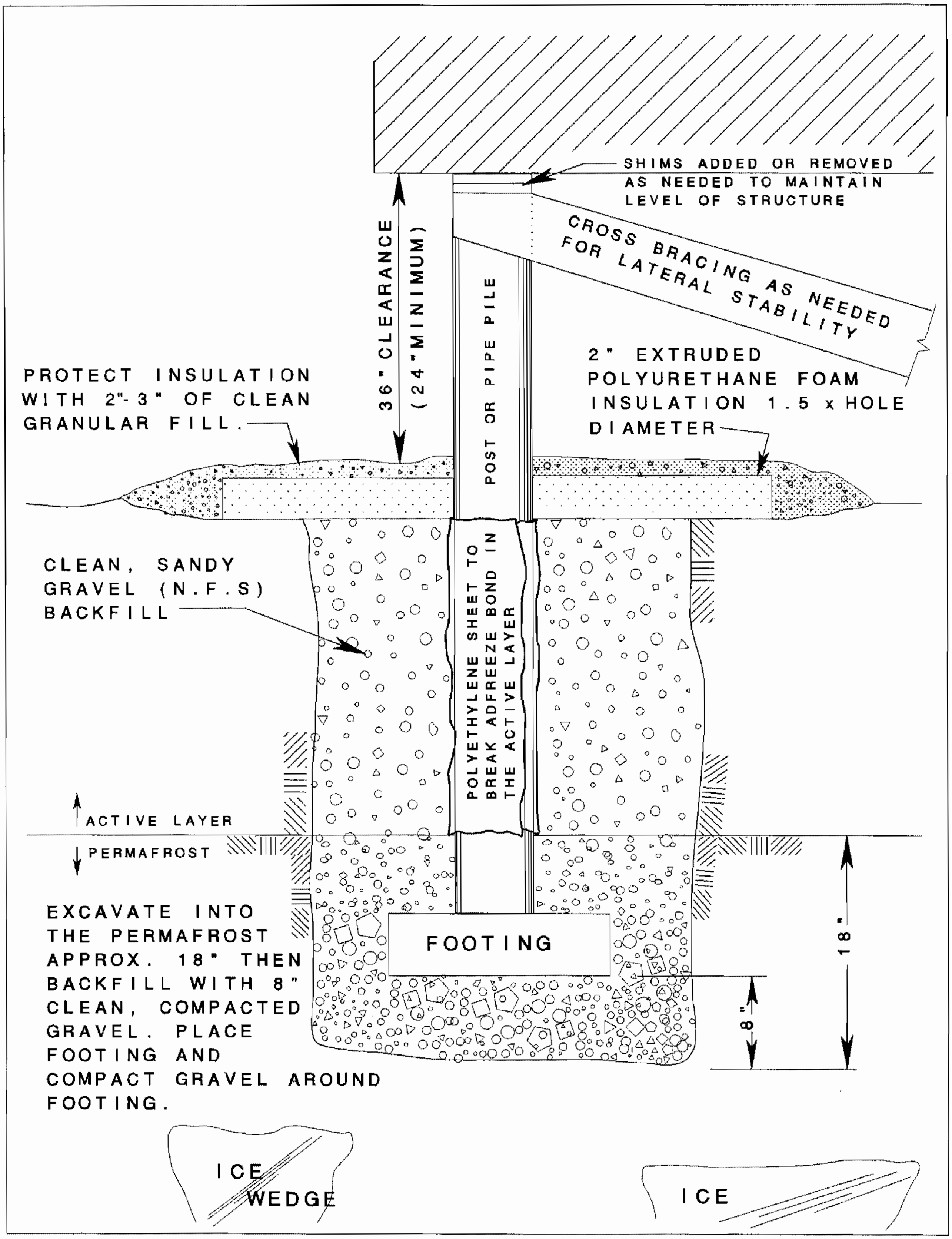

Figure 3.9 Shallow foundation not anchored in the permafrost. Note: This type of foundation requires periodic releveling, see text.

permafrost but it will also 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 that will even slightly interfere with free air circulation during the winter months.

4. In the active layer the adfreeze bond between the supporting pilings, posts or piers must be eliminated or reduced 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.

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.

The Trans-Alaska pipeline uses multiple thermal breaks in their vertical support members (VSMs) between the hot oil and the permafrost in the form of joints with very small contact area, air spaces between warm and cold surfaces, and high thermal resistance layers between contacting surfaces. Wood is a high thermal resistance material so that the entire wooden pile provides a 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 conductivity material at the joint between the building and the pile to stop heat flow from the building into the pile and on into the permafrost. Surface insulation on the aboveground portion of the piling may be required to prevent heat from the sun or the environment from warming the pile and then flowing down the pile into the permafrost.

3.3 Natural Convection Pile Foundation

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 thus enhancing 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 obtain their working fluid from the environment (e.g. cold air drawn in by a blower), or they have a captive working fluid like the red alcohol sealed in a glass thermometer. Closed devices 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 all single-phase, however there are also some 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 the openings on the same end of the device or "air ducts" if the openings are on opposite ends of the tube. Fig. 3.10 shows several natural convection devices.

Some additional varieties of devices are: 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. If the device is designed to support

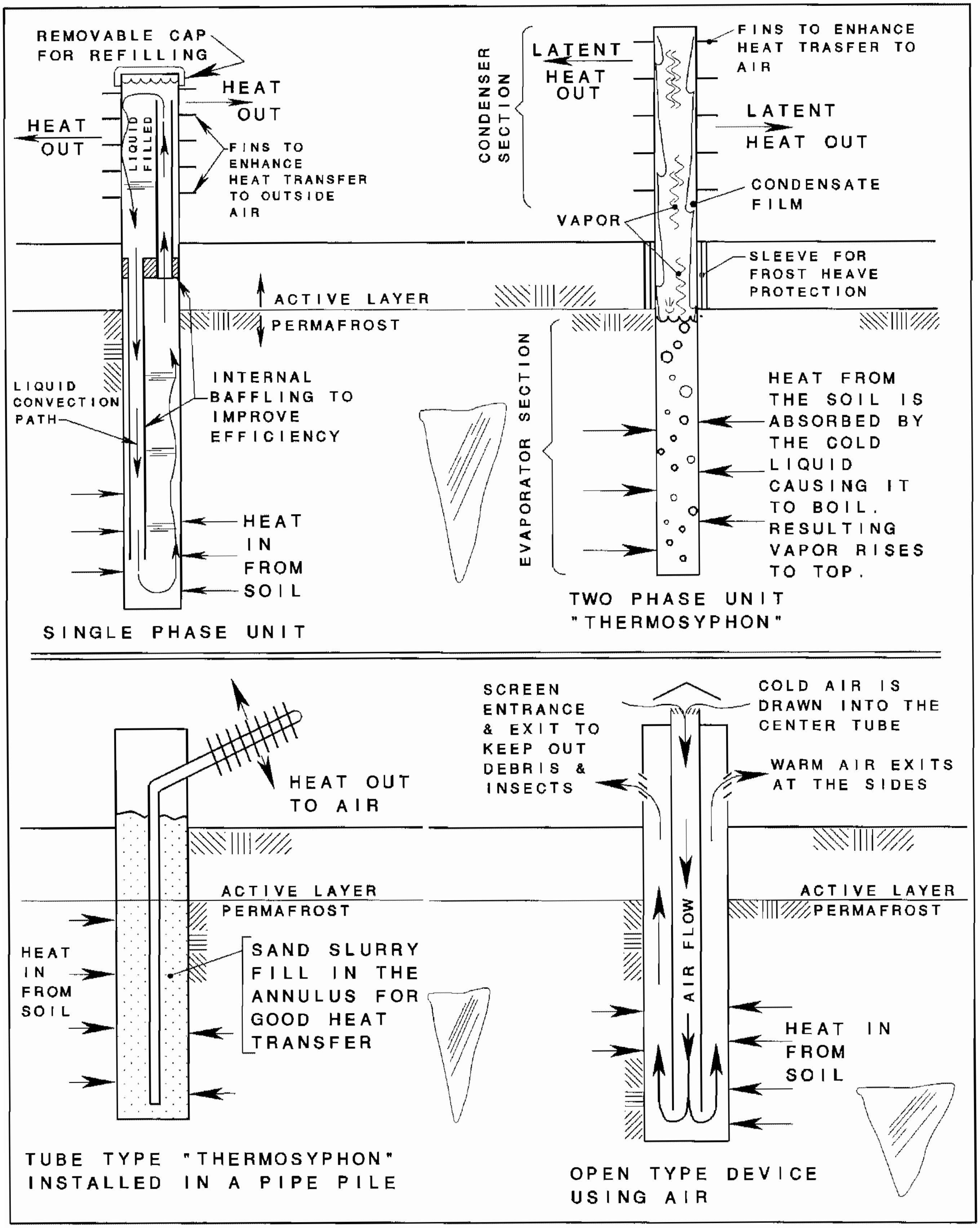

Figure 3.10 Four typical natural convection devices

a structural load 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 perhaps the only) manufacturer of these devices at the time of this publication in 2000 is Arctic Foundations Inc. of Anchorage, AK.

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 Devices (All Single Phase)
Air Convection Pile - has openings on the same end
Air Duct - has openings on opposite ends
Closed devices (Thermal Tube or Thermotube)
Single-Phase - **Convection Tube** or **Convection Loop**
2Phase - **Thermosyphon** or **Heat Pipe** (has internal wick) or thermo-probe
Load Bearing Devices - Thermopile

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

3.3.2 Mode of Operation

Natural convection devices have been used with some success to protect the underlying permafrost. There are several configurations but basically they all involve a long tube or pipe filled with a working fluid and partly buried in the ground. They are installed in the soil beneath the structure with one end of the tube extending vertically into the cold winter air above the surface and the remainder of the tube buried in the ground. The buried end of the tube may extend into the permafrost, or if the tube is installed on an angle, 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 usually a non-freezing liquid. During the winter, when the air temperature is colder than the soil temperature the liquid in the top of the tube (the above ground portion of the device) is cooled through the tube wall by the cold outside air. This portion of the tube usually has fins on the outside to increase the surface area of the wall and to enhance the heat transfer from the liquid inside to the outside air. Since cold liquid is denser and thus heavier, the colder fluid next to the wall sinks to the bottom of the tube, displacing warmer fluid and setting up a convection loop that forces the warmer fluid up the center of the tube to the top. After it reaches a few feet below the surface, the descending fluid is colder than the surrounding soil and heat from the soil warms the fluid thus cooling the soil until it is nearly the same temperature as the outside air. The fluid convection loop inside the tube transfers heat from the soil below the surface to the outside air above the surface much faster than heat can travel through the layers of soil to the surface thus the soil near 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. The convection circulation continues with warmer fluid from the bottom of the tube rising to the top where it is cooled and then continuing the circuit back down the walls to collect more heat from the soil. This cycle continues as long as the air temperature is a few degrees colder than the soil temperature and stops when the air warms to the same temperature as the soil. Therefore during the summer, the units cease operation and are idle; they do not run in reverse.

A two-phase unit (a thermosyphon) works in nearly the same manner except that the working fluid and pressure are chosen so that the fluid changes phase during the operation. The tube must therefore 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 to be one that will boil at a temperature near the soil temperature (i.e. when the pressure of the gas in the top of the tube falls below the vapor pressure of the liquid in the bottom of the tube). When the thermosyphon is first filled,

the tube contains liquid in the bottom and vapor of that liquid in the top (Figure 3.11). 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. When the air temperature above ground falls below the condensation temperature of the gas in the top of the tube, vapor 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 heat needed to change the liquid to a gas (called the "latent heat of evaporation") during boiling is very large and is drawn from the soil surrounding the buried portion of the tube. The amount of vapor produced is limited by the amount of latent heat that can be drawn from the soil. Since the vapor is much less dense than the liquid, it rises to the top of the tube (the condenser section) where it comes in contact with the colder aboveground wall of the tube where it gives up its latent heat causing it to condense back to a liquid. 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 tube but boiling in the liquid in the bottom produces 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 at a higher level of activity. A new dynamic state of equilibrium is achieved and heat transfer out of the soil increases proportionately.

The cycle continues as long as the temperature above ground is colder than that below ground; this applies to both single-phase and two-phase units. When warm weather arrives and the temperature of the outside air rises above the equilibrium temperature established inside the tube, condensation ceases and pressure rises until boiling stops. The tube is then in a stable condition with less dense vapor on top and heavier liquid on

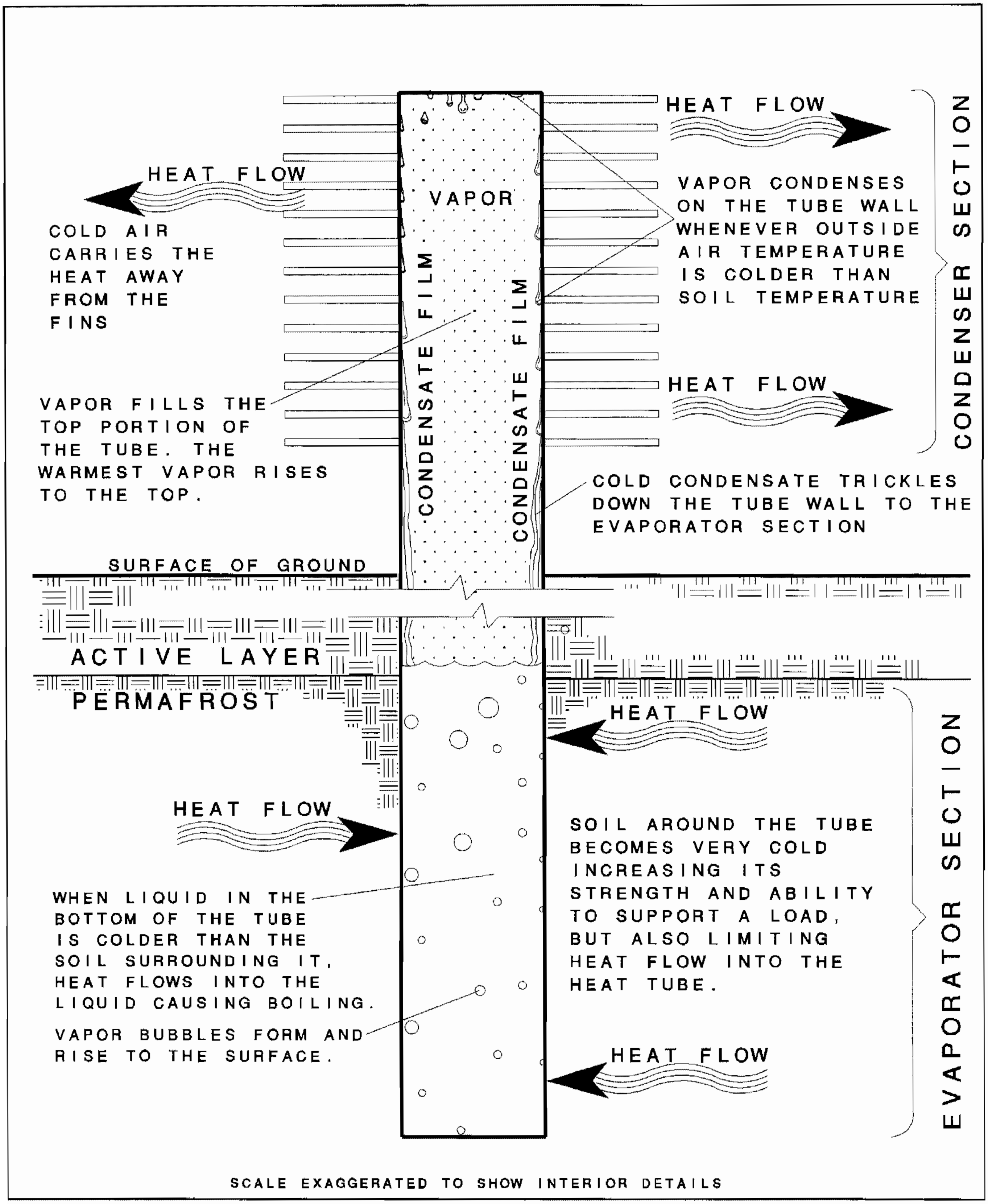

FIGURE 3.11 Details of a two-phase heat tube operation

the bottom. The convective action ceases as does heat transfer out of the soil; the device remains dormant as long as the air temperature is warmer than the soil.

3.3.3 Limitations on Operation

The total thermal resistance of the heat transfer path including the convection circuit, thermal resistance of the tube walls, air films on the surfaces etc. is what limits the amount of heat that can be removed from the soil. 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 (figure 3.11). 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. Therefore, these devices work best when they are well exposed to winter weather, especially wind.

The internal thermal resistance of the working fluid is much lower in the two-phase systems than in the single-phase systems therefore the 2-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 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 couple of years) the heat must move through so much frozen soil that the controlling parameter for the amount of heat that can be removed from the ground is the thermal resistance of the frozen ground around the pipe. This thermal resistance is the

same for both devices so that in the long term both devices remove heat at about the same rate (Johnson 1971).

In the condenser portion of the pipe (the above ground 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. Since the temperature at which these devices need to begin to operate is generally between 25°F and 30°F (–4°C to -1°C) (slightly below the freezing temperature of water), each fluid must operate at a different pressure. 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." Since thermosyphons are more efficient internally, they can be smaller and lighter than convection tubes of the same capacity. See McFadden and Bennett 1991 for more information on thermosyphon working fluids.

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 have been built in moderately well equipped home workshops. To increase their efficiency, internal baffling should be added to segregate the upward and downward moving convection currents and to deliver the coldest fluid to the bottom of the tube, and the warmest fluid to the top (figure 3.10), but the baffling can be fabricated from locally available materials. It is important to seal the tubes well since the working fluid in them is usually detrimental

to the frozen soil. If it leaks it may cause the permafrost to thaw. This, of course, will seriously worsen the problem they were installed to correct.

3.3.5 Monitoring the Operation of Convection Devices

Determining if a convection tube is operating is a difficult problem, 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 in the finned section will be a few degrees warmer than the surrounding cold air. A thermistor taped to the pipe just below the fins will measure the pipe wall temperature and show if the unit is 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.

On thermosyphons with higher working pressures, 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 is an indication 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 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 these 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 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 with both their evaporator and their condenser sections set to a positive slope from the bottom to the top. This will allow the normal buoyancy process of convection to work. The slope can be very small, even approaching level, 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 steeper than 15 horizontal units to one vertical unit are recommended for the buried portion of the pipe. This is to give some protection against a negative slope developing along the pipe caused by settlement or frost heaving. Thermosyphons should be installed prior to initial construction and can be laid in trenches in the fill or active layer beneath the site. They should be placed so that the upper end of the evaporator section is near the interface with the permafrost. 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 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. If there is any possibility of a hydrocarbon spill such as heating fuel or gasoline, then refer to section 2.2.7 Chemical Stability of Foam Insulation. In this case, insulation is very effective because it reduces the amount of heat getting to the permafrost while the thermosyphons bypass the insulation to maintain winter freeze-back.

3.4 Surface Foundations

3.4.1 Post and Pad Foundation

One of the least expensive approaches to permafrost foundation design is the surface foundation. The surface foundation is most commonly used for small homes and buildings, but it has been successfully used for warehouses and supply buildings. This foundation requires considerable maintenance and needs periodic releveling (at least twice per year). The supported structure must be built to tolerate a small amount of differential vertical movement without permanent structural damage. This foundation meets the criteria for an acceptable permafrost foundation in that it protects both the permafrost and the building from destroying each other.

The 'post and pad' is the most commonly used foundation of this type. A drawing of the details of a post and pad foundation is shown in Fig. 3.12.

Like all of the foundations in this category, the post and pad foundation rests on top of the surface (or at least in the top layers). Posts of pressure-treated "all weather" wood, pipe or concrete support the building several inches to a few feet above the surface. As discussed above, steel and concrete provide much lower resistance to heat flow than wood does. This is an important consideration when permafrost is present. If marginal Permafrost (permafrost that is close to thawing) is present, then steel and concrete are less desirable than wood for this application.

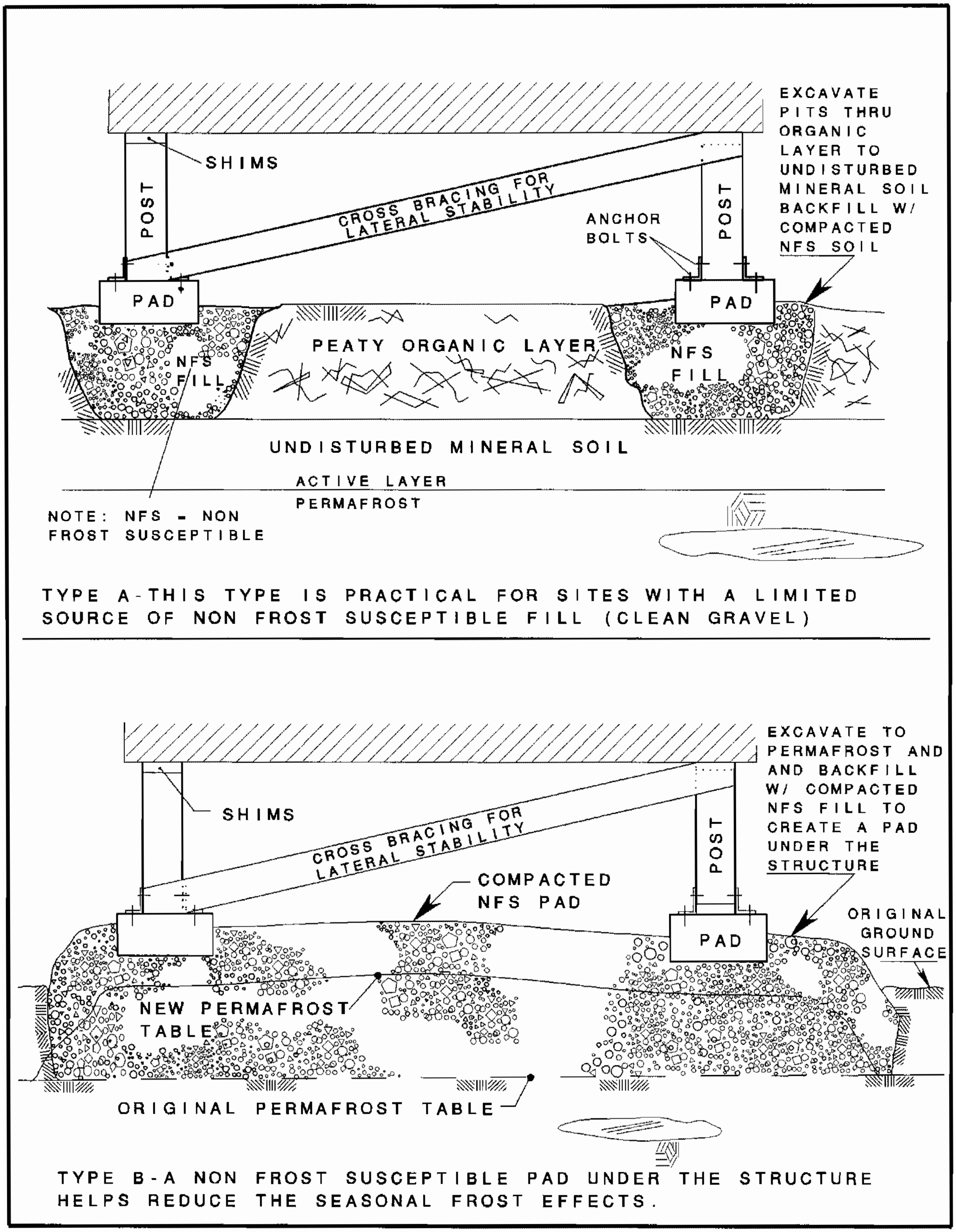

Figure 3.12 Post and pad foundation details. In type B the permafrost will rise into the gravel pad as thermal equilibrium is reestablished and help reduce seasonal frost movement.

A pressure-treated wood or a concrete pad is used to distribute the load from each individual post to keep the stress on the soil low enough so that the foundation will not sink into the active layer during summer. Since the conditions at a given site can vary widely, the size of the pad required to prevent sinking will also vary. The best rule of thumb in this case is the larger the pad area in contact with the ground the better. If the soil is relatively dry then a moderate pad will suffice, but soils that are wet, or moist much of the time may require considerably larger pads to accomplish the task.

Whenever wood 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 f it is frequently exposed to moisture, the joint between the post and pad will likely collect enough moisture to sustain decay organisms, so if the post is also wood, it too should be made from treated wood.

To best prepare the site, place and compact a non-frost-susceptible granular fill that extends at least 6 ft (1.8 m) beyond the perimeter of the building on all sides. In remote sites where gravel is costly or very expensive, however, 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 and peat until the undisturbed mineral soil is exposed. Where the organic soil layer (peat etc.) is more than two or three inches thick it may be necessary to backfill the resulting small surface excavations with non-frost-susceptible (NFS) material such as clean well graded gravel to maintain the level of the 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 must be excavated until it is deep enough to allow a layer of compacted sand at least 12 in. (305mm) 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 be a minimum of 2 ft (610 mm). The object is to provide an unimpeded airway for winter air circulation between the building and the ground. 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, insulation also may have to be placed in the gravel fill on the ground to further protect the permafrost. 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 experiences 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 remove it when the air temperature drops below freezing, but this is a logistics problem that is difficult to implement.

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 lighter weight construction often found in pre-built or "mobile" homes. "Duck Bill" anchors and cables are often used for anchoring smaller structures on permafrost soils.

Since this foundation is supported on the surface rather than in it, the foundation and the structure will rise and fall as the active layer heaves. This creates a maintenance requirement for the building to be releveled. At each post the building must be raised with an adequate jack and shims must be added or removed between the post and the building to restore the structure to a level condition. This must be done whenever differential movement becomes noticeable which is usually during the fall freeze-up or the spring thaw. If anchor bolts are used between the structure and 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, this releveling exercise will take place at least twice yearly. At sites where frost action is severe, it may be necessary to relevel several times during the transition between freezing and thawing.

Surface foundations are best for use at sites in which heaving potential is low, but if the required maintenance is performed as needed, the foundation will withstand most differential heave situations. 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 solution for smaller, lightweight, temporary construction. It is quite popular in remote, undeveloped areas of the north since is can be constructed by one or two persons and where large equipment is unavailable.

3.4.2 Adjustable Post and Pad Foundation

To make the maintenance chore easier and quicker, the posts of a post and pad foundation can be replaced with mechanical jacks. Then whenever an adjustment is needed, it is a quick and simple task to insert the jack bar and raise or lower that position in the foundation. To further simplify the procedure a "water level" can be installed all around the structure to give the elevation of each jack in the system. Differential settlement is then easily noted at each position and can be adjusted as needed to keep the building in perfect level. Water levels are easy to make by using a tubing loop (copper or plastic) that encircles the building with vertical "standpipes" at each jack location. A reservoir mounted above the level of the tubing loop provides a reserve of liquid to fill the loop and the standpipes (figure 3.13). After initial leveling of the building, the reservoir is filled with a non-freezing liquid such as water and ethylene glycol, and its level is permanently marked. The reservoir will fill every standpipe and the level of each one is marked. If any portion of the building is heaved or settles, the level in that standpipe will show the differential vertical movement. It is then a simple matter to activate the jack and relevel the building. Another ideal but more expensive solution is the use of a laser level for this

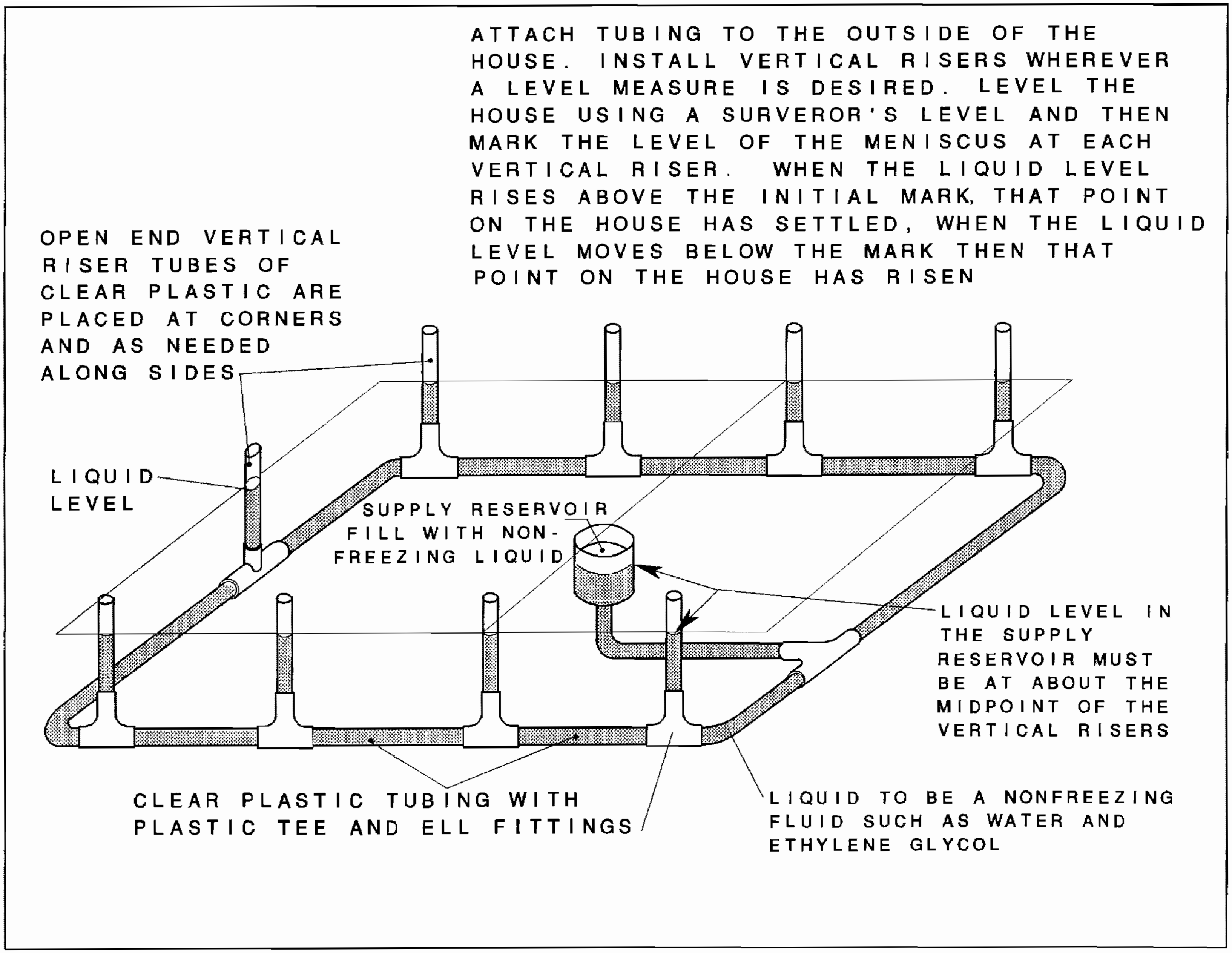

FIGURE 3.13 Details for level measurement system using a water level

purpose. 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 is only applicable to smaller buildings that can be raised by mechanical jacks and individual labor.

3.4.3 Rigid Three Dimensional Truss Foundations

Still another surface foundation that has found success in permafrost regions is the rigid three-dimensional truss-type foundation. This is a commercially available pre-manufactured foundation that resembles the structures used for work in space. It is custom made to the building size for which it is to be used and shipped unassembled to the site. The frame consists of aluminum tube members flattened on each end and connected by aluminum node pieces at the top and bottom to form approximately three-foot square cells. The cells are interconnected at each node to form a three-dimensional "truss-type" framework beneath the entire building. Like most trusses, there is a degree of flexibility to the overall structure, so the building must be able to accommodate some flexing without structural damage. Fig. 3.14 shows one of these foundations installed under a small two bedroom home.

3.4.4 Sill Foundations

"Timber sill," and "Skid" foundations also belong to the surface foundation category. Instead of posts and pads, two or three timber beams run longitudinally underneath the structure. Steel beams have also been used, but steel is not recommended if permafrost is present, for the same reasons mentioned in the post and pad discussion. The skid foundation is particularly applicable to very small buildings that need to be moved from one location to another. The beams are rounded or beveled at each end to make the building easier to pull. The timbers of these "sill foundations" do not elevate the structure above the surface as high as needed for a permanently heated structure on permafrost terrain, but they will usually be adequate for a building that is normally unheated and is frequently moved.

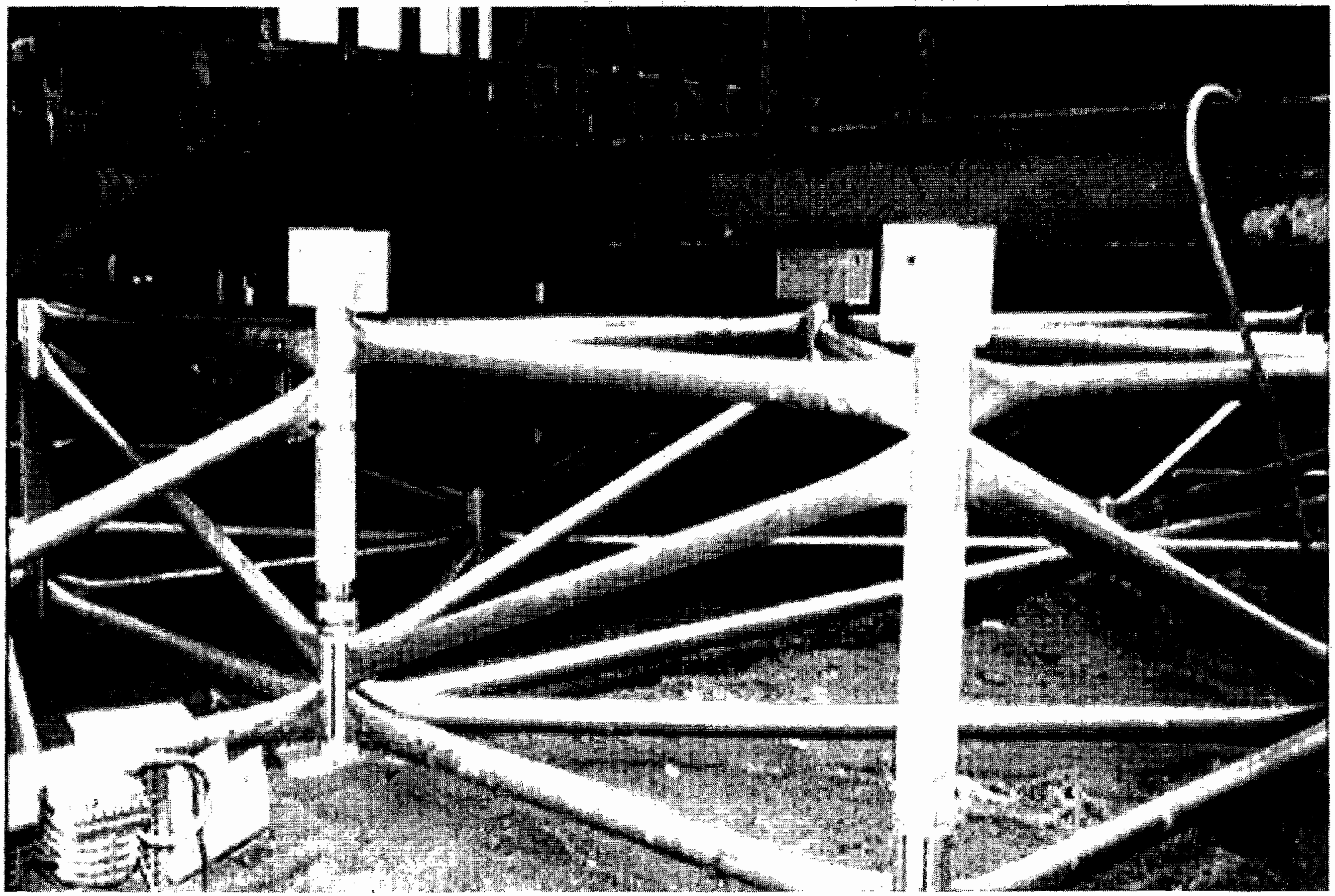

Figure 3.14 Three dimensional truss-type foundation manufactured by Triodetic Corporation of Canada.

3.4.5 Refrigerated Pad Foundations

Some buildings, such as aircraft hangars or heavy equipment shops, require a floor that can support very heavy loading. It usually is not economically practical to elevate such buildings, and it is better to have the floor slab resting on the ground. For these applications the refrigerated slab approach has been used successfully in many locations underlain by permafrost. The principle is the same, to prevent heat from the structure from getting to the permafrost. A thick, compacted, non-frost-susceptible gravel pad is placed on the cleared site. Insulation is buried near the top of the pad over its entire area. The pad must be thick enough (usually 4 to 6 ft (1.2 to 2 m)) to provide enough space to bury heat collection devices within it. Heat that escapes through the floor and enters the pad must be collected and dispersed to the air above the site to prevent it from reaching the permafrost. Several types of heat collection devices have been used in these designs; including thermosyphons, air tubes, ventilated ducts and convection loops. The thermal analysis necessary to determine the number and placement of the heat collection devices in this type of foundation is complex and daunting. This analysis is best left to engineers, who are familiar with the complex heat transfer problems involved. Success with this system has varied from good to bad and both designers and owners have learned several object lessons to avoid. Maintenance of the heat collection devices must be performed on a regular basis or the foundation will likely fail. For a more complete discussion of this type of foundation see McFadden and Bennett, 1991.

3.5 Final Considerations

3.5.1 Air Flow Beneath the Elevated Foundation

It is important to remember that all elevated foundations rely on free circulation of air beneath the building to protect the permafrost. You must not allow this feature to be compromised by allowing the space under the building to be used for storage or by letting debris or snow accumulate there. To ignore this maintenance chore will destroy the ability of the foundation to protect the permafrost and will eventually result in its failure. Anything that discourages the free flow of air below the building must be eliminated.

Although the temptation to add skirting around the building for aesthetic purposes is strong and may be advantageous in the summer, after a few seasons, the skirting is invariably forgotten and left in place during the winter thus destroying the function of the air space. For this reason it is prudent to avoid the use of skirting around the air space beneath the structure. It cannot be mentioned too often that this space beneath the house **must not be used for storage**. Boxes, snow-machines, etc. will impede the flow of cold air during the winter and will trap drifting show to further compound the problem.

3.5.2 The Surrounding Site

The area surrounding the building is also important to its stability. Be sure that the pad on which the building is constructed extends well beyond the building itself. If the surrounding area in the immediate vicinity of the building must be cleared, the thermal regime will be changed and, unless actively protected, the permafrost beneath this area will deteriorate. This will be detrimental to such things as water or sewer lines that connect to the building causing endless maintenance problems and will eventually affect the permafrost under the building itself, especially if the cleared zone is paved with asphalt. It is best to keep a buffer zone around the building that is free of cleared ground or is revegetated to restore the original thermal balance, although re-vegetation will not restore the transpiration advantages associated with the original moss cover.

3.5.3 Access to the Site

If a driveway needs to connect to the building, it should be covered with a thick layer of non-frost-susceptible fill, but it should be left unpaved. If possible it should approach entirely on the north or northeast side of the building and should be kept clear of snow in the winter. The south and southwest exposures are the most vulnerable since they get the majority of the sun. If trees or other cover can be positioned so that they shade the building on these sides it will reduce the thermal input of the sun. Plan access to the site to approach from the north and northeast sides as much as possible, and consider leaving or replanting any vegetation that will shield the road or the building from the sun. Vegetation, even grass, reduces heat input from the sun and the warm summer air.

APPENDIX

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