INITIAL PERMAFROST ENGINEERING RESEARCH IN ALASKA

By

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INITIAL PERMAFROST ENGINEERING RESEARCH IN ALASKA

A

THESIS

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By

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Abstract

Past permafrost engineering research and projects can aid modern permafrost engineering. The knowledge base of lessons learned among engineers is important, especially between generations of engineers, so history does not repeat itself. Uncovering the history of permafrost engineering, and its compilation, summarization, and analysis, is beneficial for the Alaskan engineering community. This master's thesis is devoted to the early years of permafrost engineering in Alaska with projects carried out from the Gold Rush era to shortly after WWII. The projects include: thawing technology developed by gold miners, Alaska Highway road design and construction with its influence, and early comprehensive research by the Permafrost Division of the U.S. Army Corps of Engineers' St. Paul District, particularly the development of the test site, the Fairbanks Research Area, along Farmers Loop Road. Each of these projects has been successfully adapted to modern practices, laying the foundation of permafrost engineering.

Table of Contents

List of Figures

List of Tables

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Cysewski, M.H. and Y. Shur. 2009. Pre-Thawing: From Mining to Civil Engineering, a Historical Perspective. In *Cold Regions Engineering 2009: Cold Regions Impacts on Research, Design, and Construction: proceedings of 14th Conference on Cold Regions Engineering, August 31-September 2, 2009, Duluth, Minnesota,* ed. J. J. Hinzmann and H. D. Mooers, 22-31. Reston, Virginia: American Society of Civil Engineers.

Chapter 1 Introduction

Permafrost exists under about twenty percent of the world's land area. In contrast, more than eighty percent of Alaska is underlain by permafrost. Problems due to thawing of ice-rich permafrost, such as differential settlement, plague Alaskan infrastructure. Inappropriate design and maintenance of roadways, airports, railroads, pipelines, and buildings constructed on permafrost have resulted in damage or destruction of these facilities (Péwé 1993).

The lessons learned from these experiences provide an opportunity to avoid the mistakes of the past, and to build on the successes. For example, the Trans-Alaska Pipeline System (TAPS) – one of the most famous permafrost engineering feats – was designed and constructed using past engineering research and projects. TAPS was aligned to avoid ice-rich permafrost as much as possible using aerial photographic interpretation (McFadden and Bennett 1991, 42). Adapting aerial photographic interpretation to permafrost terrain was one of the first Alaskan permafrost engineering research projects in the 1940s. TAPS engineers also studied the design and construction of the Davidson Ditch, a mining water supply system built in 1928. TAPS and the Davidson Ditch have similarities that include pipeline design, permafrost excavation procedures, and logistics (McFadden and Bennett 1991, 511).

1.1 Research Purpose

Past permafrost engineering research and projects document a century of rich Alaskan history that can aid modern permafrost engineering. Underrating knowledge gained through experience results in mistakes tending to repeat themselves. The few existing books on permafrost engineering cover construction on permafrost from predominately theoretical point of view. Furthermore, like any compiled subject book, the content is generalized and cannot cover every single issue. When an infrequent problem is encountered, an engineer should look for historical references. Information on past projects and research are spread across numerous conference proceedings and buried in countless technical reports. Uncovering the history of permafrost engineering, and its compilation, summarization, and analysis, is beneficial for the Alaskan engineering community. This research would also increase public awareness to highlighted examples of past significant permafrost engineering.

1.2 Research Summary

This master's thesis is devoted to the early years of permafrost engineering in Alaska with projects and research carried out from the Gold Rush era to shortly after WWII. Projects include:

- thawing technology developed by gold miners;
- road design and construction experience including the influence of the Alaska Highway;
- early comprehensive permafrost engineering research conducted by the Permafrost Division of the St. Paul District of the U.S. Army Corps of Engineers, particularly the development of the research test site, the Fairbanks Research Area, along Farmers Loop Road.

The sections of each chapter are labeled with "Background," "Engineering," or "Analysis." The background sections provide a history that triggered the engineering project or research. The engineering sections detail past permafrost engineering research or projects. The analysis sections are the modern uses or author's own thoughts.

The first contributors to permafrost engineering in Alaska were the gold miners. The early miners learned engineering on permafrost the hard way. Starting with thawing permafrost with fire and heated rocks, they shortly discovered steam thawing, and later developed cold-water thawing. These thawing techniques were later adapted by Russian miners, and then by civil engineers for pre-construction thawing of permafrost.

The Alaska Highway construction did not directly contribute much to modern permafrost engineering road design and construction. It did trigger the initial comprehensive research on permafrost engineering techniques in the United States.

The Permafrost Division under the St. Paul District of the U.S. Army Corps of Engineers was the first group to systematically study permafrost engineering methods in the United States. The Permafrost Division research program contributed to the body of knowledge in permafrost, including:

- The n-factor method which allowed the correlation of air temperatures to ground surface temperatures.
- Methods of predicting thermal properties of Alaskan soils through a contract with Miles S. Kersten.
- A manual on aerial photographic interpretation for Alaskan terrain developed Purdue University research through a contract.
- Creation of the Fairbanks Research Area, the first permafrost engineering research site in the United States. On this site, they experimented on long-term vegetation modifications, runway test sections, and building foundations.

Through these activities the Permafrost Division helped lay the foundation for permafrost engineering.

Each of these projects and research has been successfully adapted into modern engineering practice. The results of this work introduce the accomplishments of Alaskan pioneers in permafrost engineering to current and future engineers and scientists.

Chapter 2 Mining Thawing Research

Gold miners may not come to mind when thinking of permafrost engineering, but they were the first American permafrost engineers. Miners looked for ways of thawing the permafrost in order to remove the thawed gold-bearing deposits. Miners also developed ways of building houses and roads on permafrost as part of living in the north, but the gold miners are really known for their development of thawing techniques for permafrost. These thawing techniques were later incorporated into current civil engineering practices of pre-construction thawing.

2.1 Background – Gold Rushes

The Klondike Gold Rush started in 1897 (Rickard 1909). While the Klondike is in Canada, most Americans at the time thought it was in Alaska. The more popular routes to the Klondike were even through Alaska, including up the Yukon River or through the Alaskan White or Chilkoot Passes. Once the Klondike claims filled up, the miners started to look for gold in Alaska. The Nome Gold Rush then started in 1899 (Naske and Slotnick 1979). The Fairbanks gold rush started in 1903 (Cole 2008). The Fairbanks District became the largest gold producer in Alaska (Szumigala, Hughes, and Harbo 2009).

In the Klondike, Nome, and Fairbanks Gold Rushes, the miners were looking for placer gold. This placer gold is concentrated in the bottom of old creek beds, known as pay streaks. In the Fairbanks area, the "pay" dirt is typically the top few feet of bedrock and the bottom few feet of the overlying gravel, which is then covered by a thick layer of frozen silt. The bedrock is weathered schist, and so soft that the gold would penetrate crevices in the bedrock. The softness of the bedrock was advantageous for miners as explosives were not needed to excavate (Rickard 1909). The frozen silt is organic-rich and ice-rich, colloquially called "muck" (Boswell 1979). In the Klondike, the frozen silt layer is commonly 4 to 20 feet (1.2 to 6 meters), and the depth to bedrock, including the gravel and silt layers, ranged from 30 to 100 feet (9.1 to 30.5 meters) (Canada

Department of the Interior 1915). In Nome, the depth to bedrock was shallow, ranging from 5 to 25 feet (1.5 to 7.6 meters) (Herbert 1934). In Fairbanks, the silt layer greatly varied from a few feet (one meter) thick near creeks and up to 200 feet (61 meters) thick near hill sides (Boswell 1979). The gravel layer in Fairbanks ranges from 5 to 100 feet (1.5 to 30.5 meters) (Herbert 1934, 61).

2.2 Background – Drift Mining

Initially, drift mining was the common method of mining in all three of the gold rushes. The mining methods were already adapted for frozen ground before the Klondike Gold Rush, within the Forty-Mile and Circle districts in Alaska. With no machinery available, the miners thawed the permafrost with small fires, and used picks to break up the soil and carry it away. The vertical mine shafts would be excavated during the winter to prevent water infiltration from surface run-off and streams (Rickard 1909). In addition, the cold winter air would create a chimney effect within the mine shaft and pull out the smoke and carbon monoxide created by the fires. During the spring, the miners would abandon the mines for the summer due to smoke (Morse 2003). Later, steam thawing was developed and excavation could be done year-round (Rickard 1909).

Once the miners hit bedrock, they would tunnel laterally or “drift” along the bedrock following or looking for the pay streak, shown in Figure 2.1. The frozen ground provided all of the structural support for the tunnels, and timbering was not needed. After thawing with fires, they would hoist the thawed dirt to the surface in buckets using a windlass, and later with steam thawing and steam-powered hoisting machinery. They would stockpile the gravel in large piles on the surface, where it would refreeze. Once spring came and melted the frozen streams, the miners used the water in their sluice boxes to separate out the gold (Rickard 1909). With this method, a miner’s “whole equipment consisted of a pan, pick, shovel, a bucket made out of a whiskey-barrel or a hide, fire-wood, a hemp rope, two or three sluice-boxes each 10 or 12 feet long, and muscle, and more muscle, and persistence” (Rickard 1909, 210).

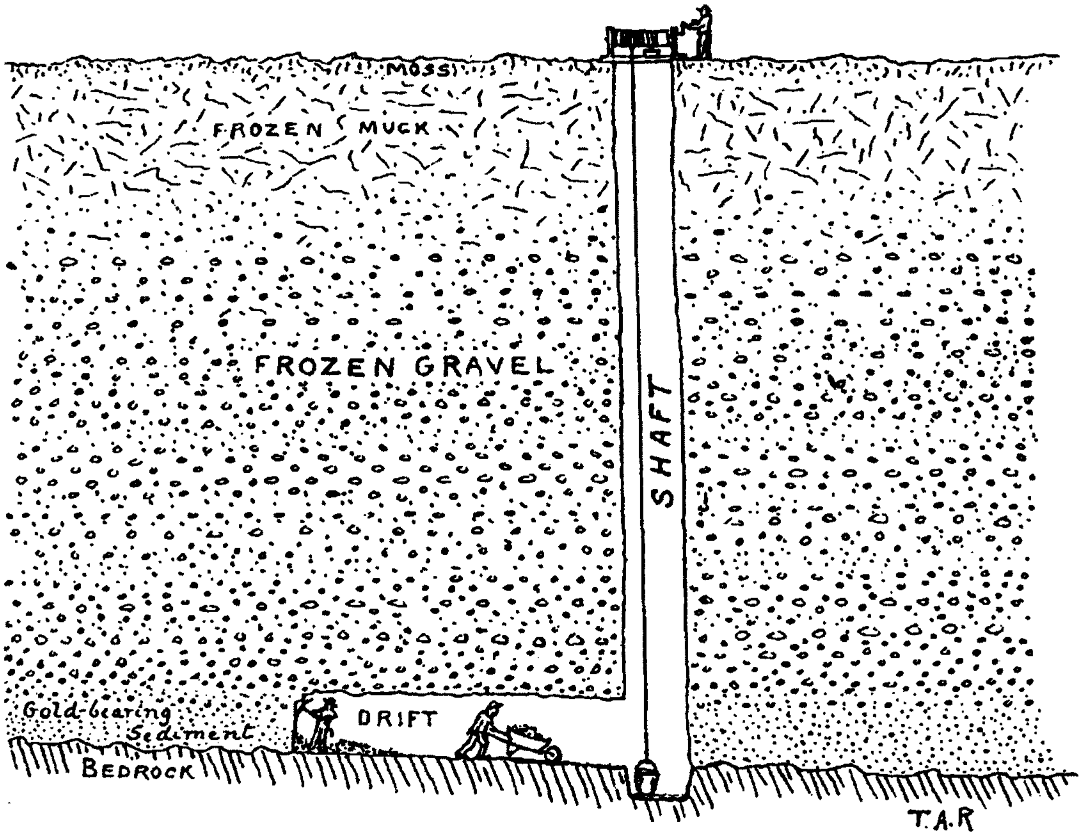

Figure 2.1. Diagram of early drift mining. Diagram from Rickard 1909, 211.

2.3 Engineering – Steam Thawing

Clarence J. Berry is credited to have discovered steam thawing in 1898 in Dawson, the same year gold was discovered in Nome. Berry noticed that the steam coming from a hoisting engine's exhaust hose had thawed the ground it was lying on (Janin 1922, 1). The exhaust hose could easily be pushed into the frozen silt, which allowed for deeper thawing within the ground. However, the flexible hose could not penetrate into the frozen gravels. This led to the development of rigid steam points that could be driven into the frozen gravels (Ellis 1915a, 2).

The first steam point design was a tool-steel rod encased within an iron pipe, where the steam would flow between the iron pipe and rod. But, this point would fail with hard driving into frozen gravel. The miners then tried welding two gun barrels together, which proved a better design. The gun barrels got upgraded to hydraulic steel pipe, which became the basis of the steam point design (Ellis 1915a, 2).

Steam points were manufactured locally, therefore the designs varied due to the manufacturer's or operator's opinions and needs depending on site conditions (Ellis 1915a). The typical steam point is shown below in Figure 2.2. This steam point is a 3/4-inch (1.9-centimeter) hydraulic steel pipe with a 3/8-inch (0.95-centimeter) tube within. The lengths varied from 6 to 16 feet (1.8 to 4.9 meters), with the 8-foot length being the most common. It had a solid steel head on its back end for hammering into the frozen gravel. Just in front of this hammering head is a connection for a rubber hose that carried the steam from the lateral header. The lateral header is the main steam pipe that would be one of several coming from the boiler. The front end of the steam point had a pointed bit with a 1/4-inch (0.64-centimeter) orifice where the steam exits (Rickard 1909).

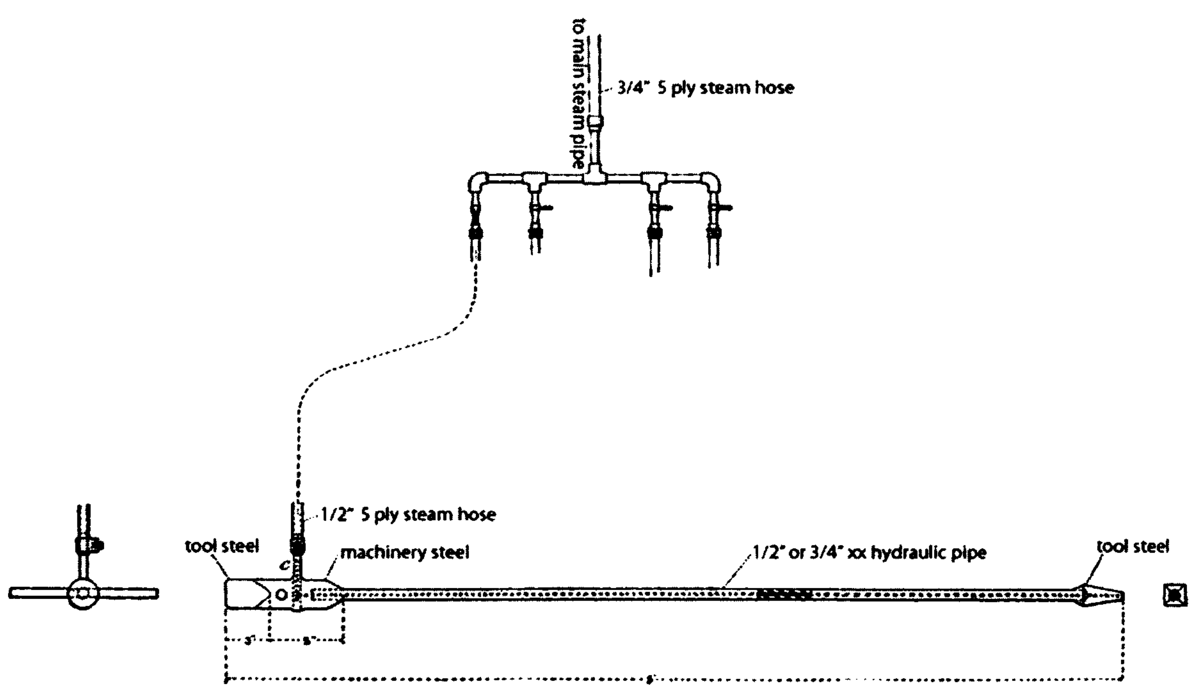

Figure 2.2. Diagram of a typical steam point and connection. Diagram adapted from Purington 1905, 85.

There were three types of bits used in the Fairbanks area, based on the site conditions. The diamond or square shaped bit was used in looser gravels, where the bit simply wedged the gravels apart. The chisel bit was used in more compact gravels or where there were boulders that had to be drilled through. The 4-cornered or Burleigh bit was used in very compacted gravels (Ellis 1915a).

The points were driven sideways between the bedrock and gravel layers, seen in Figure 2.3 and 2.4. Figure 2.3 is a diagram showing the set up during the driving process and Figure 2.4 is a photo showing the installed steam points. The points were commonly placed in a row, 3 feet (0.91 meters) apart. While, steam points were used to drive the holes, a cheaper pipe, called a sweater, was placed in the hole to fully thaw the ground. The more expensive steam points would get stuck as the gravels thawed and collapsed (Ellis 1915a). The sweaters commonly were 3/8 to 1/2 inch (0.95 to 1.27 centimeter) iron pipe (Wimmler 1927, 126).

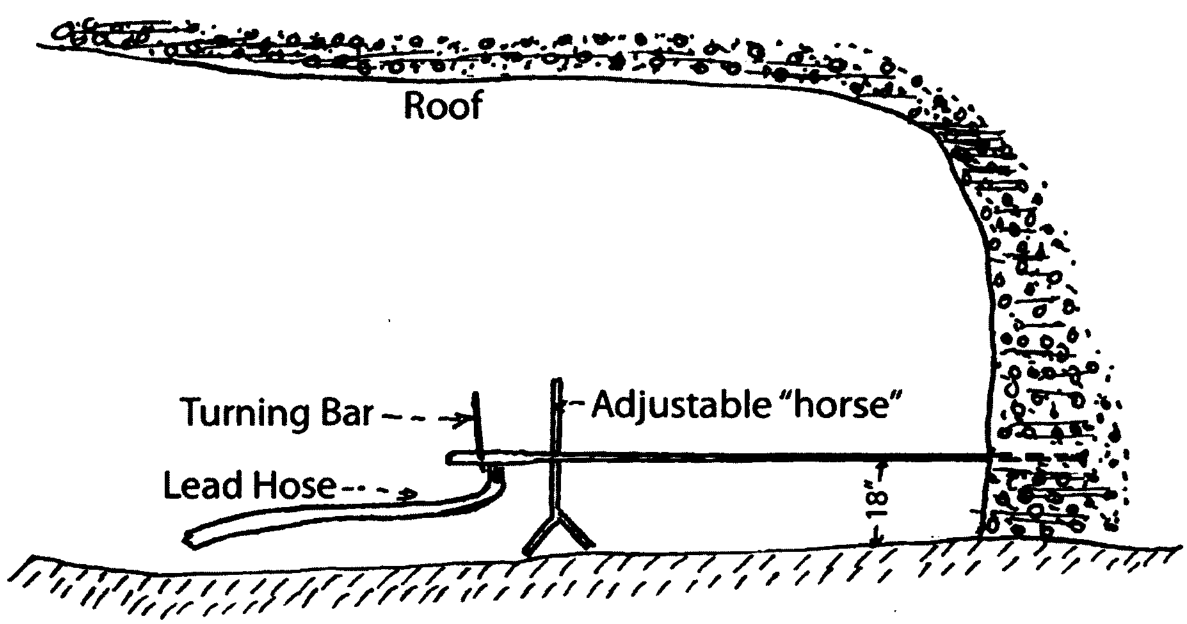

Figure 2.3. Diagram of steam point driving within a drift mine. Diagram adapted from Ellis 1915b, 25.

The time it took to thaw the frozen gravels varied, depending on the compaction of the gravels, soil composition (mainly if clay inclusions existed), steam point depth into the wall, and steam point spacing. In ideal conditions, the steam points would thaw a 5-

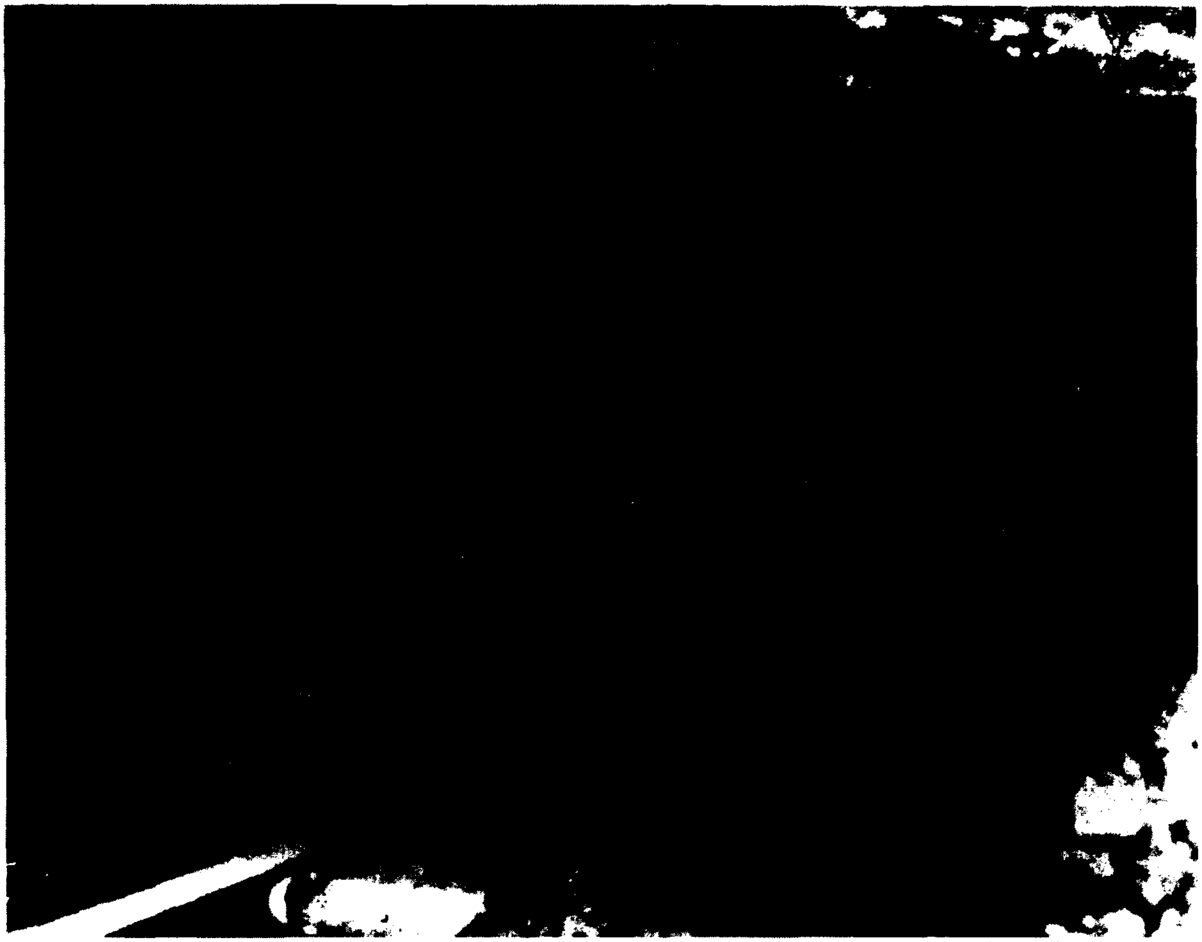

Figure 2.4. Drift mining in frozen ground on Seward Peninsula, Alaska. Photo by R. H. Sargent, 1924. Photo from U.S. Geological Survey Photographic Library ID. Alaska, no. 120.

foot (1.5 meters) tall section of the gravels in 9 hours, with the steam points being 9 feet (2.7 meters) long and spaced 3 feet (0.9 meters) apart (Ellis 1915a, 5).

2.4 Background – Dredging

Mining methods evolved from drift mining to dredging. Fundamentally, a dredge, seen in Figure 2.5, is a floating barge with bucket-elevators that would gather all of the gravels for sluicing (Rickard 1909). Dredging in Alaska started in Nome around the turn of the century, however many of the attempts were unsuccessful due to lack of technology development in permafrost (Rickard 1908). Dredging in Fairbanks started in the 1920s, with a large-scale operation under the Fairbanks Exploration Company (F.E. Co.), a subsidiary of the United States Smelting, Refining and Mining Company (USSR&M). At the peak of dredging in 1940-1942, eight dredges ran in the area (Boswell 1979).

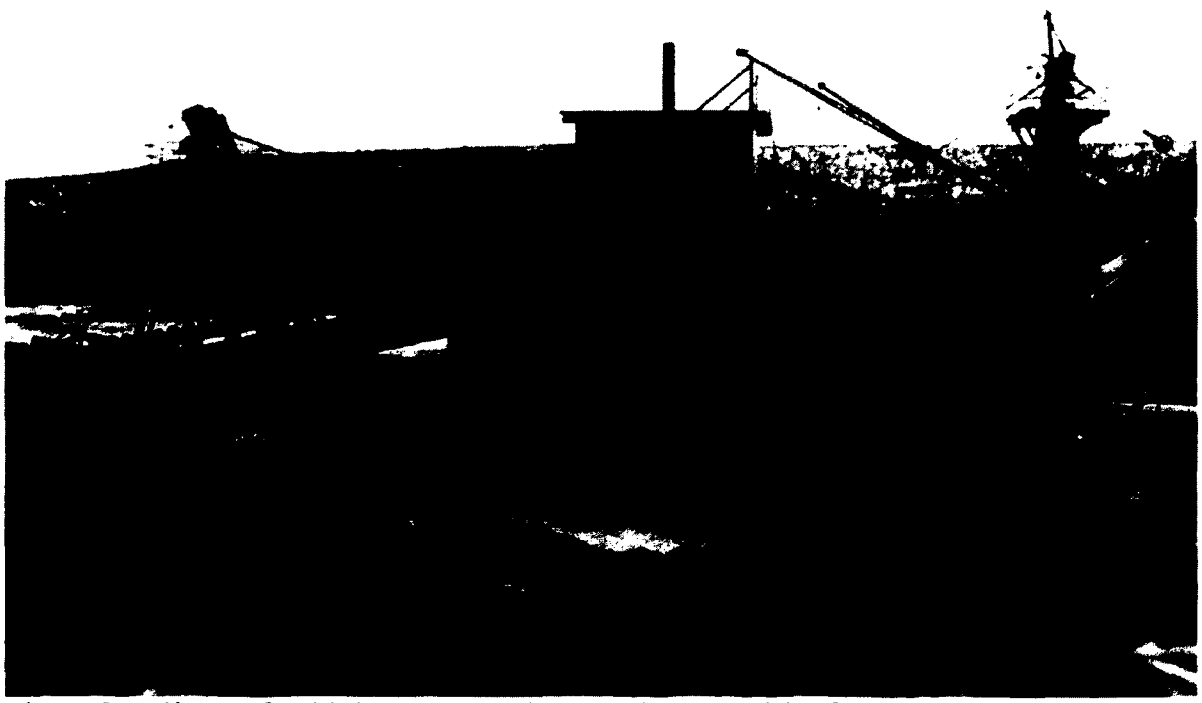

Figure 2.5. Photo of gold dredge on Esther Creek near Fairbanks. Photo by R.E. Wallace, June 1945. Photo from USGS Photographic Library, ID. Wallace, R.E. 131.

Dredging could not begin in Fairbanks until the completion of the Alaska Railroad in 1923. The railroad allowed heavy equipment transport and brought in cheap coal fuel. The last element needed for dredging was lots of water delivered to the mining fields, which was solved with the construction of the Davidson Ditch. The 90.5-mile (145.6-kilometer) ditch was built in 1928 near Fairbanks (Boswell 1979, 11).

The dredging process in Fairbanks started with site preparation, where the miners used water cannons, or "hydraulic giants," to strip the thick layer of overburden silt (Boswell 1979). The next step was to thaw the frozen gravels. Steam thawing proved ineffective for large surface areas. The shape of the thawed area around the point was an inverted cone, leaving frozen mounds between the points. When the dredges tried to process these frozen mounds, it would damage the machinery (Janin 1922). Solar radiation and running surface water was a cheaper way of thawing large surface areas, but the process was very slow (Ellis 1915a). Experimentation of thawing with cold water, or water at its natural summer temperature, started in the late-1910s near Nome. There are two cold thawing methods that are called the Miles Method, the preferred method in Fairbanks, and the Pearce Method (Janin 1922).

Just before WWII, "gold mining was the sole support of many interior communities and was Alaska's second largest employer, the second largest importer of industrial goods, and second largest territorial taxpayer" (Cole 1989, 63). WWII was the main factor behind the decline of gold mining in Alaska. First, there was the lack of supplies to provide maintenance on the dredges during the war. Then, in 1942, the War Production Board declared gold mining a nonessential industry and miners were ordered to stop. The decision was heavily criticized as most of the miners did not have skills to move into other industries, and their mines were stripped and allowed to deteriorate past recovery by end of the war. By 1950, the partially recovered industry produced only 40% of the 1940 gold production (Cole 1989). The mines that suffered were the small mines. The F.E. Co. continued dredging until 1963 (Boswell 1979).

2.5 Engineering – The Miles Method

John H. Miles of the Alaska Mines Corporation of New York got a patent (U.S. Patent, 1,339,036) for his method on May 4, 1920. Simply, this method (Figure 2.6) used pressurized cold water, or unheated water at its natural summer temperature. The water was pumped into the gold-bearing gravels by pipes just above the bedrock, where it spread outward and flowed upward around its thawed edges. Gradually, the thawed cylindrical holes would grow larger, merge, and thaw the entire area (Janin 1922).

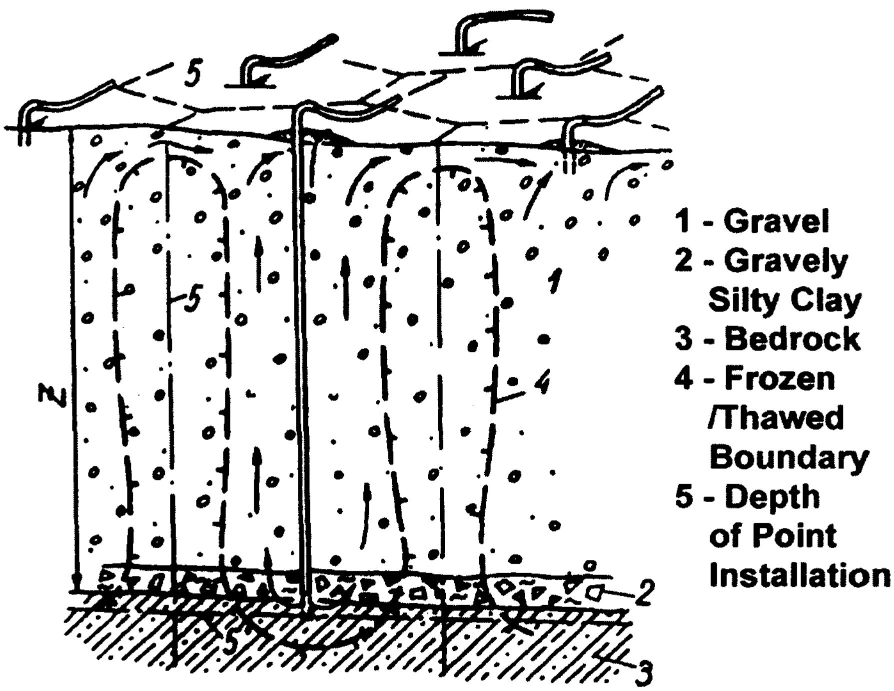

Figure 2.6. Diagram of the Miles Method (arrows indicating water flow). Diagram adapted from Gol'dtman, Znamenskiy, and Chistopol'skiy 1970.

John H. Miles conducted his own thawing experiments in 1917 within the Nome District. His experiments used water at different temperatures and phases, including: three superheated steam (590˚F/310˚C), three saturated steam (248˚F/120˚C), two warm-water (105˚F/41˚C), and two cold-water (52˚F/11˚C). Steam points were used for steam and warm-water thawing, while the cold-water thawing simply used a 2-inch (5-cm) diameter pipe. They were all placed in 42-foot (12.8 meter) holes, pre-drilled down to the bedrock. From top to bottom, the soil was tundra, muck, quicksand, clay, and fine gravel, as shown below in Figure 2.7. The figure also shows the cross sections of the resulting thawed areas, where thawed areas are conical or cylindrical in shape. Miles calculated what he called "the thawing efficiency", which is the energy used to run the boiler compared to the calculated energy used to melt the ice (latent heat) in the soil. While Miles did not use the boiler for the cold-water thawing, for the thawing efficiency he calculated the amount of energy needed to heat the water from 32°F (0°C) to 52°F (11°C). The thawing efficiencies are listed in Table 2.1, along with the duration of thawing, volume of the thawed zone, calculated energy spent per hour to run the boiler, and calculated energy used per hour to the melt ice (Weeks 1920, 370).

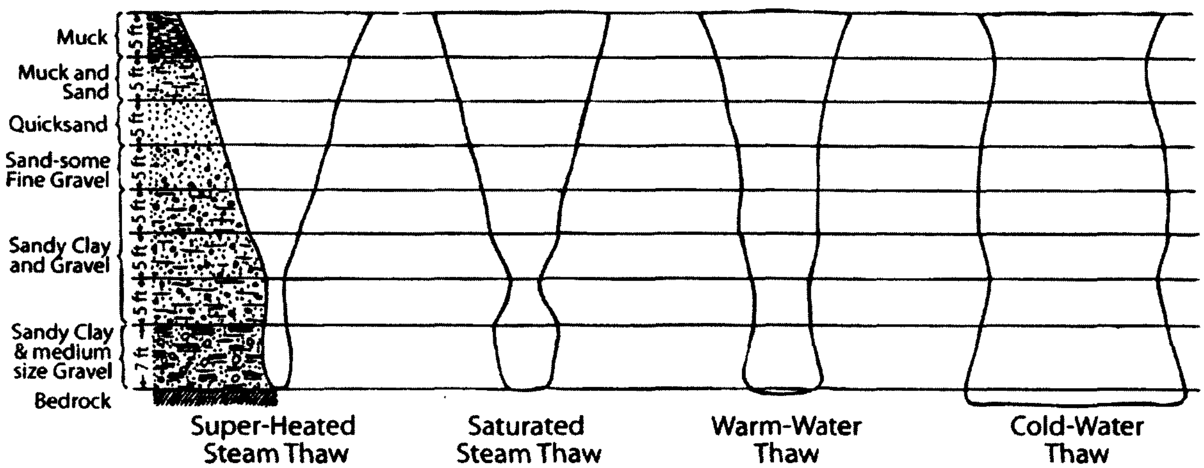

Figure 2.7. Diagram of Miles' thawing comparison results. Diagram adapted from Weeks 1920, 369.

Table 2.1. Miles' thawing comparison results. Results from Weeks 1920, 370)

	Duration (Hours)	Thawed Volume (ft^3 (m^3))	Energy Spent (BTU/h (kW h))	Energy Used (BTU/h (kW h))	Thawing Efficiency (%)
Superheated Steam	156	2,943 (83)	787,500 (231)	30,240 (8.9)	3.8
Saturated Steam	98	2,241 (63)	630,000 (185)	36,720 (10.8)	5.8
Warm-Water	67	2,187 (62)	422,800 (124)	52,272 (15.3)	12.3
Cold-Water	192	13,797 (391)	200,400 (58.7)	114,912 (33.7)	57.4

Looking at Figure 2.7, the steam thawed holes are in the shape of inverted cones that would result in frozen mounds in between the points. Miles observed that after a few hours into the steam thawing, hot water would pool at the surface around the point and would continue to get hotter as the steaming continued. Miles concluded that heat was being wasted and with little thawing happening at depth. The warm water thawed holes were more cylindrical in shape with near vertical walls to the bedrock, where it would not leave frozen mounds at depth. However, again, warm water was surfacing and pooling, and heat was still being wasted (Weeks 1920). "This led me [Miles] to think that thawing was a slow process, and that it was not a concentrated heat that was necessary, but a uniform circulation of water with just a few heat units to give up" (Weeks 1920; 368). Miles then tried cold-water thawing to see if it was a more efficient method of thawing large areas.

The cold-water thawed hole was a relatively large cylinder. Miles theorized that the water flowed along the bedrock to the outermost edges of a thawed hole, then return to the surface, instead of returning to the surface near the point as it did with steam thawing. Over time, as the hole grew larger, the out flowing water got colder and colder as the heat in the water was being used to thaw the ice in the gravels. Miles then concluded that the rate of water going into the thaw pipe should be dependent on the out flowing water temperature in order to maximize efficiency, where the out flowing water temperature should be just above freezing. His theory of why the water flowed out at the edges of the thawed hole and not next to the pipe is that, "the ground in thawing forms a porous streak between the frozen and thawed area, and the water finds less resistance in this channel than in the thawed area" (Weeks 1920; 368). In the process, the thawed gravels would settle, separating from the frozen gravels. Miles concluded that cold-water thawing was the most effective and economical method in thawing gravels because it did not require any expensive heating. The large thawed area down to the bedrock meant that it was easier to eliminate frozen mounds for dredging (Weeks 1920).

For the dredging site preparation, the cold-water points were driven into the gravels in a staggered grid pattern, shown in Figure 2.6. Every other row in the grid was offset a distance equal to half the distance between the point spacing. Two points from one row and one point from the neighboring row would form an equilateral triangle. The pattern efficiently overlapped the cylindrical thawed zones and insured no frozen mounds between the points. The typical spacing of the points in the equilateral triangle was 16 feet (4.9 meters) for a thaw depth of 45 feet (13.7 meters) or less, or 32 feet (9.8 meters) for a thaw depth greater than 45 feet (13.7 meters). The rule of thumb for the time it took to thaw the ground was 1.5 days per foot of depth for a 16-foot (4.9 meters) spacing and 2.5 days per foot of depth for a 32-foot (9.8 meters) spacing (Boswell 1979, 20-21).

2.6 Engineering – The Pearce Method

In 1918 and 1919, Edward E. Pearce and Iver Johnson developed the Pearce Method within the Candle Creek district on the Seward Peninsula. Simply, the Pearce Method uses the flow of surface water to thaw the soil by encouraging the flow through the soil from a higher point to a lower point, shown in Figure 2.8. As the water flows over frozen soil boundary, it will gradually thaw the ground downward to the bedrock (Janin 1922, 16).

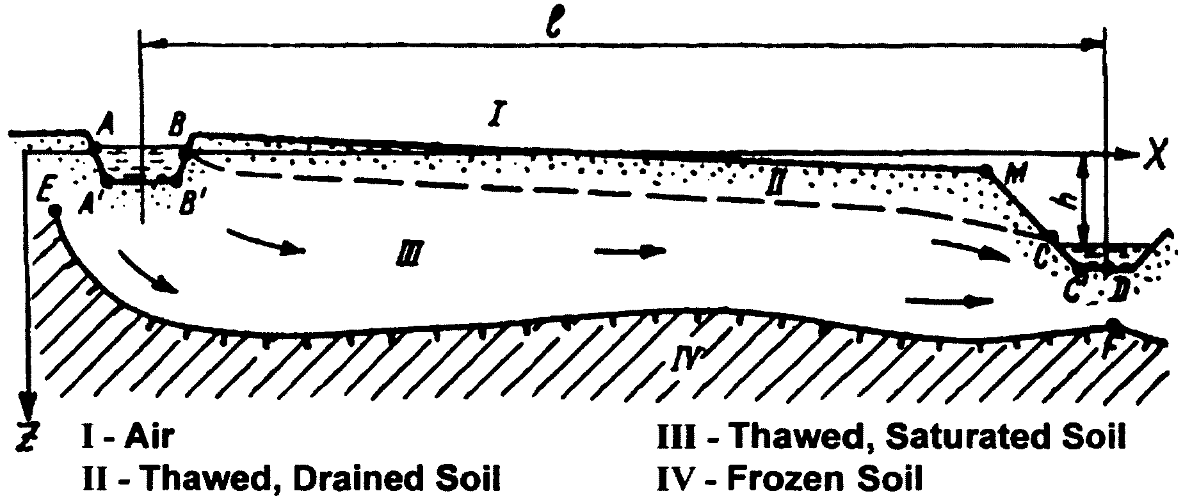

Figure 2.8. Profile diagram of the Pearce Method (arrows indicating water flow). Diagram adapted from Gol'dtman, Znamenskiy, and Chistopol'skiy 1970.

The cold-water thawing experiment Pearce and Johnson conducted in 1919 is depicted in Figure 2.9. Part A of the diagram is the aerial view, Part B is the lengthwise

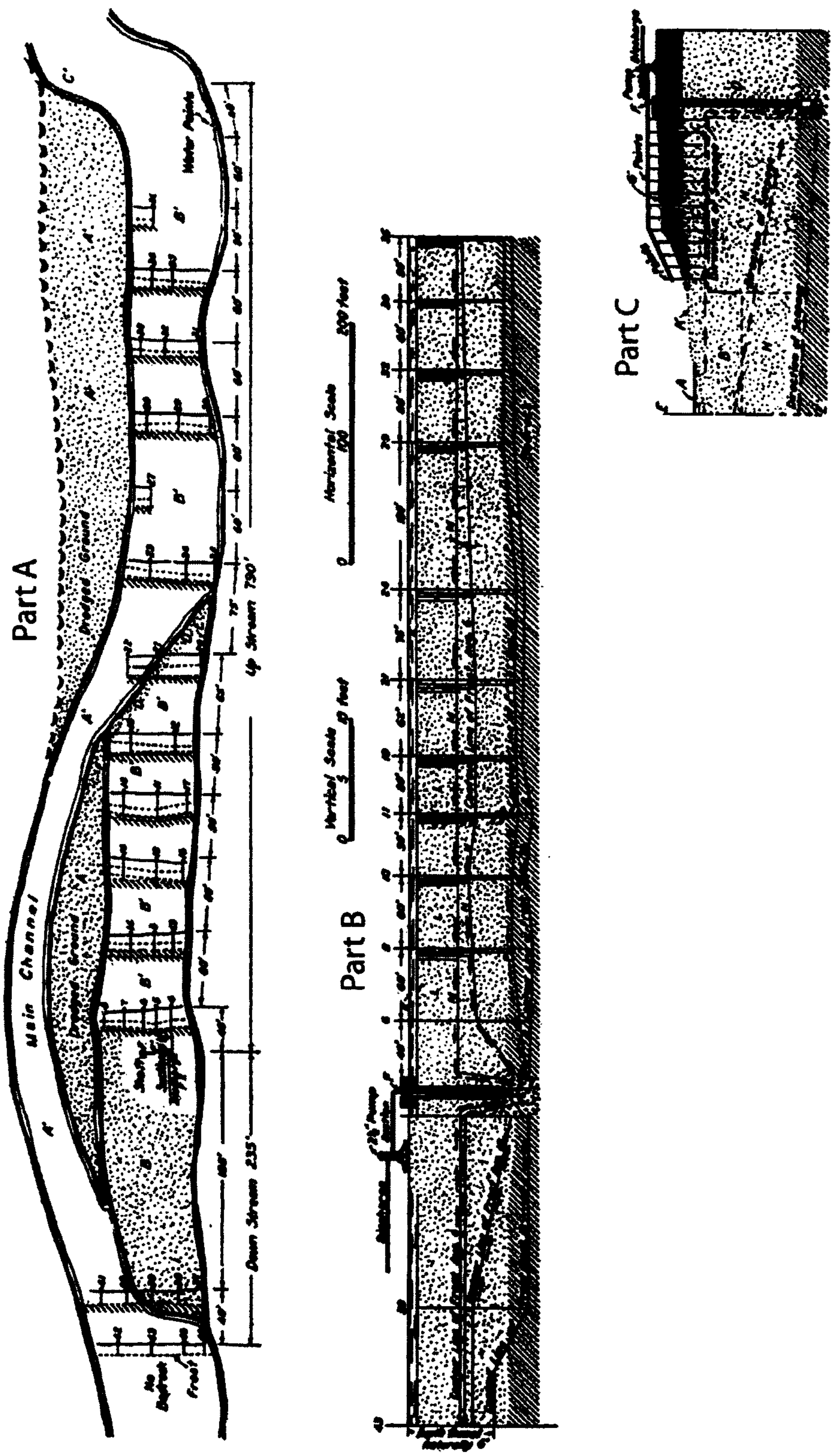

Figure 2.9. Map of Pearce's test site. Diagram adapted from Pearce, E.E. 1922, 154.

cross section view, and Part C is the widthwise cross section view of test site. The creek is shown in white and the intended thaw area is marked with B'. The soil, from top to bottom, consists of a thin top layer of frozen muck, frozen gravels, and the bedrock. A 9-foot (2.7-meter) deep shaft, located at point F, was built to the top of bedrock. A pump was placed in the shaft to draw out infiltrating water, and to encourage water flow down to the bedrock at the center of the test area (Pearce 1922).

To encourage the creek to flow over the test area, the experimenters dug shallow trenches at the outermost edges of the test area, marked with E and E'. In some areas, a surface layer of muck prevented the top portion of the gravel layer from thawing by solar radiation, which prevented the creek water from flowing through these frozen gravels. Cold-water points, from the Miles Method, were used to start the thawing process in this top portion of gravels. The cold-water points are depicted in Part C with the black top layer depicting the muck and sod on top of the gravel. The cold-water points were only used long enough to thaw the top portion of gravel, underneath the muck, to start the water flow through the gravel (Pearce 1922).

The deepening thawed boundary is depicted in Part B with contour lines and their corresponding dates. On August 4, when they started to pump from the shaft, the seasonal thaw depth was at 3.5 feet (1.1 meters). After 15 days of cold-water thawing and only 80 hours of pumping water from the shaft, the area was thawed to the bedrock. The final thawed area was 790 feet (241 meters) upstream from the shaft and 235 feet (72 meters) downstream from the shaft, with average width of 60 feet (18 meters) and an average depth to bedrock of 9 feet (2.7 meters), and no frozen mounds (Pearce 1922).

2.7 Engineering – Russian Application and Adaptation

Both the steam thawing and cold-water thawing methods were adapted and improved upon in Russia. The steam point was initially called "American needle" in Russia, and the word "point" became part of the technical vocabulary in Russian arctic engineering. A person operating the steam point was called a "pointist." The Miles Method was first used in Russia from 1936 to 1938 on the gold mining operation at the creek Malyj Urkan. It was later widely used on numerous gold mining operations in the Magadan area. Instead of hammering points, Russian miners installed them in rotary-drilled holes, which made their installation much faster. By using this method, many millions of cubic meters of frozen overburden and gravel were thawed on placer mining sites with depths up to 130 to 160 feet (40 to 50 meters) (Perl'stein 1979).

Theoretical analysis and laboratory experiments were used to find the most technically sound and economical applications of the method (Gol'dtman, Znamenskiy, and Chistopol'skiy 1970; Perl'stein 1979). Figure 2.10 depicts the laboratory modeling results of thawing frozen soils with uniform layers. It was found that the shape of the thawed zone around a cold-water point depends on soil properties. Layers of lower hydraulic conductivity will have slower thaw. "In soils of low hydraulic conductivity at the contact with bedrock and in ice-rich and organic soils near surface, a radius of thawing is sufficiently smaller than in gravel and gravely sand" (Gol'dtman, Znamenskiy, and Chistopol'skiy 1970). In general, it was found that a higher rate of water leads to greater thawing. But, excessive water flow will erode channels, which will then concentrate the flow of water and slow the overall thawing (Gol'dtman, Znamenskiy, and Chistopol'skiy 1970).

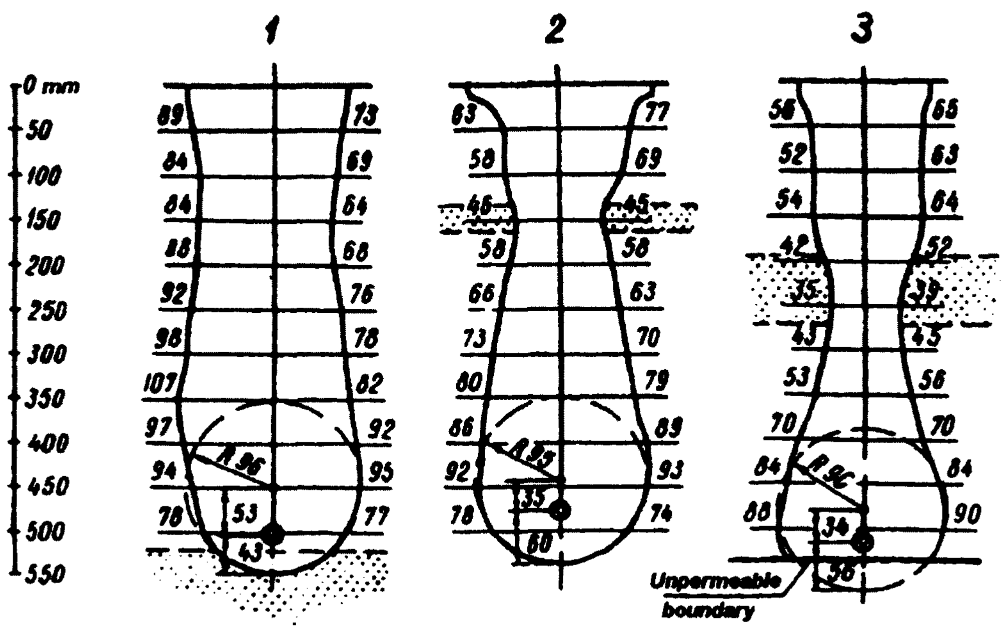

Figure 2.10. Diagram of laboratory modeling results of cold water thawing. Diagram from Gol'dtman, Znamenskiy, and Chistopol'skiy 1970.

For planning, it is necessary to know the approximate thawing time, which depends on soil properties, rate of water flow, and water temperature. Russian scientists developed theoretical and empirical methods of evaluating expected time of thawing, which produced a set of tables. Figure 2.11 is an example of one of these tables, where time (T) is dependent on the flow rate (W) and the distance between water points for the listed specific set of conditions (Gol'dtman, Znamenskiy, and Chistopol'skiy 1970). It was found that the Miles Method is the most effective in coarse soils of high hydraulic conductivity, where the water penetrates the thawing soil and convective heat transfer directly affects the frozen soil. In fine-grained soils, such as silt, clay, and peat, heat transfer is mainly conductive instead of convective; this is slower with this thawing process (Perl'stein 1979).

The Pearce method was also widely used in gold mining operations of the Kolyma region. In Russia, this method was called the percolation and drainage method of thawing. It was found that this method could be effectively used if the average permeability of the thawed soil is not less than 130 feet/day (40 meters/day) and the minimal permeability of the layers is not less than 30 feet/day (10 meters/day). For sloping sites with a hydraulic gradient of 0.1 to 0.2, the method can be used when an average permeability is at least 65 feet/day (20 meters/day). The water channel length from the source to the drain was usually kept between 65 to 260 feet (20 to 80 meters). River water was used in the summer when its temperature was more than 37°F (3°C) (usually the water thawing index should be greater than 1400°F-days (800°C-days)). The natural river water was used in areas where the air thawing index is greater than 1800°F-days (1,000° C-days). Heated water has also been used at several occasions (Gol'dtman et al., 1970).

2.8 Analysis – Steam Versus Cold-water Thawing

For the cold-water thawing method, good permeability is needed. Essentially, the thawing is caused by the flow of water going through the soils. Problems related to low permeability can be seen in Pearce's experiment in the area of ground covered by a layer

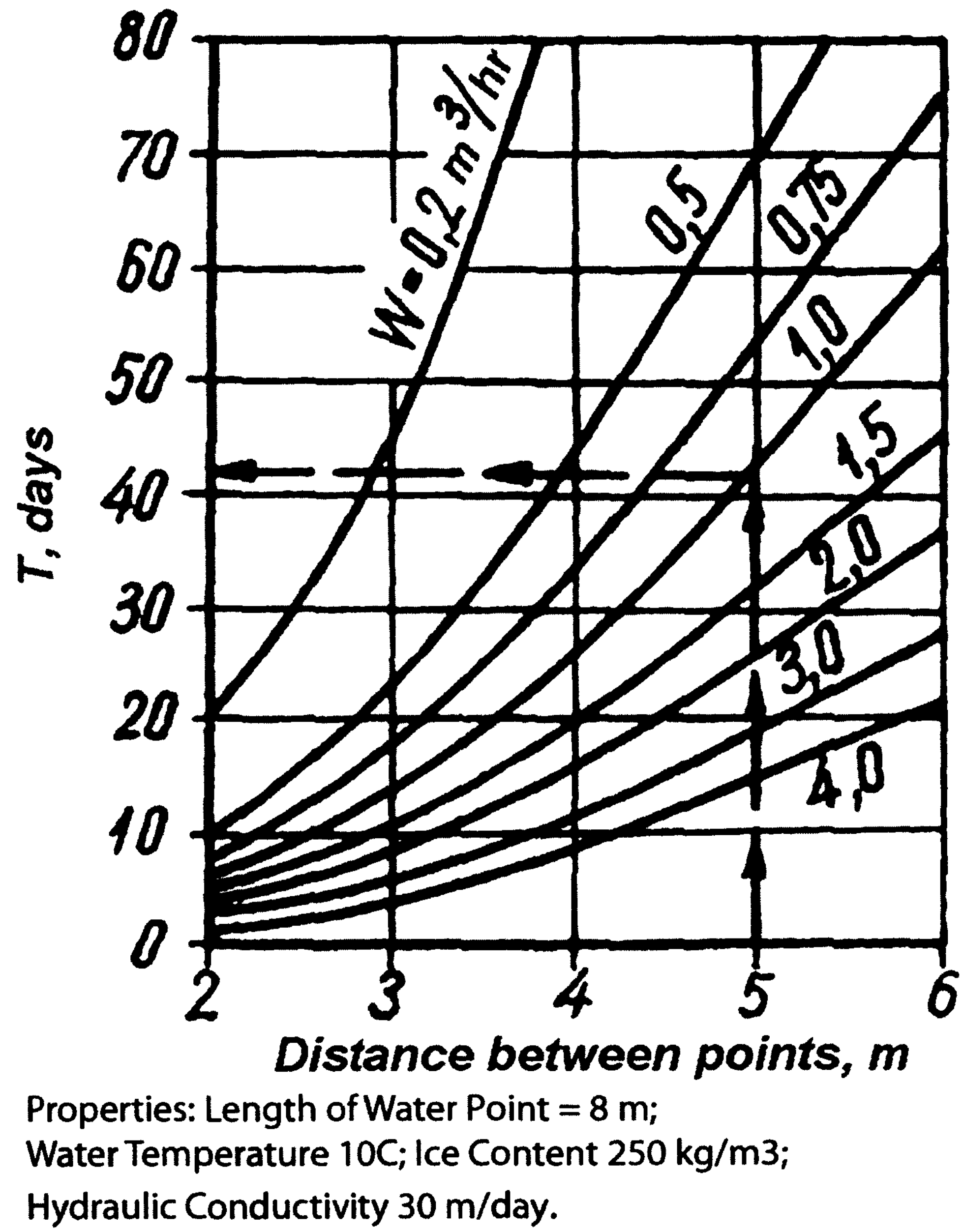

Figure 2.11. Diagram of estimated time of thaw for the Miles Method. Diagram from Gol'dtman, Znamenskiy, and Chistopol'skiy 1970.

of muck and in the Russian experiments with the layers of different hydraulic conductivity. Without this water flow, the heat transfer would be more based on conduction. The thermal conductivity of fine-grained soils tends to be lower than coarse-grained. Therefore, cold-water thawing would be inappropriate for low hydraulic conductivity soils, or soils containing a high amount of fine-grained material, since the flow of water is impeded and conduction is lower.

In Miles' experiment, the hydraulic conductivity was overlooked and the clay content could have affected his results. The clay was in the lower layers. Looking at the cold-water thawed cross section, clay content did not seem enough to impede the flow of water. But, the clay might have been enough to limit the conduction, or the steam could have baked the clay and then greatly impeded the flow of condensed hot water through the soil at depth. Without knowing more details about the soil conditions, this is all speculation. However, this still does not lessen this experiment's conclusions on the efficiency of cold-water thawing.

2.9 Analysis – Current Uses

Steams points are the preferred method of thawing used in construction, and are considered the fastest method. The modern steam points included closed systems and open systems, where the open system is basically the steam point design the miners used. Closed systems used a double-walled probe where the condensation returns to the boiler. The advantage of the closed system is that it does not increase the soil's water content, however it is rarely used and not as efficient as open systems. For certain soils, such as fine-grained soil, open system steam probes can be driven into the ground with light hammering or under its own weight. These steam probes are 0.75- to 1-inch (19- to 25-millimeter) diameter, heavy or extra-heavy steel pipe with a conical nozzle tip. For coarse-grained soils, the holes have to be installed using an auger or churn drill. Afterwards, steam pipes made of light tubing are placed in the drilled holes. The Russians have adapted steam probes with pneumatic and vibratory drivers (Esch 2004).

Several buildings in Fairbanks, Alaska were built with pre-construction steam thawing of permafrost. These include the Fairbanks Airport Post Office in 1979, the Big Dipper Recreation Center in 1981, the Lathrop High School gymnasium in 1986, and the West Valley High School gymnasium and theater in 1998 and 1999 (Esch 2004). An example pre-construction thawing with steam, the Fairbanks Airport Post Office pre-thawing was accomplished within 105 days of periodic steaming with 315 steam points installed to a depth of 40 feet (12.2 meters) over a 9,678 square-foot (2,950 square-meter) area (Esch 2004; McFadden and Bennett 1991).

It was found that in coarse-grained soils, such as sands and gravels, and weathered bedrock, the settlement was minimal. Water thawing can only be used for well-drained, coarse-grained soils, or problems related to excessively high water content can develop. Cold-water thawing is still the cheapest way under the right conditions, such as in coarse-grained soils (Esch 2004).

Steam thawing can also be used for pile installation, but only if the mean annual permafrost temperature is below 20°F (-6.7°C). If the permafrost is too warm, the ground will take a substantial amount of time to freezeback. This freezing is crucial in providing the bearing capacity for the pile. In addition, the long freezeback process can frost jack the pile. If the pile must be installed with pre-thawing, then freezeback must be aided by artificial freezing, such as thermal piles (U.S. Depart. of the Army 1983, 4-114).

Overall, pre-construction thawing should only be used in discontinuous permafrost areas, where climate does not actively try to create permafrost. The permafrost thickness should be relatively shallow, in order to completely thaw. For non-thaw stable soils, the soil will need to be consolidated or excavated and filled with non-frost susceptible soil, such as sands and gravels, after artificial thawing (Andersland and Ladanyi 2004, 167).

2.10 Conclusion

Artificial thawing was developed by the driven nature of gold miners, where each problem faced was creatively solved with limited resources. Steam thawing was developed as a way to thaw gravels in the tunnels of drift mines; but was found not as effective for thawing large surface areas needed for dredging. Cold-water thawing was developed as a more economical and energy effective way of thawing gravels ahead of dredging. The miners' methods and techniques of thawing are still used today with relatively little change. It should be cautioned that pre-construction thawing of a site should only be used under certain circumstances in discontinuous permafrost areas. In addition, thawing for pile installation should only be used in colder permafrost that allow for good freezeback of the pile.

Chapter 3 Alaska Highway Influence

> "'Guts and tractors built that road,' remarked a hard-bitten Colonel of engineers – one of several who led troops into the North to hack the Alcan Highway through the wilderness. The remark is symbolical, for it was the fortitude of men – officers and soldiers, engineers and contractors – and the stamina of American construction equipment that built 1,636 miles [2,633 kilometers] of new route and rebuilt 162 more miles [261 kilometers] of old trail, all in one short construction season" – Harold W. Richardson (1942, 83).

The enthusiastic words of journalist Richardson are just one of numerous examples of the prevailing spirit spoken of the Alaska Highway construction. Alaska suddenly became accessible and permafrost, the strange geological phenomenon, became widely known. But, did the Alaska Highway engineers provide significant advancement to road construction over permafrost? Barely. However, the influence given to permafrost research was significant. The Alaska Highway construction brought U.S. government and military interest to permafrost engineering, creating organization and funding for comprehensive permafrost engineering research.

3.1 Background - Reasons for Construction

Alaska became strategically important in the sphere of defense plan to protect the continental United States. As tensions grew with Japan, the United States started to worry that Japan could occupy Alaska and launch attacks on the continental United States with long range bombers (Conn, Engelman and Fairchild 1964, 224). The U.S. Navy made plans to build new air and submarine bases in Alaska, while the U.S. Army was tasked to defend the bases (Conn, Engelman and Fairchild 1964, 224; Twichell 1992, 45). After the December 7th, 1941 attack on Pearl Harbor, defending Alaska became more important (Bezeau 1985, 21). The two defensive reasons to build the Alaska Highway were to have a land-based communication line and a supply line, in case sea lanes were compromised.

3.2 Background – Route Selection

Four possible highway routes were proposed, but a fifth route combining two of the routes was chosen by the U.S. War Department. This route connected the airfields of the Northwest Staging Route (Twichell 1992, 55). The Northwest Staging Route was conceptualized before Pearl Harbor, as a series of connecting airfields from the continental U.S. through Canada to Alaska. The airfields in Canada include: Edmonton, Grande Prairie, Fort St. John, Fort Nelson, Watson Lake, and Whitehorse. In Alaska, the airfields were Northway and Big Delta with the destination being Ladd Field in Fairbanks. The highway initially aided the completion of the airfields and later supplied them (Twichell 1995, 169).

The chosen route from Dawson Creek, BC to Delta Junction, AK, seen in Figure 3.1, angered numerous people as it did not service populated areas that would have benefited from the Alaska Highway (Twichell 1995, 167). But, the airmen that flew the Northwest Staging Route during WWII did benefit from the Alaska Highway (Twichell 1995, 169). While the Northwest Staging Route avoided the bad coastal weather (Bezeau 1985, 26), the mountains and lack of navigational markers made the route still treacherous. In January 1942, of the first 38 U.S. planes that flew the Northwest Staging Route only 11 made it to Fairbanks. A combination of inexperienced pilots, winter weather, the long distance between airfields, and the lack of navigational markers were the problems (Twichell 1992, 53).

After the 1942 summer construction of the highway, the Northwest Staging Route became part of the Alaska-Siberia (ALSIB) ferry route for the delivery of warplanes under the Lend-Lease Program. These warplanes were also often filled with supplies from the U.S. to U.S.S.R.'s combat front with Germany. On the U.S. side, 7,926 planes were flown from the continental U.S. through Canada to Fairbanks where they were delivered to U.S.S.R. pilots. From there, the Russian pilots flew the warplanes to Nome, then across Siberia to the Eastern Front. On the Northwest Staging Route, only one in sixty planes crashed with only fifteen pilots lost (Twichell 1995, 170).

For the novice pilots, the highway itself became the much-needed navigational marker. The highway ensured supplies with room and board during their two-day flight. For emergency landings, there were numerous roadside airstrips or landings could be made on a straight strip of the highway itself. The survivors of crashes were able to bail out close to the highway where they could be easily found by rescue parties (Twichell 1995, 169-170).

3.3 Background – Tote Road

In reality, the Alaska Highway was built to be a pioneer or tote road for the military to use to deliver supplies to Alaska, not a road for commercial or civilian transportation. The road that was built from March to November 1942 (Huntley and Royall 1945) by 10,607 U.S. Army soldiers (Morgan 1992, 1) was only a survey and supply road. The final work to bring it up to tote road standards was done by the U.S. Public Roads Administration (PRA) (Twichell 1992, 68).

The substantial work done by the PRA and hired civilian contractors are often overlooked. The 14,100 civilian workforce was overseen by five management firms under the PRA with a staff of 1,800 (Twichell 1985, 58), compared to the 10, 607 U.S. Army soldiers (Morgan 1992, 1). During the 1942 summer, the PRA had to help the army to complete the entire length of supply road before winter. The following 1943 summer, the PRA continued their substantial improvements to the army's road. In the end, the PRA only used two-thirds (970 miles (1561 kilometers) out of 1,420 miles (2285 kilometers)) of the army's road with the rerouting of some sections. Solely, the PRA constructed 450 miles (724 kilometers) of the road and completed 99 out of 133 bridges needed by the end of October 1943. The PRA's work became the foundation of today's highway and many of their bridges were still in use in 1985 (Twichell 1985, 63).

3.4 Engineering – Permafrost Problems

Permafrost is encountered as far south as 94 miles (151 kilometers) north of Dawson Creek, but the permafrost boundary is generally considered north of Whitehorse.

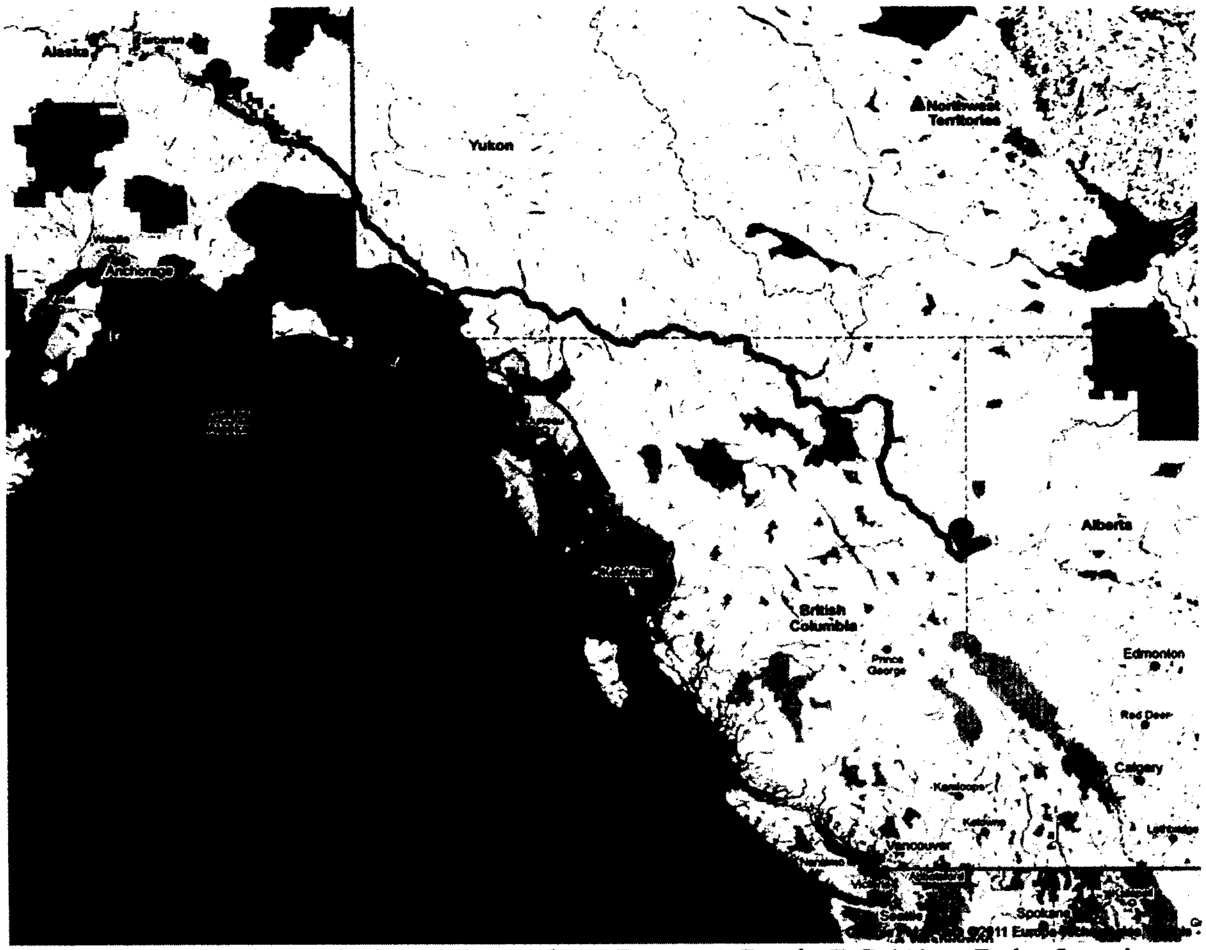

Figure 3.1. Map of the Alaska Highway from Dawson Creek, BC (A) to Delta Junction, AK (B). Map from Google Maps.

Specifically, permafrost is prevalent from 200 miles (322 kilometers) north of Whitehorse in both mineral and organic soils (Brown 1970, 115-116). Muskeg, now called peatland, is organic-rich wetlands (van Everdingen 2005, 54) that are high in water content with very low bearing capacity (MacFarlane 1969, 6). Peatlands occur throughout the length of the Alaska Highway, but are underlain by permafrost on the northern stretches.

The commander of the project was Brigadier General William M. Hoge, who had no knowledge of permafrost. For peatlands, "avoiding it, excavating it, or corduroying it" (Twichell 1992 204) was the process. The common road building process started with bulldozers side-by-side pushing aside the trees, leaving the dirt and peat to dry out in the sun (Twichell 1992, 204-205). But when it came to permafrost, removing the insulating vegetation caused it to thaw. Attempting to excavate ditches to drain the water away allowed the heat to penetrate deeper and caused the road to settle. One stretch of ditched road settled 10 to 15 feet (3.0 to 4.6 meters) (Brown 1970, 116). "Permafrost quickly dissolved into a slush that was futile to excavate, impossible to drain, and incapable of drying" (Twichell 1992, 209). It was realized that keeping permafrost frozen was the only way, and the crews had to find new road building techniques with trial and error (Twichell 1992).

The final road building process was an expansion of the corduroy road practice, which dates back to four thousand years ago in England. The practice was laying planks across soil to spread the weight over the ground surface (MacFarlane 1969, 150-151). For permafrost, any vegetation disturbance would cause it to thaw. The trees and brush were cut by hand and only cleared to the width of the road. The road base layer started with the cut vegetation, then was overlain by more logs or branches and brush, which was then compacted by bulldozers. Then the road was covered with 2 to 4 feet (0.6 to 1.2 meters) of unfrozen dirt and gravel (Twichell 1992, 209-210) from local gravel sources that were luckily prevalent in the area (Brown 1970, 116). Later, the typical road building practice required at least a 6-foot (1.8-meter) fill height to keep the permafrost frozen (MacFarlane 1969, 245).

Other cold regions-related problems included icings, sometimes called aufeis, where seeping water from streams, rivers, lakes, or springs continually creates layers of ice on an ice surface (van Everdingen 2005, 38). The ice creates a road hazard and damages road foundations, bridges, and culverts. Continual maintenance, adequate drainage, and preventing the water from reaching the road are ways to fix the problem. Prevention is the best method by recognizing icing sources and relocating the road (Thomson 1966, 529). Along the Alaska Highway, there were 126 major icings and 95 minor icings, with 68% of the major icings occurring in relation to permafrost (Brown 1970, 119).

Even with modern road building practices, other engineering lessons can be learned from the Alaska Highway. Just to mention, they include: the lack of qualified workers, working in cold conditions, operating and maintaining equipment, long supply lines, lack of construction materials, and short construction seasons (Bennett 1991, 4).

3.5 Analysis – "No permafrost research or expertise"

"'Actually,' Hoge said, 'I doubt that any American knew anything about it until I discovered a great deal about the perma-frost end of it. Everyone talked about muskeg and everybody talked of mountains and crossing lakes and rivers, but they never heard of perma-frost which was the worst thing we had to contend with.'" (Greenwood 1985, 48). Brigadier General Hoge was the commander of the construction of the Alaska Highway. Was he right in that there was not expertise in building on permafrost? Much of the history literature of Alaska Highway construction also supports Hoge, such as permafrost was not encountered on the Richardson Highway (Twichell 1992, 205) and before WWII only Russians had done scientific studies on permafrost and their information was not attainable (Dod 1966, 293). These statements are untrue. There was experience on building roads on permafrost; it was just not sought out in the construction of the Alaska Highway.

The early road builders in the United States and Canada were the gold miners with the major infrastructure facilitated by private companies and governmental works.

The following diagram, Figure 3.2, is from a 1905 U.S. Geological Survey Bulletin on methods and costs of placer mining in Alaska. Specifically, the diagram shows how the public works department of the Yukon Territory built wagon roads in the Klondike. Similar to the Alaska Highway construction, they left the moss and permafrost in place and used a variation of the corduroy road design (Purington 1905, 225). The Alaska Road Commission also had experience in building roads over permafrost, particularly with lessons learned in building the Richardson Highway, which was upgraded from a pack trail to a wagon road in 1910. The Commission came to the same road building conclusions, leaving the permafrost undisturbed and utilizing corduroy roads (Bennett 1991, 5). However, the Alaska Road Commission had not published a report on how to construct roads on permafrost until 1952, ten years after the Alaska Highway construction (Naske 1986, 249). For modern practices, gravel is generally end dumped over the vegetation, and driving over the vegetation is avoided (Andersland and Ladanyi 2004, 291).

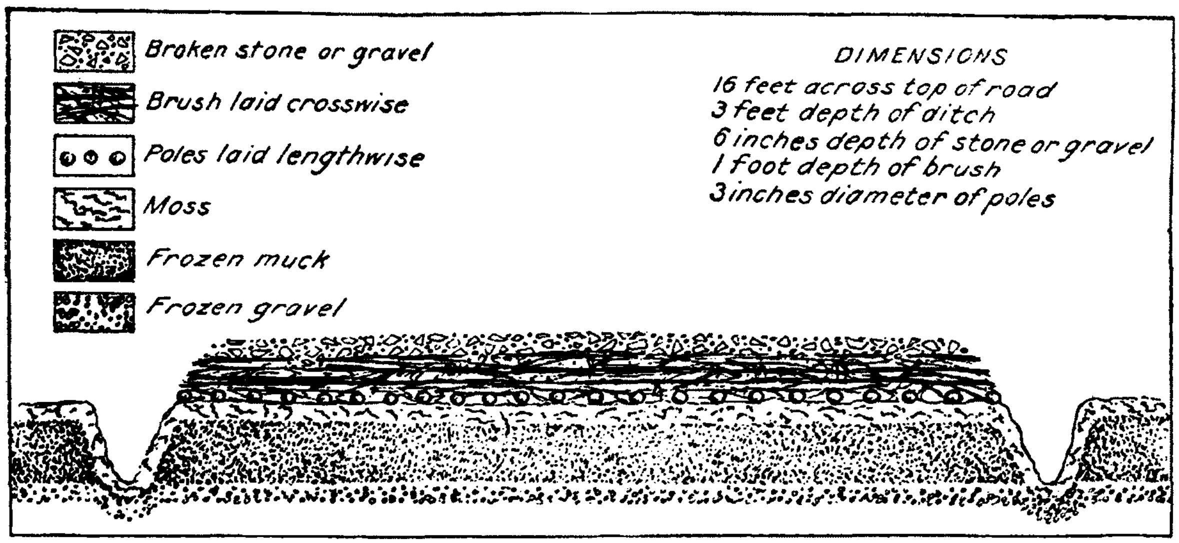

Figure 3.2. Diagram of wagon road profile from the Klondike. Diagram from Purington 1905, 225.

There were people experienced in building roads on permafrost; they were just not involved in the construction of the Alaska Highway. The Territorial Governor Ernest

Gruening had even urged the military to use the unemployed miners as part of their workforce, but Corps of Engineers decided it was cheaper to send troops than gather a local workforce in Alaska (Dod 1966). One aspect not understood is the information gap from the Alaska Road Commission and the Corps of Engineers. The likely reason expertise was not sought out before construction was:

> "The engineers had a job to do. They were building to meet critical deadlines, under pressure of national and wartime emergencies. Roads, airfields, and landing strips were built, utilities installed, buildings constructed; all in record time. With every new problem that arose, engineers had to learn the hard way, what they could do, and what they could not do, on permafrost." (Barnes 1946, 9).

Basically, the rapid pace of construction prevented thoughtful planning.

3.6 Analysis – Influence on Permafrost Research

There was some permafrost research done in the United States before WWII. Ernest de K. Leffingwell studied permafrost in the Canning River region, Alaska in 1919 (Leffingwell 1919). Stephen Taber started studying frost heaving and segregated ice in the mid-1910s (Black and Hardenberg 1991). But, there was no comprehensive published work on construction on permafrost in English. The Russians, however, had been extensively researching and writing on permafrost engineering since the construction of the Trans-Siberian Railroad from 1896 to 1914 (Shiklomanov 2005).

After the numerous permafrost problems, the U.S. Army Air Forces' Air Transport Command hired Siberian-born, Stanford geologist Siemon Muller to write a report on permafrost and engineering (French and Nelson 2008a). Muller's 1943 report, which later became a book, was called *Permafrost or permanently frozen ground and related engineering problems*. The book is based mostly on the work of five Russian authors, with the bibliography being mostly Russian with only a handful of American and other foreign sources (Muller 1947). He also observed the second season of the Alaska Highway construction along with other field trips throughout Alaska from 1943 to 1945 (Muller 2008, xxvii). Muller became known as the "father" of permafrost research in

North America, and coined the word "permafrost." However, the same year Stephen Taber published a monograph, "Perennially Frozen Ground in Alaska: Its Origin and History." While Taber's monograph was overshadowed by Muller's report, both are equally comprehensive, but Taber's focuses on science and Muller's on engineering (French and Nelson 2008b).

Approximately eight months before the end of WWII, the Office of the Chief of Engineers formed the Permafrost Division under the St. Paul District of the U.S. Army Corps of Engineers (Wright 1986). "The chief objective of this long-range program [Permafrost Division] is to determine by cumulative field data and laboratory findings a set of definite answers to certain specific questions raised by the problem of general service construction in permafrost regions" (Barnes 1946, 11). This initial research is the first comprehensive, detailed study on construction methods on permafrost in the United States, which is discussed in the following chapters. With military and also public interest, permafrost engineering research became organized and funded, which continues today with the Permafrost Division's successor, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

3.7 Conclusion

While the Alaska Highway began for strategic defense, today it holds public interests as a destination and is a throughway for cargo, citizens, and tourists. The adventurous construction provided a needed distraction for the U.S. citizens during WWII and captured the hearts of the public. The builders repeated mistakes made before, but eventually came to the same conclusions on practices that were developed before and still followed today. The photos from the Alaska Highway also have provided a famous lessons learned example for the following generations of engineers in the potential catastrophes that could be triggered when dealing with permafrost. While few advancements in permafrost engineering were gained from the construction practices of the Alaska Highway, it did introduce permafrost and its engineering difficulties to the military and the public. With government funding, permafrost engineering research was organized in a comprehensive manner by the Corps of Engineers.

Chapter 4 Initial Works of the Permafrost Division

The Permafrost Division of the St. Paul District of the U.S. Army Corps of Engineers was created in 1945, "to determine design methods and construction procedures to be used in the construction of airfields on permanently frozen ground" (Wright 1986, ii). They were the first military research group to study permafrost, with projects including the n-factor, thermal properties of soil, aerial photo interpretation, and airfield and building design which is discussed in Chapter 5. The projects they initiated became the foundation of modern permafrost engineering.

4.1 Background – History of CRREL

The Office of the Chief of Engineers called a conference in St. Paul, Minnesota, in January 1945, on the problems associated with WWII construction of airfields and the Alaska Highway, as discussed in the previous chapter. The Permafrost Division was founded after this conference, and a field station was set up in Alaska. The field station would be run by the Alaskan unit, consisting of one enlisted person, six engineers, nineteen staff, and thirteen laborers (Wright 1986, 5-6). Their first location was at Northway Airfield, where they studied the runway, a hangar, and several small buildings, starting in February 1945. It was observed that the buildings with air spaces between the bottom of the building and the ground surface had the least permafrost degradation (U. S. Army. Corps of Engineers. St. Paul District 1950). It was then decided that there was a higher demand for research in the Fairbanks area. So in September of 1945, they moved their field office to Ladd Field (later renamed Fort Wainwright). Here, they studied barracks, a hospital, and power plants. Most importantly, they created the Fairbanks Research Area, a 135-acre research site along Farmers Loop Road, as discussed in Chapter 5 (Wright 1986).

In 1953, the Permafrost Division of the St. Paul District merged with the Frost Effect Laboratory of the New England Division of the U.S. Army Corps of Engineers, and was named the Arctic Construction and Frost Effects Laboratory (ACFEL). Then, in

1961, ACFEL merged with another Corps of Engineers organization called the Snow, Ice, and Permafrost Research Establishment (SIPRE) to form the Cold Regions Research and Engineering Laboratory (CRREL). Then CRREL was briefly called the U.S. Army Terrestrial Science Center (TSC), for a year, in 1968 (Wright 1986). CRREL's main office and laboratory is in Hanover, NH with field offices in Fairbanks and Anchorage, AK. In brief, the Permafrost Division of the St. Paul District was one of the roots of the U.S. Army CRREL, which has been significant to permafrost engineering history. One of the authors of the first issue of *The Northern Engineer* stated that,

> One of the most obvious signs that an engineer is involved in cold regions engineering is his treasured horde of CREEL [misspelled CRREL] publications. Since there exists no text on cold regions engineering, the CREEL reports have become the guide to the practicing engineer, be he military or civil (*The Northern Engineer* 1968, 4).

4.2 Engineering – N-Factor

The Permafrost Division was the first to propose the use of a correlation factor between air freezing indices and surface freezing indices, and air thawing indices and surface thawing indices, for different surfaces. Air temperature data are commonly available for settlements while surface temperature data are not. To test this theory, the Permafrost Division measured surface temperatures of different types of surfaces at the Fairbanks Research Area on Farmers Loop Road (U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: 25). This correlation factor is now known as the "n-factor," and is commonly used by engineers today (U.S. Depart. of the Army 1988, 2-11). The n-factor takes into account thermal properties of the material, net radiation absorbed by the material, and several other heat transfer factors (U. S. Army. Corps of Engineers. St. Paul District 1950).

The ground surfaces studied included taiga vegetation in the states of undisturbed, cleared, and stripped, which is detailed in Chapter 5. In addition, they studied gravel, concrete, and asphalt surfaces. The air and ground surface temperatures were measured in the summer of 1947 and the winter of 1947-1948, where the ground surface temperatures were measured with embedded thermocouples. The n-factors were calculated by dividing the surface thawing/freezing index by the air thawing/freezing index for each surface type, with the calculated n-factors shown in Table 4.1 (U. S. Army. Corps of Engineers. St. Paul District 1950).

Table 4.1. N-Factor results (U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: 26).

Type of Surface	Summer N-Factor	Winter N-Factor
Spruce trees, brush and moss over peat soil	0.37	0.29
Cleared of trees and brush but with moss in place over peat soil	0.73	0.25
Silt loam cleared and stripped of trees and vegetation	1.22	0.33
Gravel	2	0.7
Concrete	2.03	0.77
Bituminous	2.19	0.72

4.3 Analysis – N-Factor

The published Permafrost Division's results were only from measurements taken over one year. Since then, some surfaces have been retested and expanded upon, including the gravel, concrete, and bituminous asphalt as seen in Table 4.2 (Andersland and Ladanyi 2004, 59).

Table 4.2. Common N-Factors Information from Andersland and Ladanyi 2004, 59.

Type of Surface	Summer N-Factor	Winter N-Factor
Gravel	1.3 – 2.0	0.9 – 0.95
Concrete	1.3 – 2.1	0.7 – 0.9
Asphalt	1.4 – 2.3	0.9-0.95

In comparison, the Permafrost Division's winter n-factors for gravel and asphalt are lower than normal. This could have been caused by not clearing away all of the snow from above the embedded thermocouples for concern of damaging them. The error could also be due to the ground surface temperature measurements being taken at the Fairbanks

Research Area on Farmers Loop Road, while the air temperatures were taken at the Weeks Field (currently near the Noel Wien Library) (U. S. Army. Corps of Engineers. St. Paul District 1950). This is a distance of approximately 3 miles (5 kilometers) and an elevation difference of approximately 65 feet (20 meters). The difference in elevation is problematic for Fairbanks, due to often persistent winter temperature inversions.

Overall, the n-factor was a revolutionary idea from the Permafrost Division that is still used today. It is included in almost every permafrost engineering book, including the Army/Air Force's Technical Manual (TM 5-852) on Arctic and Subarctic construction methods (U.S. Depart. of the Army 1988). The n-factor allows an engineer to use local air temperature data with an n-factor for taiga vegetation to get a rough estimate of the depth of the active layer, and then use an n-factor for asphalt to get a rough estimate of permafrost degradation under a road to be built in the area.

4.4 Engineering – Thermal Properties of Soil

The St. Paul District contracted Miles S. Kersten from the Engineering Experiment Station of the University of Minnesota in 1945. The purpose of his research was, "to determine under varying conditions of temperature, moisture, bulk density, and composition the thermal properties of representative soils and organic material from Alaska" (Kersten 1949, 1). Kersten tested soils from Alaska and the northern continental United States. The Alaskan soils were sent by the Permafrost Division, as representative of soils in permafrost areas. The continental U. S. soils were supplemented to test for texture and mineral composition effects (Kersten 1949, 1).

The soils from Alaska consisted of Chena River Gravel, Fairbanks Sand, Fairbanks Silt Loam, Fairbanks Silty Clay Loam and Fairbanks Peat taken from Fairbanks, Alaska. From Northway, Alaska, there was Northway Sand, Northway Fine Sand, and Northway Silt Loam. Lastly from Healy, Alaska, there was Healy Clay. From the continental United States is crushed gray granite, Dakota Sandy Loam, and Ramsey Sand Loam from Minnesota. From South Dakota, there was crushed quartz, fine crushed quartz, and crushed potash feldspar. From Illinois, there was Standard 20 to 30 Mesh

Ottawa Sand and Standard Graded Ottawa Sand. Lastly, there was crushed trap rock from Wisconsin and Lowell Sand from Massachusetts (Kersten 1949, 5-7). Kersten's samples were all reconstituted in the lab at varying moisture contents, instead of using the natural moisture contents and soil structures (Kersten 1949).

Kersten's team developed their own thermal conductivity testing apparatus, after having difficulties trying to test at a variety of moisture and density conditions with their original apparatus used to study building materials. The new apparatus was a pipe placed in the center of a larger pipe, where the soil was placed between the inner and outer pipes. The diagram of the apparatus is depicted below in Figure 4.1. The apparatus was set up for radial heat flow, where the inner pipe was heated and the outer pipe was cooled. There were two thermocouples for each of the cooled and heated sides (Kersten 1949).

To study the affect of moisture content and density, the researchers varied moisture contents at a specific densities and varied densities at a specific moisture contents. The temperature between the inner and outer pipes would be kept at an interval of 10F° (5.6C°). For example, for a mean temperature of 70°F (21.1°F), the outer pipe would be 65°F (18.3°C) and the inner pipe would be 75°F (23.9°C). The majority of the soils were tested at mean temperatures of 70°F, 40°F, 25°F, and -20°F (21°C, 4°C, -4°C, and -29°C). The test procedure consisted of setting the outer pipe's (the cold face) temperature and adjusting the inner pipe's (the hot face) temperature until the thermocouple read the correct inner pipe temperature. The heater would continue to be adjusted until the temperature readings were within a quarter of a degree of the desired temperature and the thermal conductivity reading held steady with less than one percent variation for five hours. The voltage and amperage of the main heater were also recorded. These voltage and amperage readings were used to calculate the rate of heat flow, and then to calculate the thermal conductivity of the soil (Kersten 1949).

Kersten observed moisture migration in some of the sandy soils towards the outer pipe (the cold face) and towards the bottom of the apparatus. But for the thermal

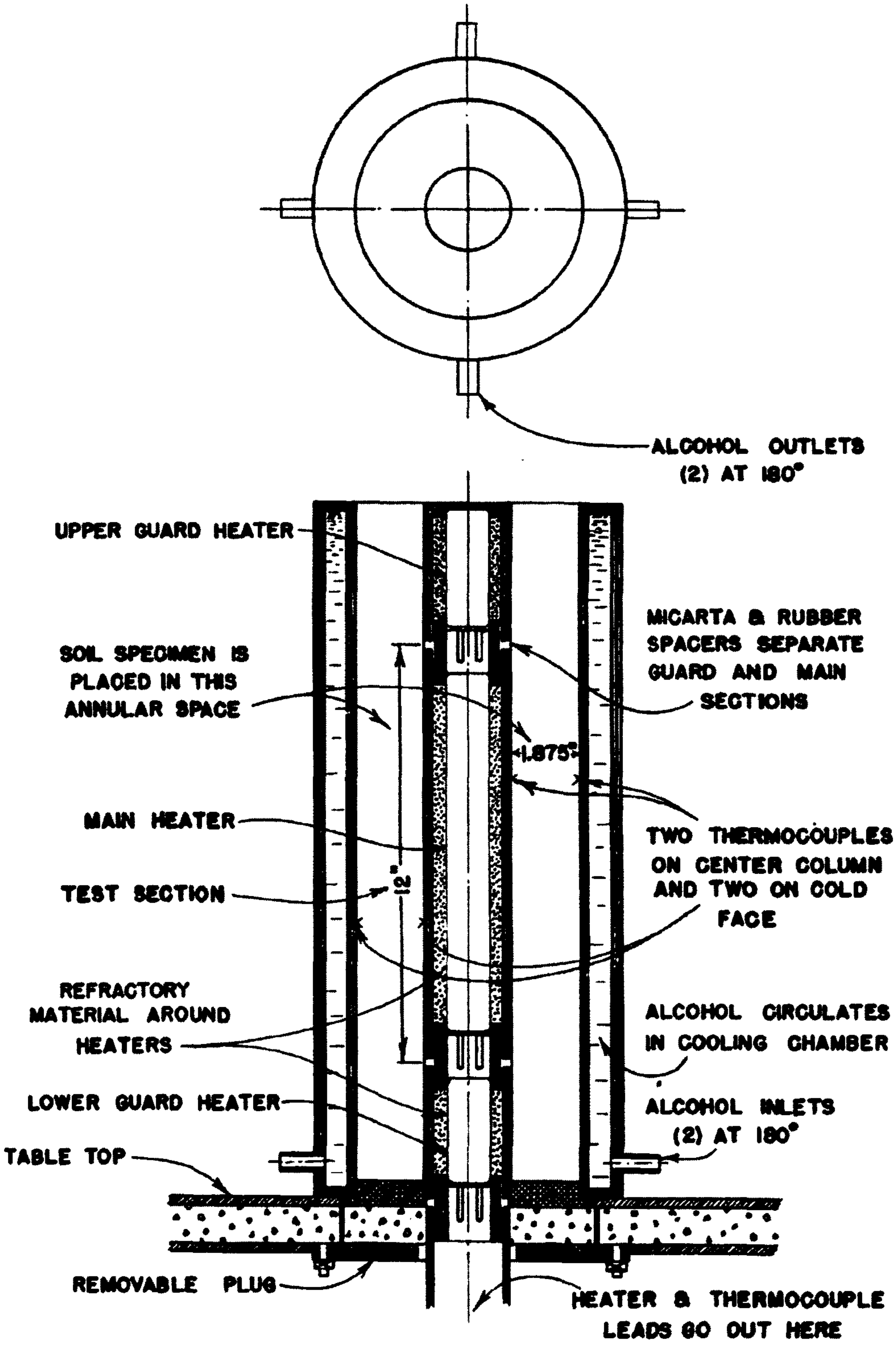

Figure 4.1. Diagram of thermal conductivity testing apparatus. Diagram from Kersten 1949, 14.

conductivity calculations, the moisture contents were averaged over the entire sample (Kersten 1949, 32).

Kersten's conclusions about his thermal conductivity results are listed below:

- For unfrozen soils, the thermal conductivity increases slightly with temperature.
- For frozen soils, the thermal conductivity does not change appreciably between 25°F (-4°C) and -20°F (-29°C). For higher moisture contents, the thermal conductivity increases slightly with decreasing temperature.
- The difference between the unfrozen and frozen thermal conductivities depends on the moisture content. As the moisture content increases, the frozen thermal conductivity becomes increasingly greater than the unfrozen thermal conductivity. But for low moisture contents, up to 6% gravimetric moisture content for sandy soils and up to 12% for fine-grained soils, the frozen thermal conductivity is less than the unfrozen thermal conductivity.
- As the density increases, the thermal conductivity increases.
- As the moisture content increases, the thermal conductivity increases, up to saturation.
- For saturated unfrozen soils, decreases in density caused decreases in the thermal conductivity. For saturated frozen soils, the changes in density had no well-defined relationship to the thermal conductivity for fine-grained soils.
- For soil texture, coarse-grained soils have the highest thermal conductivity with fine-grained soils having the lowest, and sandy loam is in between the two. But, fine-grained soils tend to have higher moisture contents in the field.
- For mineral composition, sandy soils with high quartz content have a higher thermal conductivity than ones that do not. Soils with high clay content have a relatively low thermal conductivity, but this could be related to the fine-grained texture more than the mineral composition. For the crushed rocks, the relationship to mineral composition, from highest to lowest influence on thermal conductivity, is the following: quartz, potash feldspar, granite, and trap rock.

- For the quartz samples, the angular samples were 20-50% greater than the rounded samples due to either the particle contact or the character of the quartz.

The most significant result of the experiments is being able to predict the thermal conductivity of Alaskan soils for thermal-related calculations. Kersten formed four equations for unfrozen and frozen states of silt and clay soils and sandy soils, where soils greater than 50% silt and clay belong in the silt and clay group. The equations marked "a" are English units, where "k" is thermal conductivity with units of BTU per square foot per inch per hour per degree Fahrenheit, "*w*" is percent gravimetric moisture content, and "γ_d" is dry unit weight with units of pounds per cubic foot (Kersten 1949). The equations marked "b" are SI units, where "k" is watts per meter per degree Kelvin and "ρ_d" is dry density with the units being grams per cubic centimeter (Andersland and Ladanyi 2004, 46-47)

Silt and clay soils, unfrozen

$$k = [0.9 \log_{10}(w) - 0.2](10)^{0.01\gamma_d} \quad (3.1a)$$

$$k = 0.1142\ [0.9 \log_{10}(w) - 0.2](10)^{0.6243\rho_d} \quad (3.1b)$$

Silt and clay soils, frozen

$$k = 0.01\ [(10)^{0.022\gamma_d}] + 0.085\ [w(10)^{0.008\gamma_d}] \quad (3.2a)$$

$$k = 0.001442\ [(10)^{1.373\rho_d}] + 0.01226\ [w(10)^{0.4994\rho_d}] \quad (3.2b)$$

Sandy soils, unfrozen

$$k = [0.7 \log_{10}(w) + 0.4](10)^{0.01\gamma_d} \quad (3.3a)$$

$$k = 0.1442\ [0.7 \log_{10}(w) + 0.4](10)^{0.6243\rho_d} \quad (3.3b)$$

Sandy soils, frozen

$$k = 0.076\ [(10)^{0.013\gamma_d}] + 0.032\ [w(10)^{0.0146\gamma_d}] \quad (3.4a)$$

$$k = 0.01096\ [(10)^{0.8116\rho_d}] + 0.00461\ [w(10)^{0.9115\rho_d}] \quad (3.4b)$$

In addition to the equations, there is a set of graphs developed from the equations shown below in Figures 4.2-4.6. The equations and the graphs have an accuracy of ± 25% for predicting the thermal conductivity (Kersten 1949). This is acceptable because natural soils vary that much within one site location due to lack of soil homogeneity (Andersland and Ladanyi 2004, 47).

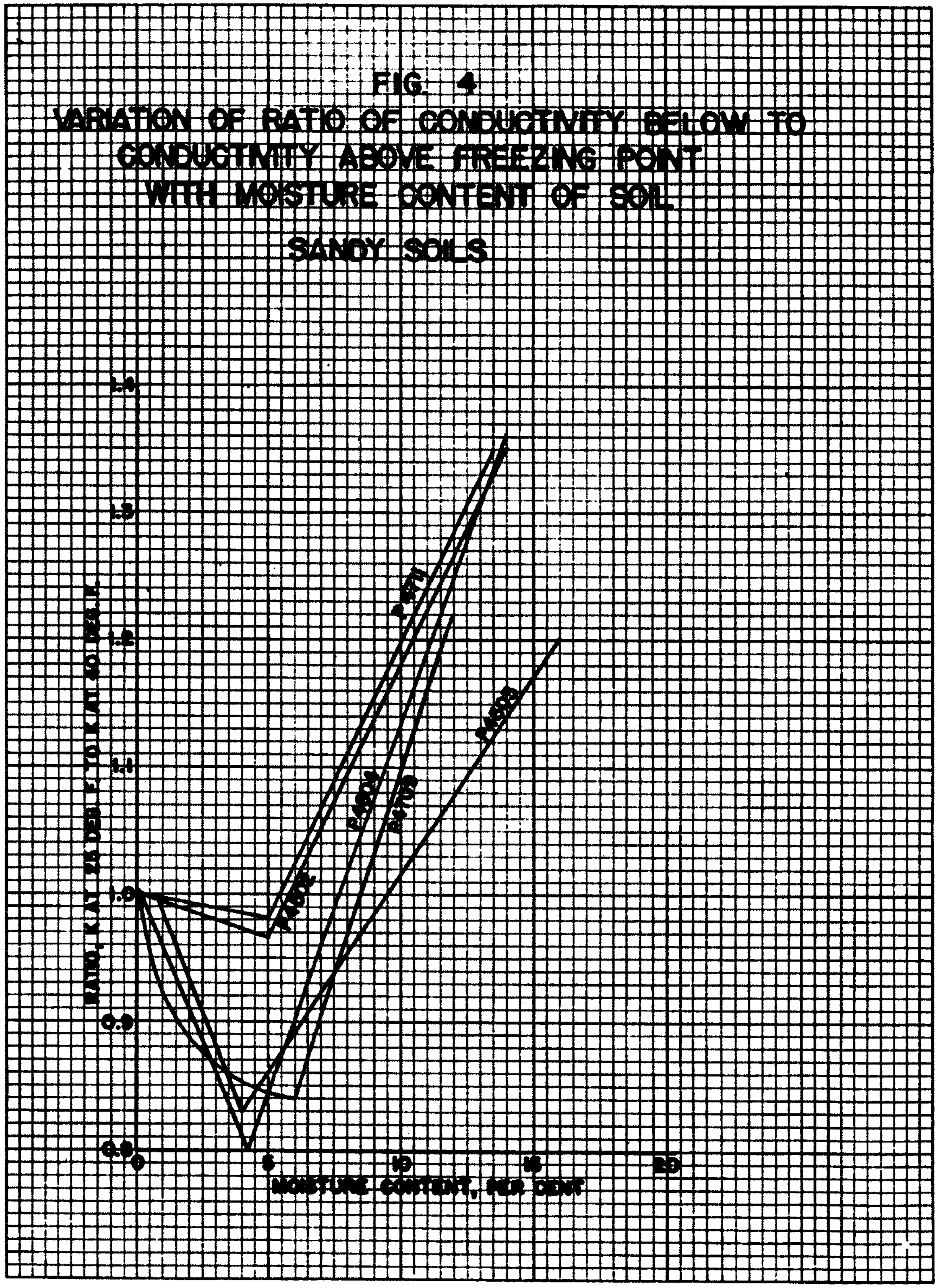

Figure 4.2. Graph of sandy soil thermal conductivities ratio (mean temperatures of 25°F (-4°C) over 40°F (4°C) across moisture content). Graph from Kersten 1949, 37.

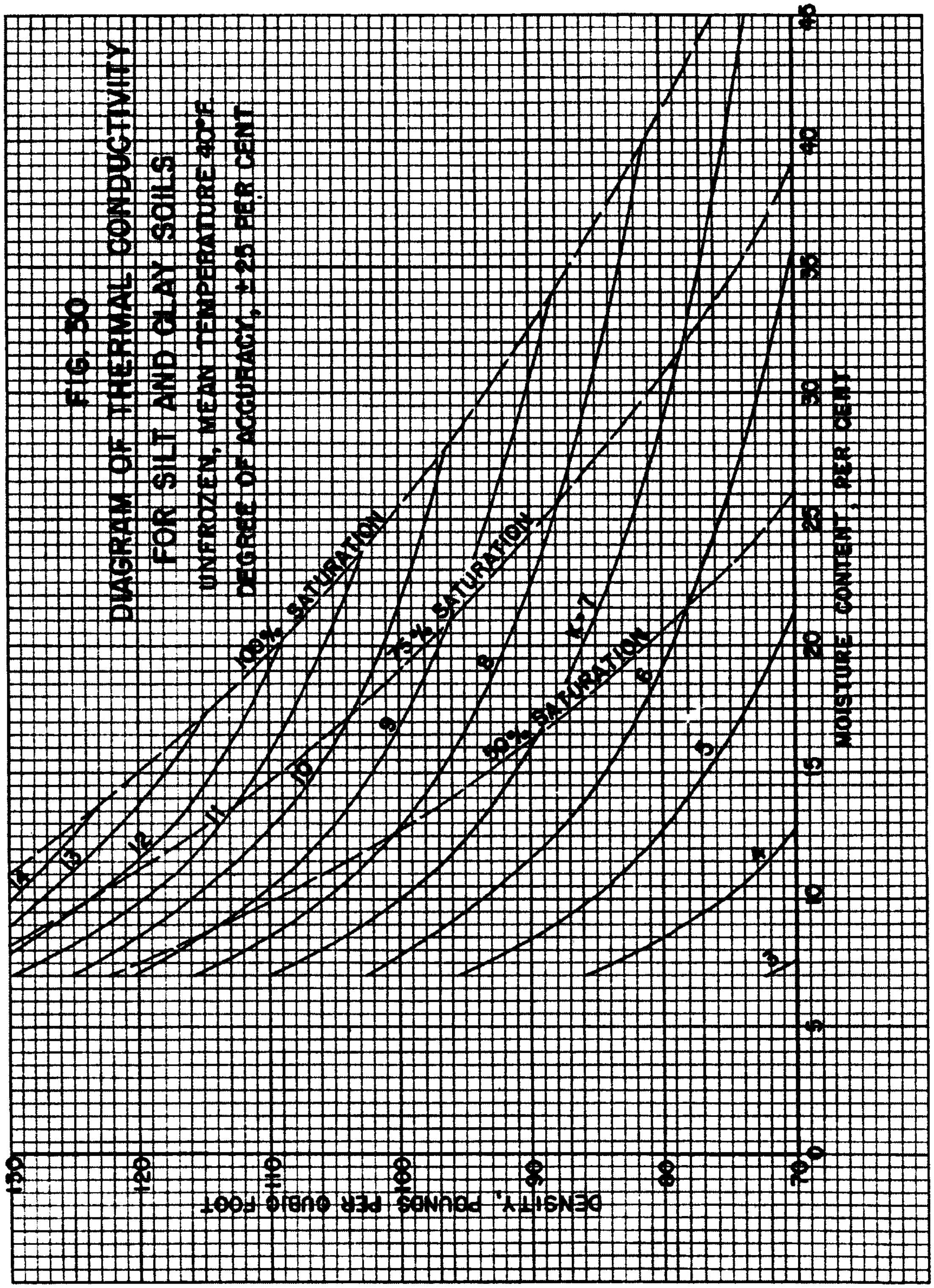

Figure 4.3. Graph of thermal conductivities of unfrozen silt and clay soils. Graph from Kersten 1949, 86.

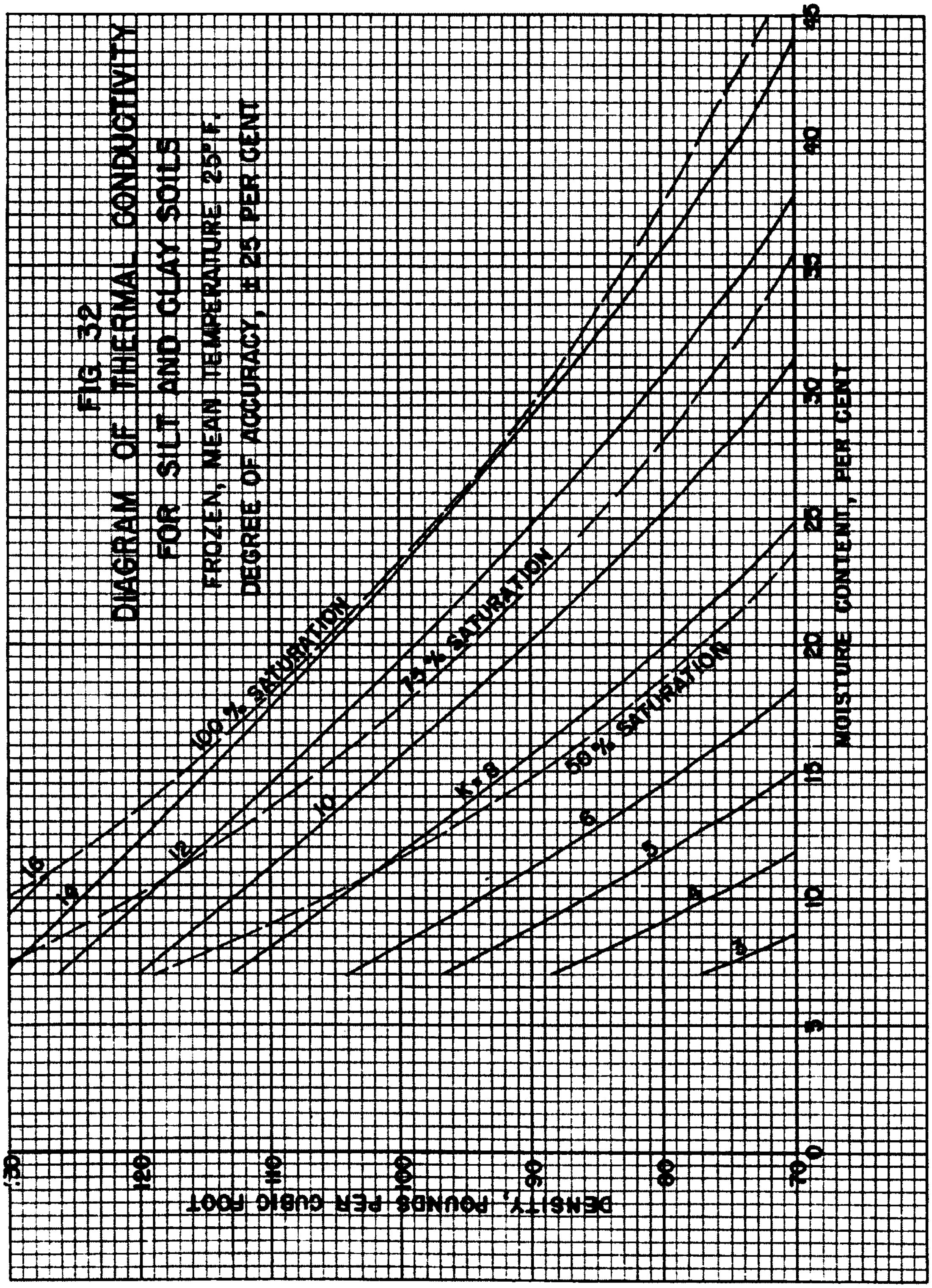

Figure 4.4. Graph of thermal conductivities of frozen silt and clay soils. Graph from Kersten 1949, 88.

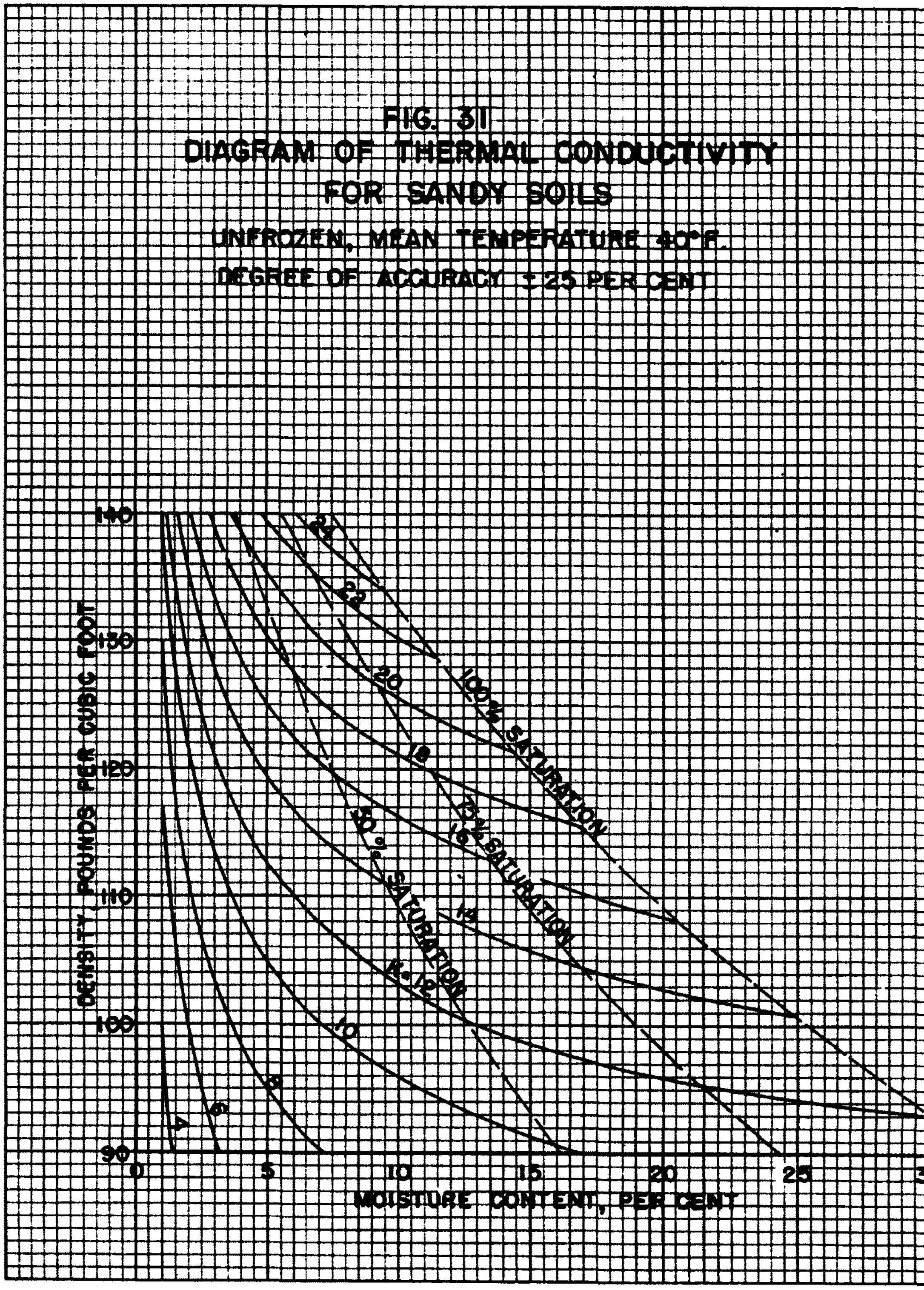

Figure 4.5. Graph of thermal conductivities of unfrozen sandy soils. Graph from Kersten 1949, 87.

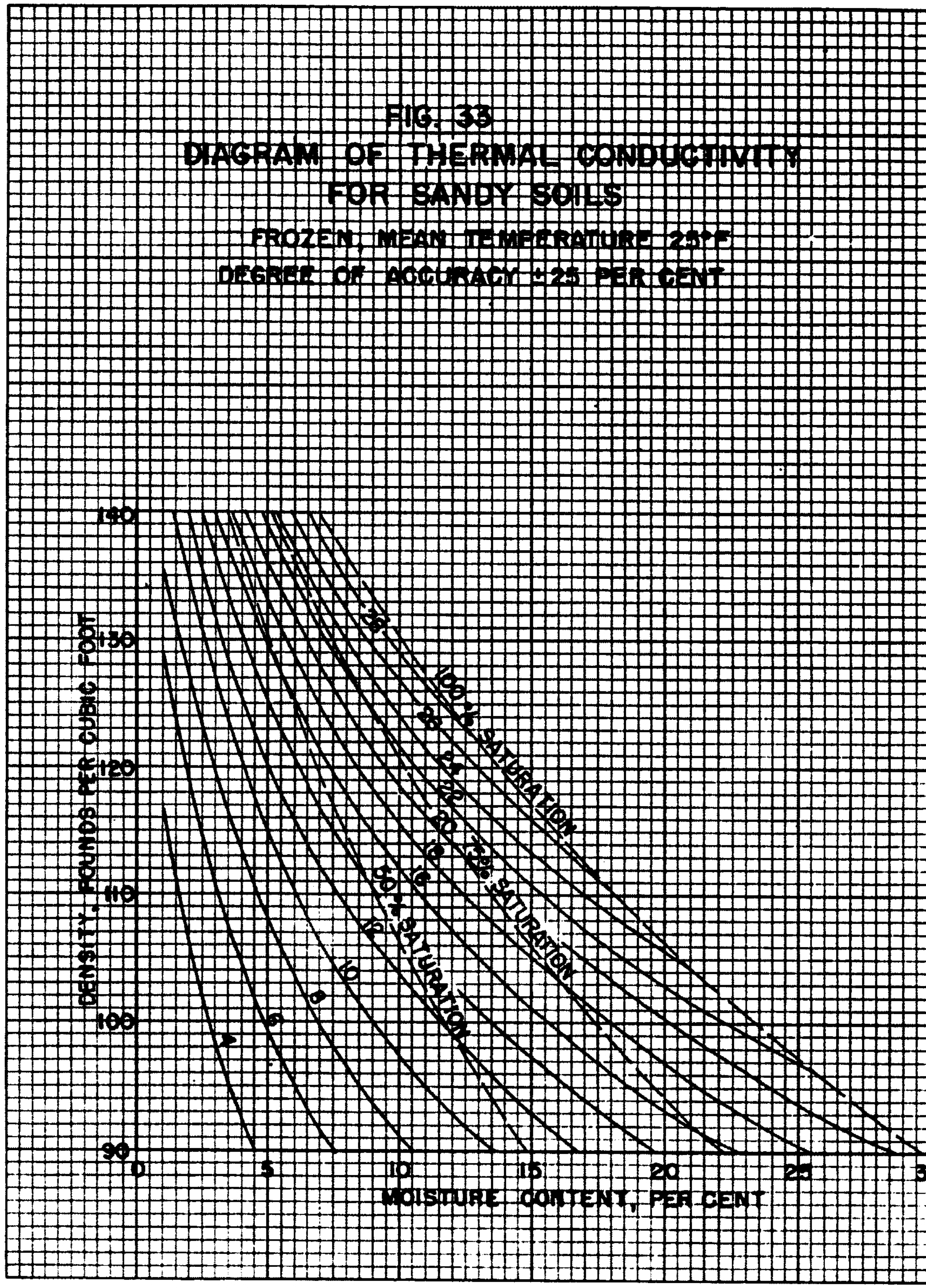

Figure 4.6. Graph of thermal conductivities of frozen sandy soils. Graph from Kersten 1949, 90.

Kersten also conducted specific heat measurements using a calorimeter. He found that the specific heat does not vary appreciably between soil types. For decreasing temperature, the specific heat only slightly decreased, specifically 0.19 BTU/lb-°F for 140°F and 0.16 BTU/lb-°F for 0°F (Kersten 1949).

4.5 Analysis – Thermal Properties of Soil

Compared to later research, Kersten's results did have limitations. Kersten used steady state measurement methods for measuring thermal conductivity. This permitted moisture migration within the sample, which Kersten noted and neglected. With later research, it was found that steady state measurement methods tend to underestimate when compared to transient measurement methods, such as with a thermal probe (Farouki 1981).

Kersten's samples did not have good representation for high quartz content. Therefore, his equations greatly underpredict coarse-grain soils with high quartz content. His equations also overpredict for low quartz content. Therefore, Kersten's equations should only be applied to coarse-grained soils with intermediate quartz content, and definitely not for high quartz content (Farouki 1981).

Kersten did not test saturated samples, but extrapolated his results to saturation. His equations overpredict for soils with a degree of saturation above 0.9. But for frozen fine-grained soils, Kersten's equations matched within ±30% of measured thermal conductivity values from a later experiment (Farouki 1981). Kersten also reconstitute his samples, therefore his equations may not take into account natural cryostructures. Kersten's equations cannot be applied to ice-rich permafrost with ice contents well above saturation, as Kersten did not include these in his experiment.

Kersten's observation on unfrozen thermal conductivity being greater than the frozen thermal conductivity at low moisture contents is accurate. Later, it was concluded that at low moisture contents the water between the grains is removed to form ice. This increased the porosity and reduces the contact between the grains, therefore reducing the thermal conductivity (Farouki 1981, 45).

While later research does give more accurate predictions, such as Johansen's method, but Kersten's equations are simpler to use. In addition, work has been done to compile his graphs into six graphs. The graphs include the frozen and unfrozen thermal conductivities for coarse-grained, fine-grained and organic-rich fine-grained soils. With its limitations, Kersten's work is still practical for engineering work today with most natural soils (Andersland and Ladanyi 2004, 47). But, engineers should be aware of its limitations.

For specific heat, Kersten was close on his measurements for mineral soils. The typical specific heat used in calculations for mineral soil is 0.17 BTU/lb-°F. But when working with organic soils, which Kersten did not test for, the specific heat that is used is 0.40 BTU/lb-°F ((Andersland and Ladanyi 2004, 51).

4.6 Engineering – Aerial Photo Interpretation

The Permafrost Division of the St. Paul District contracted the Engineering Experimental Station of Purdue University for, "developing a technique for predicting permafrost conditions and soil characteristics from aerial photographs" (U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: 12). From 1945 to 1948, the Purdue team studied various permafrost areas throughout Alaska. Their work consisted of collecting field data to pair with photographs already taken by the Army Air Force. When there were no photographs for a given area, the Army Air Force would plan to take the photographs around the same time the Purdue team would be collecting their field data (U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: 12).

Aerial photo interpretation was of interest for the Civil Aeronautics Administration during WWII, to aid in the location of airports. After WWII, the Purdue research was done for the utilization of aerial photos in Alaska, for the following reasons:

> "In a relatively undeveloped region, such as in the Territory of Alaska, aerial photographs can be used to great advantage – particularly since the Territory is not adequately mapped for military or civilian use in locating airports, highways, railroads, bases, etc. When it is known that some engineering structure is to be

built in a particular region, the air photos of the region should be studied and, in a few hours' time, a general engineering map can be produced which will show the good, poor, and intermediate soil areas evaluated on the basis of anticipated performance of engineering structures. Thus, the poor soil areas can be eliminated almost entirely by study of aerial photographs and the field investigation can be concentrated on those areas best suited to construction" (Frost 1950, viii).

The Purdue team concluded that the most important landscape features for engineering works are topography, surface features, texture of soil or rock-soil materials, and vegetation. Topography is used to identify surface drainage, as water is needed for ice formation in "detrimental permafrost" (Frost 1950, 4). The surface features can identify permafrost features, such as ice wedge polygons, and other features include the drainage patterns, gullies and their shapes, muskegs or swamps, vegetation, slope and exposure. Changes in vegetation, along with other indicators, can identify problem areas. But vegetation alone can be misleading when identifying permafrost. While soil texture cannot be directly identified from aerial photos, it can be estimated from the natural-soil forming processes. To identify permafrost, it is important to look for the changes in surface features and vegetation, as they will differ for the frozen and unfrozen conditions across a similar soil texture (Frost 1950, 4).

Ernest G. Stoeckeler accompanied the Purdue team during their summer field trips and studied the relationship between vegetation and permafrost. For identifying the vegetation through aerial photographs, there are only a small number of forest types in permafrost areas including white spruce-paper birch forests, muskeg-swamp forests, aspen-poplar stands, high brush, and tundra. However, spruce-birch forests can grow both in frozen and unfrozen soils, but they can differ in height, composition, and density. A person with good spruce-birch forest knowledge and high quality photos can be decent at predicting permafrost conditions. The biggest limitation for identifying permafrost from vegetation is if the permafrost table depth is greater than 6 feet (1.8 meters). This causes little or no effect on the tree growth with the exception of deep-rooted trees such as balsam poplar, cottonwood, and jack pine. Therefore, vegetation is only an indicator for shallow permafrost, while topography, drainage, and other features can be used as indicators for deeper permafrost (Stoeckeler 1949).

Along with their photo examples, the Purdue team also sketched vegetation sequences. The diagram below, Figure 4.7 is of a stream-deposited terrace in a discontinuous permafrost zone (Frost 1950).

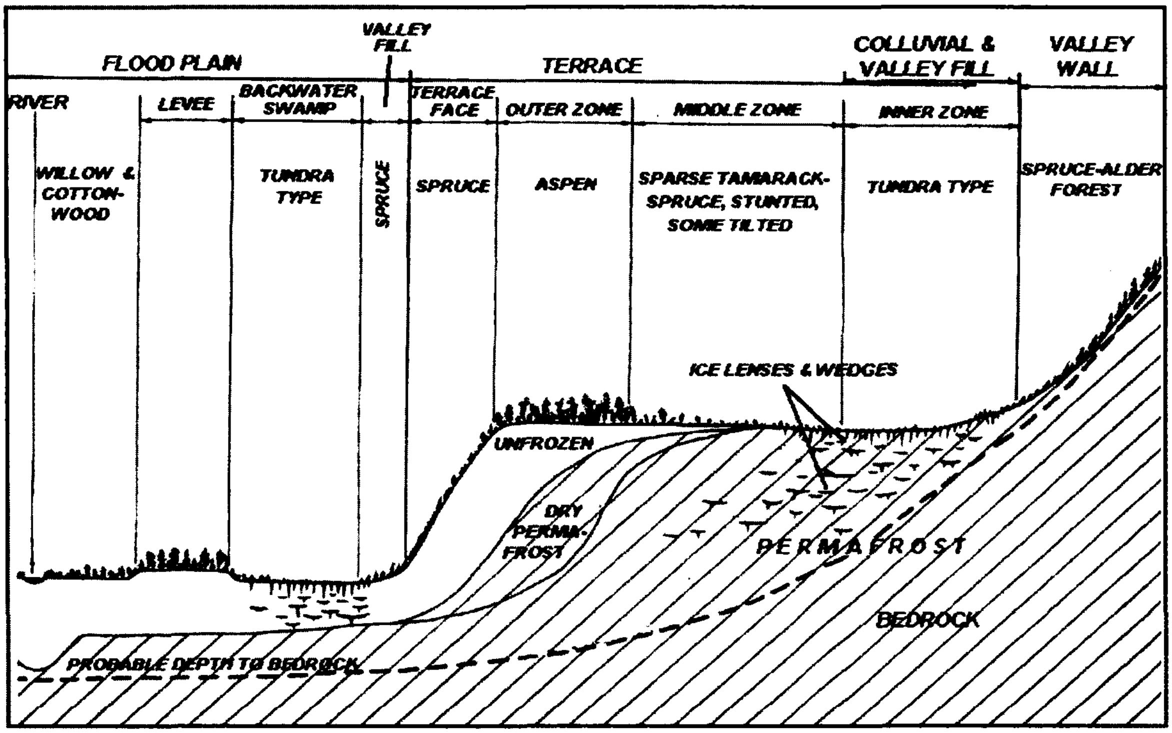

Figure 4.7. Diagram of permafrost and vegetation sequence profile. Diagram adapted from Frost 1950, 58a.

4.7 Analysis – Aerial Photo Interpretation

The two-volume report, *Evaluation of Soils and Permafrost Conditions in the Territory of Alaska by Means of Aerial Photographs*, provides a good introduction to photo interpretation and permafrost features. The report introduces Alaskan geology, climate, vegetation, and permafrost features. It also has copious amounts of black and white photographs as examples, which would be a good resource for engineers and geologists without permafrost knowledge. The reports also discuss the limitations of aerial photos with emphasis on how it does not replace ground surveys, for example vegetation can be misleading.

While aerial photo interpretation was not a new idea, the Purdue University team was the first to apply it to permafrost regions. They developed the first manual that could be used for Alaska. Their work was extensive and comprehensive and allowed it to become the basis of further work. Ernest G. Stoeckeler's work is possibly the most significant finding, as vegetation is one of the biggest limitations in surface identification of permafrost. The permafrost-vegetation sequence profile sketches are possibly the first of its kind in permafrost literature. The Purdue team's report aided the aerial photo interpretations for the Trans-Alaska Pipeline System route (Kreig and Reger 1982, 12) and development of the landform terrain analysis called the "Alaska Methodology" that is used today (Kreig and Metz 2005, 5).

4.8 Conclusion

The n-factor and Kersten's thermal conductivity equations and graphs are still used today for estimating depth of thaw and freeze. Both are still taught in arctic engineering classes and are in almost every frozen ground engineering book, including the U.S. Army/Air Force's Technical Manual (TM 5-852) on Arctic and Subarctic construction methods. The Engineering Experimental Station at Purdue University, along with Ernest G. Stoeckeler, developed the first manual on aerial photograph interpretation in Alaska, which was expanded upon and eventually used for the Trans-Alaska Pipeline System route selection and the development of the "Alaska Methodology" for terrain analysis. Their further work on design and construction at the Fairbanks Research Area is discussed in the Chapter 5. The Permafrost Division's work and contracted work were revolutionary and set the foundation for growth in the permafrost engineering field.

Chapter 5 Initial Research at Fairbanks Research Area

The Fairbanks Research Area was created in 1945 by the Permafrost Division of the St. Paul District, Corps of Engineers. Their purpose for the site was "providing an opportunity to observe various types of structures erected on permafrost under conditions that would be known and recorded from the beginning to the conclusion of operations" (U. S. Army. Corps of Engineers. St. Paul District 1950, app. III: 1). The initial research at the site included: ground and pavement surface studies, runway foundation studies, and building and piling foundation studies. Their design and construction studies were the first of its kind in the United States, and provided the basis for further development.

5.1 Background – Fairbanks Research Area

The Permafrost Division of St. Paul District, Corps of Engineers and their other works are discussed in Chapter 4. The Fairbanks Research Area, like its creator, has gone through numerous name changes. It was renamed in 1953 to the Alaska Field Station, when the Permafrost Division merged into the Arctic Construction and Frost Effects Laboratory (ACFEL). Then, in 1961, the site was renamed to Fairbanks Permafrost Experiment Station, when ACFEL merged into the Cold Regions Research and Engineering Laboratory (CRREL) (Wright 1986). The Fairbanks Permafrost Experiment Station remains its name today (Henry and Bjella 2006), but with a few naming errors since 1961. In one paper, the site was referred to as the Farmers Loop Road Field Station within the text of a paper and on the same page there was a diagram labeled the Alaska Field Station, when at the time the site should have been called the Fairbanks Permafrost Experiment Station (Linell 1973, 688). This paper only looks at the initial work done at the site, so the site will be referred to as the Fairbanks Research Area.

The Fairbanks Research Area site was chosen because of its close proximity to Ladd Field (later renamed Fort Wainwright). The undisturbed 135-acre site was bought in September of 1945 (Wright 1986). It is located on the east end of Farmers Loop Road in Fairbanks, Alaska, mapped below in Figure 5.1. Construction began at the site in April

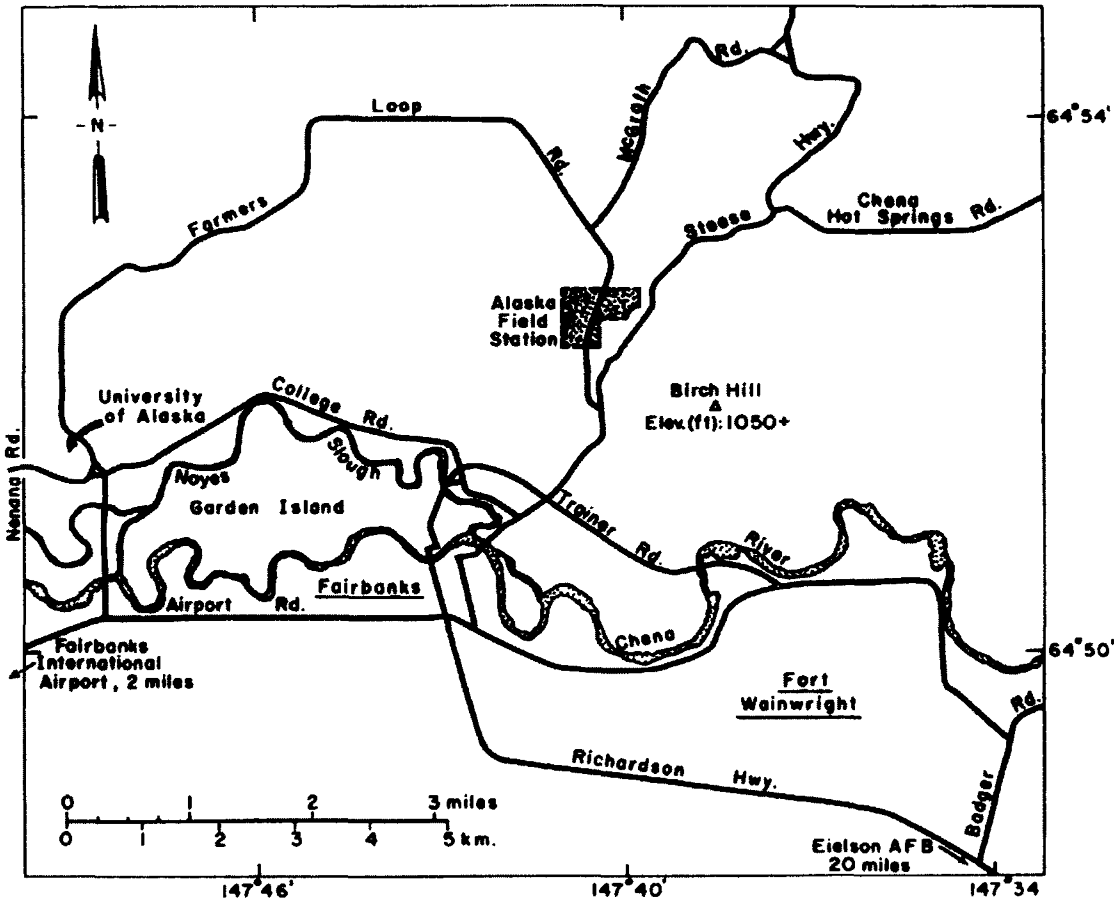

Figure 5.1. Map of the Fairbanks Research Area (Alaska Field Station). Map from Smith et al. 1973, 737.

1946 with the stripping and clearing for the ground surface studies (U. S. Army. Corps of Engineers. St. Paul District 1950). The researchers also resided and worked within the constructed test buildings (Lobacz and Quinn 1963).

The site is located on a gentle west-facing slope. An early photo of site is pictured below in Figure 5.2, where Farmers Loop Road is running below Area No. 2 and No.3. The original depth to the permafrost table ranged from 3 to 6 feet (0.9 to 1.8 meters) with the bottom of the permafrost being greater than 160 feet (49 meters). The soil is silt with some layers of peat and silty sand, underlain with sand and gravel at 250 feet (76 meters) (U. S. Army. Corps of Engineers. St. Paul District 1950; Lobacz and Quinn 1963). The permafrost is ice-rich, with a higher concentration of ice lenses within 10 feet (3 meters) of the ground surface (Haley 1955). The vegetation is subarctic taiga forest with spruce trees, brush, and thick moss ground cover (Linell 1973). The Fairbanks area is within the discontinuous permafrost zone and the permafrost temperature is close to 32°F (0°C).

The Fairbanks Research Area was divided into three areas. Area No. 1 was for ground and pavement surface studies, Area No. 2 was for runway foundation studies, and Area No. 3 was for building and piling foundation studies (U. S. Army. Corps of Engineers. St. Paul District 1950).

Numerous other research projects have been conducted on the site. Research has continued on buildings, piles, and roads (Henry and Bjella 2006). Many of the later research projects were conducted by non-CRREL employees, so some of these projects can be impossible to find information on. More recently, it became a National Geotechnical Experimentation Site in 2003 and part of the Circumpolar Active Layer Monitoring Network (CALM) in 2005 (Douglas et al. 2008).

5.2 Engineering - Ground and Pavement Surface Studies

The ground surface studies, also known as the "Linell Plots", are named after the author Kenneth Linell (1973) (Douglas et al. 2008; Henry and Bjella 2006). Its purpose is to study how permafrost reacts to common construction surface conditions. The study was started in Area No.1 in 1946. The ground surface studies consisted of three 200 feet

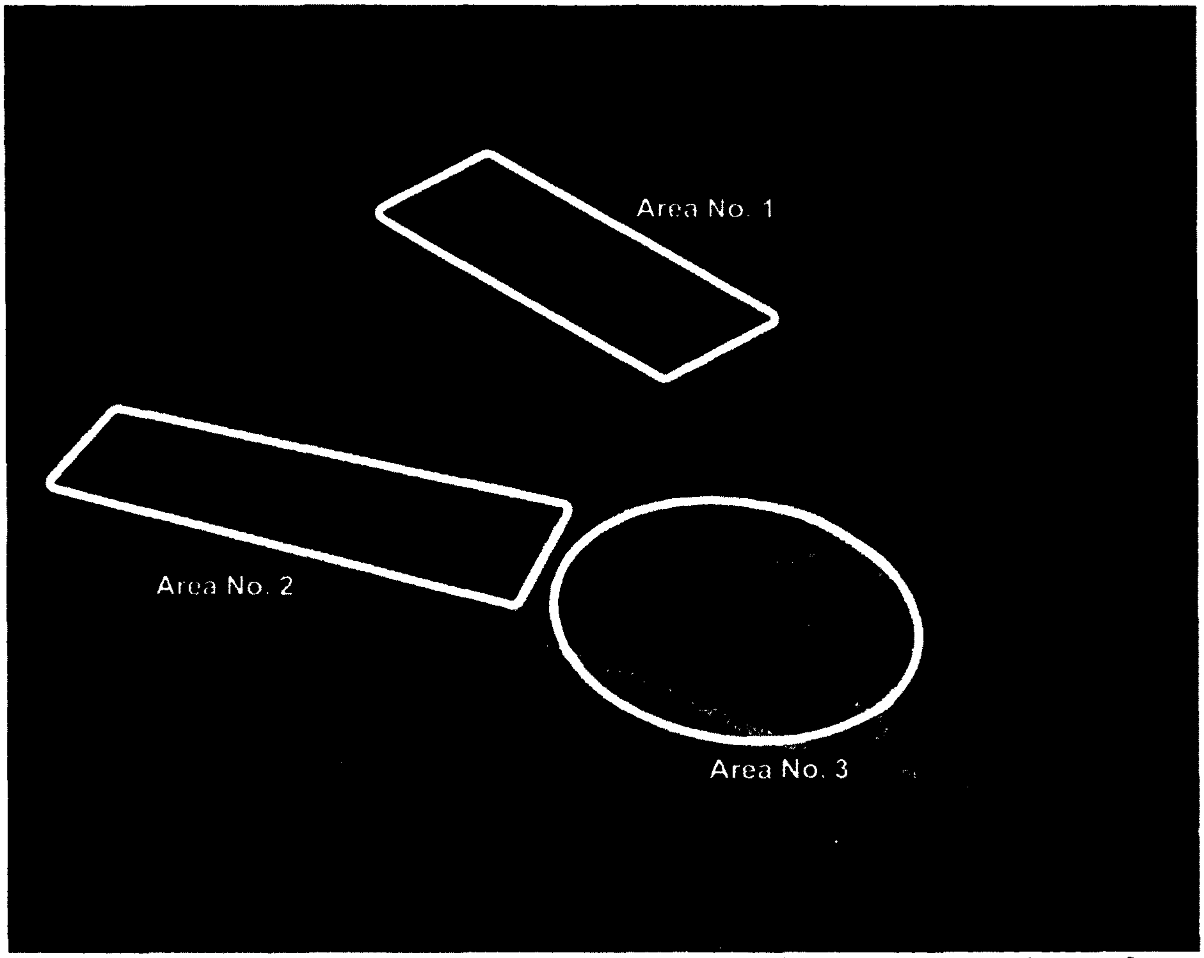

Figure 5.2. Photo of the Fairbanks Research Area. Photo from U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: Inside Cover.

by 200 feet (61 meters by 61 meters) sections, mapped in a later publication below in Figure 5.3. Section A was the control and left undisturbed. Section B was cleared of trees and bushes, cut about a foot (0.3 meters) above the moss cover and the trunks and roots were left in place. Section C was cleared and stripped to a soil depth of 16 inches (41 centimeters). Sections A, B, and C are pictured below in Figure 5.4. The pavement study was in section D. This 30 by 90 feet (9 by 27 meters) section, not labeled on map, is southwest of the ground surface studies (U. S. Army. Corps of Engineers. St. Paul District 1950; Linell 1973).

Sections A, B, and C were maintained in these conditions for 26 years, in order to study the long-term effects of the modified vegetation. Section B did have new plant growth move in, consisting of taller brush. For the most part, the sites had remained exactly the same as pictured in the above photos. Foot traffic was even limited to protect the snow and moss cover (Linell 1973, 689).

Linell measured from the center of each section with thermocouples for temperature and probing for permafrost depth, the results are shown in Figures 5.5 and 5.6 below. Figure 5.5 is presented with the air freezing and thawing indexes. Figure 5.6 depicts the changes of thaw depths over the years in a more idyllic way. While the permafrost table in Section A stayed about the same, it thawed to a depth of approximately 15 feet (4.6 meters) for Section B and 22 feet (6.7 meters) for Section C (Linell 1973).

Section B had surprising results. Commonly, it was thought that leaving the low vegetation and organic mat intact would prevent permafrost degradation. These results show that leaving the low vegetation and organic mat intact does not prevent long-term permafrost degradation with permafrost conditions close to 32°F (0°C). In colder permafrost, leaving the organic moss mat intact is common, with good results. It was believed that the low vegetation aided the thaw because it "partially supported the winter snow cover in section B and reduced its density as compared to either section A or C" (Linell 1973, 690). This caused the section to have the smallest freezing index of all

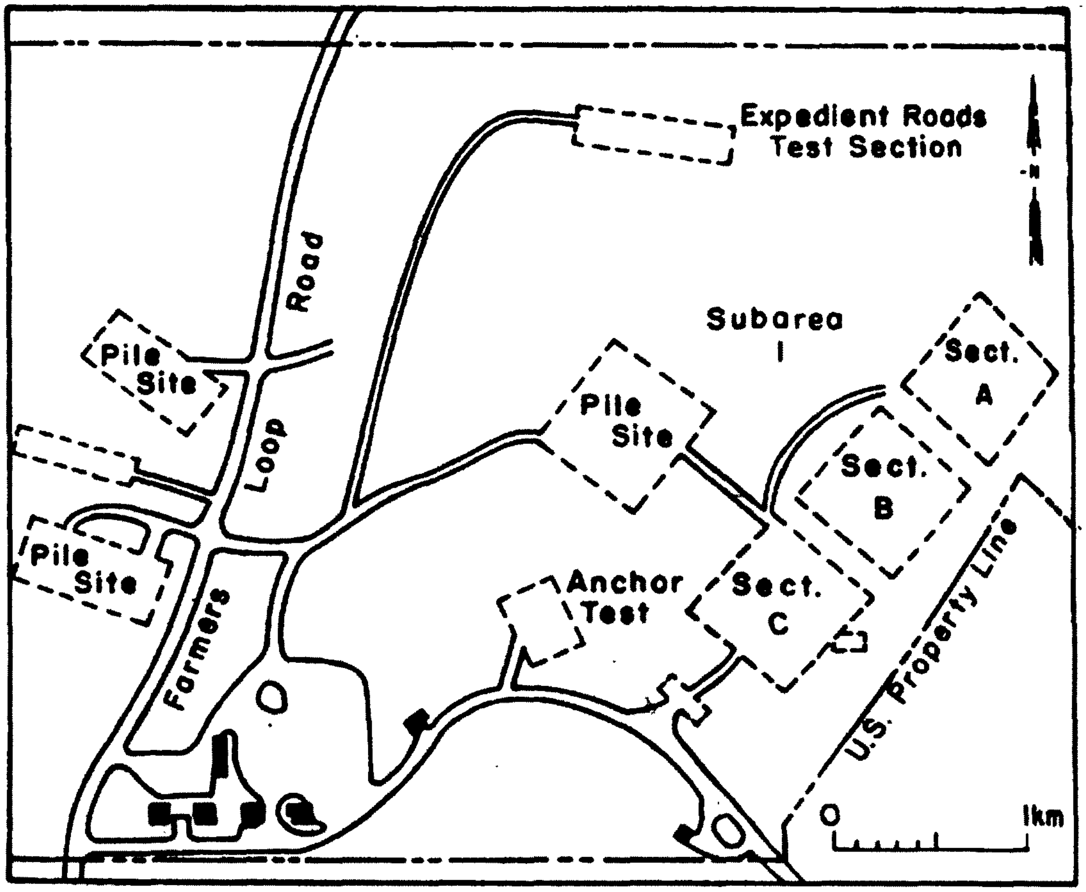

Figure 5.3. Map of Area No. 1 (Sections A, B, and C in the lower right of the map). Map from Linell 1973, 688.

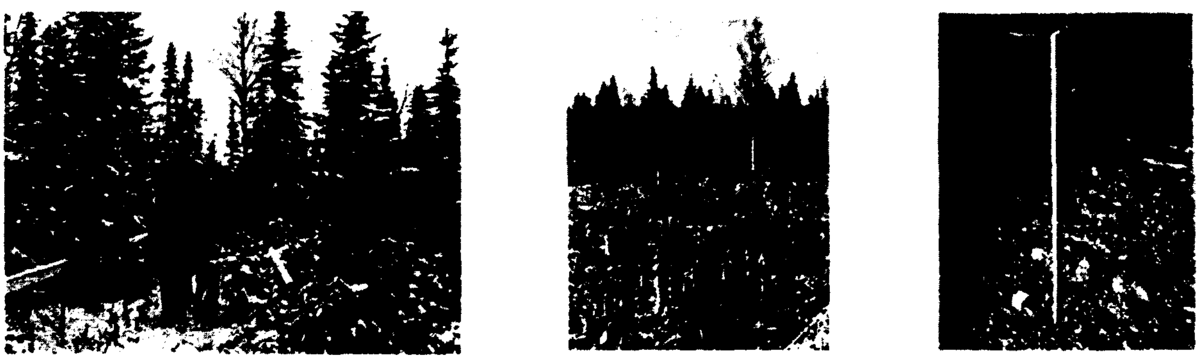

Figure 5.4. Photos of vegetation modification test plots in Area No. 1. Photos from U. S. Army. Corps of Engineers. St. Paul District 1950, app. III: 5.

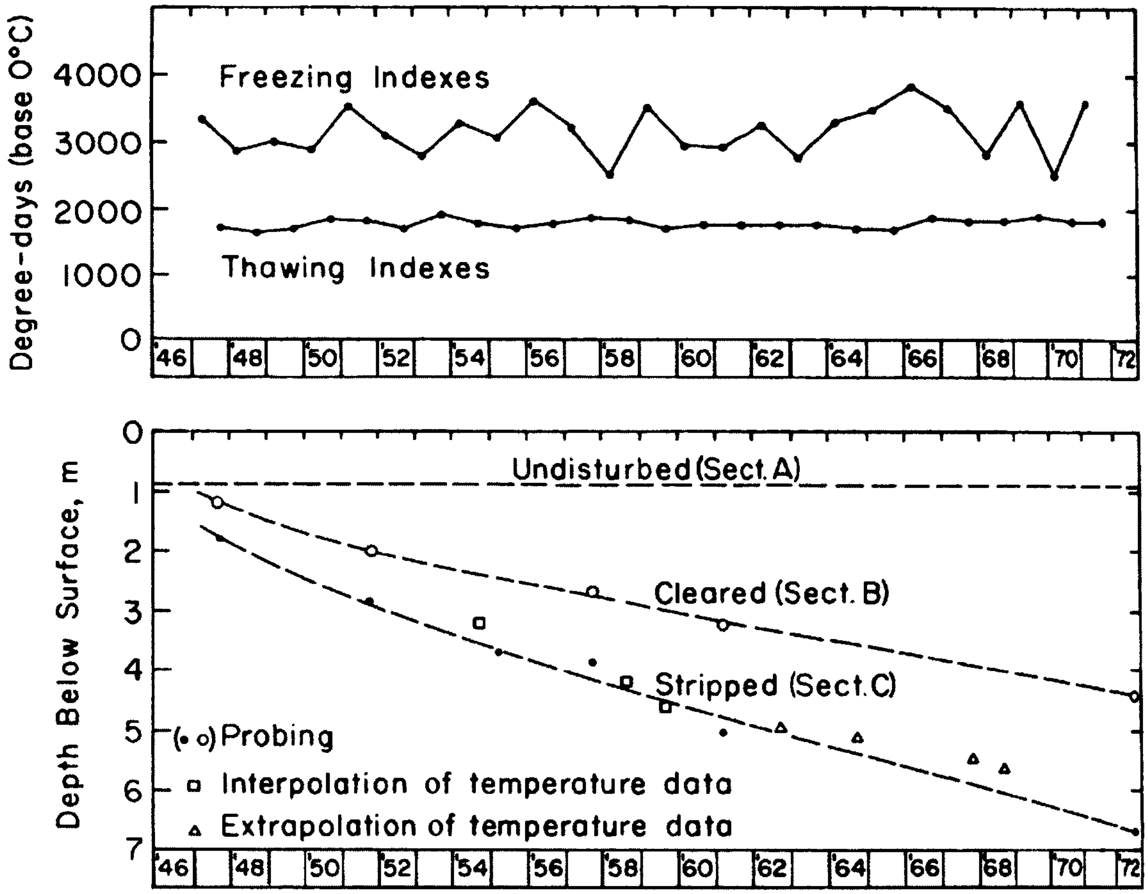

Figure 5.5. Graphs of air freezing and thawing indexes (top graph) and thaw depth (bottom graph) in Area No. 1. Graphs from Linell 1973, 690.

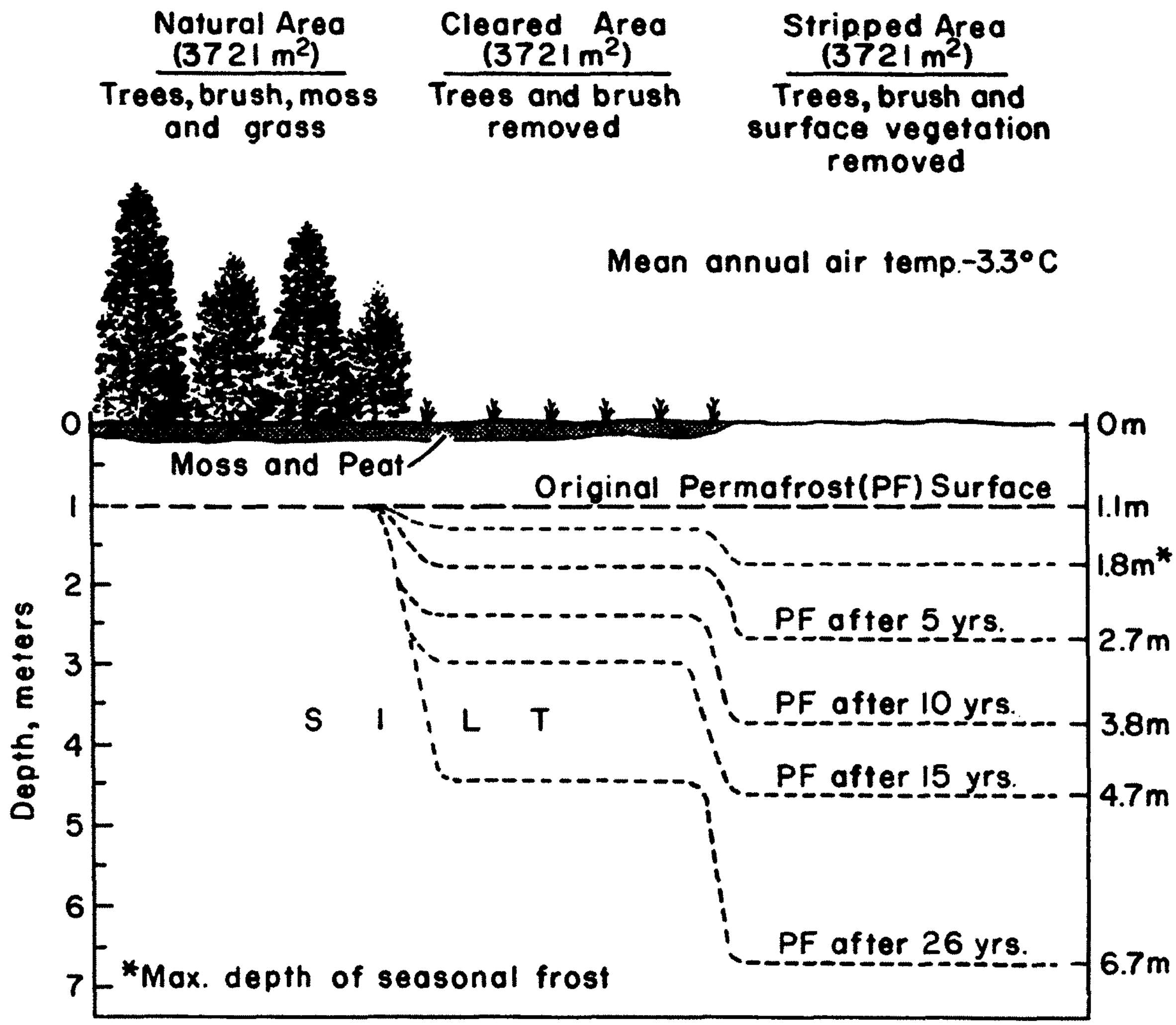

Figure 5.6. Diagram of thaw depth of Area No. 1. Diagram from Linell 1973, 691.

three. Section B is important for construction because a building site is usually cleared beyond the building footprint as well as along the sides of roads (Linell 1973).

Section D studied the effects of color surfaces of concrete on permafrost degradation. A 30-foot by 90-foot (9-meter by 27-meter) section was cleared and stripped to a depth of 12 inches (30 centimeters), then backfilled to the original ground level with sand. It was then paved with 6 inches (15 centimeters) of concrete. The concrete was sectioned into thirds for surface color, where one was painted black, one was white, and one was left unpainted as a control. After a year of data measurement, the Permafrost Division concluded that the color had no affect on permafrost degradation. The depth of thaw during the summer and vertical settlement and heave were similar, but this is only after one year of study (U. S. Army. Corps of Engineers. St. Paul District 1950).

5.3 Analysis – Ground and Pavement Surface Studies

For Section D, color has a huge affect on albedo or reflectivity, and differences would probably have been observed with continued study, which was later proved in a different research project at the site (Berg and Aitken 1973). Today, the black painted section has greatly subsided and is under standing water.

The Linell Plots were recently measured in 2007, 35 years after Linell concluded his research. The researchers used direct current electrical resistivity to measure the permafrost depth. They added their data to the figures from Linell's paper, shown in Figure 5.7 and Figure 5.8. The vegetation in Section B has grown back and the permafrost thaw depth is the same. The permafrost has either remained at same depth, or continued to degrade after 1972 and then rebounded back to the 1972 depth. There was also a thin layer of frozen ground found at a depth of 5 feet (1.5 meters), possibly signifying the reformation of the permafrost. After 1972, thermal pile research was conducted in Section C, and only sporadic vegetation has grown back. The thaw depth in Section C has continued to degrade from 22 to 32 feet (6.7 to 9.8 meters) (Douglas et al. 2008).

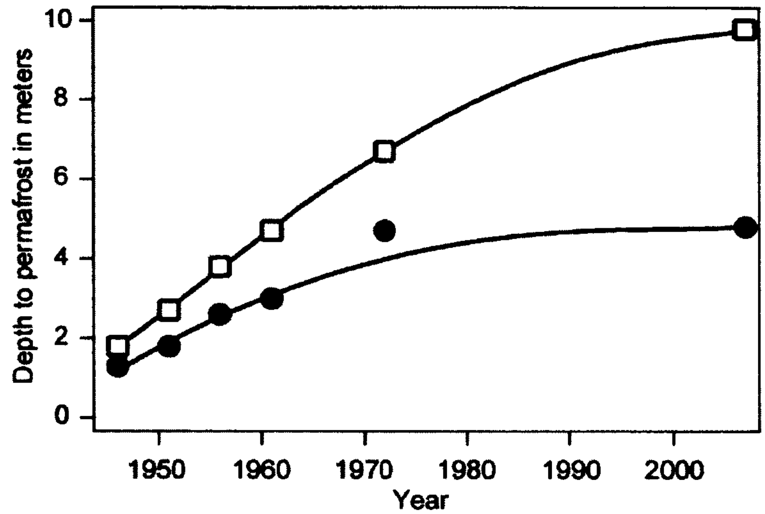

Figure 5.7. Graph of thaw depth of Sections B (black) and C (white). Graph from Douglas et al. 2008, 377.

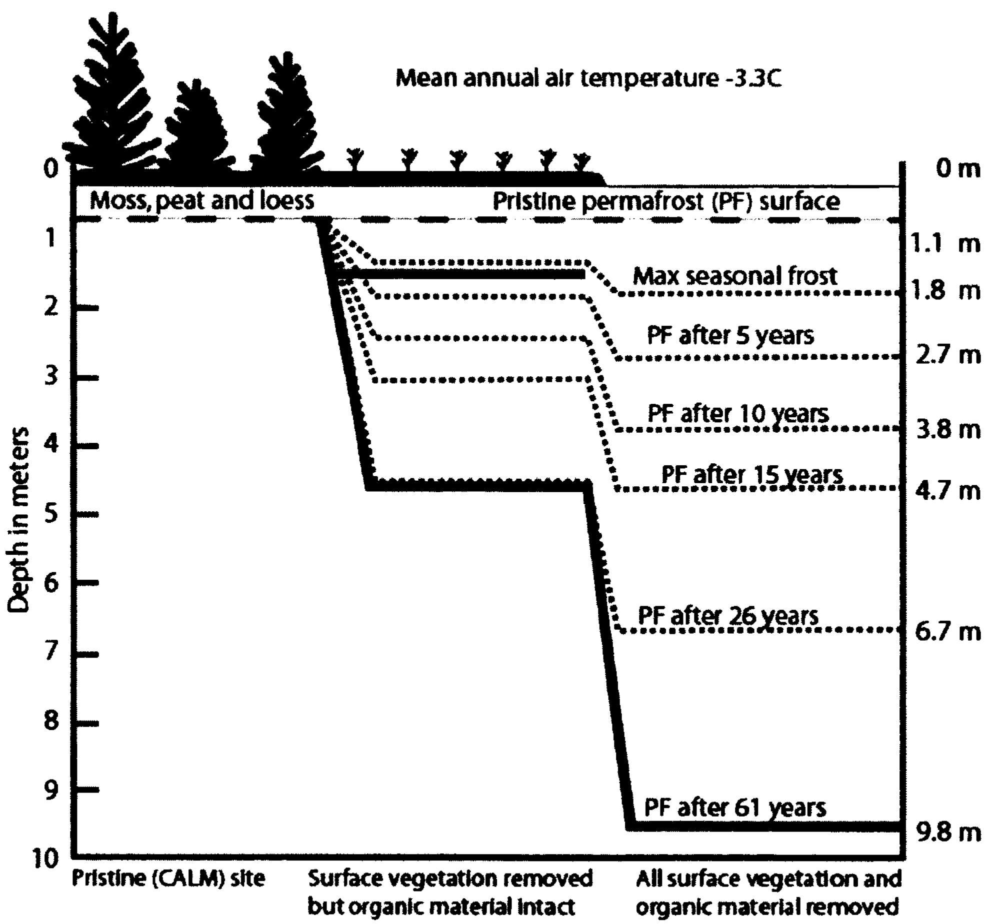

Figure 5.8. Diagram of Thaw depth of Area No. 1. Diagram from Douglas et al. 2008, 377 (adaptation of a figure from Linell 1973).

5.4 Engineering – Runway Foundation Studies

The focal point of the Permafrost Division's research was to develop design and construction techniques for airfields over permafrost. The runway foundation studies were conducted in Area No. 2, which ran parallel to Farmers Loop Road, shown in Figures 5.9 and 5.10. There were 26 runway test sections, where each section was 50 feet by 50 feet (15 meters by 15 meters). The test sections had different base courses consisting of sand or sand and gravel at different thicknesses. The runway surfaces were mostly asphalt along with concrete and gravel. They used different insulations consisting of P.C. Foamglas, cell concrete, zonolite concrete, compacted spruce logs and branches, and compacted moss. However, a majority of the sections did not have insulation. A few test sections were constructed in the winter and spring instead of the summer (U. S. Army. Corps of Engineers. St. Paul District 1950).

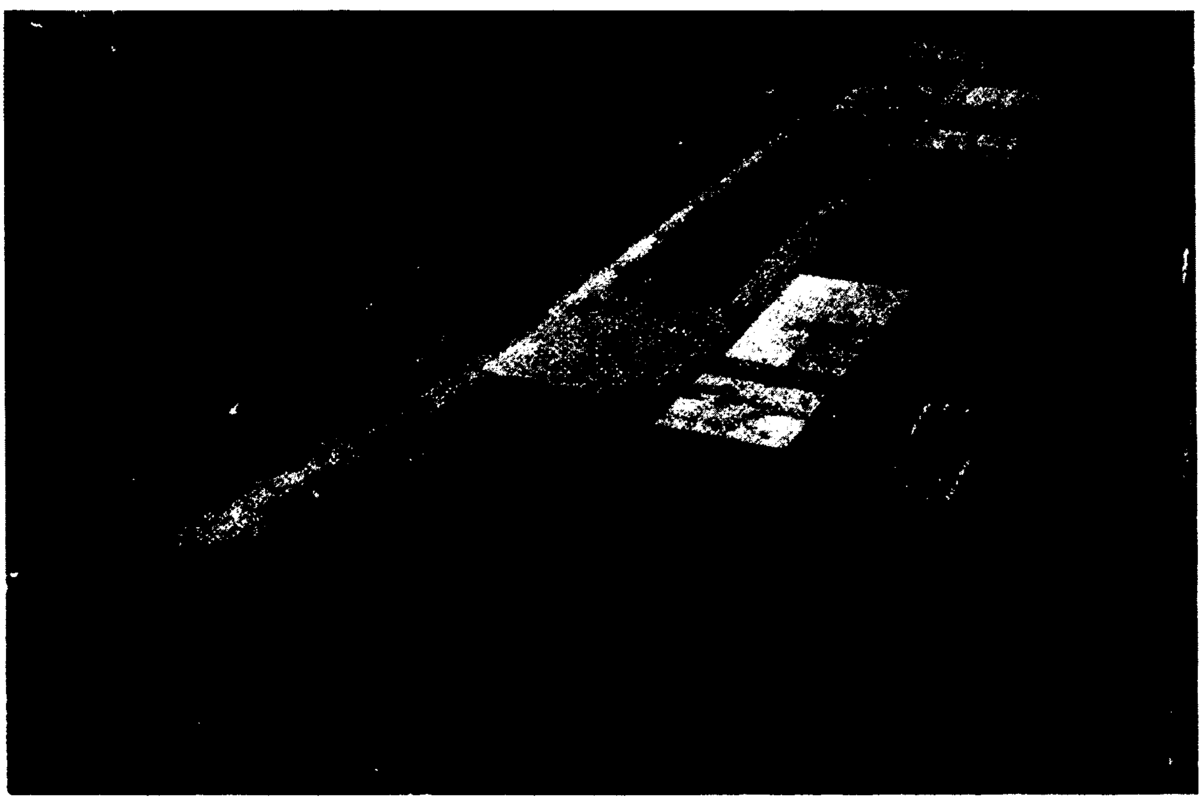

Figure 5.9. Photo of Area No. 2. Photo from U. S. Army. Corps of Engineers. St. Paul District 1950, app. III: 9.

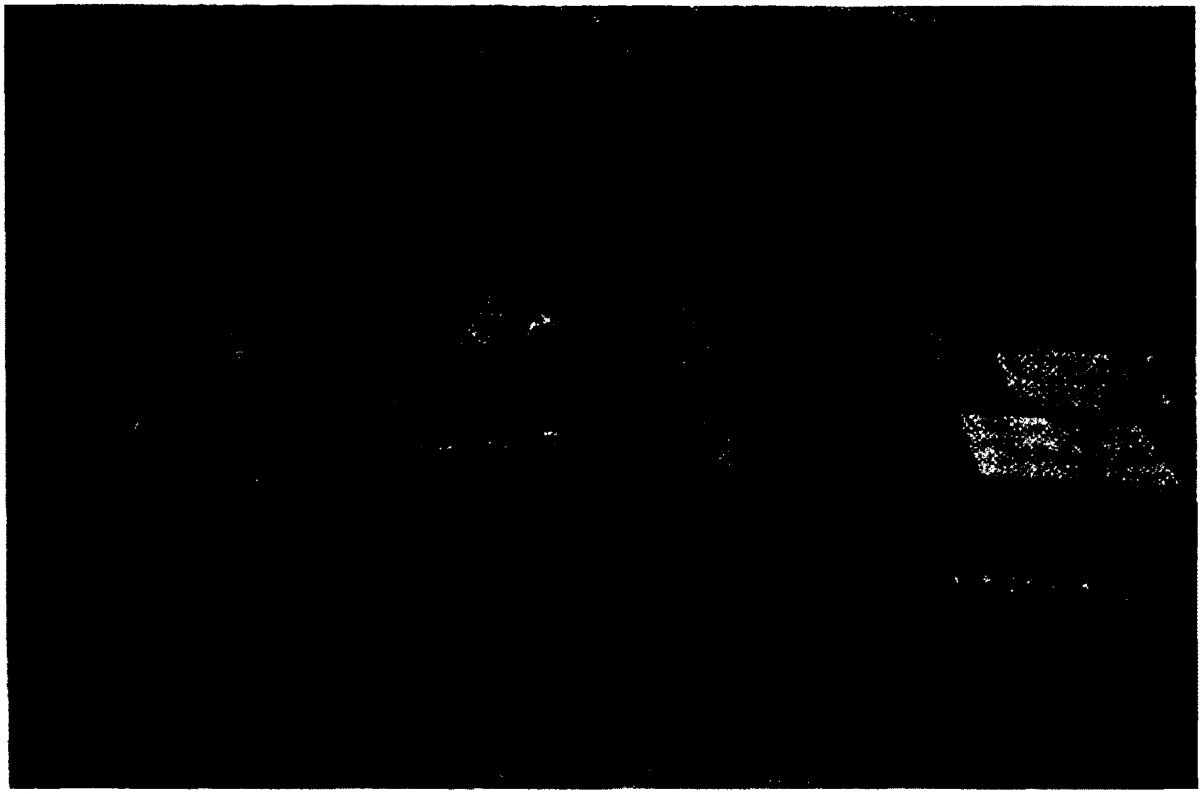

Figure 5.10. Photo of Area No. 2. Photo from U. S. Army. Corps of Engineers. St. Paul District 1950, app. III: 9.

Ironically, the runway results were poor, and the monitoring of the sections was quickly abandoned by researchers. Even the St. Paul District admitted, "it can be said that sections in Area No. 2 were generally no more effective in retarding thaw than the cleared and stripped Section C of Area No. 1" (U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: 46). However, they were able to make some conclusions of what does not work. First, insulation is not effective on permafrost close to 32°F (0°C), because, "the ground temperature below the insulation is cooler in summer and warmer in winter than if the insulation were not present. The net effect is that the mean annual ground temperature is about the same whether or not insulation is used" (U. S. Army. Corps of Engineers. St. Paul District 1950, Main Report: 41). Second, the construction season has no effect on preventing permafrost degradation. The hypothesis for winter construction was that trapping the colder ground temperatures beneath the road insulation would prevent thawing. Nevertheless, for the same reason that insulation does not work, the soil will eventually lose this cold reserve (U. S. Army. Corps of Engineers. St. Paul District 1950).

5.5 Analysis – Runway Foundation Studies

Insulation can be effective on colder permafrost. But for warm permafrost, insulation, such as polystyrene foam, can only slow the rate of thaw and settlement. To prevent thawing in warm permafrost, there is a need for artificial cooling underneath the insulation, such as thermosyphons (Esch 1996).

With further testing, winter construction still has no long-term benefit for thaw prevention, the colder temperatures usually only last for one to three years. There can be benefits with winter construction when working ice-rich permafrost, with giving a stable work area that would otherwise become problematically muddy during the summer (Esch 1996).

5.6 Engineering – Building and Piling Foundation Studies

The building and pile studies were conducted to find better methods of design and construction of military buildings in the arctic and subarctic. The building and pilings studies were conducted in Area No. 3, mapped in detail below in Figure 5.11. Buildings No. 1 through No. 8 were 16-foot by 16-foot (4.9-meter by 4.9-meter), prefabricated test buildings that were constructed in 1946. Buildings No. 9 through No. 11 are 32-foot by 32-foot (9.8-meter by 9.8-meter), wood-frame test buildings that were constructed in 1947 (U. S. Army. Corps of Engineers. St. Paul District 1950; Lobacz and Quinn 1963).

The building designs varied with the type of floor and type of foundation, which are summarized below in Table 5.1. All of the buildings were heated during the winter to simulate an average home. Buildings No. 1 through No. 8 were kept at an average of 63.7°F (17.6°C), while the living quarters of Buildings No. 9 and No. 10 were kept at 72°F (22.1°C) and the garage of Building No. 11 was kept at about 61°F to 64.5°F (16.1°C to 18.1°C) (U. S. Army. Corps of Engineers. St. Paul District 1950).

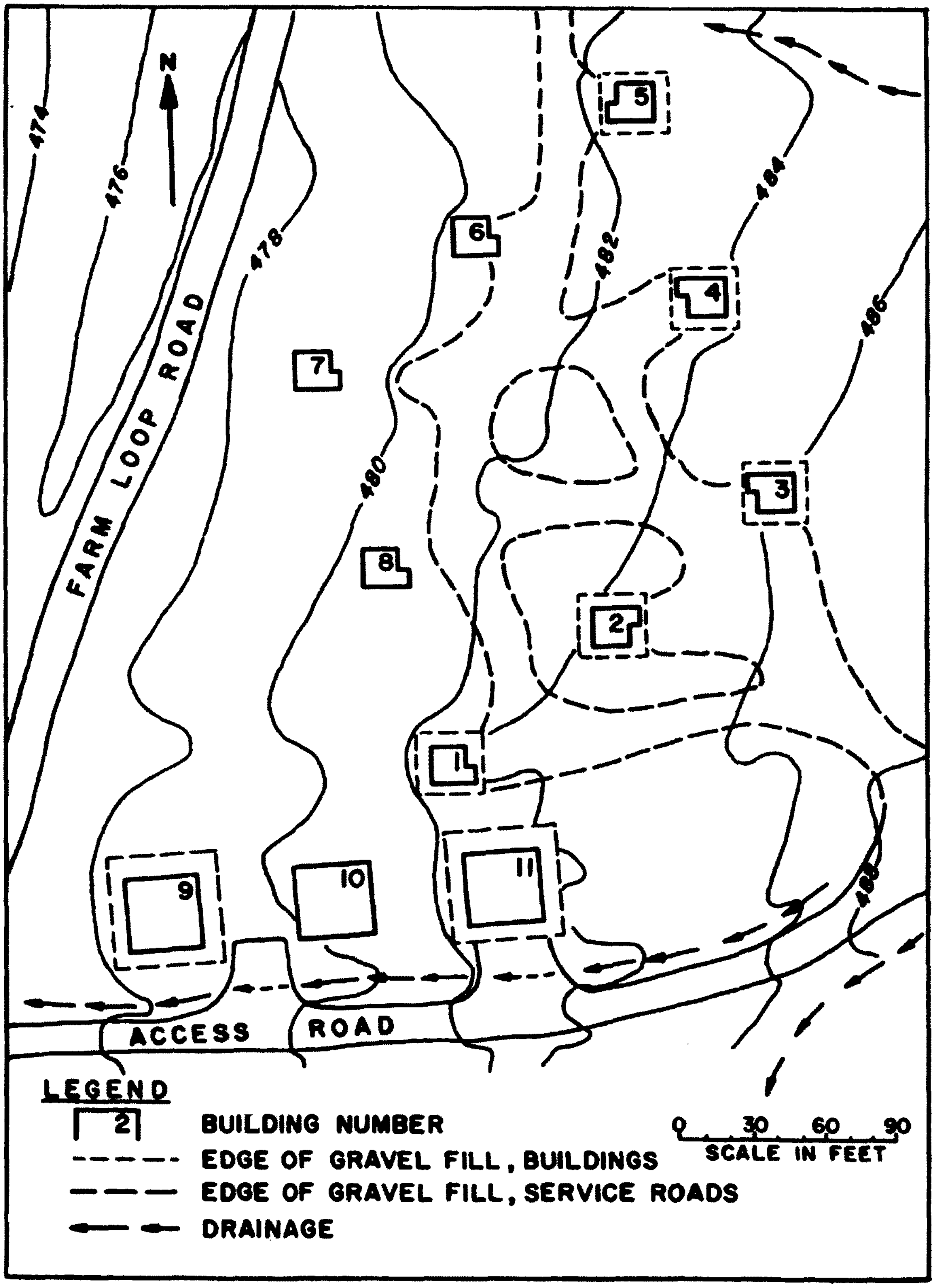

Figure 5.11. Map of the buildings in Area No. 3. Map from Lobacz and Quinn 1963, 247.

Table 5.1. Types of building foundation and the time period of study in Area No. 3. Information from Lobacz and Quinn 1963, 248.

Bldg. No.	Type of Floor	Type of Foundation
1	4-in. concrete slab	4-ft river-run gravel
2	2 by 4-in joists, 16-in. O.C.; wood floor above and wood sheathing below. Rock wool batt insulation between joists.	4 by 4-in. mud sills on 4-ft river-run gravel
3	Same as No. 2	4 by 4-in. mud sills on 2-ft river-run gravel
4	Same as No. 2 except rock wool batts removed 2 Jan. 47	4 by 4-in. mud sills on 6-ft river-run gravel
5	Same as No. 2	4 by 4-in. mud sills on 4-ft river-run gravel and 6-in. cell concrete
6	Same as No. 2	Posts and pads, beam 2-ft above ground, no skirting
7	Same as No. 2	Posts and pads, beam 2-ft above ground skirting
8	Same as No. 2	4 by 4-in mud sills on 3-in pads on natural ground
9	Double wood floor on 2 by 4-in. joists, 16-in. O.C.; rock wool insulation batts between joists	2 concrete slabs (upper 6 in., lower 9 in.) separated by 3-ft concrete piers; lower slab on 5.6 ft river-run gravel
10	Double wood floor on 2 by 8-in. joists, 16-in O.C.; 0.5 in. insulation board beneath the joists and 3-in. vermiculite, loose fill insulation between joists	Piling in natural ground, 4-ft air space to flooring, wood skirting around air space
11	18-in. concrete slab with 4 by 12 by 12-in. hallow clay tile ducts	5-ft river-run gravel

The photos below include: an overview photo of all of the buildings (Figure 5.12), a photo of Buildings No. 9 and No. 10 that were used as residence and Building No. 11 that was used as a garage (Figure 5.13), a diagram of Building No. 9 with the concrete pier foundation (Figure 5.14), a diagram of Building No. 10 on pilings (Figure 5.15), and a diagram of Building No. 11 with the hollow clay tile foundation (Figure 5.16).

Figure 5.12. Photo of the Area No. 3. Photo from U. S. Army. Corps of Engineers. St. Paul District 1950, app. III: 13.

Figure 5.13. Photo of Building 9, 10 and 11. Photo from U. S. Army. Corps of Engineers. St. Paul District 1950, app. III: 16.

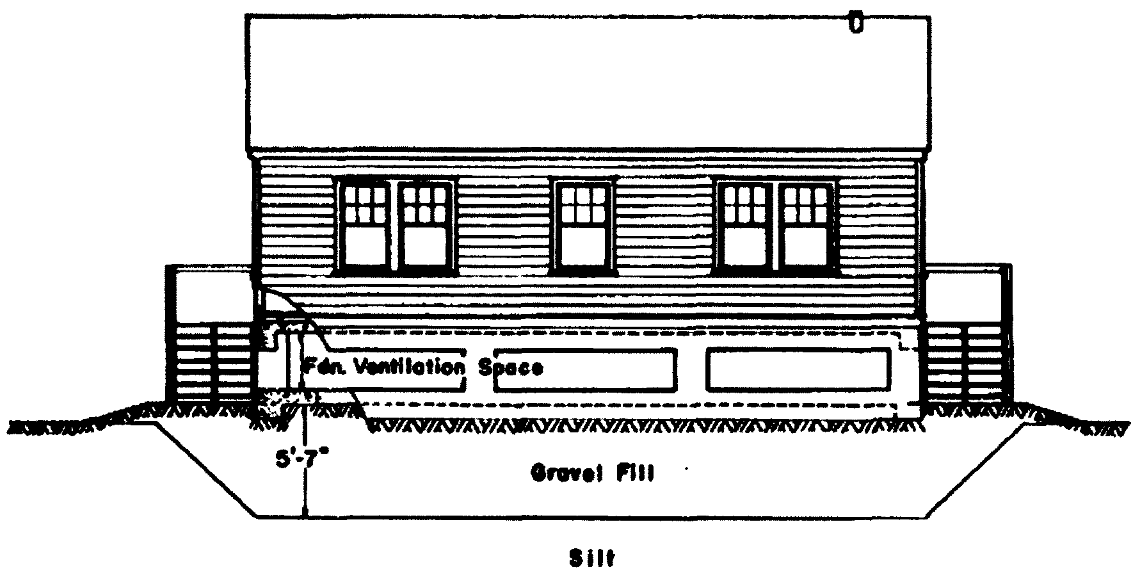

Figure 5.14. Diagram of Building No. 9 (concrete slabs separated by concrete piers on gravel fill). Diagram from U.S. Depart. of the Army 1983, 4-60.

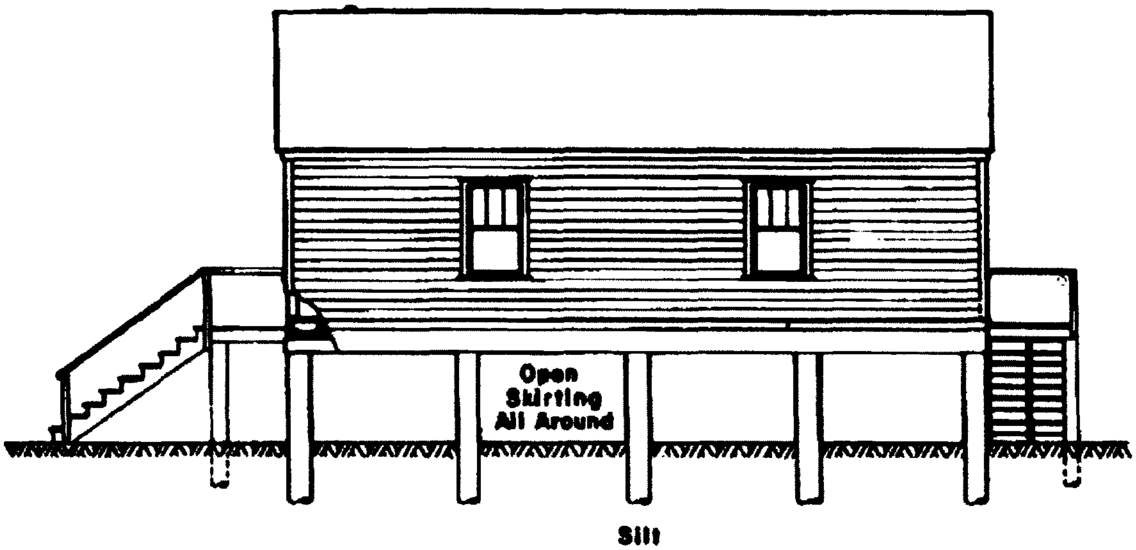

Figure 5.15. Diagram of Building No. 10 (32 ft square building on pilings). Diagram from U.S. Depart. of the Army 1983, 4-62.

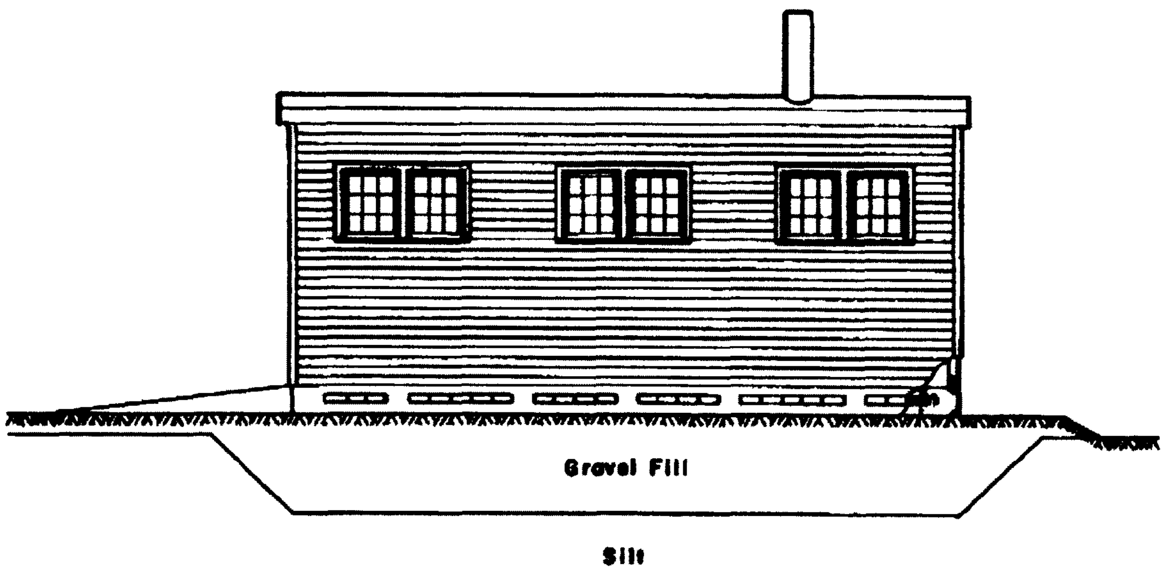

Figure 5.16. Diagram of Building No. 11 (concrete slabs with hollow clay tiles on gravel fill). Diagram from U.S. Depart. of the Army 1983, 4-64.

The results showed that the buildings with open air spaces underneath the building did not have permafrost degradation. Under buildings No. 6 through No. 10, the active layer was able to refreeze completely during the winter with no, or very minimal, permafrost degradation (Lobacz and Quinn 1963).

Building No. 9, with the concrete pier foundation, did, however, have permafrost degradation at the south side of the building. The access road was on that side of the building, and it was concluded that the drainage ditch of the access road caused the differential thaw (Haley 1955). Figure 5.17 shows the progression of the permafrost degradation under Building No. 9. This building, however, had a very rigid foundation that remained strong during the differential settlement, which just resulted in the whole building tilting (U.S. Depart. of the Army 1983). This tilt was about 1 to 2 inches (2.5 to 5 centimeters) in 1954, seven years after construction (Haley 1955).

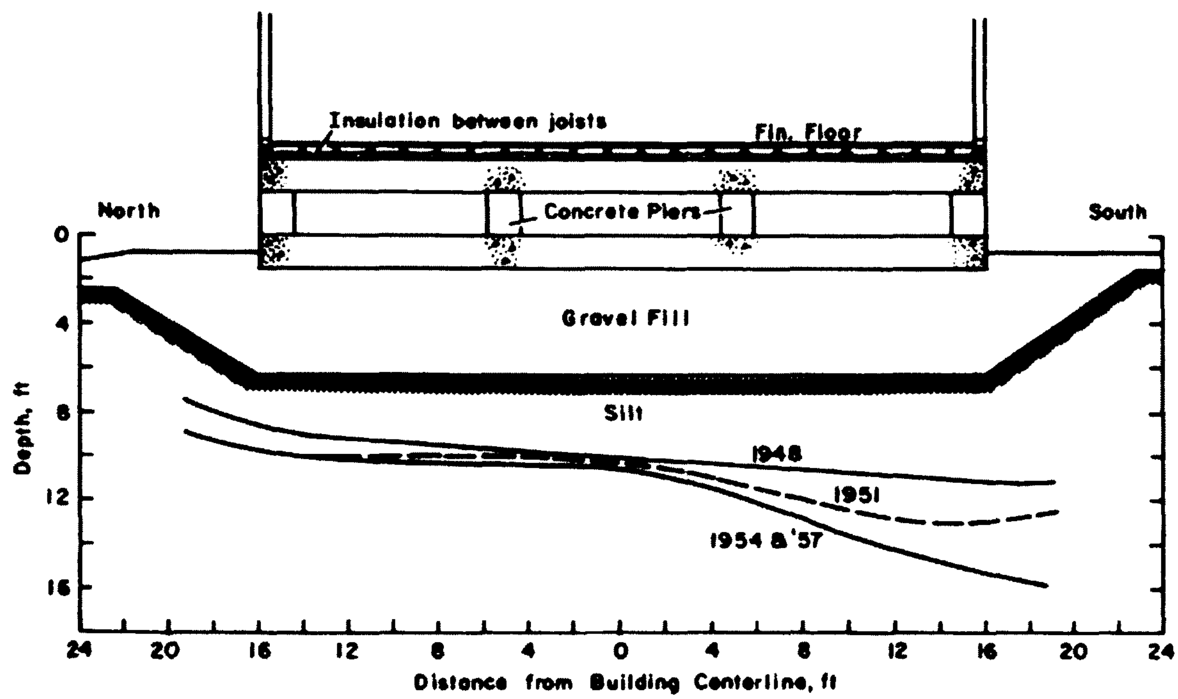

Figure 5.17. Diagram of permafrost degradation under the south side of Building No. 9 Diagram from U.S. Depart. of the Army 1983, 4-60.

The buildings without open air spaces beneath, all had permafrost degradation, these include Buildings No. 1 through No. 5 and Building No. 11. Figure 5.18 shows the progression of the freezing front under Building No. 4, which would be typical for the test buildings with insulated wooden floors. Looking at the diagram, the center of the foundation remains unfrozen throughout the winter. In some cases, a portion of the gravel fill and a thin layer of the silt would freeze. But, the ground never refroze completely and the permafrost degraded over time. Buildings No. 1 through No. 5 had an average permafrost degradation rate of 9 to 12 inches (23 to 30 centimeters) per year, shown along with Building No. 11 in Figure 5.19 (Lobacz and Quinn 1963).

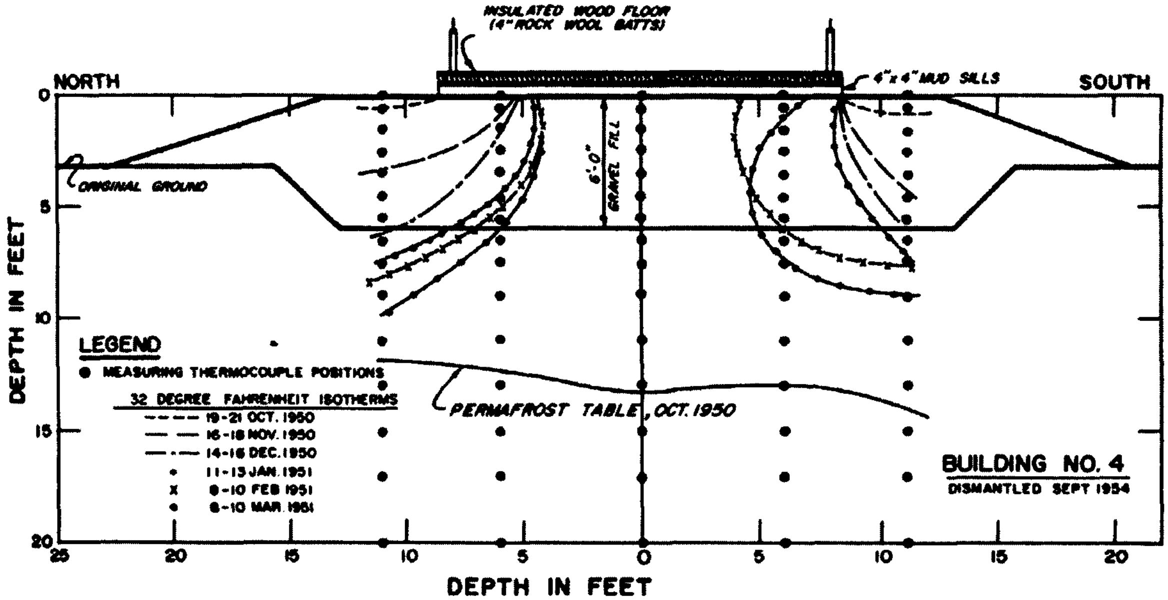

Figure 5.18. Diagram of the progression of freezing isotherms under Building No. 4. Diagram from Lobacz and Quinn 1963, 249.

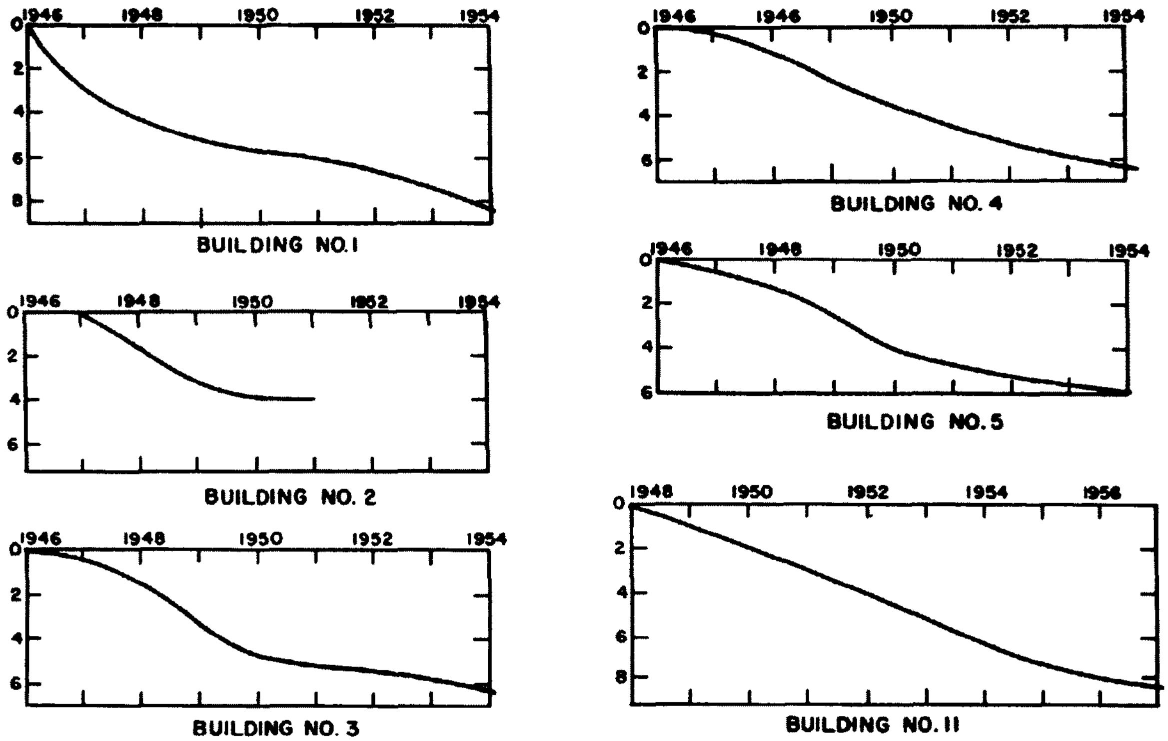

Figure 5.19. Graphs of permafrost degradation at the center of the buildings (in feet). Graphs from Lobacz and Quinn 1963, 250.

Building No. 1 had one of the worst permafrost thaw depths. The building's uninsulated concrete floor performed worse than the wooden floors, as concrete is more thermally conductive than wood (Lobacz and Quinn 1963). In 1954, the southwest corner of Building No. 1 had settled 18 inches (46 centimeters), while the northeast corner had only settled 9 inches (23 centimeters). "This [differential settlement] resulted in considerable cracking of the foundation slab and separation of floor slab and walls" (Haley 1955, 4).

The hollow clay tiles of Building No. 11 were supposed to circulate the cold winter air, preventing thaw degradation. But, the tiles were not effective and the permafrost thawed 8 feet (2.4 meters) in 10 years, matching the thaw depth of Building No. 1. Figure 5.20 depicts the settlement of the corners under Building No. 11, with the southwest corner settling 2.6 feet (0.79 meters) in 19 years. The building kept settling even after the researchers stopped heating it (Lobacz and Quinn 1963; Linell and Lobacz 1980).

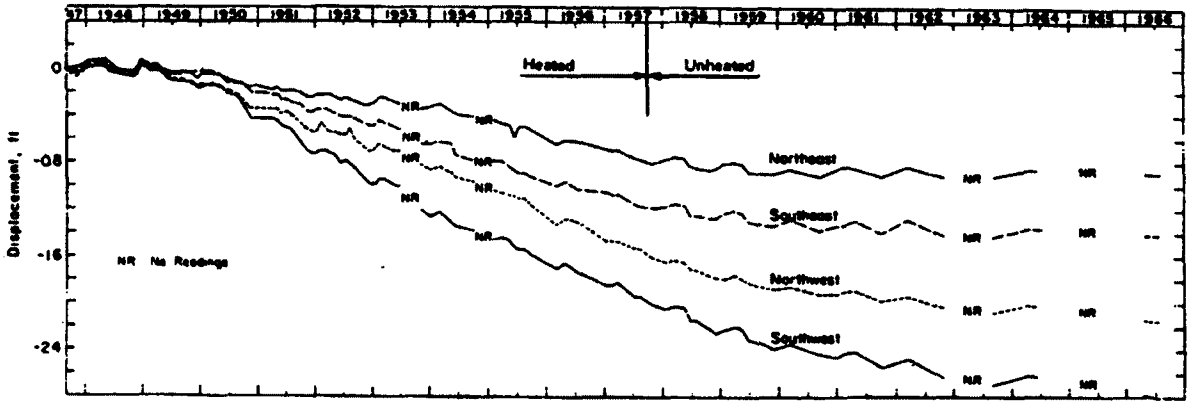

Figure 5.20. Graph of settlement of the corners of Building No. 11. Graph from Linell and Lobacz 1980, 125.

Frost heaving was negligible for the buildings without air spaces, because the silt did not freeze. The buildings with open air spaces, but without gravel pads, did experience some frost heaving, but still performed fairly well. These included Buildings No. 6 through No. 8, where the seasonal frost heave and settlement was only about 2.5 to 5 inches (6.1 to 12.2 centimeters) and fairly uniform. Overall, there were no progressive changes in the foundations' displacement. Figure 5.21 shows the displacement of the corners of Building No. 6, which would be typical for Building No. 7 and No. 8 as well. All three buildings were able to handle the small seasonal frost heave and settlement without structural damage. The open air space buildings, with gravel fill, retarded some of the seasonal frost heave and settlement of the active layer (Lobacz and Quinn 1963).

Building No. 10 experienced frost jacking of its piles. Figure 5.22 shows the frost jacking displacement, where the southwest corner pile jacked approximately 7 inches (18 centimeters). The frost jacking was caused by the soil not freezing back around this pile, while the other 19 piles of the foundation did successfully freezeback without any problems. This lone pile was cut, and a jack was installed in line with the pile. The building was able to remain structurally sound with periodic adjustments of the jack. The four piles for the porch, also depicted in Figure 5.22, experienced frost jacking. These porch piles were only installed in the active layer and did not have the weight to

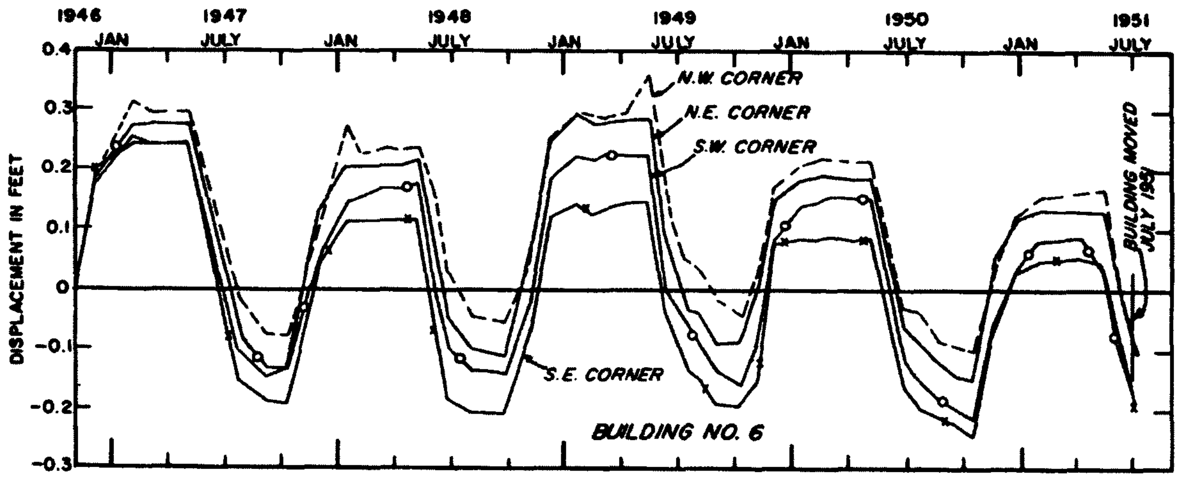

Figure 5.21. Graph of vertical displacement of the corners of Building No. 6. Graph from Lobacz and Quinn 1963, 251.

counteract the heaving (Linell and Lobacz 1980). "The importance of bonding all piles to permafrost was vividly demonstrated in this instance" (Lobacz and Quinn 1963, 251). All the piles were installed with steam thawing, along with two Navy steel monotube piles. These two Navy monotube piles also did not freezeback, and were loaded 30 days after installation. These piles settled greatly, and immediately after loading (U.S. Depart. of the Army 1983). Freezeback is important to achieve the adfreeze bond around the sides of the pile, as this provides all of the friction on the pile that supports the loading (U.S. Depart. of the Army 1983, 4-128).

Overall, open air space foundations are the most efficient way to dissipate heat from buildings. During the summer, the shaded ground is kept cooler. Combined with no snow cover in the winter it allows the ground to develop colder ground temperatures than it would have naturally. Removing the snow around the building will provide a greater depth of freeze in the soils around the house and allow for better circulation of the winter air underneath the house (Haley 1955; Lobacz and Quinn 1963).

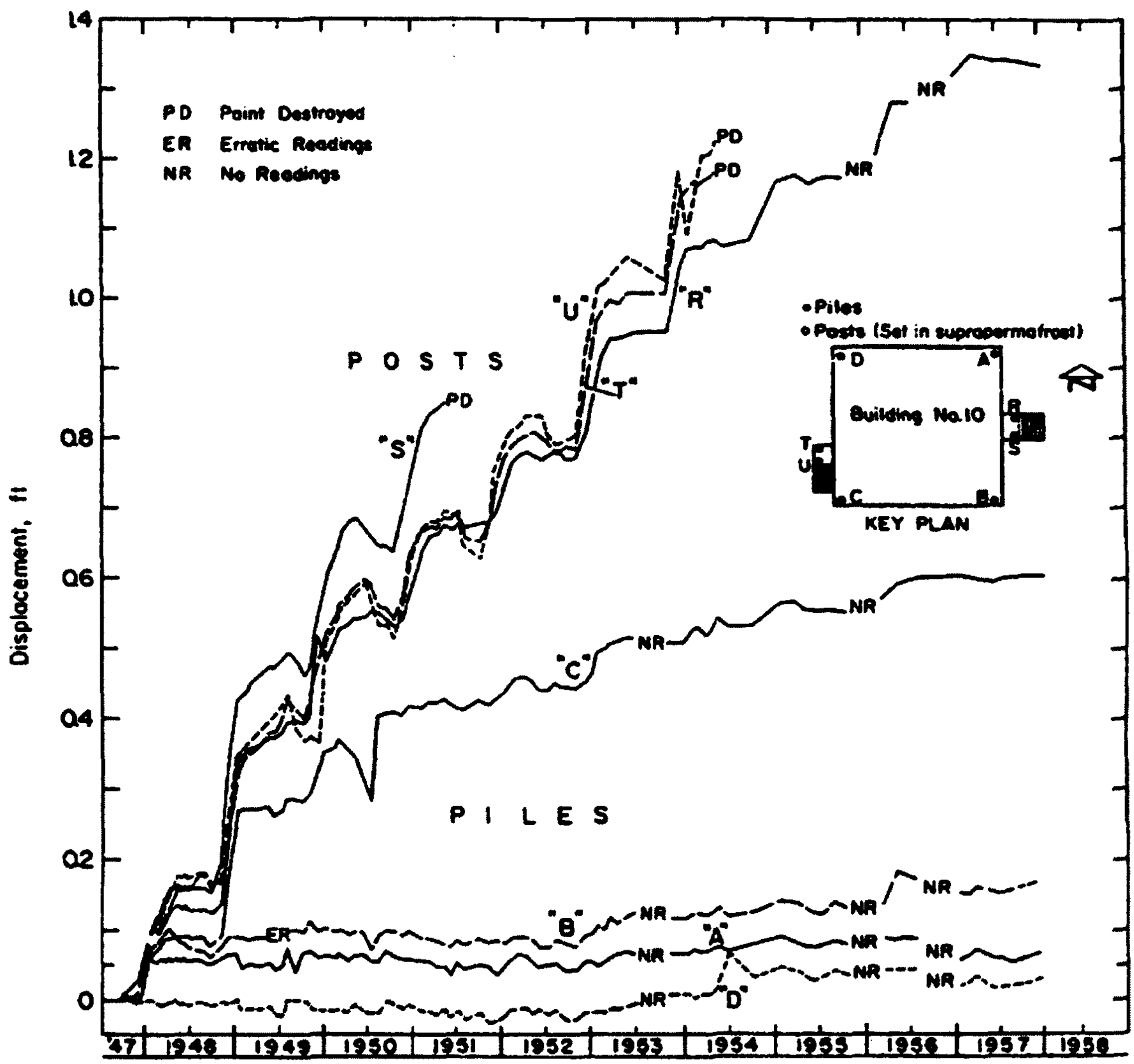

Figure 5.22. Graph of frost jacking of piles on Building No. 10. Graph from Linell and Lobacz 1980, 124.

5.7 Analysis – Building and Piling Foundation Studies

Building designs with open air space foundations remain popular today. When keeping the permafrost frozen, the natural air circulation is the most economical. For buildings without open air spaces, artificial cooling is needed, such as thermosyphons. For piling designs, current literature stresses the importance of freezeback for the structural stability of the pile (Andersland and Ladanyi 2004). As discussed in chapter 2, steam thawing for pile installation should only be done if the mean annual permafrost temperature is below 20°F (-6.7°C). Above this temperature, the pile should be aided in the freezeback with artificial freezing, such as thermal piles (U.S. Depart. of the Army 1983, 4-114).

5.8 Conclusion

The Fairbanks Research Area has had extraordinary impact on permafrost engineering, especially since it was the first permafrost engineering research site in the United States. The Linell Plots were the first to look at the long-term effects of clearing and stripping. The researchers developed the basis for building foundations designs, along with the details towards better road designs. The test buildings and piles were used in the development of the Army/Air Force's Technical Manual on Arctic and Subarctic Construction, TM 5-852. The site was one of the first ground temperature monitoring sites, which makes it very useful for a historic comparison for climate change research. Overall, much of the study echoes the key aspects of permafrost engineering techniques.

Chapter 6 Conclusion

The history of permafrost engineering in Alaska began with early gold mining activities over a hundred years ago. During the early years, the main contributors to the permafrost engineering science were miners, not engineering professionals. They were men with a need and the ingenuity to meet that need. This makes their accomplishments and contributions to the modern permafrost engineering even more impressive. Their methods of thawing permafrost are widely used in modern practice, and are known around the Arctic by the names of their inventors.

WWII is also an important era to permafrost engineering science. The difficulties constructing the Alaska Highway triggered the first book on permafrost engineering and the first comprehensive research program. The accomplishments by the Permafrost Division of the St. Paul District of the U.S. Army Corps of Engineers in their first few years are exceptional and have not been repeated in the United States, including:

- The development of the n-factor method and the evaluation on the essential types of ground surfaces for construction.
- A method of predicting thermal conductivity of soils, developed from first comprehensive database on thermal conductivity of frozen and unfrozen soils.
- The application of aerial photograph interpretations to permafrost investigations and compilation of the first database on permafrost-related landforms.
- The comparative analysis on the performance of different types of foundations and embankments on permafrost.

The results were widely accepted in modern practice and used in the preparation of Army/Air Force's Technical Manual on Arctic and Subarctic Construction, TM 5-852. The Fairbanks Research Area later became operated by CRREL, and renamed to the Fairbanks Permafrost Experimental Station, which has housed countless research projects in the last 65 years.

Permafrost engineering cannot be conducted solely on theoretical methods, because of the variability of site conditions and soil properties. Experience is key for an engineer making design decisions. Knowing the history of permafrost engineering allows the engineer to extend his/her experience base. A carefully compiled history is a necessity as it provides a central resource of information that is spread across journals, books, and conference proceedings. The knowledge base of lessons learned among engineers is important, especially between generations of engineers, so history does not repeat itself.

This thesis provides a start to the process of compiling, summarizing, and analyzing of the history of permafrost engineering in Alaska in an effort to provide the reader a resource for permafrost engineering. This thesis addresses some of the early construction projects and research in Alaska from the Gold Rush era to the shortly after WWII. The history of permafrost research and lessons learned are beneficial for solving permafrost-related problems and for increasing public awareness. Each of these projects has been successfully adapted to modern practices, laying the foundation of permafrost engineering.

References

Andersland, Orlando B. and Branko Ladanyi. 2004. *Frozen ground engineering*, 2nd ed. Hoboken, NJ: John Wiley & Sons.

Barnes, Lynn C. 1946. Permafrost: A challenge to Engineers. *The Military Engineer* 38 (243): 9-11.

Bennett, F. Lawrence. 1991. Permafrost and mud: Some glimpses into the history of Alaskan construction. *The Northern Engineer* 22 (4): 4-10.

Berg, Richard L. and George W. Aitken. 1973. Some passive methods of controlling geocryological conditions in roadway construction. In *Permafrost: North American contribution [to the] Second International Conference*, 581-586. Washington, D.C.: National Academy of Sciences.

Bezeau, M. V. 1985. The realities of strategic planning: The decision to build the Alaska Highway. In *The Alaska Highway: Papers of the 40th Anniversary Symposium*, edited by Kenneth Coates, 25-35. Vancouver: University of British Columbia Press.

Black, Patrick B. and Mark J. Hardenberg, eds. 1991. *Historical perspective in frost heave research: The early works of S. Taber and G. Beskow.* CRREL Special Report 91-23. Hanover: U.S. Army Cold Regions Research and Engineering Laboratory.

Boswell, John C. 1979. *History of Alaskan operations of United States Smelting, Refining and Mining Company.* Fairbanks, AK: Mineral Industries Research Laboratory, University of Alaska.

Brown, Roger J. E. 1970. *Permafrost in Canada: Its influence on northern development.* Toronto: University of Toronto Press.

Canada Department of the Interior. Mining Lands and Yukon Branch. 1915. *The Yukon Territory: Its history and resources*. Ottawa, Ontario, Canada: Canada Department of the Interior.

Cole, Dermot. 2008. *Fairbanks: A gold rush town that beat the odds.* Fairbanks, Alaska: University of Alaska Press.

Cole, Terrence. 1989. Golden years: The decline of gold mining in Alaska. *Pacific Northwest Quarterly* 80 (2): 62-71.

Conn, Stetson, Rose C. Engelman, and Byron Fairchild. 1964. *Guarding the United States and its outposts*. Washington D.C.: Office of the Chief of Military History, Department of the Army.

Dod, Karl C. 1966. *The Corps of Engineers: The war against Japan*. Washington D.C.: Office of the Chief of Military History, Department of the Army.

Douglas, T.A., M. Torre Jorgenson, M. Z. Kanevskiy, V. E. Romanovsky, Y. Shur, and K. Yoshikawa. 2008. Permafrost dynamics at the Fairbanks Permafrost Experimental Station near Fairbanks, Alaska. In Vol. 1 of *Proceedings of the Ninth International Conference on Permafrost: University of Alaska Fairbanks, June 29-July 3, 2008*, ed. D.L. Kane and K.M. Hinkel, 373-378. Fairbanks, AK: Institute of Northern Engineering.

Ellis, Hubert. I. 1915a. Thawing Methods at Fairbanks. *Engineering and Mining Journal* 100 (1): 1-6.

———. 1915b. Mining methods at Fairbanks. B.S. Thesis, University of Washington.

Esch, David C. 1996. Section 5: Roads and airfield design for permafrost conditions. In *Roads and airfields in cold regions: a state of practice report,* ed. Ted S. Vinson, co-ed. James W. Rooney and Wilbur H. Haas, 121-149. New York, New York: American Society of Civil Engineers.

———. 2004. Chapter 7: Thawing techniques for frozen ground. In *Thermal analysis, construction, and monitoring methods for frozen ground*, ed. D.C. Esch, 239-257. Reston, Virginia: American Society of Civil Engineers.

Farouki, Omar T. 1981. *Thermal properties of soils.* CRREL Monograph 81-1. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

French, Hugh M. and Frederick E. Nelson. 2008a. Introduction. In *Frozen in time: Permafrost and engineering problems*. Reston, Virginia: American Society of Civil Engineers.

———. 2008b. The permafrost legacy of Siemon W. Muller. In Vol. 1 of *Proceedings of the Ninth International Conference on Permafrost: University of Alaska Fairbanks, June 29-July 3, 2008*, ed. D.L. Kane and K.M. Hinkel, 475-480. Fairbanks, AK: Institute of Northern Engineering.

Frost, Robert E. 1950. *Evaluation of soils and permafrost conditions in the territory of Alaska by means of aerial photographs*. 2 vols. St. Paul, MN: U.S. Army Corps of Engineers.

Gol'dtman, V.G., Znamenskiy, V.V., and S.D. Chistopol'skiy. 1970. *Hydraulic thawing of frozen soils* (In Russian). Magadan: VNII-1.

Greenwood, John T. 1985. General Bill Hoge and the Alaska Highway. In *The Alaska Highway: Paper of the 40th Anniversary Symposium*, ed. Kenneth Coates, 39-53. Vancouver, BC: University of British Columbia Press.

Haley, James F. 1955. *Thawing beneath buildings constructed on permafrost near Fairbanks, Alaska*. Arctic Construction & Frost Effects Laboratory Miscellaneous Paper 12. Boston: U.S. Army.

Henry, K. S. and K. Bjella. 2006. History of the Farmer's Loop Permafrost Research Site, Alaska. In *Cold regions engineering 2006: Current practices in cold regions engineering*, ed. Michael Davis and Jon E. Zufelt. Reston. VA: American Society of Civil Engineers.

Herbert, Charles F. 1934. Gold dredging in Alaska. B.S. Thesis, Alaska Agricultural College and School of Mines.

Huntley, Theodore A. and R. E. Royall. 1945. *Construction of the Alaska Highway.* Washington.

Janin, Charles. 1922. *Recent progress in the thawing of frozen gravel in placer mining.* U.S. Bureau of Mines Technical Paper 309. Washington, DC: Government Printing Office.

Kersten, Miles S. 1949. *Laboratory research for the determination of the thermal properties of soils: final report.* Arctic Construction & Frost Effects Laboratory Technical Report 23. St. Paul, MN: U.S. Army Corps of Engineers.

Kreig, Raymond A. and Michael C. Metz. 2005. Lessons learned from fifty years of terrain evaluation in northern regions especially as applied to major pipelines. In *Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines [Conference Proceedings]* June 2004. London: Institution of Civil Engineers.

——— and Richard D. Reger. 1982. *Air-photo analysis and summary of landform soil properties along the route of the Trans-Alaska Pipeline System.* Alaska Division of Geological & Geophysical Surveys Geologic Report 66. College, AK: Alaska Division of Geological & Geophysical Surveys.

Leffingwell, Ernet de K. 1919. *The Canning River Region, northern Alaska.* U.S. Geological Survey Professional Paper 109. Washington, DC: Government Printing Office.

Linell, Kenneth A. 1973. Long-term effects of vegetative cover on permafrost stability in an area of discontinuous permafrost. In *Permafrost: North American Contribution [to the] Second International Conference*, 688-693. Washington, D.C.: National Academy of Sciences.

——— and Edward F. Lobacz. 1980. *Design and construction of foundations in areas of deep seasonal frost and permafrost.* CRREL Special Report 80-34. Hanover: U.S. Army Cold Regions Research and Engineering Laboratory.

Lobacz, E. F. and W. F. Quinn. 1963. Thermal regime beneath buildings constructed on permafrost. In *Proceedings of the Permafrost International Conference,* 247-252. Washington, D.C.: National Academy of Sciences.

MacFarlane, Ivan C., ed. 1969. *Muskeg engineering handbook.* Toronto: University of Toronto Press.

McFadden, T.T and F.L. Bennett. 1991. *Construction in cold regions: a guide for planners, engineers, contractors, and managers.* United States of America: John Wiley & Sons.

Miles, John H. 1920. Method of thawing ground. U. S. Patent 1,339,036, filed Feb. 1920, and issued May 4, 1920.

Morgan, Lael. 1992. Writing minorities out of history: black builders of the Alcan Highway. *Alaska History* 7(2): 1-13.

Morse, Kathryn. 2003. *The nature of gold: An environmental history of the Klondike Gold Rush.* Seattle, WA: University of Washington Press.

Muller, Siemon William. 1947. *Permafrost or permanently frozen ground and related engineering problems.* Ann Arbor, MI: J. W. Edwards. (orig. pub. 1943)

———. 2008. *Frozen in time: Permafrost and engineering problems.* Reston, Virginia: American Society of Civil Engineers.

Naske, Claus-M. 1986. *Paving alaska's trails: The work of the Alaska Road Commission.* Lanham, MD: University Press of America.

——— and Herman. E. Slotnick. 1979. *Alaska, a history of the 49th State.* Grand Rapids, MI: William B. Eerdmans Publishing Company.

Pearce, E.E. 1922. Cold-water thawing of frozen gravel. *Mining and Scientific Press*, 124 (February 4), 154-156.

Perl'stein, G.Z. 1979. *Water and thermal impact on frozen soils in North-East of USSR* (in Russian). Novosibrisk: Nauka.

Péwé, Troy L. 1993. *Geologic hazards of the Fairbanks area, Alaska.* Alaska Division of Geological & Geophysical Surveys Special Report 15. Fairbanks, AK: Alaska Division of Geological & Geophysical Surveys. (Orig. pub. 1982)

Purington, Chester Wells. 1905. *Methods and costs of gravel and placer mining in Alaska.* U.S. Geological Survey Bulletin No. 263. Washinton, DC: Government Printing Office.

Richardson, Harold W. 1942. ALCAN – America's glory road: Part I – Strategy and location. *Engineering News-Record* December 17: 83-96.

Rickard, T. A. 1908. Dredging on the Seward Peninsula. *Mining and Scientific Press* 97 (November 28): 734-740.

———. 1909. *Through the Yukon and Alaska.* San Francisco, CA: Mining and Scientific Press.

Sargent, R.H. 1924. Drifting in frozen ground. U.S. Geological Survey Photographic Library ID. Alaska, no.120. Photograph. http://libraryphoto.cr.usgs.gov/cgi-bin/show_picture.cgi?ID=ID.%20Alaska,%20no.%20120 (accessed March 18, 2013).

Shiklomanov, Nikolay I. 2005 From exploration to systematic investigation: development of geocryology in 19th- and early-20th-Century Russia. *Physical Geography* 26 (4): 249-263.

Smith, North, Richard Berg, and Larry Muller. 1973. The use of polyurethane foam plastics in the construction of expedient roads on permafrost in Central Alaska. In *Permafrost: North American Contribution [to the] Second International Conference*, 736-745. Washington, D.C.: National Academy of Sciences.

Stoeckeler, E. G. 1949. *Identification and evaluation of Alaskan vegetation from airphotos with reference to soil, moisture and permafrost conditions.* Preliminary Paper. St. Paul, MN: U.S. Army Corps of Engineers.

Szumigala, D.J., Hughes, R.A., and Harbo, L.A., 2009, Alaska's mineral industry 2008. Alaska Division of Geological & Geophysical Surveys Special Report 63. Fairbanks, AK: Alaska Division of Geological & Geophysical Surveys.

The Northern Engineer. 1968. U.S. Army Terrestrial Science Center at Hanover, New Hampshire. *The Northern Engineer* 1(1):4, 8.

Thomson, S. 1966. Icing on the Alaska Highway. In *Permafrost International Conference; proceedings,* 526-529. Washington, D.C.: National Academy of Sciences.

Twichell, Heath. 1985. Cut, fill and straighten: The role of the Public Roads Administration in the building of the Alaska Highway. In *The Alaska Highway: Paper of the 40th Anniversary Symposium,* ed. Kenneth Coates, 54-64. Vancouver, BC: University of British Columbia Press.

———. 1992. *Northwest epic: the building of the Alaska Highway.* New York: St. Martin's Press.

———. 1995. The wartime Alaska Highway: Boon or boondoggle? In *Alaska at War: 1941-1945: the forgotten war remembered: papers from the Alaska at War Symposium, Anchorage, Alaska, November 11-13, 1993*, 167-172. Anchorage: AK: Alaska at War Committee.

U. S. Army. Corps of Engineers. St. Paul District. 1950. *Comprehensive report: investigation of military construction in arctic and subarctic regions, 1945-1948.* Main report and 3 appendices. Vicksburg, MS: Army-MRC.

U.S. Depart. of the Army. 1983. Chap. 4, Arctic and Subarctic Construction, Foundations for Structures. In *Technical Manual TM 5-852-4/AFM 88-19.* Washington, DC: Depart. of the Army and the Air Force.

———. 1988. Chap. 6, Arctic and Subarctic Construction, Calculation Methods for Determination of Depth of Freeze and Thaw in Soils. In *Technical Manual TM 5-852-6/AFM 88-19.* Washington, DC: Depart. of the Army and the Air Force.

van Everdingen, Robert O. 2005. *Multi-language glossary of permafrost and related ground-ice terms.* Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. (Orig. pub. 1998)

Wallace, R.E. 1945. Gold dredge on Esther Creek, Fairbanks. U.S. Geological Survey Photographic Library ID. Wallace, R.E. 131. Photograph. http://libraryphoto.cr.usgs.gov/cgi-bin/show_picture.cgi?ID=ID.%20Wallace,%20R.E.%20%20131 (accessed March 18, 2013).

Weeks, W.S. 1920. Thawing frozen gravel with cold water. *Mining and Scientific Press,* 120 (March 13), 367-370.

Wimmler, Norman L. 1927. *Placer-mining methods and costs in Alaska*. U.S. Department of Commerce Bureau of Mines Bulletin 259. Washington, DC: Government Printing Office.

Wright, Edmund A. 1986. *CRREL's first 25 years: 1961-1986*. Hanover, NH: Cold Regions Research and Engineering Laboratory.