ALTERING THE THERMAL REGIME OF SOILS BELOW HEATED BUILDINGS

IN THE CONTINUOUS AND DISCONTINUOUS PERMAFROST ZONES OF ALASKA

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ALTERING THE THERMAL REGIME OF SOILS BELOW HEATED BUILDINGS IN THE CONTINUOUS AND DISCONTINUOUS PERMAFROST ZONES OF ALASKA

A

DISSERTATION

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

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Fairbanks, AK

May 2016

Abstract

This research investigates the impacts of thermal insulation on the thermal regime of soils below heated buildings in seasonally and perennially frozen soils. The research provides practical answers (A) for designing frost-protected shallow foundations in unfrozen soils of the discontinuous permafrost zone in Alaska and (B) shows that applying seasonal thermal insulation can reduce the risk of permafrost thawing under buildings with open crawl spaces, even in warming climatic conditions.

At seasonal frost sites, this research extends frost-protected shallow foundation applications by providing design suggestions that account for colder Interior Alaska's air freezing indices down to 4 400 °C·d (8,000 °F·d). This research includes field studies at six Fairbanks sites, mathematical analyses, and finite element modeling. An appendix includes frost-protected shallow foundation design recommendations. Pivotal findings include the discovery of more pronounced impacts from horizontal frost heaving forces than are likely in warmer climates.

At permafrost sites, this research investigates the application of manufactured thermal insulation to buildings with open crawl spaces as a method to preserve soils in the frozen state. This research reports the findings from using insulation to reduce permafrost temperature, and increase the bearing capacity of permafrost soils. Findings include the differing thermal results of applying insulation on the ground surface in an open crawl space either permanently (i.e., left in place), or seasonally (i.e., applied in warm months and removed in cold months). Research includes fieldwork in Fairbanks, and finite element analyses for Fairbanks, Kotzebue, and Barrow. Pivotal findings show that seasonal thermal insulation effectively cools the permafrost. By contrast, Fairbanks, Kotzebue, and Barrow investigations show that permanently applied thermal insulation decreases the active layer, while also increasing (not decreasing) the permafrost temperature.

Using seasonal thermal insulation, in a controlled manner, satisfactorily alters the thermal regime of soils below heated buildings and provides additional foundation alternatives for arctic buildings.

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List of Abbreviations

Abbreviation	Definition
ASCE	American Society of Civil Engineers
AFI	air freezing index
ATI	air thawing index
CL	centerline
CCHRC	Cold Climate Housing Research Center
CRREL	Cold Regions Research and Engineering Laboratory
EPA	United States Environmental Protection Agency
EPS	expanded polystyrene rigid insulation
EPSCoR	Experimental Program to Stimulate Competitive Research
FPSF	frost-protected shallow foundation
GDP	gross domestic product
HUD	United States Department of Housing and Urban Development
IRC	International Residential Code
IRMA	inverted roof membrane assembly
MAST	mean annual soil temperature
NAHB	National Association of Home Builders
NCDC	National Climate Data Center
NFS	non-frost susceptible
NOAA	National Oceanic and Atmospheric Administration
NIST	National Institute of Standards and Technology
NWS	National Weather Service
PF	Permafrost

PTF	Permafrost Technology Foundation
SEI	Structural Engineering Institute
SI	Systèm International units
TM	technical manual
UAF	University of Alaska, Fairbanks
UFC	Unified Facilities Criteria
XPS	extruded polystyrene rigid insulation

Acknowledgements

Permit me to acknowledge many supporters. First, I heartily acknowledge the people living in rural Alaska. Wisdom passed on to me over about 35-years of engineering design and construction experiences with generations of indigenous people provided the fundamental motivation for this research. Working side-by-side with local inhabitants in about 50 villages along the Yukon, Kuskokwim, and Koyukuk Rivers, and along Alaska's west coast has helped spur me on. With great respect for our native way of handing down learning from one generation to another, I intend open dissemination of this research to those interested. Freely the Alaskan people have given to me. Freely I make this research available to others. If you use my work, please show professional credit.

Funding for equipment and services for this ongoing research came from Cold Climate Housing Research Center (CCHRC), from the Experimental Program to Stimulate Competition in Research (EPSCoR), and from the Permafrost Technology Foundation (PTF). Recognizing the importance of quick funding for incidental equipment, PTF permitted me to establish a direct account, which I could access quickly after normal work hours or on weekends. PTF helped save many research hours with their consideration.

Faculty and staff, here at UAF, continue to provide an encouraging and patient environment for the extended learning time needed for this research. The ongoing support from and relationships with my committee members validates that I made the correct choice by accomplishing this research here at the University of Alaska, in Fairbanks. Drs. Barnes, Ahn, Hulsey, and Shur have been both motivational and challenging throughout this venture.

The editing efforts from Cynthia and Amy Steiner are valued and appreciated more than I can easily express. I am convinced this is a better work due to their resolve.

I am delighted to acknowledge my most patient wife, Mary Beth, at my side as a primary supporter, empowering the extended absences while completing this work.

Chapter 1 General Introduction

1.1 Investigating Practical Insulation Methods for Arctic Soils

This research evaluates the thermal impacts of manufactured thermal insulation on the thermal regime of seasonally and perennially frozen foundation soils. These methods apply both in the discontinuous permafrost zone and in the continuous permafrost zone (Figure 1). Authors from around the globe caution us about climate change. Esch and Osterkamp (1990), for example, alerted us that climate change models predict warming air temperatures, and that, "the response of the underlying permafrost to a long-term rises in air temperatures will depend on thermal processes at the earth's surface and within the seasonally thawed 'active layer.'" Further, they quote from earlier work that, "Two general solutions to the problems associated with thawing permafrost are to either preserve it by positive heat removal methods or to eliminate it by various prethawing methods. New methodologies need to be developed for these solutions" (Esch & Osterkamp, 1990, p. 6). UFC 01 (2004a) defines permafrost as soil remaining in a frozen state for more than two complete years.

For seasonal frost sites, without permafrost below, I investigated extending frost-protected shallow foundation technology into regions with colder winters than included in current design methods. FPSF methods keep soils below buildings warm by confining and directing heat flow into the soils. My investigations included six Fairbanks sites, mathematical analysis, and finite element modeling.

For sites with permafrost below, I investigated using insulation methods to preserve cold soils conditions. Insulation methods for permafrost sites intend to minimize the active layer and alter the permafrost temperatures. For permafrost sites, my investigations included one field site, and numerous finite element analysis for Fairbanks, Kotzebue, and Barrow.

In my over 35-years' experience in northern Alaska design and construction I have observed many soil and climate realities regarding building foundations. Two primary thermal zones, called discontinuous permafrost and continuous permafrost, exist in northern Alaska (Figure 1). I have accomplished projects in over 50 villages encompassing both of these northern regions. Having personally experienced many frost related building foundation realities (both successes and failures), I have had a long-growing interest in continuing the science for building foundation solutions.

The intellectual merit of this research relates to the extended design methods for frost-protected shallow foundation systems in a discontinuous permafrost zone colder than included in current design guides. In addition, the merit comes from new understandings I provide for seasonal insulation methods in the continuous permafrost zone. This research provides specific foundation alternatives to consider for arctic buildings, alternatives that are also applicable for permafrost zones faced with warming climate.

I use a monograph style (not manuscript) for this dissertation. As background, I originally developed two fundamentally different mitigation-methods as individual manuscripts, for separate submission to publishers. These two parts are uniquely different. I present them separately.

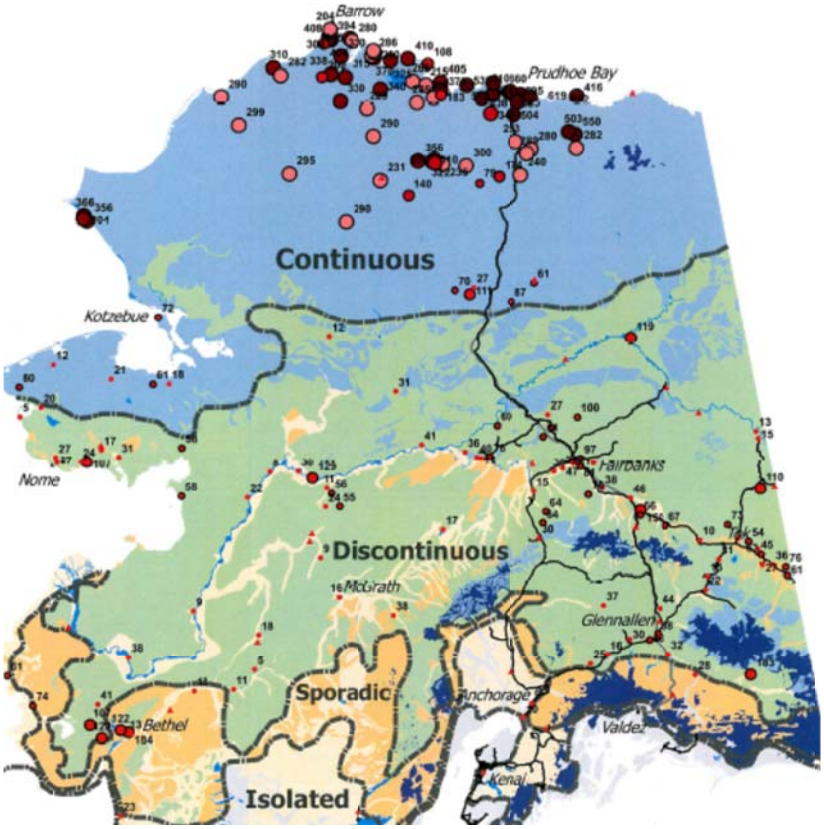


Figure 1. Continuous (colder temperatures) and discontinuous (warmer) permafrost zones in Alaska. Map used by permission of the Institute of Northern Engineering, University of Alaska.

This dissertation builds upon not only the works from researchers who have gone before, but also upon the lived experiences of the people of rural Alaska. Their fundamental contribution comes from their experiences living close to the land. Their ingenuity and practical application of low technology and lower-cost methods has motivated this research.

This research applies to multiple worldwide demographic communities. I specifically want these research results to be readily accessible to people beyond just the scientific community. My audience includes engineers, contractors, and the broader public. Because of my intended broader impact, I include both Système International (SI) units and U.S. customary units in this dissertation. As a governing standard, I use the "Guide for the Use of the International System of Units (SI)" Special Publication 811, 2008 Edition, published by the National Institute of Standards and Technology, U.S. Department of Commerce (NIST, 2008). At the time of writing, this 90-page conversion-standards guide was available free of charge for download at the following website, http://physics.nist.gov/cuu/pdf/sp811.pdf. Note this standard uses units differently than some contemporary colleagues. For example, the unit symbol °C (°F) represents both temperature and thermal interval. Specifically, the above standard omits the unit symbol C° (F°) for thermal intervals. In addition, a space (not a comma) provides the delimiter for thousands groupings. For example, the number four-thousand is written in accordance with the standard with no comma as 4 000 (NIST, 2008, p. 37). The following visual unit-conversion scales (Figure 2) apply to figures within this dissertation.

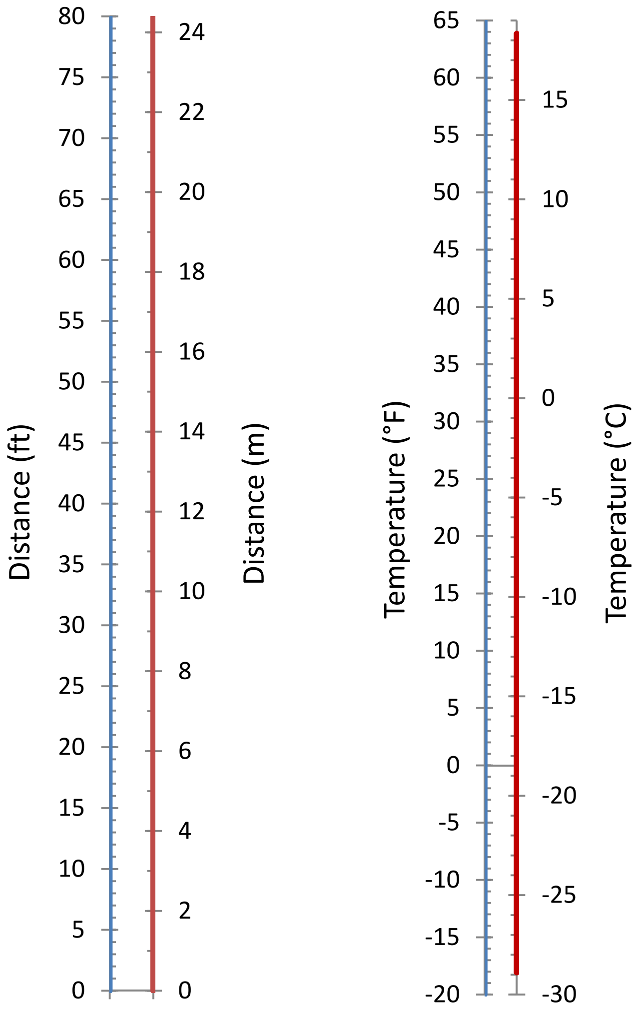


Figure 2. Visual conversion scales for distances and temperatures.

1.2 One Hypothesis, Two Parts, Different Applications

This research has two distinct parts. Both parts test the same hypothesis, as follows, “Using manufactured thermal insulation alters the thermal regime of soils below heated buildings, thereby providing foundation alternatives for arctic buildings.” I research using manufactured insulation as a possible response to warming or to cooling future air temperatures. I investigate both seasonal frost zones (with no permafrost below) and continuous permafrost zones. The goals include providing new knowledge or new insights into existing knowledge regarding frozen ground foundation engineering.

For this research, I assumed that climate might change either by becoming warmer or by becoming colder in the future.

I test the hypothesis differently for the two soil thermal-regime scenarios. First, I test foundations in thawed portions of seasonal frost zones, having no underlying permafrost. Foundations in seasonal frost zones depend upon preserving thawed soils below the foundation. Building design methods for seasonal frost protection are significantly different from methods for permafrost protection. Foundations in continuous permafrost zones depend upon structural strength from keeping the frozen soils frozen at or below their initial design temperature.

Each unique part has its own means and methods section. One goal includes empowering others to replicate this research. Each part has its own results section. Result discussions occur immediately after presenting a main result. I include lessons learned regarding equipment constraints, technological and field limitations, and software peculiarities. I display the research results using many figures and tables. I highlight the results by including a limited set of output figures in the main manuscript. I display the remaining results in the appendices.

1.2.1 Part A. Seasonal frost sites – directed heat confinement to keep footing soils thawed.

Part A applies to the warmer, non-frozen portions, of the discontinuous permafrost zone. This portion of the research extends frost-protected shallow foundation technology to regions with winters that are colder than currently included in design guides written for warmer discontinuous permafrost zones.

Frost protected shallow foundation technology applies to the more southerly seasonal frost zones (Figure 1). Seasonal frost refers to ground that is frozen in winter but thawed in summer. Building heat helps keep the ground in a thawed state. Thermal insulation, around the perimeter of the foundation, serves to help contain the building heat and direct that heat into the soils below. Alternatively, if faced with warming climate, current sensitively frozen soils (i.e., close-to-the-thawing point) may disappear altogether. This makes an FPSF system one possible alternative for soils close to the freezing point to remain in a thawed state.

Figure 3. Example: Seasonal frost site with a shallow insulated perimeter foundation.

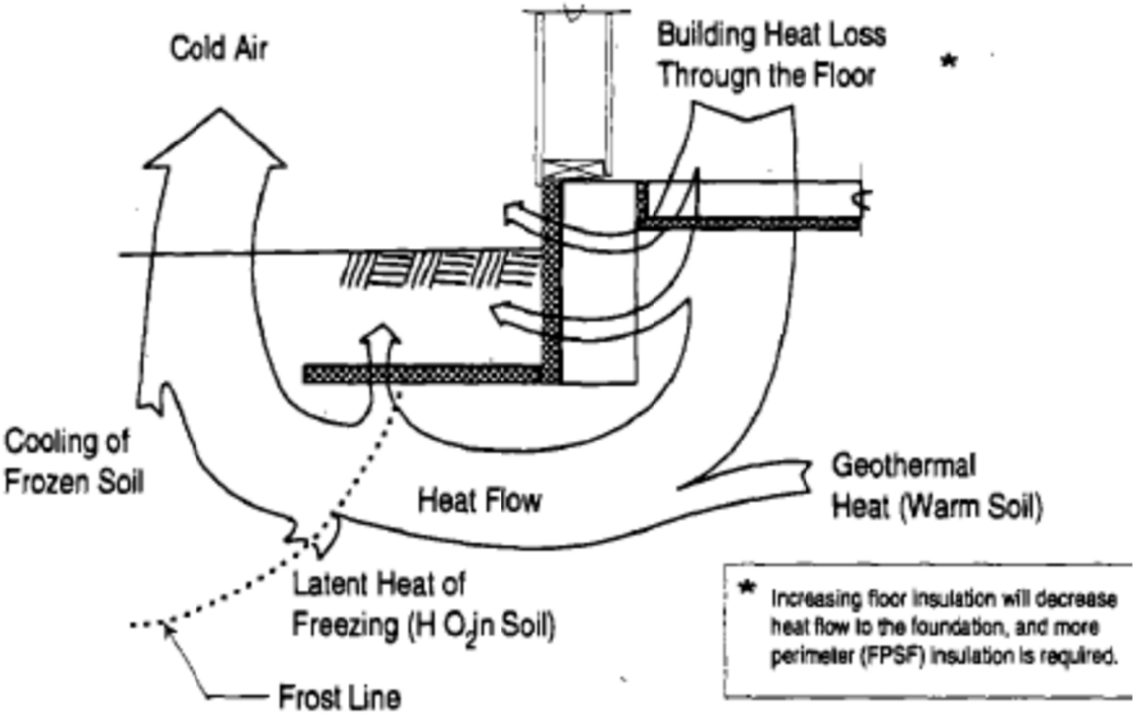


Figure 4. Heat flow under a heated building in seasonally frozen soil.
(National Association of Home Builders, 1994).

Figure 3 shows a Fairbanks home with no permafrost, subjected to seasonal frost. Figure 4 schematically shows interior building heat routed into the soils directly below the footings, confined via perimeter insulation.

I review current literature and design methods for frost-protected shallow foundations – as applied to the discontinuous permafrost zone. Next, I extend the current FPSF design methods from current design guide limitations (for warmer climates) to Interior Alaska’s colder regions of discontinuous permafrost zone. These methods may apply globally to similar discontinuous permafrost zones.

The current design guide from the American Society of Civil Engineers (ASCE) is Design and Construction of Frost-Protected Shallow Foundations, ASCE 32-01 (ASCE, 2001). This research does not change ASCE 32-01. Rather, it extends the application of the same principles into colder regions within Alaska. Earlier, Farouki and Cold Regions Research and Engineering Laboratory (CRREL) summarized similar design methods (Farouki, 1992).

Current FPSF design methods include insulation design methods for unheated buildings, which incorporates a basic assumption that soils have a mean annual soils temperature several degrees above freezing (ASCE, 2001). Unheated buildings must rely upon geothermal heat, confined by extra perimeter thermal insulation, to help keep the soils in a thawed state. That basic assumption might not apply or apply differently for Interior Alaska.

Frost protected shallow foundation design methods are not new. The newness, here, relates to the more extreme accumulated cold winter weather to which an FPSF system may be applied. I hypothesize that (A) existing frost-protected shallow foundation methods extend to colder discontinuous permafrost zones than are included in current design guides. I explore using additional thermal insulation to confine building thermal heat flow into the ground below the building. I also hypothesize that (B) the colder climate may warrant adjusting current methods to apply to these colder regions. My goal includes containing sufficient building heat to preclude soil freezing below the building footings. Maintaining unfrozen soils below the foundation footing zone reduces or eliminates the risk of seasonal frost heave.

1.2.2 Part B. Permafrost sites – restricting summer heat gain to keep soils cold.

The second scenario is for permafrost zones. Harris, Heginbottom, Johnston, Ladanyi, and Sego (1988) define permafrost as soil or rock that remains at or below 0 °C (32 °F) for at least two years. In permafrost zones, building foundations depend on preserving the frozen-state of soils either at or colder than current soil temperatures. I discuss the test methods details in separate sections, below.

For permafrost zones, I change the basic thermal soils regime assumption from a normally thawed state of soils temperatures (i.e., warmer portions of the discontinuous permafrost zone) to a frozen state of soils. These frozen segments are in the colder portions of the discontinuous zone and throughout the continuous permafrost zone (Figure 1). I hypothesize that an adaptive seasonal insulation method exists that (A) uses low technology, (B) installs easily, (C) accommodates uncertainty in climate-change predictions, and (D) allows taking immediate action.

Figure 5. Example: Open ventilated crawl space to protect permafrost under a heated building.

Figure 5 shows the fundamentally different permafrost-zone foundation design method that contrasts with seasonal frost zones. Here, the permafrost needs to stay frozen. A literature search revealed to expect decreases in foundation strength if the frozen soils temperatures warm. The seasonal frost zone FPSF method, of directing building heat into the soils, may not apply to permafrost zones. In the colder soils of the discontinuous permafrost zone as well as in the continuous permafrost zone, foundation strength relies upon the cryogenic structural interaction within the frozen soils that are in direct contact with the building foundation system. In addition, I investigate the effects from changing climate on the soils thermal regime for permafrost zone foundations.

1.3 Investigation Methods for Both Parts

In this research, I combined several investigation methods, depending upon the specific research-segment. See Table 1. I made a selected state of the art literature review based upon the specific topic areas covered. I did not readily find literature on seasonal insulation, exposed to warmer climates. That is one of my ongoing reasons for this research. I performed field studies on existing buildings both for frost-protected shallow foundations and for seasonal insulation. I performed numerical analyses for frost-protected shallow foundations only. I deemed the other segments of my research too complicated to translate easily to numerical analysis. Therefore, I focused my efforts on providing new finite element analyses. I had significant research funding restraints. I am quite grateful for the limited equipment funds, and limited site-opportunities. Please see the acknowledgements. I had no funding at all for researcher time. Therefore, I focused my personal efforts on providing least-first-cost results for proof of concepts.

Thermal finite element analysis (modeling) remains one powerful engineering tool. While numerical analyses (mathematics) may yield improved answers, it becomes increasingly difficult to describe complex in-situ conditions with numerical methods. Here, I presented 35 years of modeling results without taking 35 years of time. I attempted to use the limited site investigations effectively. The thermal modeling serves to highlight likely salient features and to investigate multiple problem mitigation-alternatives in a more reduced timeframe.

The three primary heat flow mechanisms include conduction (heat conveyance via direct contact), convection (heat conveyance via fluid motion), and radiation (heat convection through space without direct touch or fluid motion). For this research, I considered convection and radiation heat transfer as negligible. I assumed the soils approximate a homogenous stratum, with limited convective air loops within the soils. I assumed that these small convective air loop effects are included within the thermal conductivity factors I used. Therefore, I used conductive heat transfer as primary heat transfer mechanism.

The general form of the heat conduction equation includes terms for

(Heat in) – (Heat out) + (Heat generated) = (Heat stored)

Incropera and DeWitt (2002) show the general form of the heat transfer equation, evaluated from Fourier's law, as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho\cdot c_p\frac{\partial T}{\partial t}$$

The first three terms are changes of temperature (T) with respect to distances along the x, y, and z Cartesian coordinate system. These first three terms represent the (Heat in) – (Heat out). The fourth term (the $\dot{q}$ term) represents heat generated; which is usually zero for geotechnical soil considerations. The right side of the equation sign represents (Heat stored), which is the change of temperature (T) with time (t) of volumetric heat capacity (aka. sensible heat). Sensible heat is the soil mass density (ρ, units: kg/m^3, lb/ft^3) multiplied by the specific heat at constant pressure (c_p, units: J/(kg·°C), Btu /(lb·°F)). I used site investigations, and conformal mapping mathematical analyses, and finite element modeling to evaluate this heat transfer equation. I evaluated both one-dimensional heat flow and two-dimensional heat flow.

In-situ site investigations take more time than finite element analyses. My limited number of site investigations exposed unforeseen variables. In addition, I encountered and overcame the often-anticipated problems associated with equipment malfunctions. I used the site investigation results to help validate and to help calibrate the modeling results. One example of validation was internally checking the model results for snow cover compared with no snow conditions. One example of calibration was to check the similarities of isotherm shape between numerical analysis, site investigation results, and thermal modeling. Just as importantly, I used the site investigations to explore more fully the salient features associated with the thermal regime of soils faced with climate change.

Table 1.
Research Selection Set

	State of the Art Review	Field Studies	Numerical Analyses	Finite Element Analyses
Frost-protected Shallow Foundations	X	New	New	New
Permanent Insulation	X	Out of Scope	Out of Scope	New
Seasonal Insulation	X	New	Out of Scope	New
Seasonal Insulation for Climate Warming	Not Available	Out of Scope	Out of Scope	New

Chapter 2 General Background for Both Parts

In this section, I discuss frozen ground engineering principles common to both parts of this manuscript. Here, I discuss the principles of primary stresses within soils due to freezing action, of air freezing and thawing indices, and of geothermal heat flux.

2.1 Forces in Frost Susceptible Soils

2.1.1 Basal freezing pressures.

Soils expand with freezing. The following definitions follow Harris, et al. (1988) and Domaschuk (1982). Basal freezing pressures refer synonymously to frost heaving stresses. These pressures arise from the freezing action developing at the ice-to-water interface within a soil system. Frost action is not only from the 9% expansion of in-situ water becoming ice, but also from water that may migrate to the freezing front from fine-grained soil capillarity. Unrestrained, these pressures may result in frost heaving – upward or outward soil movement. When restrained, these pressures may attain values as high as 1 MPa (145 lb/in^2 or about 21 000 lb/ft^2) (Harris et al., 1988). Gold (1985) included information from Penner's 1970 results showing large pressures developed by frost action. It took a 130 kN (30 000 lb) force on a 30 cm (12 in) diameter plate to restrain the frost heaving pressures on that clay ground. That converts to about 1 840 kPa (38 500 lb/ft^2).

These basal soil pressures may have horizontal components as well as vertical. Beskow (1935) considered saturated soil. He explained how to understand ice formation by considering an adsorption-water film nearest the freezing front. Manz (2011) summarized several authors' reports and explained the nanometers-thick premelted water film within the frozen fringe. Recently Peppin and Style (2012) reported that the geophysical phenomenon of freezing soils remains not fully understood.

McFadden and Bennet (1991), in their chapter on foundations in frozen soils, reported that a foundation wall also conducts thermal energy. They cautioned readers to recall that heaving forces are perpendicular to the freezing front. Further, these horizontal frost-heaving forces may topple or buckle a sub-grade wall. The common element from the researchers mentioned here included understanding that freezing ground stresses arise from water movement and from ice formation across the freezing front, and in opposite direction to the heat flow. They agree these stresses resulted perpendicular to the freezing isotherm. If the freezing isotherm is horizontal, then these pressures are vertical, usually upward. However, with a sloped freezing isotherm, these forces have both a vertical and a horizontal component.

Basal pressures act directly upon the structure, commonly at an angle to the structure. Basal pressures use units of force-per-unit-area (kPa or Lb /in^2). Basal pressures arise from the soil freezing action. As the soil around a structure freezes and expands, the soil exerts pressure on the structure. Basal pressures (also called stresses) refer to this pressure bearing upon the structure, at the structure-to-soil interface (Domaschuk, 1982). Domaschuk reported maximum basal pressures of 226 kPa to 3 035 kPa (32 lb/in^2 to 440 lb/in^2), depending both on the specific test method used as well as on the soils type.

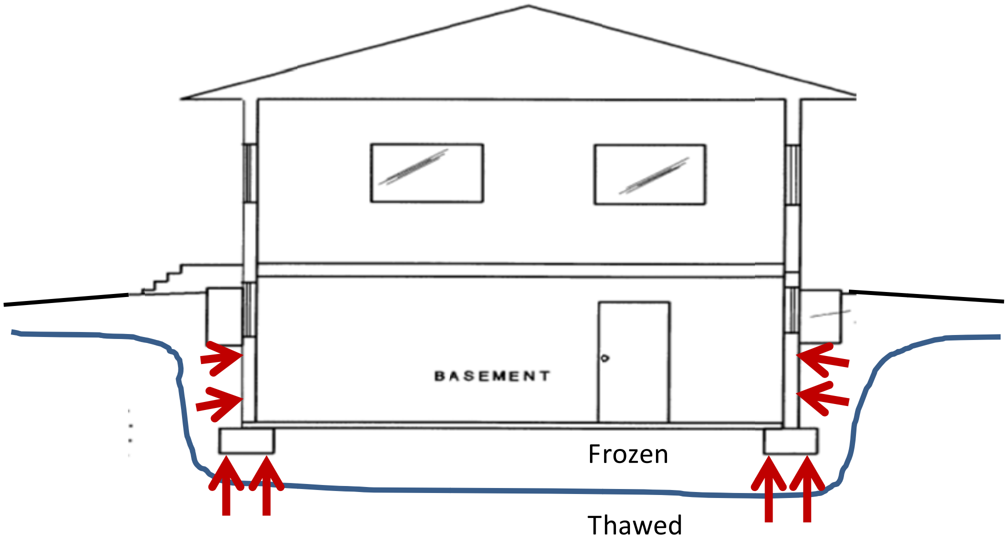


Figure 6. Frost heaving (basal) stresses act perpendicular to the freezing line.
These frost-heaving stresses may act horizontally as well as vertically.
The red arrows (added by author) show the action-orientation for the basal stresses.
(Figure adapted from McFadden, 2001, Figure 5.11.)

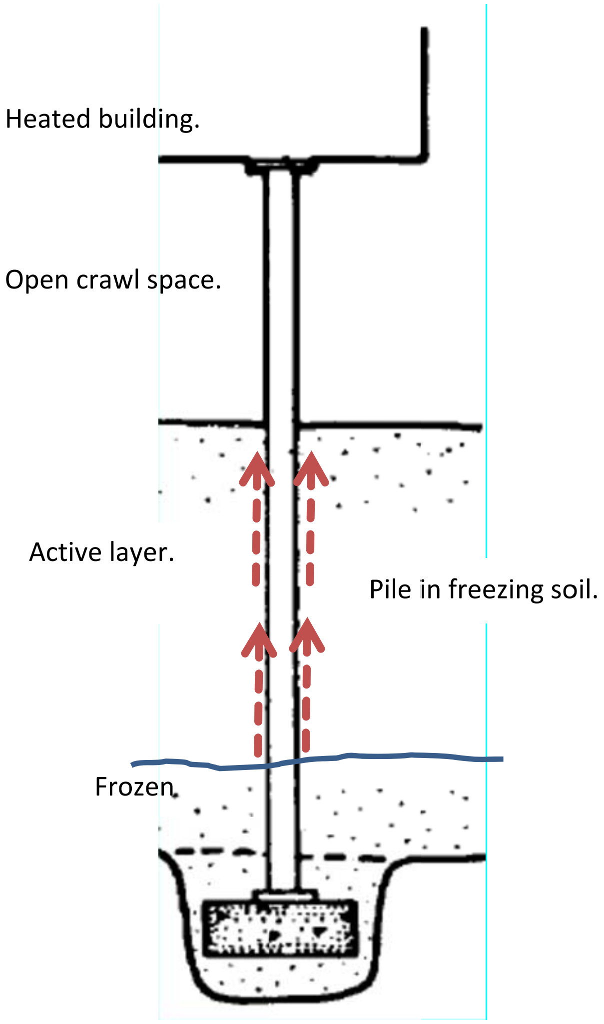


Figure 7. Tangential stresses arise from freezing soil bonding (adhering) to structural surfaces. An example includes soil in the active layer bonding to pile surfaces. Simply stated, tangential stresses (red arrows) represent the glue-strength of ice and soil in contact with structures. (Figure adapted from UFC 2004b, Figure 4-17.)

Visualize the magnitude that basal pressures may attain. The amount is similar to having the entire empty-weight of a full-sized four-wheel drive pickup truck, 2 700 kg (5 900 lb), placed on the area of one's hand, about 10 cm by 15 cm (about a 4 in by 6 in photograph).

2.1.2 Tangential freezing stresses.

Tangential freezing stresses contrast with basal freezing pressures. Tangential freezing stresses use the same units as Basal pressures; force-per-unit-area (kPa or Lb /in^2). Tangential freezing stresses also arise from the soil freezing process. Here, though, the soil adheres (bonds) to surfaces contained within the freezing soil. Tangential stresses act along the structural surface, not at an angle to it. These tangential stresses commonly provide the forces for jacking piles out of the ground.

Péwé and Paige (1963) reported (from Mueller in 1945) that tangential adfreezing strength between the ground and the piles varies with soils moisture content, ground temperature, and pile surface characteristics. McFadden (2000) reports usable adfreeze bond stresses to 275 kPa (40 psi). Ladanyi and Foriero (1998) reported adfreeze bond stresses to 230 kPa (33 lb/in^2). Domaschuk (1982) summarized several authors' widely varying adfreeze stress values from 116 kPa to 2 756 kPa (16 lb/in^2 to 400 lb/in^2) depending upon soil type, moisture content, test method, and structural material.

Structural design parameters include both restraining the basal freezing pressures (acting perpendicular to the freezing front, at an angle to the structural surface) and restraining the tangential freezing stresses (acting in alignment with the structural surface). Basal pressures tend to bow and deform floor or wall systems within freezing soils. Tangential stresses tend to jack piles out from the ground.

2.2 Air Freezing Index

One quantitative way to describe the amount of cold weather in a winter is by air-freezing index (AFI). An air-freezing index is the cumulative number of days below freezing multiplied by the degrees the temperature is below the freezing point. Similarly, the air-thawing index is the number of days above freezing multiplied by the degrees the temperature is above the freezing point.

Climatologists measure the AFI by accumulating, on a daily basis, the products of the temperature degrees below freezing and the time-duration of that frost condition. That summation of these daily products, over the course of the entire winter season, becomes the usable AFI. For Scandinavia, Farouki (1992) represented this freezing index in units of °C·h. In America, climatologists reported the AFI in units of °F·d or °C·d (ASCE 32-01, 2001; NAHB, 2004).

Designers use the AFI as a combined indicator of the length and magnitude of the value of temperatures below freezing. Since it is freezing index, the numerical value is stated as a positive number. For example, an outside air temperature of -19.44 °C (-3 °F), for one day, represents a freezing index of 19.44 °C·d (32 –(-3) = 35 °F·d). If that temperature remained constant for 180 days, then the AFI for the entire winter would be 19.44 °C x 180 d = 3 500 °C·d (35 °F x 180 d =6 300 °F·d).

The Fairbanks area design AFI index used depends upon the life expectancy for the building. Shorter life buildings use a design AFI closer to the average. Longer life buildings use a higher design AFI. Here, I have used common life expectancies for buildings of 30, 50 and 100 years.

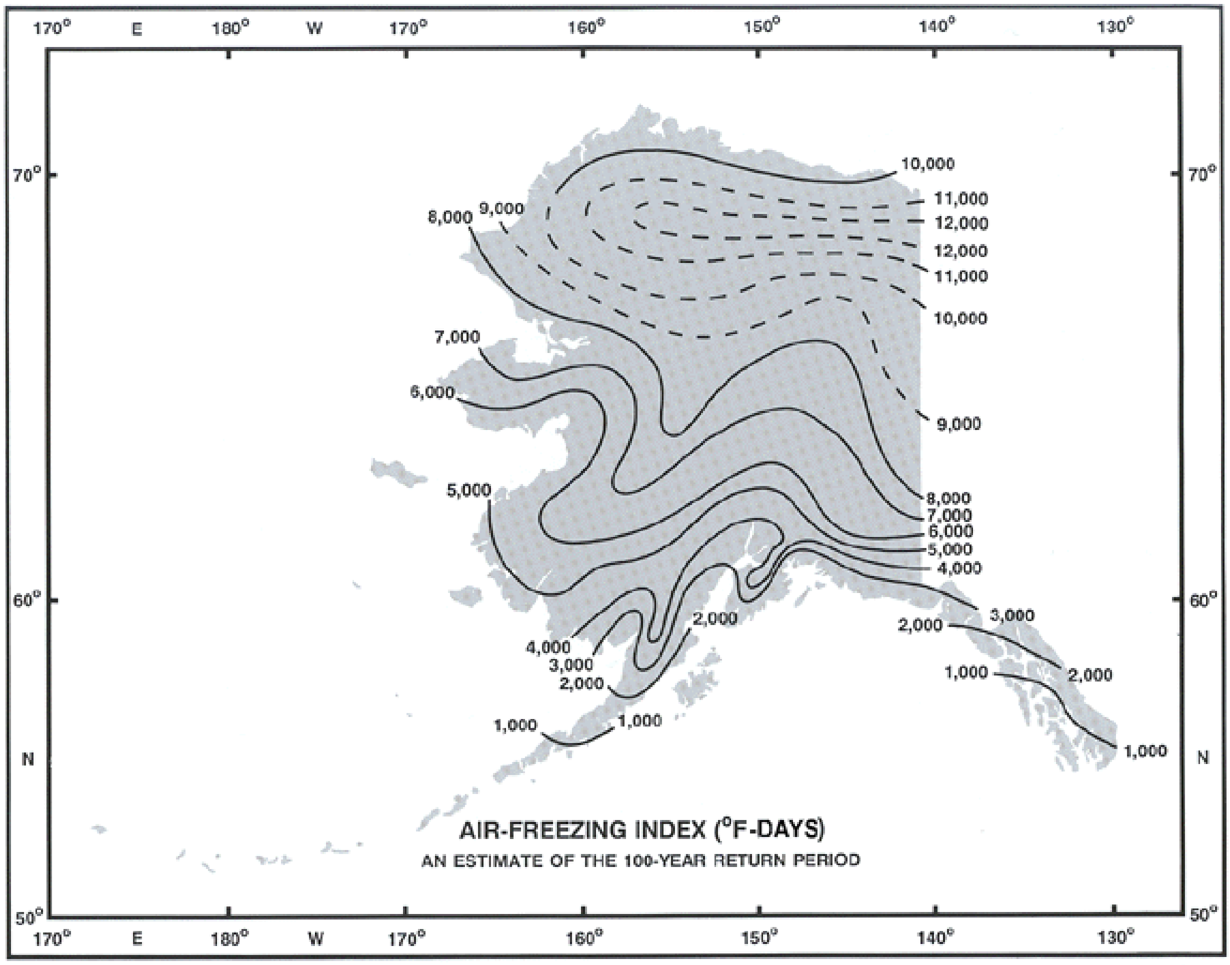


Figure 8. Map showing the estimated Alaska air-freezing index (AFI) for a 100-year return period.
Retrieved from http://www.ncdc.noaa.gov/oa/fpsf/fpsfmaps.html .
Fairbanks is located at 64° 48' N. Latitude, and 147°, 45' W. Longitude.
Data from the National Climatic Data Center, NOAA Satellite
and Information Service, (NCDC-NOAA), show Fairbanks having
a 100-year return period design AFI of about 4 056 °C·d (97 333 °C·h, 7 000 °F·d).

According to the National Weather Service, Alaska Region (NWS-AK, 1998), there are recorded weather data from 1904 to present. In 1998, when checked, only 558 days of data were missing (Randy Settje NWS, personal communication, September 1998). This 95-year record showed the following coldest AFI-on-record for specific winters in Fairbanks (Table 2). I chose the Fairbanks design air freezing indices for this research by combining (A) Recorded weather data from the National Weather Service for

Alaska, (B) Map information from the National Climate Data Center (Figure 8), and (C) Hartman and Johnson (1984), Plate 34. I used design AFIs that are higher than average to account for desired return periods. The air thawing index (ATI) is the accumulation of daily above-freezing temperatures, totaled in the same manner as the AFI.

Table 2.
Coldest Winters – Air Freezing Indices (AFI), 1904-1998

from Historical Data *

Winter of…	(°C-d)	(°C-h)	(°F-d)
1932	3 651	87 613	6 571
1933	3 655	87 720	6 579
1956	4 039	96 947	7 271
1964	3 668	88 027	6 602
1966	3 947	94 720	7 104

from Literature **

	(°C-d)	(°C-h)	(°F-d)
Average	3 056	73 333	5 500
Design	3 611	86 667	6 500

I used these AFI…

Return Period	(°C-d)	(°C-h)	(°F-d)
30 years	3 611	86 667	6 500
50 years	3 889	93 333	7 000
100 years	4 056	97 333	7 300

* National Weather Service, Alaska Region, 1904 to 1998.
** Hartman and Johnson (1984) Environmental Atlas, Plate 34.

2.3 Geothermal Heat Flux

Geothermal heat flux values vary with earth location, geological time-period and other factors. Davies, J. and Davies (2010) reported geothermal heat flux values varying from 0.039 W/m^2 to 0.127 W/m^2 (0.0124 Btu / (h·ft^2) to 0.0403 Btu / (h·ft^2)). Mareschal and Jaupart (2013) reported an average Precambrian crust heat-production-value equal to 0.077 W/m^2 (0.0244 Btu / (h·ft^2). For this research, I used a continental heat flux value of 0.065 W/m^2 (0.0206 Btu /(h·ft^2), reported by Pollack, Hurter, and Johnson (1993).

PART A. FROST PROTECTED SHALLOW FOUNDATIONS – FOR SEASONAL FROST SITES

Chapter 3 Frost-Protected Shallow Foundations

3.1 Introduction and Literature Review

One continuing design-intent for conventional foundations includes placing foundation footings at depths below the seasonal frost line. This design intent applies to seasonal zones without permafrost. Permafrost below the site alters the fundamental design assumptions and requires different design methods. Without freezing below the footing, the basal frost heaving stresses do not exist. In my experience, for Fairbanks, frost depths of 2.4 m to 3.6 m (8 ft to 12 ft) are common. However, practical experiences in the Fairbanks area show that placing footings shallower than seasonal frost depths incurs satisfactory results for most cases.

Frost-protected shallow foundations apply to regions where (A) no permafrost exists ("permafrost free zones"), or (B) thawed sites within larger regions where sites with permafrost sites also exit (“discontinuous permafrost zones”). Seasonal frost heave protection accompanies one of three environmental factors. Basic arctic engineering principles teach us to preclude seasonal frost action by eliminating one or more of the three “Ws,” as follows: water, wicking, and winter. Water refers to available moisture that may move to the freezing front. Wicking refers to wicking soils with small enough pore sizes between individual soil particles such that water may move via capillary action and by other methods related to small pore spaces. Winter refers to the freezing action in soils resulting from outside freezing weather. FPSF systems preclude seasonal frost action by restricting and directing heat flow, out from a heated building, in to the soils directly below the building. Building heat flow which enters the soils restrains the frost line to a position outside of the footings (Figure 4).

In use since the early 1960s (Farouki, 1992), frost-protected shallow foundation systems are not new. Developed in Scandinavia, rather than placing footings 1.1m (42 in) below the surface (Figure 9), ASCE (2001) shows these foundation systems may be placed about 0.3 m to 0.4 m (12 in to 16 in) below the surface. Figure 10 shows this as hv. Providing a more detailed thermal design permits this shallower depth. An FPSF system directs sufficient thermal heat flow from a heated building, into the ground below, to keep soils above the freezing point.

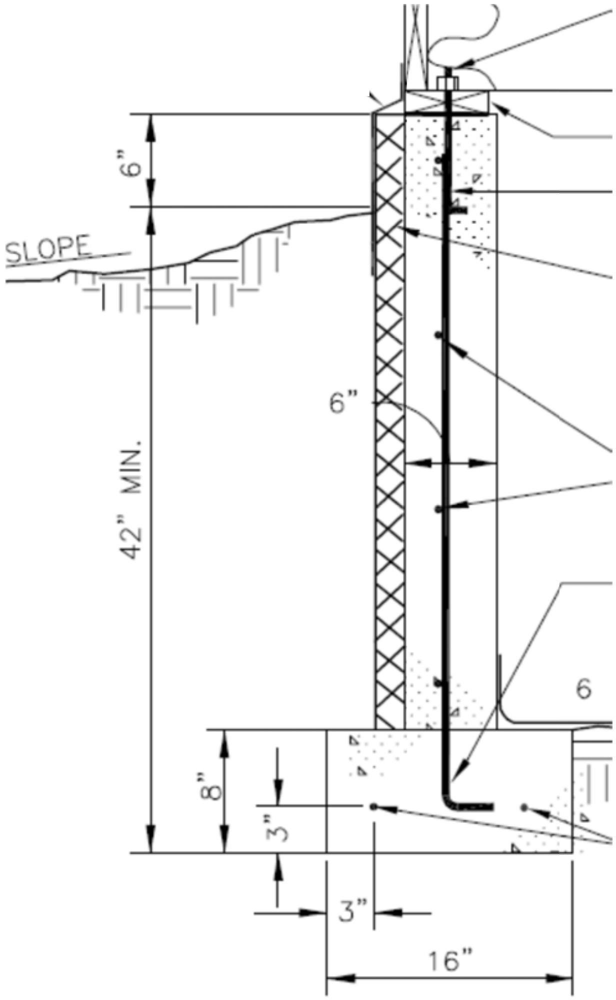


Figure 9. SFD-2, a City of Fairbanks standard foundation detail.
City of Fairbanks standard foundation details show the bottom of footings placed less than 1.1 m (42 in) below grade. Winter soils freeze-depths may easily extend deeper (COF, 2008).

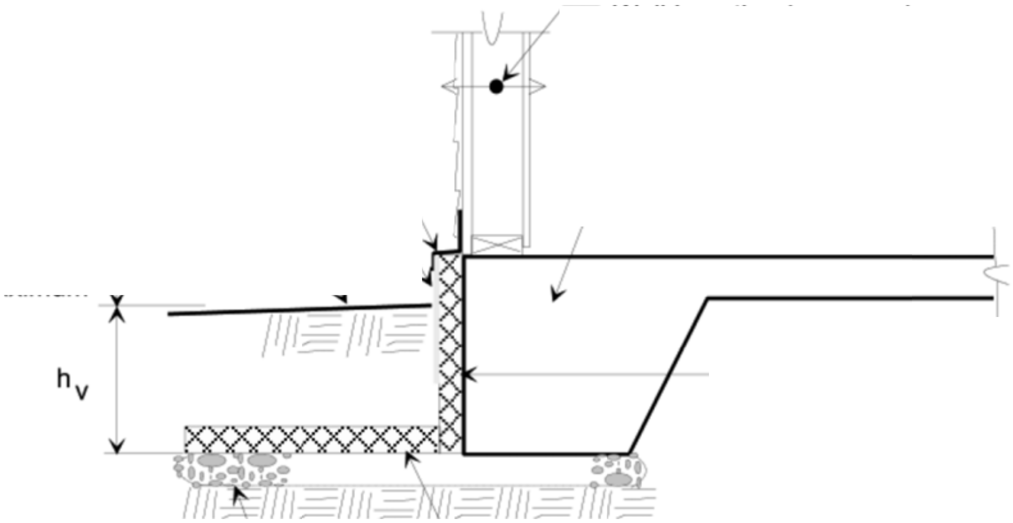


Figure 10. A frost-protected shallow foundation penetrates about 0.4m (16 in). Interior heat confinement serves to maintain thawed soils below the footings.

An FPSF system uses thermal insulation, around the foundation perimeter, to contain building heat in the soils below the building. This thermal insulation protects the foundation system from freezing below the footings and from seasonal frost heaving forces. An FPSF system typically penetrates less than two feet into the ground – well above the seasonal frost depth for most of Interior Alaska. An FPSF system confines building heat within the soils below the foundation system. This confined heat restricts seasonally frozen soils to regions outside of and away from the foundation zone. The soils below the footings and foundation zone remain thawed. Keeping soils thawed removes the risk of seasonal frost heave. Some of the reasons to use FPSF systems include (A) reducing the excavation needed, (B) reducing the concrete foundation materials needed, and (C) providing a flat floor system for improving accessibility.

Reducing the required depth foundation excavation decreases the building cost and the labor time needed for installation. The 2004 Revised Builder's Guide to Frost-Protected Shallow Foundations reports varying cost savings for an FPSF system. Colder regions, like Alaska, realize greater cost savings than warmer regions (NAHB, 2004). Another source indicates an annual construction savings estimated at $300 million (Steurer, 1996). In a case study for an FPSF system at Galena, air control tower, the construction supervisor reports accomplishing an FPSF system in about half of the time needed for a conventional foundation (Danyluk, 1997).

Environmental impacts on sensitive land warrant appropriate care and response. Depending upon site specifics, reduced excavation also means reduced site disturbance.

Reducing the concrete needed for the foundation saves cost and time. In addition, it reduces the amount of energy needed for obtaining cement resources. The EPA (1998) reported the combustion fuel needed for the Portland cement manufacturing kilns as the primary source of POM (polycyclic organic matter) emissions. Wilson (1993) reported that important steps and process changes have occurred to minimize pollution. However, he reported that cement production is among the most energy intensive processes used in the construction industry and a major contributor to CO2 in the atmosphere.

Reducing obstructions for persons with disabilities includes providing a flat floor system without architectural barriers. The FPSF system requires no steps between a garage or loading area and the adjacent living or business area. Flat floors remove the impediment to free and equivalent travel for all persons regardless of age or disabilities.

Historically, much of the research for the current design guides and building codes came from the Scandinavian countries of Finland, Norway, and Sweden. The sea influences the climatology there more than in Interior Alaska.

Farouki (1992) summarized methods then used in Europe. As an example, this 123-page monograph showed the maximum freezing index for FPSF systems as extending only to an AFI of 60 000 °C·h (2 500 °C·d, 4 500 °F·d). That lower AFI value sufficiently answered the FPSF questions for those warmer maritime environments. That warmer maritime climate remains close to the design limitation still shown even in the newer ASCE 32 standard (ASCE, 2001).

Bondarev (1957) described permafrost degradation under the maternity hospital in Vorkuta, Russia. The design called for insulating the crawl space in summer, using 50 cm (20 in.) of slag and removing the insulation in winter. Instead of installing insulation in the whole crawl space, placement only occurred for one-third of the crawl space. Instead of 50 cm (20 in) thick insulation, installers provided only 10 cm to 15 cm (4 in. to 6 in). The insulation remained in place during the winter and became permanent. Not surprisingly, the soil temperature under the insulated crawl space portion warmed by 2°C to 3°C (3.6°F to 5.4°F) more than under the uninsulated area (Bondarev, 1957).

The American Society of Civil Engineers (ASCE, 2001) has produced the SEI/ASCE 32-01 standard, "Design and Construction of Frost-Protected Shallow Foundations." This is the current standard commonly used for designing frost-protected shallow foundations in America. This existing standard includes air-freezing indices extending down to 2 500 °C·d (60 000 °C·h) (4 500 °F·d). This current limit is measured by an Air Freezing Index of 2 500 °C·d (60 000 °C·h, 4 500 °F·d).

This research extends the ASCE methods to include regions with colder soils. Regions, in Interior Alaska, may have mean annual soils temperatures (MAST) within about 0.8 °C (1.5 °F) of the soil freezing point. In this arctic environment, in the thawed portions of the discontinuous permafrost zone (Figure 1), geothermal heat may not be enough to keep unheated building foundations above freezing. I investigated whether or not providing more heat-confinement, via more perimeter insulation, may suitably keep the freezing isotherm out from below the building foundation.

In a building, corners are coldest. Along a long wall, methods consider approximating heat flow as two-dimensional. At corners, though, building heat may escape either from the long wall or from the end wall. At corners, the heat flow more closely approximates three-dimensional flow (Figure 11).

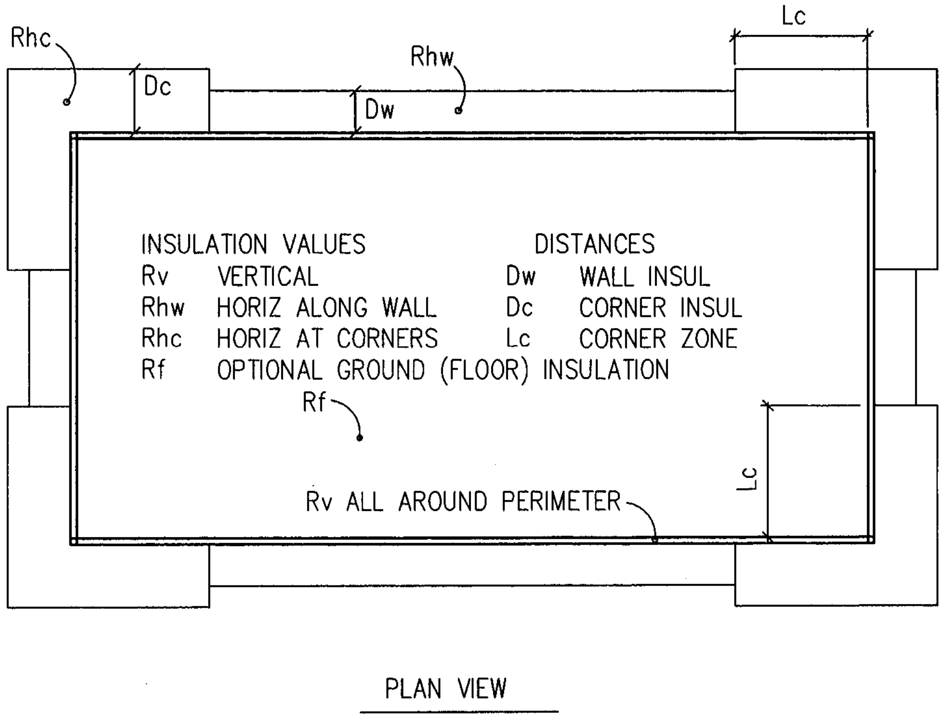


Figure 11. A plan view sketch showing a frost-protected shallow foundation.
This sketch shows a bird's eye view, looking from far above a simple rectangular building.
The sketch shows symbols, nomenclature, and distances used for installing insulation.
Note the corner zone lengths (Lc) requiring extra thermal value and extents for insulation.

In China, Hong and Jiang's (1988) investigation of eleven full-size houses over a period of ten years, documented about a 30 % deeper frost depth at corners (177 cm, 70 in), than the shallower frost depth along the long walls (135 cm, 53 in) (Hong and Jiang, 1988). Current codes and design guides agree with placing about one-third extra insulation thermal resistance value (Rhc) at corners, plus extending the horizontal insulation distance about one-third further away from the foundation (Dc).

Current projections for climate-change anticipate warming conditions. However, I also respond an invitation to address the possibility of climate cooling. The air freezing indices available during this research included almost 100 years of data. I used actual data from the three coldest years on record for my 100-year design air-freezing index. I preferred using actual 100-year data for a 100-year recurrence interval, not just averaging the three coldest years within the last 30 years. In order to accommodate a possible climate-cooling scenario, I decided to extend my investigation to include a 10 % colder extreme winter. Therefore, I investigated climate conditions down to 4 400 °C·d (106 600 °C·h, 8 000 °F·d). This would extend current U.S. design guide applications to regions almost 80 % colder than covered in current design guides.

This research serves to extend knowledgeable use of an FPSF system into colder northern Alaska regions. This research expands the understanding of the thermal regimes in foundation zones below heated buildings. Included, here, are heat-containment recommendations for builders, for the design community, and for consideration in future building- code revisions. These results extend the understanding of thermal regimes below FPSF systems located in regions between 2 500 °C to 4 400 °C·d (4 500 °F·d to 8 000 °F·d).

I investigated this hypothesis, “Using manufactured thermal insulation alters the thermal regime of soils below heated buildings and provides additional foundation methods for arctic buildings.” For seasonal frost areas I hypothesized, "Where no permafrost exists below heated buildings, manufactured insulation may be used around building perimeters to help contain building heat, thereby precluding seasonal frost heaving damage even with winters almost 80 % colder as shown in current design guides.”

3.2 Field Studies, Six Sites in the Seasonal Frost Zone

3.2.1 Insulation types and long-term effective thermal resistivity.

Construction included providing rigid foam thermal insulation for each FPSF site investigated. Rigid foam comes in two primary types: extruded polystyrene (XPS) and expanded polystyrene (EPS). Extruded polystyrene (XPS) is forced through a mold. Toothpaste, squeezed from its tube, exemplifies the polystyrene extrusion process. Popcorn, expanded by cooking, analogizes the expanded polystyrene process. Construction methods, for the six sites investigated, utilized XPS insulation.

The American Society of Civil Engineers (2001) specifies using “effective thermal resistivity” values (i.e., R-value per inch) for long-term thermal resistance determinations (Table 3). The reductions from nominal values to reduced effective values depend upon insulation types and installation orientation. I refer the reader directly to ASCE 32-01 for a more thorough discussion. The 2006 IRC specifies installing only XPS for horizontal wing insulation application (ICC-IRC, 2006).

Extruded polystyrene has long been the insulation of choice for horizontal subgrade installations (Esch, 1986; Weinstein, 1994). In contrast, both ASCE 32-01 and the 2004 NAHB allow both XPS and EPS for horizontal application (ASCE, 2001; NAHB, 2004). I have also excluded specific evaluations of long-term effective thermal resistivity for different insulation types. For this report, I used the long-term effective thermal resistance values provided in ASCE 32-01.

Table 3.
Foam Insulation, Long Term Effective Thermal Resistivity

Insulation Type per ASTM C578	Nominal Resistivity	Effective Resistivity Long Term	
	Per 25 mm (1 in) (m^2 °C)/W (ft2 °F hr) /(Btu in)	Vertical Around Perimeter (m^2 °C)/W (ft2 °F hr) /(Btu in)	Horizontal Out from Footing (m^2 °C)/W (ft2 °F hr) /(Btu in)
EPS Type II (Expanded)	0.70 (4.0)	0.56 (3.2)	0.46 (2.6)
EPS Type IX (Expanded)	0.74 (4.2)	0.60 (3.4)	0.49 (2.8)
XPS Type VI (Extruded)	0.88 (5.0)	0.79 (4.5)	0.70 (4.0)

Data taken from American Society of Civil Engineers (2001), ASCE 32-01, Appendix A

3.2.2 Six field locations.

I chose and instrumented six different Fairbanks sites to investigate the impacts of differing conditions on FPSF design. I used data from the thermistor strings (A) for calibrating the finite element models, and (B) for validating that the model applied sufficiently correctly to different soils conditions.

1. Named “Timberland,” this 650 m^2 (7 000 ft^2) commercial building has office spaces and assembly areas. Located within the Fairbanks city limits, on a dry gravel site, the water table for this building is about 3.6 m to 4.6 m (12 ft to 15 ft) below the building depending upon season. This site’s uniqueness included being the only site that used the higher values of thermal resistance investigated here. The thermistor layout for Timberland closely resembled that shown in Figure 13 with two thermistor strings at a corner, and two strings toward the middle of a long wall.

The contractor installed an FPSF system I prescribed for this investigation. Along the long wall, the thermal values (Rv and Rhw in Figure 11) were 3.5 m^2 °C/W (20 ft^2 hr °F/Btu). The long-wall insulation extended (Dw) out from the long walls 0.9 m (36 in). At the corners, the increased thermal value (Rhc) was 4.4 m^2 °C/W (25 ft^2 hr °F/Btu). The corner zone insulation extended further out (Dc) from the corner a total distance of 1.2m (48 in). Each corner zone distance (Lc) was 3 m (10 ft) long. This amount of insulation is about 50% greater than the current maximum shown in ASCE 32-01 (ASCE, 2001).

2. Named “Merlin,” this 325 m^2 (3 500 ft^2) residence has multiple two-car heated-garages with a personnel door between. Located in the hills, north of Fairbanks, on a fractured schist site, the reported water table is deeper than 30 m (100 ft). The site’s uniqueness included the cleared-of-trees hill-side-site, the orientation permitting instrumenting the southwest face of the building, and the ability to instrument near multiple garage door openings. The thermistor layout for Merlin had two thermistor strings located near a corner, and two thermistor strings located between the overhead doors.

Construction methods at Merlin site included an FPSF system that used insulated forms for the vertical insulation. Along all walls, the contractor reported an EPS total thickness of 12 cm (4.75 in) with a vertical thermal value (Rv) of 2.8 m^2 °C/W (16 ft^2 hr °F/Btu). The horizontal insulation (Rhw) was XPS with a thermal value of 1.4 m^2 °C/W (8 ft^2 hr °F/Btu). The horizontal distance (Dh) reported as uniform around the entire building, extended out a horizontal distance (Dw) of about 0.6 m (24 in). Corner zones had no increased insulation thermal values or increased extents away from the foundation.

3. Named “Goshawk,” this 325 m^2 (3 500 ft^2) residence also has multiple two-car heated-garages. Located in hills north of Fairbanks but lower than Merlin, Goshawk is on a silt and shale site, with a reported water table deeper than 30 m (100 ft). The site’s uniqueness included trees on the site, an orientation that permitted instrumenting the north side of the building, and in a fashion that resembled Figure 13 with two thermistor strings at a corner, and two strings toward the middle of a long wall. Construction methods reported for Goshawk site were the same as for Merlin site.

4. Named “Violin,” this 300 m2 (3 200 ft^2) residence had a partially completed garage when instrumented. That means I could instrument inside the footing zone, in warm space. I used smaller drilling equipment to fit within the garage. Located in a valley, about 8 km (5 mi) west of Fairbanks, Violin is on a rocky schist site overlain by about 1 m (3 ft) of silty sand. Like Merlin and Goshawk, the Violin site had insulation about the maximum shown in current design guides for regions with warmer climate.

I chose Violin site because I could change the thermistor string layout. I placed all five strings in a single row, extending from just inside the building from the footing, then outside of the building to a distance of 7.6 m (25 ft). The thermistor strings were all on the south face of the building. I wondered about the effects from the reflective albedo from the light-colored unfinished wall surface upon the thermal results.

5. Named “Bonita,” this 1 100 m^2 (12 000 ft^2) former construction shop and warehouse is currently a training center with offices and assembly spaces. Located just south of the Fairbanks city limits, on a dry gravel site, the water table for this building is, like Timberland, at about 3.6 m to 4.6 m (12 ft to 15 ft) below the building depending upon season. Here too, instrumentation resembled Figure 13 with two thermistor strings at a corner, and two strings toward the middle of a long wall.

I chose the Bonita site because the building has no perimeter insulation at all. Still, there were no readily evident indicators of frost heaving distress. Having assessed over 500 northern Alaska Arctic buildings during my engineering career to date, I have observed this ‘no readily evident distress’ condition in several Fairbanks residential and commercial buildings. I wanted further investigation for this ‘no perimeter FPSF insulation at all’ condition.

6. Named “Army,” this 750 m^2 (8 000 ft^2) apartment complex also has no perimeter insulation at all. Located in lowlands northwest of Fairbanks, other buildings near to this site have known permafrost below. This Army site has distinctly visible building distress, particularly in the northeast corner, not evident in any of the other sites investigated. I estimated more than 15 cm (6 in) of differential vertical movement over a horizontal distance of about 3.6 m (12 ft). The plywood siding at the Army site was literally tearing apart at its seams. This building uses a post and pad foundation system with an enclosed and heated crawl space. Domestic water lines, routed in the crawl space, depend upon sufficient crawl space heat to limit the risk of freezing. Instrumentation resembled Figure 13.

I chose the Army site to investigate if providing an FPSF system might help stabilize the foundation system by providing a closer-to-uniform thermal system below the building.

3.2.3 Monitoring methods.

At each site, I installed five thermistor strings. "Answers.com" defines "thermistor" as "A resistor made of semiconductors having resistances that vary rapidly and predictably with temperature."

A thermistor is different from a thermocouple (Figure 12). "Answers.com" defines "thermocouple" as, "A thermoelectric device used to measure temperatures accurately, especially one consisting of two dissimilar metals joined so that a potential difference generated between the points of contact is a measure of the temperature difference between the points" (http://www.answers.com/thermocouple?cat=technology).

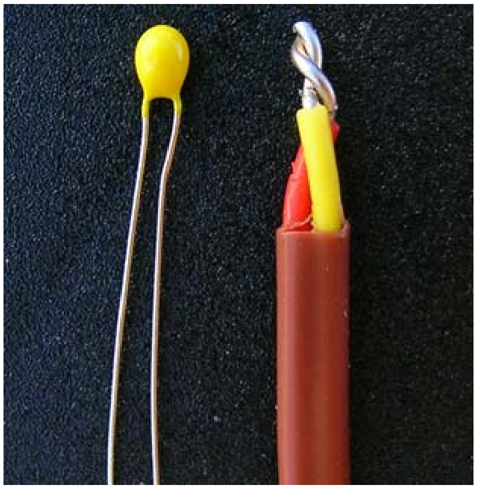


Figure 12. A thermistor (Left) or a thermocouple (Right) measures electrical resistance.
I used only thermistors. A thermistor measures about 1/16th inch wide.
Calibration charts permit converting from resistance to temperature.

Apogee Instruments makes the following comparisons: Thermistors require no reference temperature, yield a larger signal, utilize inexpensive wire and require multiple steps in datalogger programming. Thermocouples, by comparison, require an accurate reference temperature, yield a smaller signal, use a more expensive wire, and have easier datalogger programs (retrieved from http://www.apogeeinstruments.com/oxygensensor_techinfoTHERM.htm).

Manufactured by Alpha Technics, in California, Alpha thermistors (Type 14-A-5001-C2) were used at four sites. Alphas were calibrated to measure 5000 Ohms at 25^{o}C, and measure 16,332 Ohms at 0^{o}C. Manufactured by YI Precision Temperature Group, in Ohio, YSI thermistors (Model 44033) were used at two sites. YSI thermistors were calibrated to measure 2,252 Ohms at 25^{o}C and measure 7,355 Ohms at 0^{o}C.

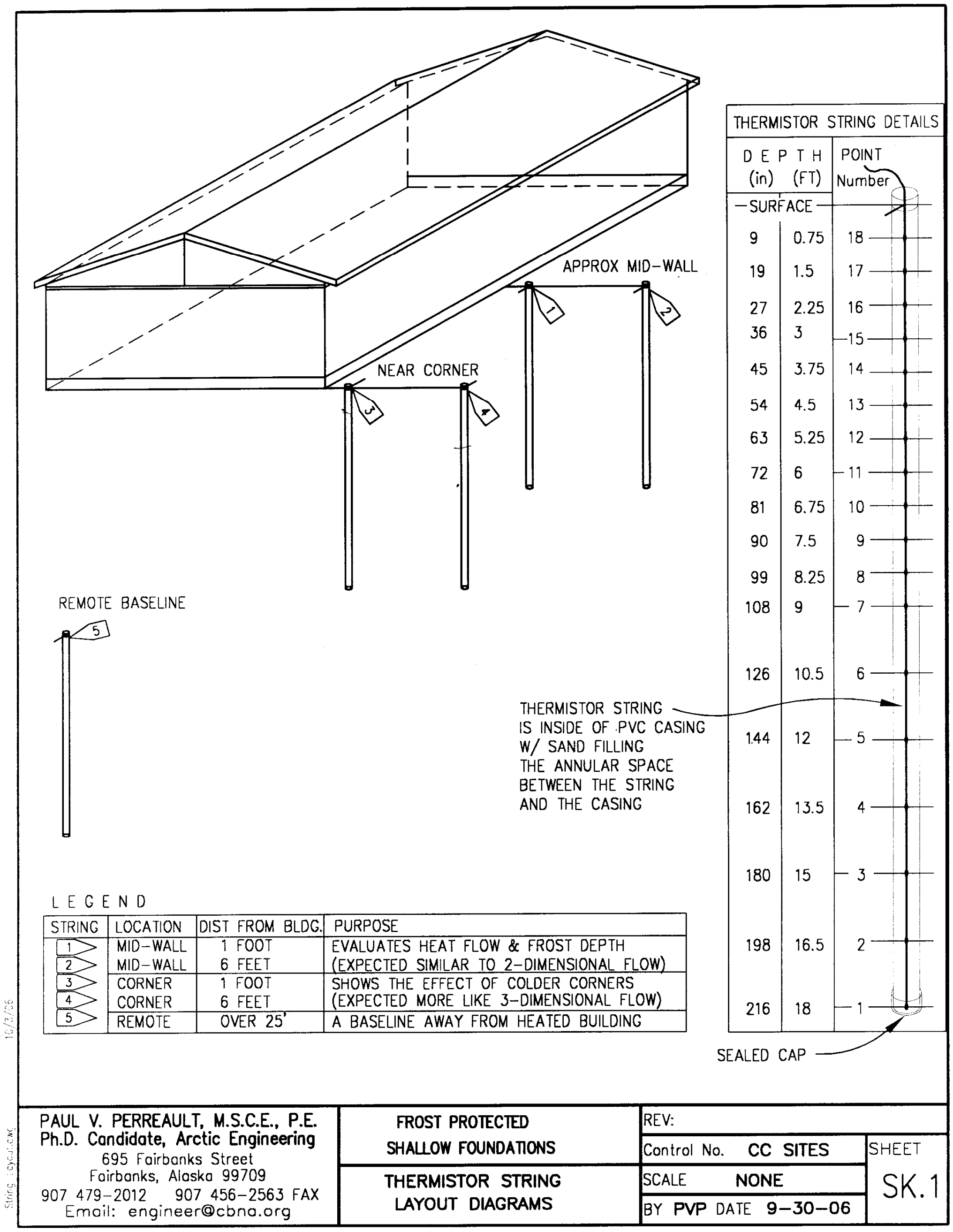
Thermistor string layouts remained approximately constant for five of the six sites (Figure 13). One pair of thermistor strings measured soil temperatures near the corner. From the work of others, I expected higher heat flow in the corner zones. A second pair measured temperatures along a longer wall. For each pair, I installed one thermistor string as close as practical to the building and a second about 2 m (6 ft) away. I also provided a remote thermistor string for baseline measurements without heat influence from the building. Thermistor string distances reported for specific sites refer back to this same figure.

I collected data starting in 2004, for several years. I determined and revised the thermistor string layout before installation. The final layout used closely spaced thermistors in the top of the soils regions, followed by larger spacings in the bottom portions. I installed five thermistor strings at each of these sites (90 thermistors total per site). I installed two strings along the long wall, to approximate two-dimensional heat flow. I installed two strings close to the corners, where I expected colder three-dimensional heat flow conditions. I installed the fifth string about 7.6 m (25 ft) away from the building, to approximate ambient conditions.

By contrast, I used a different thermistor string layout at Violin site. At Violin site, I aligned five thermistor strings in one row, outward, perpendicular to the building. The garage floor was unfinished soil. Therefore, I placed the first thermistor string inside the garage, in heated space, near the inside edge of the footing. I placed these thermistor-strings at distances of -0.1m (just inside of the building), 0.1 m (just outside of the building), 0.6 m, 2.1 m, and 7.6 m, (-0.5 ft, 0.5 ft, 2 ft, 7 ft, and 25 ft) from the footing. I installed the remaining four strings out from the building. Here, the driveway excavation remained uncompleted and out-of-level for the garage. However, I placed the top thermistor for each string approximately level. This meant that the two distant-most thermistor strings (at 2.1 m, and 7.6 m) had up to 0.6 m (2 ft) of soil cover over the thermistor-strings that the closer strings did not have.

I used two different thermistor types in this research. Product literature indicated that both types measured temperatures more accurately than thermocouples. Product literature also indicated the thermistors had close to linear temperature-resistance properties in the freezing temperature range, which I valued as the important point-of-interest in this research. For this research, I installed and measured temperatures from over 500 thermistors. Readings began in spring, 2004 and continued for three years or until thermistor failure.

Figure 14 and Figure 15, below, show the drilling operation. The driller used solid stem augers for drilling into the soils. I installed white Polyvinyl Chloride (PVC) pipe into each hole. Then, I inserted the pre-manufactured thermistor strings into each pipe. I wanted to emphasize conductive heat transfer, while limiting convective heat loops within the annular space around each thermistor string and its installation pipe. I filled the annular space between the thermistor string and its pipe-wall with ordinary traction sand. I chose not to use fluids that may leak should the monitoring tube walls break over time.



THERMISTOR STRING DETAILS

DEPTH (in)	DEPTH (FT)	POINT Number
9	0.75	18
19	1.5	17
27	2.25	16
36	3	15
45	3.75	14
54	4.5	13
63	5.25	12
72	6	11
81	6.75	10
90	7.5	9
99	8.25	8
108	9	7
126	10.5	6
144	12	5
162	13.5	4
180	15	3
198	16.5	2
216	18	1

LEGEND

STRING	LOCATION	DIST FROM BLDG.	PURPOSE
1	MID-WALL	1 FOOT	EVALUATES HEAT FLOW & FROST DEPTH
2	MID-WALL	6 FEET	(EXPECTED SIMILAR TO 2-DIMENSIONAL FLOW)
3	CORNER	1 FOOT	SHOWS THE EFFECT OF COLDER CORNERS
4	CORNER	6 FEET	(EXPECTED MORE LIKE 3-DIMENSIONAL FLOW)
5	REMOTE	OVER 25'	A BASELINE AWAY FROM HEATED BUILDING

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FROST PROTECTED SHALLOW FOUNDATIONS

THERMISTOR STRING LAYOUT DIAGRAMS

REV:
Control No. **CC SITES**
SCALE **NONE**
BY **PVP** DATE **9-30-06**
SHEET SK.1

Figure 13. A sketch showing the layout used for thermistor string installations.

I installed two pairs of thermistor strings. One pair, near the corner, measured heat flow in the corner zones. The second pair, away from the corner zone, measured heat flow along the walls. The remote thermistor string provided baseline data.

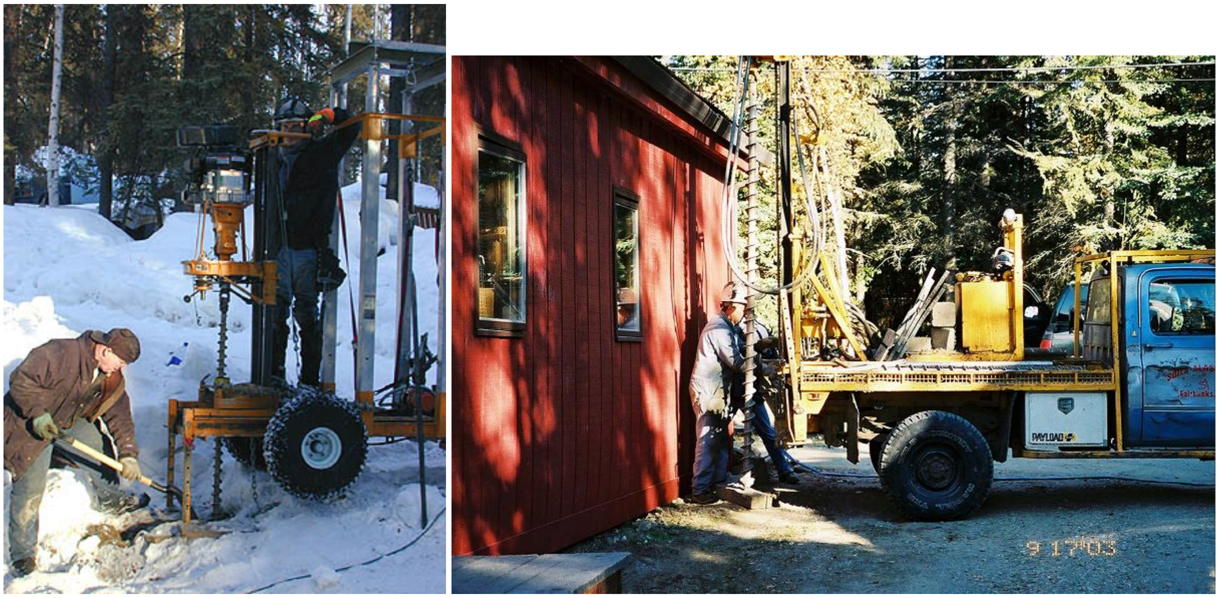

Figure 14. Different size drill rigs for boring holes for thermistor strings.
(Left) Violin: The irregular terrain presented options for creative solutions.
(Right) Army: Obstructions, such as roof overhangs, limited drill-rig-closeness to buildings.

Figure 15. Using a smaller drill rig permitted boring thermistor holes closer to the building.
During the drilling operation, we used screens to protect the building.

I collected data onto a CR10X Measurement and Control Module (datalogger). Campbell Scientific, Inc. manufactured the dataloggers. In order to input data from 90 thermistor points into one datalogger, I needed to combine three AM 16/32 Multiplexers with each datalogger. I computer programmed the multiplexers to sequentially take temperature samples and "log" those results onto the datalogger.

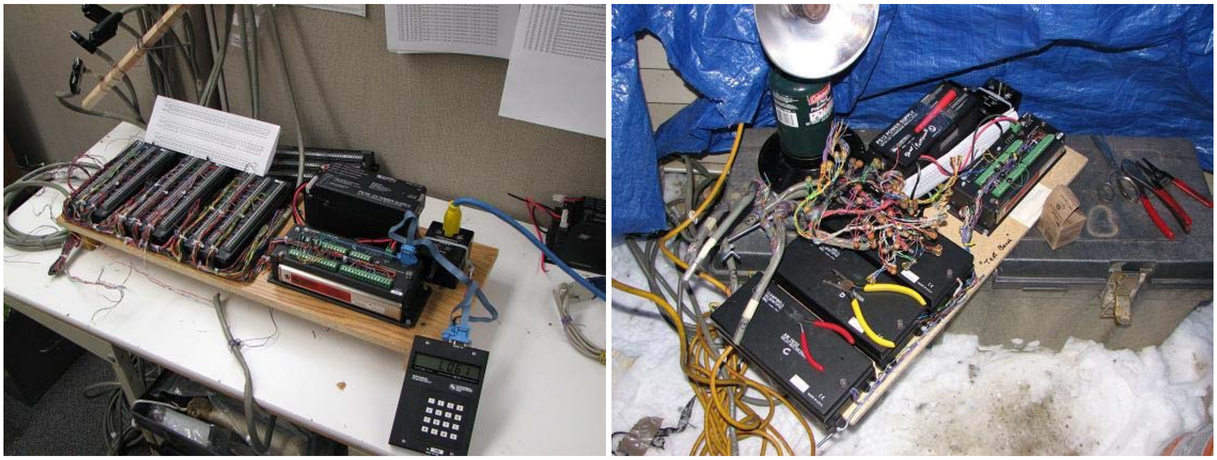

Figure 16. Prewired dataloggers at the office, then field-installed during cold weather.

Figure 16 shows bench preparation at the office followed by cold weather field installation. Figure 17 shows the data recording operation from a fixed datalogger station onto a laptop computer, and from a mobile datalogger station. One laptop computer failed in the cold weather.

Figure 17. Fixed and mobile platforms for downloading data.
(Top Left and Right) Hardwired dataloggers at two sites.
(Bottom) A mobile station for Timberland, Bonita, Army and Violin sites.

3.2.4 Field results and discussions.

3.2.4.1 Timberland results and discussion.

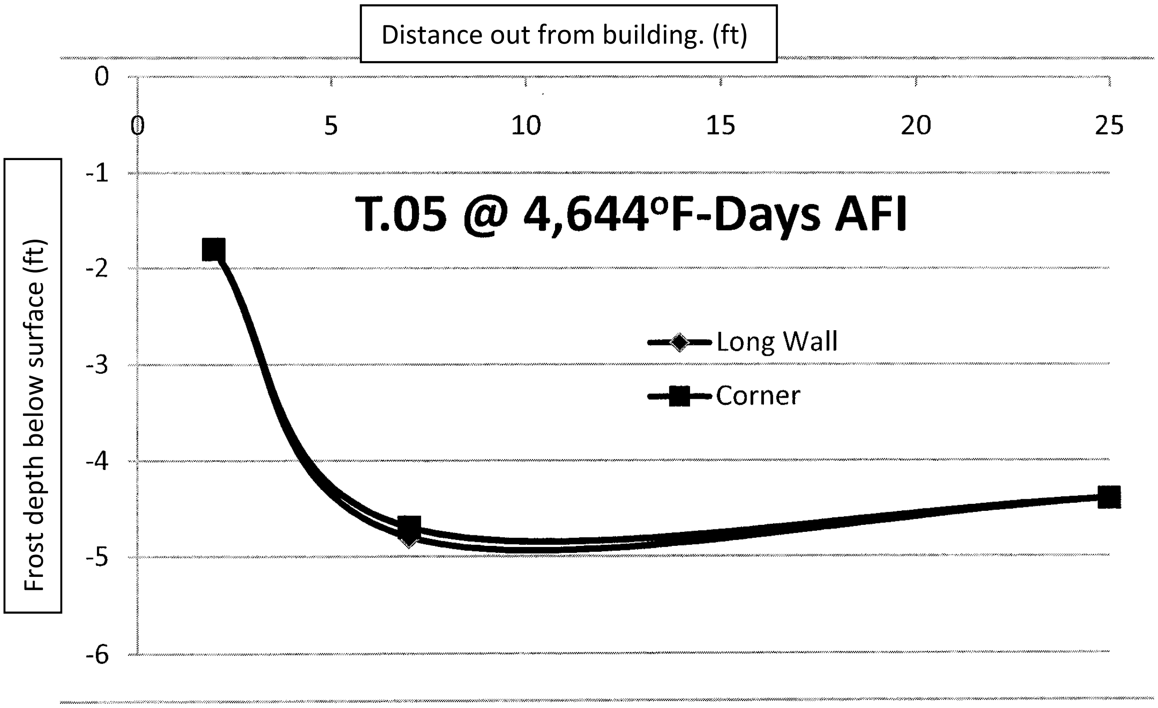

Figure 18. Timberland site: Shallow freezing lines likely to remain out from below footings. The plot shows distance out from the building along the top axis and depth on the side axis. One plot shows long wall results; the other shows corner zone results. The building (as shown in Figure 13) is to the left of location zero. These plotted lines show the depth to the frost line, as follows: close to the building, farther out, and at the distant baseline.

Each site investigated had a building in place that drilling equipment needed to avoid hitting (Figure 14 and Figure 15). That meant the closest monitoring hole for thermistors remained about 0.3 m to 0.6 m (1 ft to 2 ft) away from the building. I plotted the freezing isotherm for each site. Using extrapolation, I observed the freezing isotherm projection into the foundation region. Timberland results, for example, show the freezing isotherm projecting into the horizontal wing insulation (Figure 10) outside of the footing. Depth below the ground surface is shown on the left axis. Distance out from the building, as shown in Figure 13 is along the top axis.

The Timberland FPSF thermal design uses the design suggestions included in this dissertation (Appendix A). The overlapping freezing isotherm results from Timberland site (Figure 18) clearly show the corner-zone benefit (A) from adding about 30% thermal resistance above the long-wall insulation value and (B) from increasing the corner zone horizontal insulation extents about 30% further out than along the long-wall. This added corner insulation thermal value and increased extent out from the building did in fact overcome the three-dimensional heat flow effect within the corner zone. These results from the Timberland site help validate the 30% corner zone increases also recommended by Hong and Jiang (1988).

As shown as Dc and Lc in Figure 11, the corner zone distance varies with the design freezing-index. A ratio analysis shows common elements. The insulation extent out from the long wall (Dw) is about 1/3 the suggested corner zone distance (Lc) along the wall. Restated, as one example, results from this design guide shows a long-wall insulation projection (Dw) of 0.6 m (2 ft) should have a corner zone length along the wall (Lc) of about 1.8 m (6 ft).

A ratio analysis provides good results for thermal resistivity. The horizontal wall resistance (Rhw) times a 1.3 factor yields the suggested corner zone resistivity (Rhc). For example, an along-the wall thermal resistivity (Rhw) of 2.8 m^2·°C/W (R16, 16 ft^2·h·°F/Btu), the Timberland results suggest an increased corner zone thermal resistivity of 3.5 m^2·°C/W (R20, 20 ft^2·h·°F/Btu) to reduce the risk of the frost line extending below the footings.

These Timberland results showed insulation quantity and extents sufficiently confined and directed the building heat to keep the freezing isotherm out from below the footings. The overlapping isotherms showed that the increased corner zone thermal resistance and extents satisfactorily accounted for the additional heat flow at corners.

3.2.4.2 Merlin results and discussion.

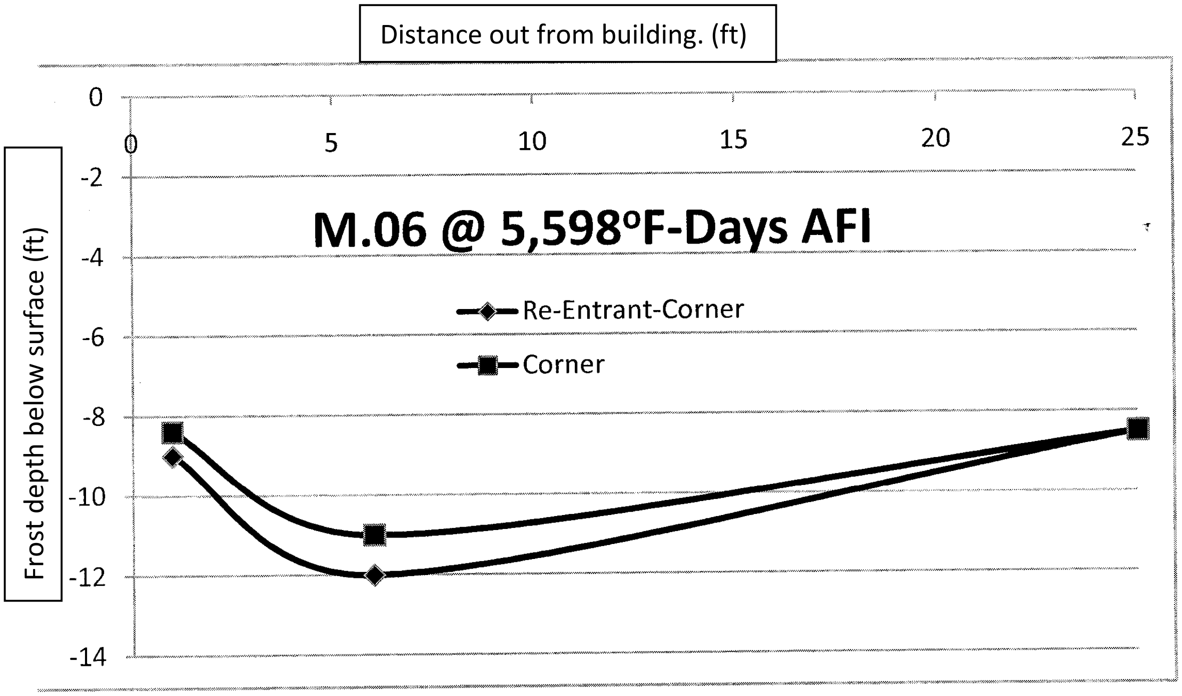

Figure 19. Merlin site: Deep soil freezing likely to extend under the footings.
The plot shows distance out from the building along the top axis and depth on the side axis.
One plot shows long wall results; the other shows corner zone results.
The building (as shown in Figure 13) is to the left of location zero.
These plotted lines show the depth to the frost line, as follows:
close to the building, farther out, and at the distant baseline.

The Merlin site, in the hills north of Farmer's Loop road is on fractured schist. Figure 19 shows results from that site. Depth below the ground surface is shown on the left axis. Distance out from the building, as shown in Figure 13 is along the top axis. At the Merlin site, the frost penetration measured over 8-feet deep at a distance of only one foot from the foundation system. Both of these boring-sets were near corners. The upper graph displays results from the building outside corner. The lower graph displays results along the long wall. The long wall includes two overhead garage doors, separated by a personnel door, located within a re-entrant corner (Figure 15). With these larger openings in the thermal envelope, the frost depth penetrates even deeper than at the building corner. I consider this deeper frost penetration an important insight for FPSF system design. Consider treating openings in the thermal envelope near overhead-door-sized openings in the same manner as for corner zones.

The reported insulation system included (A) two-inch XPS floor insulation below the floor, (B) vertical insulation from insulated concrete forms with two-inch insulation inside and out, and with (C) two inch horizontal wing insulation extending out a distance of two feet.

Compare and contrast the corner freezing isotherm locations between Figure 18 and Figure 19. Note the Merlin drill location shown in Figure 15. Merlin results revealed several interesting aspects related to the deeper and overlapping freezing isotherm locations. I found no readily evident distress at the Merlin site. Based upon the absence of readily evident visible distress, the insulation system installed here appeared to be functioning satisfactorily from the time of building construction until now. In my opinion, this system satisfactorily passed the test of time as of my last observations. Thermal results have the following illustrative points.

Thermal results from the Merlin site showed the effects of using wall insulation thermal values (Dhw) at corners (without providing the corner increases suggested by this research). The resulting depth of the freezing isotherms indicated that freezing below the footings probably occurs at the Merlin site. The absence of readily evident frost damage, combined with the surface topography observed, indicated to me that the Merlin site would not likely have frost heave damage even with this lower amount of perimeter insulation. Thermally, the insulation helps provide heat containment as part of a thermal envelope system. In my opinion, this lesser amount of insulation does not completely function to preclude the freezing isotherm from extending into the footing zone below the foundation. These deeper frost-depths showed what I interpret as the effects (A) from not using increased thermal values and extents for corner zone insulation, and (B) from the effects of colder garages with larger overhead door openings. If the soils below were highly frost susceptible, then I would expect higher risks of frost heaving distress.

Merlin results showed increased frost depth close to overhead garage-doors, shown in Figure 15. Initially this result surprised me. After data review and reflection, I believe the freezing isotherm location is sufficiently accurate to convey a new point of information. Namely, for our colder regions in Interior Alaska, larger breaks in the thermal envelope (like overhead garage door locations), warrant special consideration as colder zones within the building thermal envelope. I return to this point in the Goshawk discussion.

3.2.4.3 Goshawk results and discussion.

The Goshawk site, also in the Fairbanks Alaska hills is founded upon a silty sand location. Figure 20 shows the deeper frost penetration near corners, relative to along a long wall. At the Goshawk site, the colder corner was adjacent to a garage entrance. The long wall measurement was adjacent to a heated room. Due to building roof overhangs and clearing, the thermistor locations near the home had little or no snow cover. The remote baseline thermistor string had snow covered ground above (Figure 13). The reported insulation system was similar to the Merlin site.

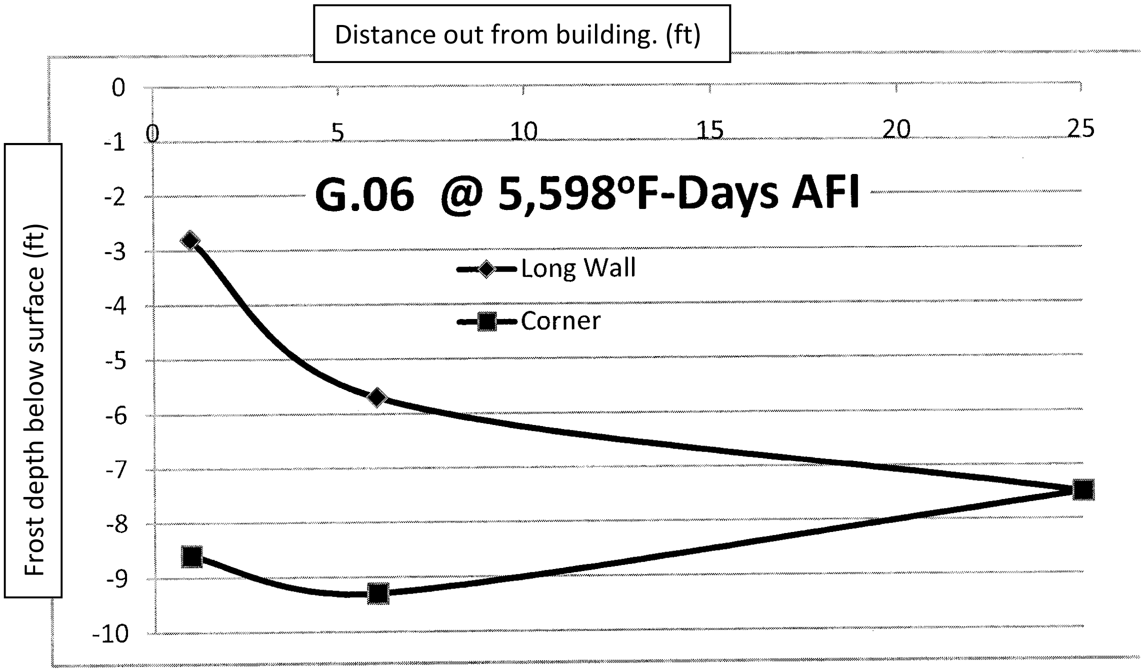

Figure 20. Goshawk site: Freezing occurs deeper at the corner than along the wall..
The plot shows distance out from the building along the top axis and depth on the side axis.
One plot shows long wall results; the other shows corner zone results.
The building (as shown in Figure 13) is to the left of location zero.
These plotted lines show the depth to the frost line, as follows:
close to the building, farther out, and at the distant baseline.

Goshawk results (Figure 20) provide further insights into thermal difference between building corners and long walls. For Goshawk site, the along-the-wall insulation amount remained constant in the corner zone. I expected to find the resulting deeper freezing isotherm in the corner zone. The long wall insulation amount appeared adequate to protect the footing zone there. Results were similar to the Timberland site (Figure 18). However, the Goshawk results also showed the increased cooling effects in corner zones when the corner-zone insulation remains the same as along the long wall. Like Merlin site, Goshawk site also showed no readily evident visual indicators of frost heave distress.

In both the Merlin and Goshawk sites, the overhead garage doors represent a discontinuity in the thermal envelope. Footings by the garage doors were colder in both locations. Localized heaving risk is typically greater at these wall penetration discontinuities, and no such heaving distress was readily evident at either the Merlin or Goshawk locations.

The results from both the Merlin and Goshawk sites combined to provide a salient thermal design input. For thermal soils protection, wall penetrations like overhead doors warrant the extra thermal R-value provided for corners. Without the extra thermal R-value, expect localized soils freezing action at the overhead doors. Consider the structural implications of frost heaving forces at these overhead door thermal penetrations. With seasonally freezing soils, other design factors become more salient. For example, designers may choose to provide NFS soils to depths below the maximum frost depth.

I caution designers to take special vigilance at thermal envelope penetrations such as garage openings. Consider treating these penetrations as corner zones. Provide the extra thermal insulation resistivity values and provide the wider horizontal projection extents. Consider especial vigilance with the subgrade soil preparation. In addition to providing the corner-zone increased insulation amounts and increased width, also provide a minimum of 0.5 m (18 in) of non-frost susceptible soils below the footings at these larger overhead door penetration.

For the colder climate zones considered here, this research shows that FPSF systems do function satisfactorily to keep the soils thawed below the footings of heated buildings. Expect unheated buildings to have frozen soils below their footings during winter. Therefore, unheated buildings with soils susceptible to frost heave (e.g., silts with a moisture source from below or above) are at more risk to frost heaving, even with the perimeter insulation amounts provided in this research.

Some designers want to use less perimeter insulation than prescribed as results from this research. One common local practice observed was using 50 mm (2 in) of insulation vertically around the perimeter; then, 50 mm (2 in) insulation horizontal wing, extending 0.61 m (2 ft) out from the foundation – all around, without any increase at corners. Locally called a “2x2x2” system, this approximates the 2006 IRC requirement for a residence long wall with an AFI of 2 500 °C·d (4 500 ^{o}F·d). Results showed that designers should expect the freezing isotherm to penetrate below the foundation footings. When subjected to frost-heaving conditions, this means a higher risk of foundation seasonal frost heave exists, especially with the presence of frost susceptible soils. Based upon this research and my experiences in the Fairbanks area, the 2x2x2 approach to perimeter insulation does not meet the intents of frost-protected shallow foundations. The 2x2x2 approach does not provide sufficient assurance that the freezing isotherm will remain out from below the footings. In fact, expect the freezing isotherm to fall well inside the footing zone when using the 2x2x2 approach.

That lesser amount of insulation, for warmer climates, may satisfy the local prescriptive thermal envelope amount. For example, the City of Fairbanks has a standard requirement for R-10 perimeter foundation insulation. Formerly, some authorities having jurisdiction considered this R-10 requirement satisfied by 50 mm (2 in) of EPS. Compliance with the newer standards includes using long term effective R-Values, requiring thicker insulation. This means, the 50 mm (2 in) horizontal insulation, extending just 0.6 m (2 ft) out from the building may serve as thermal insulation only. However, a foundation with this reduced amount of insulation (though consistent with current design guide limits) is not likely to provide frost protection for 3 600 °C·d to 4 055 °C·d (6 500 ^{o}F·d to 7 300 ^{o}F·d) winter climate for Interior Alaska.

3.2.4.4 Violin results and discussion.

Violin was the only site with five thermistor strings arranged in one line, extending out from the building garage. The thermistor string location extended out from the south facing wall, with a highly reflective bright surface. The measurements within the heated space, at floor line, were above 5.6 °C (42^{o}F), and showed that the freezing isotherm remained outside of the minimally heated space of the garage. The perimeter insulation provided met current standards (ASCE, 2001), and was not increased for Fairbanks colder design temperatures.

The Violin site had no snow cover for the first 1.5 m (5 ft) adjacent to the building. Then the snow cover increased to about 0.9 m (3ft) at the most-distant thermistor string. The ground surface also sloped upward, away from the dwelling. I installed the top thermistors almost level. The ground sloped upward away from the building. The most distant thermistor string had about 1 m (3 ft) additional soil cover above the top thermistor. Figure 14 shows the drilling equipment on the hill slope while drilling this most-distant thermistor location.

Violin results showed that the freezing isotherm intersected below the footings, not out from the footings within the exterior wing insulation. This freezing isotherm then penetrated steeply (almost

80° from horizontal) to 1.7 m (5 ft) deep at a distance of 0.7 m (2 ft) out from the wall line. From that location, the frost penetration remained about a constant 1.7 m (5 ft) deep for the full 7.6 m (25 ft) distance to the most-distant thermistor string. This steeply descending freezing isotherm, immediately adjacent to the building, brought to mind the potential for basal frost heaving stresses, discussed above.

I interpret that this steeply descending freezing isotherm resulted from (A) the cleared snow immediately adjacent to the building, combined with (B) having snow cover about 2 m (6 ft) away from the building, plus (C) minimal indoor heat within the garage. In addition, I interpret that the shallower frost penetration depth [1.7 m (5 ft) at Violin; contrasted with 2.7 m to 3.7 m (9 ft to 12 ft) at Goshawk and Merlin] possibly resulted from the higher albedo (solar reflection) of the bright white building surface.

3.2.4.5 Bonita results and discussion.

The Bonita site had no evident perimeter insulation. I did not install any insulation as part of this research, and I found no readily evident visible distress in the building. The building had evidently not heaved due to seasonal frost action. These observations, over several years, informed me that not all buildings must have heat containment to preclude seasonal frost heaving. Rather, buildings like Bonita (A) with soils conditions such that moisture wicking did not apparently occur, and (B) with surface moisture directed away from the building may not need insulation protection to preclude seasonal frost heaving. Even though the seasonal freezing isotherm may have penetrated well below the footings, the building had no readily evident visible distress discovered.

The Bonita experience helps to understand why building foundations with minimal or no insulation may still perform satisfactorily in seasonal frost zones. I have observed many other non-insulated or under-insulated foundation-systems in the seasonal frost zone not specifically discussed here. These foundations have, as one common element, non-frost susceptible soils to depths below seasonal frost action. Therefore, based on the Bonita experience, this investigator would expect under insulated (by the FPSF system recommendations included here) and unheated buildings on similar deep non-frost susceptible soils to perform satisfactorily.

3.2.4.6 Army results and discussion.

The Army site had readily evident wet surface silts. Drilling revealed permafrost at about 15 m (49 ft) deep. The thaw depth was less than the width of the building, which indicated that further permafrost thawing might occur over time (McFadden, 2001). I observed the thawed soils brought to the surface via the solid stem auger. Doré and Zubeck (2009) summarized boring methods. While being lower cost, one additional feature from drilling with solid stem augers includes poor ice recovery. The drilling operation disturbs the recovered soil. This meant that the soil cuttings I assessed at the surface as super saturated silts could have included visible ice no longer apparent due the boring method chosen. The soils cuttings, brought to the surface, had about a 5° to 10° angle-of-repose from horizontal. Restated, the wet soil cuttings flowed out over the ground like a chocolate milk shake. Water and ice particles were readily visible. While not specifically tested for moisture content, I suspected, by visual assessment, super-saturated highly-frost-susceptible silts.

For the Army site, I considered changing the foundation system from its current non-insulated heated crawl space either to (A) a heated FPSF insulated perimeter system, or to (B) an open ventilated cold crawl space. I had hoped to improve the current state of seasonal building distress by stabilizing the soils temperatures. Choosing an FPSF system could keep the subsurface soils warm. Choosing an open crawl space foundation system could keep the soils frozen.

From the deep permafrost found below this building, as well as from the permafrost reportedly found below neighboring buildings with visible distress, I concluded that keeping a warm crawl space is not optimal for this site. The depth of the permafrost found seemed consistent with the approximate age of the building (about 25 years) and with the heated crawl space serving to protect the domestic water pipes from freezing. The thermal monitoring results were not typical for an FPSF system. The winter freezing isotherm penetrated below the building, well inside of the building perimeter.

I do not recommend using an FPSF system for the Army site. I expect further heat confinement from an FPSF system to increase (not help) the rate of permafrost degradation at depth. While good for the plumbing lines routed in the crawl space, the crawl space heat is not optimal for the permafrost thermal condition at depth.

In addition, I do not recommend changing this building to an open-vented, cold-crawl-space foundation system without first providing a more in depth analysis. I would be vigilant about soils expansion from refreezing the wet silts observed. Based upon my visual observations of wet soils, I would expect considerable additional frost heaving should these soils refreeze.

The selection-set for improving the foundation conditions at the Army site now excludes additional foundation soils warming as would be provided with an FPSF system. The selection set also excludes opening the crawl space to become vented and cold. One remaining stabilizing technique improves soils stability via surface drainage to dry the soils (UFC, 2004b). For the Army site, I recommend meticulous attention to providing and maintaining surface water drainage away from all portions of this building for a distance of at least 15 m (50 ft). Pay particular attention to the north end of the building. The natural terrain slopes toward (not away from) the building. Slope the ground downward, away from the building, a minimum of 5% slope. Provide roof drainage to points away from the building. Allow no water to accumulate or to flow against or below the building. The intent is to permit the in situ thermal regime of soils to remain as it is now – reducing the likely rate of further permafrost degradation. The intent includes keeping the soils dry to reduce the amount of seasonal frost heaving that currently occurs.

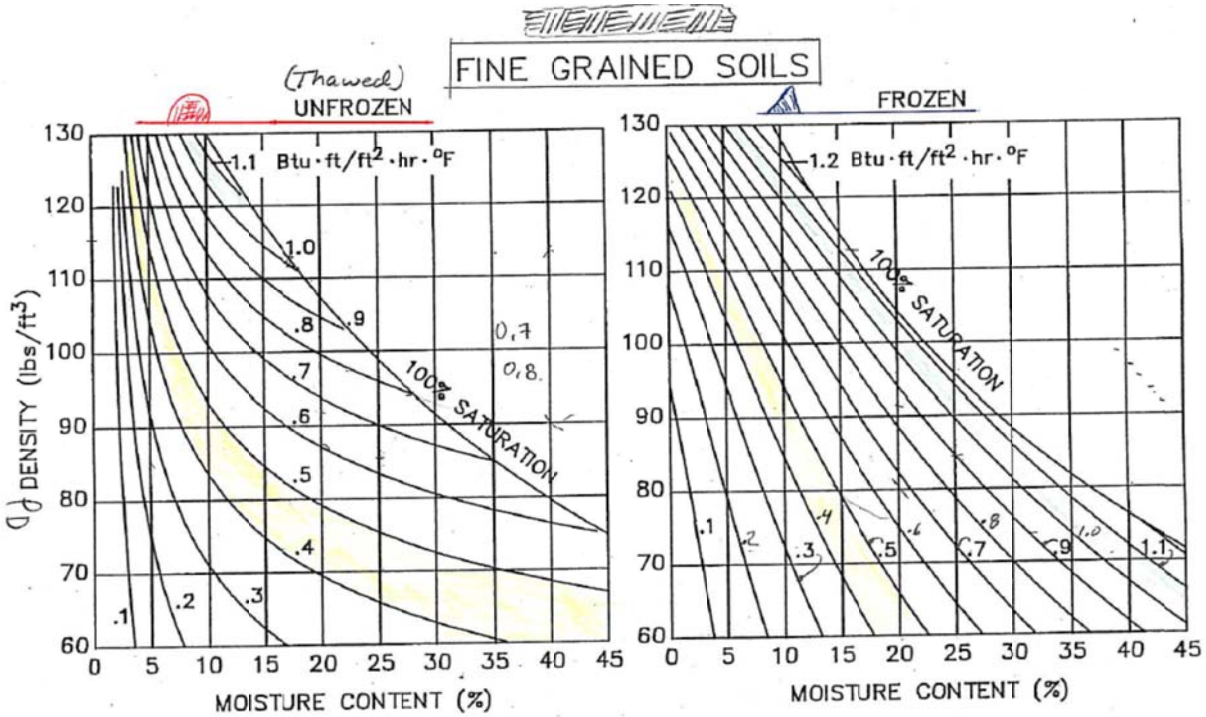

Figure 21. Kersten (1949): Thermal conductivities for fine-grained soil.

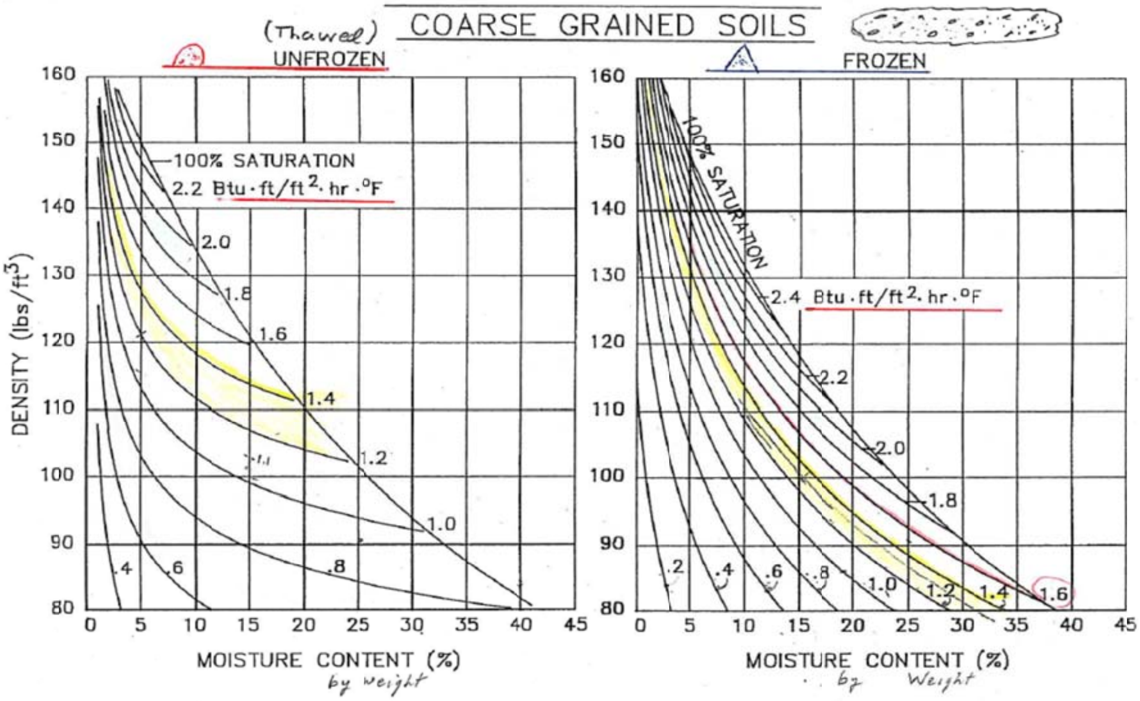

Figure 22. Kersten (1949): Thermal conductivities for coarse-grained soil.

3.3 Conformal Mapping Analysis, Results and Discussion

Conformal mapping (Lunardini, 1981) represents a mathematical tool for transforming two-dimensional curvilinear heat flow paths into a mathematically equivalent one-dimensional conductive heat flow analysis. Conformal mapping resolves a second-order partial differential equation using isothermal lines approximated by the flow tubes. The concept from physics treats the freezing isotherm as a control surface. Heat flow from the “warm inside” of-the-building to the control surface (i.e., the freezing front) equals the heat flow from the control surface out to the “cold outside.” Figure 23 demonstrates the flow tube concept. Assuming a constant heat flow through a particular heat flow "tube," the shorter tubes, with less soil, have a lower total soil R-value. Therefore, the shorter tubes (closer to the foundation) lose heat more quickly, which permits the freezing isotherm to penetrate further below the footing. Conversely, the deeper tubes, with longer distances and higher R-values, lose heat more slowly.

Dr. Yuri Shur (personal communication) developed the flow-tube analysis for soil freezing and applied it to the problem of moving freezing isotherm locations in a quasi-steady-state heat conduction analysis. Dr. Shur’s method accounts for the several analysis parameters. Parameters include (A) thawed soil conductivity (i.e., on the warm side of the freezing front), (B) the frozen soil conductivity (i.e., on the cold side of the freezing front), (C) the latent heat from the moisture content, (D) the temperature differences between inside and outside, and (E) the length of time the system is exposed to the temperature conditions. The method treats the temperature differences as constants over the period of investigation, rather than as a climatic variable with changing temperatures over the winter. I used frozen or unfrozen soils thermal conductivities, both for fine-grained soils (silts) and for coarse-grained soils (gravels) from Kersten (1949), as represented in other sources (Farouki, 1981; UFC 2004c). Figure 21 and Figure 22 show the thermal conductivities of soils with varying parameters. Figure 23 shows the flow tube concept.

The following provides a brief summary, not a complete description, of the flow tube method. Orthogonal lines remain orthogonal (i.e., perpendicular to each other). Isothermal lines remain isothermal. The initial inside and outside boundary conditions remain unchanged over the duration of the analysis.

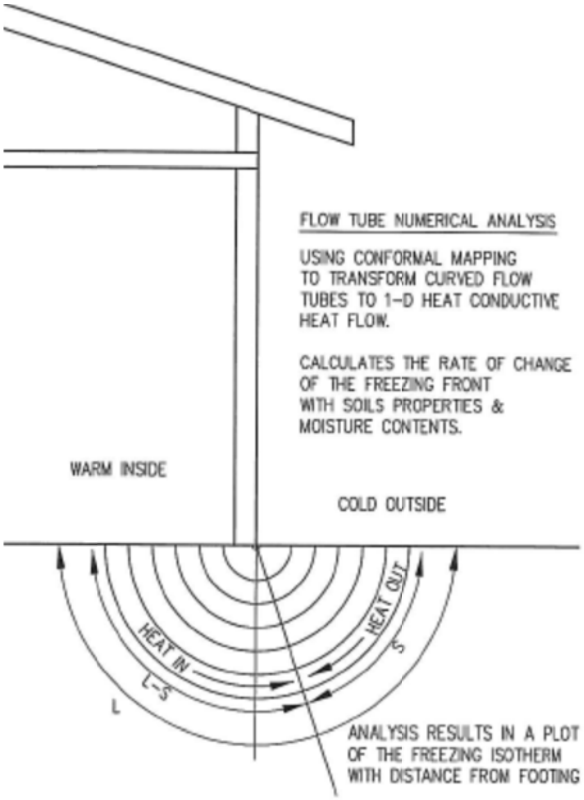

Figure 23. Conformal mapping sketch showing the flow tube analogy.
A conformal mapping mathematical analysis simulates a Laplace transform method
to solve the thermal differential equation by geometrically changing the space
from a curvilinear (semicircular) shape to straight line.

The principle of physics uses conservation of heat flux through a control volume (e.g., one heat flow tube). The energy changes involved along one heat flow tube represent changes in both sensible heat and latent heat. Between sensible heat and latent heat, latent heat dominates the heat equation. Therefore, a simplifying assumption for this analysis includes neglecting the sensible heat effects, focusing on the latent heat changes and on the changes in soils thermal conductivities between frozen and unfrozen sates.

Step 1. Determine a temperature factor, called Beta (β), using the thermodynamics principle that (A) the heat flow from the warm building to the freezing isotherm is (B) equivalent to the heat flow from the freezing isotherm to the cold outside soils surface.

$$\text{Beta} = (K_{\text{unfrozen}} / K_{\text{frozen}}) * [\,(T_{\text{inside}} - T_{\text{freezing}}) / (T_{\text{freezing}} - T_{\text{MAST}})\,]$$

where:

K unfrozen = unfrozen soils conductivity (Btu / [hr · ft · °F])

K frozen =	frozen soils conductivity	(Btu / [hr · ft · °F])
T inside=	inside building temperature	(°F)
T freezing =	0 °C (32 °F)	
T MAST =	Mean annual soils temperature	(°F)

Step 2. Determine a dimensionless time factor, called "J," the first of two different methods, which is from the freezing front.

$$J = (K_{frozen} \cdot I_{frz}) \;/\; (l^2 \cdot \rho_{dry} \cdot w \cdot L')$$

where:

I frz =	Freezing index	(°F · days)
$l^2 = (\pi\ r)^2$	Flow tube length, squared	(ft^2)
ρ_{dry} =	Dry unit weight of soil	(lb / ft^3)
w =	Water content, by weight	(%)
L' =	Water latent heat	144 (Btu/lb)

Step 3. Calculate the dimensionless time factor, "J" via the second method, which is from the warm front. The calculated freezing time from the cold outside surface (in step 2) balances the calculated thawing time from the warm interior surface (this step).

The dimensionless thaw factor, called, called Xi (ξ), varies from zero to a maximum with increasing time. The governing equation is as follows:

$$J_{\beta,\xi} = -\xi/(1+\beta) + [1/(1+\beta)^3] \cdot [\ \{1.5 + 0.5 \cdot (1-(1+\beta)\xi)^2\ \} - \{2 \cdot (1-(1+\beta)\xi)\} + \{(1-(1+\beta)) \cdot \ln(1-(1+\beta)\cdot\xi)\ \}]$$

Xi (ξ) reaches a maximum value controlled by the argument of the natural logarithm. Namely $(1-(1+\beta)\cdot\xi)$ must be > 1. Calculate β from Step 1, above. Next, calculate $\xi_{maximum.}$ Then, for a given flow tube radius, iterate on ξ until the J from Step 3 matches the J from Step 2.

Figure 24 and Figure 25, show results for silt with 20% and 30% moisture contents. Note that the wetter the soil the more the freezing isotherm projects below the footing. In addition, note the steep, almost vertical orientation of the freezing isotherm near the footing. These calculation results indicated that deep frost penetration might occur quite close to the footing, while soils below the footings remained thawed.

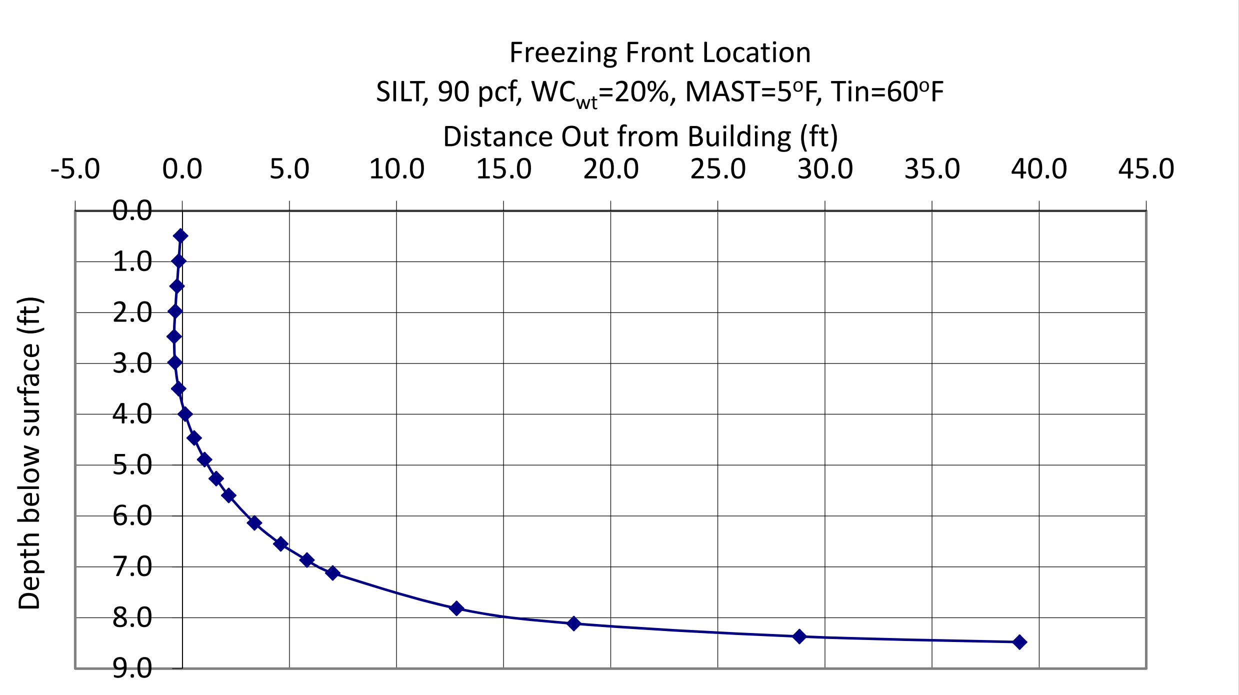

Figure 24. Results: Conformal mapping analysis for damp silt, 20% moisture content.
The distance out from the building is along the top axis. The building (not shown) is left of location zero.
This plotted line displays the calculated freezing isotherm depth.
Observe the almost-vertical orientation at the edge of the building.

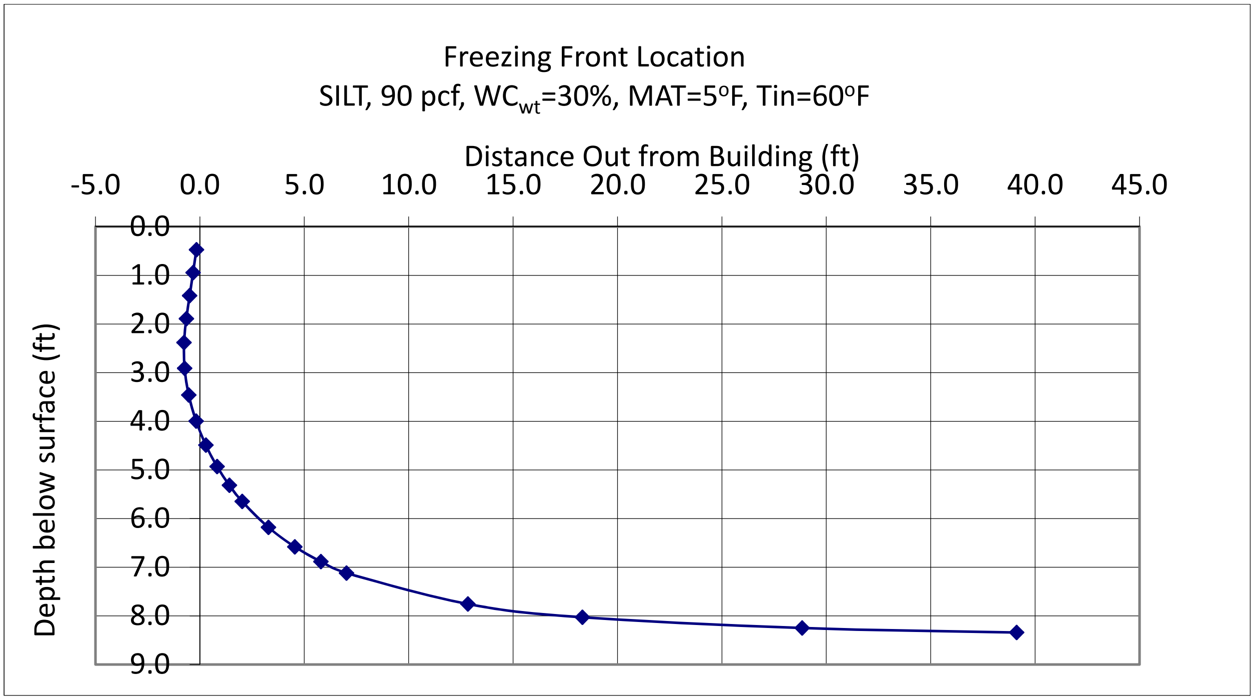

Figure 25. Results: Conformal mapping analysis for wet silt, 30 % moisture content.

3.4 Finite Element Modeling

3.4.1 Software program.

I used the TEMP/W segment within the GeoStudio 2003, Version 5.17. Build 4606, suite of programs for the frost-protected shallow foundation analyses. TEMP/W is produced by

GEO-SLOPE international, Ltd.
1400,633 – 6th Ave. SW
Calgary, Alberta, Canada T2P 2Y5.
Email, info@geo-slope.com;
Web, http://www.geo-slope.com

Developed by Geo-Slope in Calgary, Alberta, TEMP/W allows two-dimensional analyses of various configurations of buildings, soils, moisture contents, insulation parameters, boundary constraints, and climate temperature inputs. Most of the research effort is in the finite element modeling. I used site measurements and numerical methods to calibrate and validate the model. Calibration means checking to see that the model yields comparable results to a numerical analysis and to site measurements from one site. Validation means checking that the model yields comparable results to site measurements from sites with differing conditions.

I chose the TEMP/W program for several reasons. First, I had a mentor to lead the way. Dr. Goering introduced the program in his heat and mass transfer course. In addition, TEMP/W is a finite element software program for use specifically in modeling thermal changes in the ground due to environmental changes, or facilities construction such as buildings. I could use TEMP/W for moisture phase-change considerations in frozen soil. One basic assumption within the program includes having constant moisture content by volume. Moisture is neither entering nor leaving the analysis region. That means the summation of ice and water content remains constant. The program's primary focus is heat transfer through porous media including soil, water, ice, and air at the same time (Geo-Slope, 2008). In addition, the program remained available from the University for student-use during the extended time-period for this research.

3.4.2 Boundary conditions.

I modeled a winter season's cold for an average winter of 2 800 °C·d (5 000 °F·d). I increased the amount of cold, incrementally, to a total of 4 200 °C·d (7,500 °F·d), which was 1.5 times colder than average. Based on site conditions observed, the model used air temperature, without considering snow cover presence. I did not find snow-cover close to any of the buildings. However, snow did cover the remote thermistor string (at 7.6 m, 25 ft) at all six sites.

3.4.3 Material properties.

I investigated two soils types: sandy gravel and silt. I used dry condition and an approximately saturated condition. I took frozen and unfrozen thermal conductivity values for course-grained and fine-grained soils from Kersten's "Laboratory Research for the Determination of the Thermal Properties of Soils" as referenced by the Department of the Army and Air Force (1988), and by Farouki (1981). I used long-term insulation thermal resistance values (R-values) from manufacturer's literature (Table 4).

The units for heat conductance include heat flow through a unit area, along a unit distance, and for a unit of time duration. Thermal resistances, in SI units (m^2 °C/W) include the time-factor in Watts. Thermal resistances, in US customary units (ft^2 ·hr ·°F/Btu) show the time factor separately. With thermal insulation present, heat flow continues, just at an altered (i.e., slower) rate.

Several alternative insulating methods may provide the same insulation values. I chose rigid, closed cell, extruded polystyrene insulation. The modeling also used specific insulation values. Conceptually, this insulation-amount represents commonly available rigid polystyrene foam, suitable for direct-ground-contact. The thermal-resistance values modeled varied from 1.76 m^2 °C/W at 50 mm thickness to 7.0 m^2·°C/W at 200 mm thickness (10 ft^2 ·hr ·°F/Btu at 2-in thick to 40 ft^2· hr · °F/Btu at 8-in thick).

Varying insulation-values are applied directly onto surfaces of differing soils types, with differing moisture contents, with differing current outside air temperature profiles, and with climate warming profiles totaling 2.2 °C (4 °F) warmer mean annual air temperatures. For the matrix of differing conditions, I analyzed the resulting ground temperature profiles and noted the changes.

Soil thermal conductivity values came from Figure 21 and Figure 22, from class notes (Y. Shur, CE 681 Frozen Ground Engineering, taught fall 2003). These notes followed from Farouki (1981) Figures 146 through 153, which referenced Kersten (1949). I applied these charts to four cases, to dry and saturated gravel 1 922 kg/m^3 (120 lb/ft^3) and to dry and saturated silt 1 762 kg/m^3 (110 lb/ft^3).

Civil engineering soils work commonly uses water content by mass. Its units are mass of water per mass of solids (kg_water/ kg_soils solids, lb_water/lb_soils solids) expressed as a percentage by weight (Table 4). For modeling with consistent units, the Temp/W program required using thermal parameters like volumetric heat capacity with volumetric water content values (not gravimetric values). Sample calculations follow.

(A) Sample calculation for saturated silt:

1 762 kg/m^3 (110 lb/ ft^3) and 18% gravimetric moisture content.

Equation: = (w_grav) x (ϒ_soil / ϒ_water) = (w_vol), where:

w_grav = gravimetric water content

ϒ_soil = soil bulk unit weight

ϒ_water = unit weight of water 1 000 kg/m^3 (62.4 lb/ft^3)

w_vol = volumetric water content.

Calculation in SI units: 0.18 x (1 7 62 / 1 000) = 0.317 = 31.7 % volumetric water content.

Calculation in US units: 0.18 x (110 / 62.4) = 0.317 = 31.7 % volumetric water content.

(B) Sample calculation for dry gravel:

Dry gravel at 1 922 kg/m^3 (120 lb/ft^3) and 5% gravimetric water content.

Calculation in SI units: 0.05 x (1 922 / 1 000) = 0.096 = 9.6 % volumetric water content.

Calculation in US units: 0.05 x (120 / 62.4) = 0.962 = 9.6 % volumetric water content.

Table 4.
Material Properties

Material	Moisture Condition	Unit Weight	Water Content by Mass	Water Content by Volume	Thermal Conductivity (K)		Volumetric Heat Capacity (Cv)	
					Frozen	Unfrozen	Frozen	Unfrozen
		kg/m^3 (lb/ft^3)	%	%	W/m °C (Btu ft/(ft^2 °F hr)		kJ/m^3 °C (Btu/ft^3 °F)	
Gravel	Dry	1 922 (120)	5	9.6	1.64 (0.95)	2.04 (1.18)	1 932 (28.8)	1 650 (24.6)
	Saturated	1 922 (120)	15	29	4.05 (2.34)	2.80 (1.62)	1 972 (29.4)	2 575 (38.4)
Silt	Dry	1762 (110)	5	8.8	0.85 (0.49)	0.78 (0.45)	1 439 (21.45)	1 623 (24.2)
	Saturated	1 762 (110)	18	32	1.99 (1.15)	1.70 (0.98)	1 918 (28.6)	2 582 (38.5)
* Foam Insulation	Dry	28.8 (1.8)	zero	zero	0.029 (0.017)	0.029 (0.017)	37.5 (0.56)	37.5 (0.56)

*ASCE 32-01 Appendix A. EPS Type IX EPS (1.8 pcf) and XPS Type VI (1.8 pcf)

The Temp/W model represents latent heat of fusion as an apparent sensible heat. This apparent sensible heat distributes within the freezing zone as the unfrozen water content changes phase to frozen ice. For Fairbanks silt, following the work of Vyalov, Fotiev, Gerasimov, and Zolotar (1993a), I modeled unfrozen water content with a tight thermal gradient. At -3.3 °C (26 °F), I modeled all the water as frozen (0 % unfrozen). At 0 °C (32 °F), I modeled all the water as thawed (100 % unfrozen). For Fairbanks silt, Anderson and Morgenstern's (1973) work confirmed this choice. For this preliminary work, I did not include the effects of solutes on freezing point depression. In addition, I have experienced roofing foam insulation that has accumulated water content over time. However, I excluded considering water uptake into the foam insulation. I modeled the insulation water content as zero. Table 4 summarizes the soils properties input into the models.

3.4.4 Modeling results and discussion.

Sample finite element results are shown in Figure 26, below. The left side shows one example model with concrete floor, uniform soils below, and with both perimeter vertical insulation and horizontal wing insulation. In this model, the horizontal wing insulation extends two feet out from the edge of the building, just as in two of the test sites evaluated. The right side shows the freezing isotherm location after running the computer analysis. The vertical isotherm orientation is evident, as is the deflection outward from the footings, due to the horizontal wing insulation. Also evident, is the tendency for the freezing isotherm to intrude below the foundation zone at depth.

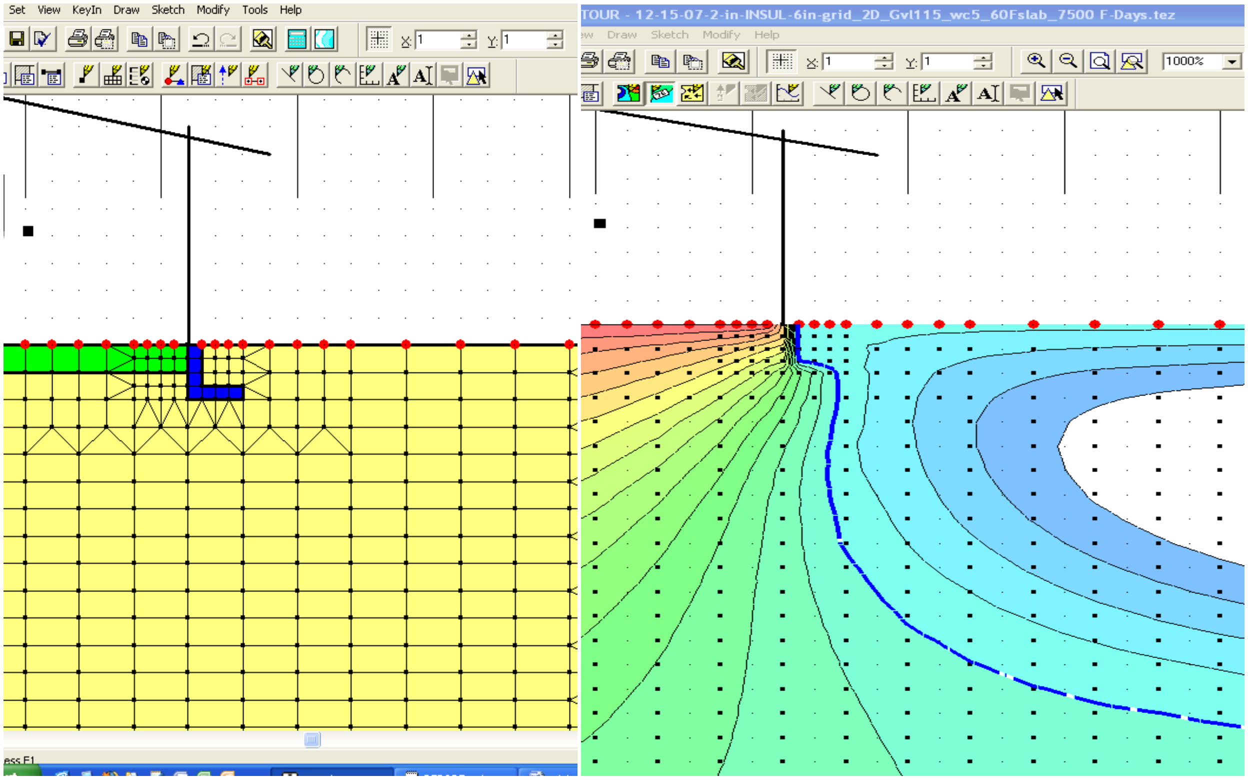

Figure 26. Temp/W print-screens: Thermal insulation changes the freezing isotherm location. Sufficient thermal insulation kept the freezing isotherm location out from below the footings. The resultant freezing isotherm shape and orientation closely approximated both the calculated results and the in situ site-measured results.

3.5 General Discussion for Frost-Protected Shallow Foundations in Interior Alaska

I presented results for this colder frost-protected shallow foundation material at the Ninth International Conference on Permafrost in June of 2008. One attendee commented that, at this colder freezing index, the ground would be continuous permafrost, not thawed sections of the discontinuous permafrost zone. However, the reported 100-year return-period freezing indices (Table 2) supported extending the frost-protected shallow foundation design method to this colder freezing-index.

This work is important because installers in Interior Alaska provide systems called frost-protected shallow foundations based upon design guides intended for warmer climates. The basis for design stops short of the amount of cold experienced in Interior Alaska. Yet, many of these installations work satisfactorily. This research serves to investigate and distinguish a depth of understanding for these differences.

3.5.1 Freezing isotherm shape is vertical and deep.

At these colder Interior Alaska AFIs, results for each site investigated show a nearly vertical freezing isotherm next to the foundation. Compare Figure 4 (NAHB, 1994) with

(A) the site output results, above (Figure 18, Figure 19, & Figure 20); and with

(B) the conformal mapping analysis results, (Figure 24 & Figure 25), as well as with

(C) the finite element modeling results, (Figure 26).

Pay attention to the rotated freezing isotherm. This nearly vertical freezing isotherm is different for our colder interior applications than in warmer climates currently covered in ASCE 32-01. From the results of my investigations, I expect the basal force horizontal-components to have additional structural implications for our colder Interior Alaska climate. I suggest the reader anticipate evaluating and providing horizontal structural restraint systems for these rotated basal forces. For my investigations, that restraint comes from the integral footing-and-floor system. However, without such a horizontal restraint system (say, for example, a gravel interior floor), I anticipate that the footings or foundation walls may move laterally inward, due to the horizontal frost heaving forces. As already reported, these frost heaving forces may achieve a magnitude as high as 132 000 kPa (19 000 lb/in^2) (Taber, 1930).

Alternatively, if the walls have sufficient horizontal restraint, then I might also expect greater risk of soils failures immediately outside of the heat-bulb influence area from the warm building. An FPSF system thermal design protects the building footing zones from freezing. I would anticipate the soils moving laterally and upward away from the building toward areas of least resistance (i.e., spalling outward toward the open air). The exterior site developments, outside of the building's confined thermal heat envelope, remain unprotected from freezing soils conditions.

Depending upon specific soil parameters, the Interior Alaska freezing isotherm may penetrate deeper into the subgrade. Temperature readouts showed 7.6 m (12 ft) at the Merlin site (Figure 19). Existing FPSF design methods for warmer climates typically specify a 30 cm to 45 cm (12 in to 16 in) non-frost susceptible (NFS) drainage layer between the in-situ soils and the FPSF footings. This deeper frost penetration, possible in colder Interior Alaska regions, may also mean that soils-at-depth become a point for further evaluation. It may not be enough to have the freezing isotherm just at the outside corner of the footing zone to reduce frost damage risk. Lateral freezing forces from deeper soils below the foundation zone may also initiate failure of the soils below the surrounding site developments.

Based upon the discovered depth of this nearly vertical freezing isotherm and upon the close proximity to the foundation, I recommend further investigations regarding the influences from soils at greater depths than previously considered.

3.5.3 Insulation discussion.

My specific investigations included (A) increased corner zone frost depth, (B) increased frost depth near building thermal-envelope penetrations, (C) vertical freezing isotherm shape, and (D) possible reverse curvature isotherm shapes that may represent increased frost heaving forces from soils at depth. My investigations excluded the type of insulation used, XPS or EPS. Recent documents have shown different requirements regarding insulation-types and installation orientation.

I have personally handled XPS insulation removed from inverted roof membrane assembly (IRMA) roofs, not foundations. Under some conditions, the rigid polystyrene used in roofs may accumulate considerable moisture. For example, I have handled XPS insulation approximating 960 kg/m^3 (60 lb/ft^3). I leave it to others to investigate how and if the rigid insulation in FPSF soil installations accumulates similar moisture amounts. My modeling, here, did not include variable moisture content for the foam insulation. I must leave future research for others to respond to questions about what specific long-term thermal resistance (R-factor) should apply in the colder regions being investigated in this work.

At the field site for seasonal thermal insulation, pieces of the rigid foam insulation broke, unpredictably, while being placed or removed from the uneven ground. We fitted the pieces together with reasonable care. Still, air gaps remained at the joints. The impacts from broken insulation and from gaps at the joints may well be reflected in the data received. For future operations, I recommend providing a leveling course of sand or gravelly sand to provide a smoother base for the insulation.

Alternatively, I recommend using flexible insulation mats similar to concrete curing blankets commonly used by contractors for cold weather concrete curing.

3.5.4 Thermistor and temperature readout discussion.

I initially chose less-expensive Alpha thermistor for measuring soil temperature. I used the datalogger temperature readouts for the first year or two. The data older than two years was no longer internally consistent. Conversations with the Alpha thermistor vendor indicated that thermistor-output-variability (wandering) had been a reported issue. I switched to the more expensive YSI thermistors, which proved more reliable. Working in the cold weather also proved to be problematic for the laptop computer equipment (Figure 17). The screen display on the laptop computer used outdoors soon became intermittent and then failed. I suspected, but did not prove, broken wires occurred between the keyboard base and the display screen, due to repeated cold weather use down to -29 °C (-20 °F). The laptop was not economically repairable. I found the easiest way to download the thermistor data was to avoid using the Campbell-Scientific dataloggers and multiplexors. I observed Soils Alaska (a local Fairbanks soils investigation firm) downloading thermistor resistance readings directly via a digital multi-meter, without using dataloggers. Because I needed the end of the season coldest-time-of-year data (not hourly or daily data), because of the multiplexor battery-life realities in cold weather, and because of the laptop lack-of-reliability realities, I decided to download the thermistor raw-resistance data directly via ohmmeter. I changed from Campbell Scientific multiplexor readouts to using a Fluke 87E industrial multimeter. The engineering manual for the Fluke 87E lists the Ohm resistance accuracy to within 0.0125 %. I measured the raw resistance data, applied the resistance-to-temperature characteristic curve for the specific thermistor, and manually calculated the temperatures.

3.5.5 Field monitoring considerations.

I include this section as a courtesy to other researchers. I hope to help others avoid some of the same field-measurement-realities I encountered. Frankly, I consider this among the most important sections in this report.

Try to keep water out of the monitoring tubes. Cap the thermistor tube-ends watertight. Attempt to keep water out of the tube. The monitoring tubes at the first two sites had open-ended tubes. In shallow water-table areas, with rising water levels, the thermistor strings would likely be continuously wet. Even though well sealed before installation, I wonder if the early thermistor failure I experienced resulted from water presence in the tubes.

Avoid convective air loops within the monitoring tubes. I apply the basic thermal premise that conductive heat transfer controls, not convection or radiation. With open monitoring tubes, convective air currents may develop and influence the temperature recordings. I recommend filling the annular space between the thermistor string and the inside wall of the tube with an inert environmentally satisfactory material. I used ordinary traction sand, which was available locally. For me, one drawback of using even minimally damp sand in well-sealed monitoring tubes was that the thermistor strings became frozen in the monitoring tubes. That meant that, after installation, I could not rely upon withdrawing the thermistor string to maintain or replace individual thermistors.

Consider damage by snow removal equipment or by contractor operations. At one site, snow removal equipment tore out the wire leads between the thermistor strings and the data logging equipment. At a second site, paving contractor equipment removed the upper 15 cm (6 in) of soils in preparation for paving. At both sites, non-readily repairable damage occurred to the wire leads between the thermistor strings and the logging equipment. Measurement recordings stopped. I recommend burying the thermistor leads between the thermistor strings and the datalogger location to a depth of at least 45 cm (18 in).

Consider using the maximum time span of the particular datalogger equipment chosen. I needed ground temperature measurements near the end of winter, at the time of maximum AFI accumulation, to measure maximum frost line penetration into the soils. I did not need by-minute readouts or even hourly readouts. The data logging equipment used monitored temperatures more frequently than I needed.

Cold weather adversely effected data gathering. Keep the laptop computer warm. My cold weather data collections via laptop resulted in very short battery life, and in a laptop failure. Wires at the flex-point where the screen attaches to the keyboard became brittle in the cold. The laptop computer monitor failed. I kept the second laptop warm in the cab of my truck, using a 110 Volt inverter to power the laptop from the vehicle.

Consider using a heated enclosure for the data logging equipment. My enclosures were unheated. Shortened battery life in the cold weather became an issue. These, among other difficulties, resulted in unreliable end-of-winter datalogger electronic readouts. I ended up using a highly accurate digital ohmmeter. I changed to manually taking the direct resistance measurements. Then, from the resistance readouts and the manufacturer's thermal equivalent equation, I manually calculated the temperatures via Excel spreadsheet.

3.5.6 Other frost protected shallow foundation considerations.

As climate change has a thawing effect on marginally frozen soils, frost-protected shallow foundation use may expand, depending upon local soils classifications and moisture conditions. If permafrost sites within the discontinuous permafrost zone become warmer, then FPSF systems may become alternatives that are more attractive. In addition, where a thin layer of permafrost exists, combined with acceptable thaw strain calculations from warming that permafrost, then an FPSF system may also be suitable.

I did not investigate the long-term thermal resistivity for thermal insulation installed within the FPSF systems used at my investigation sites. As shown by these results, footings below overhead garage doors and at reentrant corners warrant special structural design considerations as well as thermal design considerations. Treat overhead door footings and footings at reentrant corners as exterior corners. Provide the additional insulation thermal value and extents shown for corner zones.

Structural considerations may control the design. Lateral overturning loads from wind, seismic, or similar events, may require deep footings for structural restraint. Caution, I have had to reject using an FPSF system for at least one lightweight metal building needing foundation uplift restraint beyond the capacity of the FPSF system.

Do not use FPSF systems for unheated buildings in colder regions where the climate AFI exceeds the 2 500 °C·d (4 500 °F·d) limit included in current design guides, due to increased risk of frost penetration below the footings in colder regions. The exception is for unheated buildings founded upon non-frost-susceptible soils extending deeper than the maximum credible frost for that climate. Results from this research indicate potential NFS depths deeper than 4.25 m (14 ft).

Provide for heat conduction from the heated building into the soils below the footings. Do not place insulation directly below the footings for the colder climatic conditions investigated in this research. Provide the thermal bridge between heated building and the soils by omitting the insulation from directly below the footings. The thermal principal behind the current design guides permitting insulation below the footings correlates to sufficiently trapping geothermal heat applies to warmer climatic zones. With the colder AFIs for this investigation, heat from the building provides the thermal soils conditions required to restrain the freezing isotherm outside of the footing zone.

3.6 Part A – Pivotal Findings for Frost-Protected Shallow Foundations in Interior Alaska

3.6.1 Using frost-protected shallow foundation systems requires some cautions.

In this portion of my dissertation, I investigated how using manufactured thermal insulation alters the thermal regime of soils below heated buildings, thereby providing foundation alternatives for arctic buildings with no permafrost below. I studied six Fairbanks sites. Foundations at four of the sites had perimeter insulation installed – intending to provide frost protection from seasonal frost. One heated building site had a foundation on grade, but without any perimeter insulation. One heated building site had permafrost discovered later at a depth of about 15 m (49 ft). I included a mathematical analysis and several finite element models. Site results, mathematical methods, and numerical finite element analysis results agree. Frost-protected shallow foundation systems do apply for these colder climates. In Appendix A, I provide a suggested design guide for use with these colder winter conditions. Especially consider the cautions, below, for the areas immediately outside of the thermal influence from the heated building.

Research results showed that the FPSF system installed with the extra insulation prescribed in this dissertation kept the freezing isotherm out from below the footings, including the corner zones. The Timberland site showed this result. The site work, the numerical analysis, and the finite element analyses agree, showing that FPSF systems do work, even at the colder design freezing index of up to 4 400 °C·d (8 000 °F·d). Therefore, I have extended the design guide limits into colder discontinuous permafrost zones up to a 4 400 °C-d (8 000 °F-d) limit, such as Interior Alaska. For an FPSF system that relies upon perimeter insulation to contain building heat and direct that heat into the soils below the building, I recommend using the extra insulation methods presented in Appendix A.

This research revealed noteworthy exceptions. If the soils below the building at a specific site are non-frost susceptible (i.e., dry and non-wicking) to depths below the seasonal frost line, my site investigations showed using minimal or even no thermal insulation at all did not result in readily evident building distress from seasonal frost heave. The Merlin, Goshawk, Violin, and Bonita sites demonstrated this. All four sites were built upon rock, schist, or gravel soils combinations. As an example, the Bonita site does not show readily evident visible distress from frost heaving even though it has no perimeter insulation. The Bonita site is built upon river gravels extending deeper than the seasonal frost depth.

Should the soils conditions change over time, then the risks for frost heaving may increase. For example, one site investigation outside of this research showed hillside silts flowing into and through the gravels placed below the footings. The silts, in effect, contaminated the gravel. With this type of changed soil conditions, the risk of seasonal frost heave could likely change.

Frost-protected shallow foundation design methods have been in use since the 1960s. For the colder climates in Interior Alaska, I have provided additional design suggestions for FPSF systems in Appendix A. These suggestions keep the footings above freezing by directing and containing building heat into the soils immediately below the foundation. As always, designers bear the responsibility for checking with the appropriate authority having jurisdiction for using the methods, published here, as alternative means and methods to building code provisions.

Frost protected shallow foundation systems respond to climate change in two ways. With warming climates, the mean annual soils temperature increases, and the thermal insulation originally installed becomes conservative for the warmer climates. With cooling climates, the mean annual soils temperature decreases. Adjustments for the cooling include providing additional building interior heat, or, providing additional perimeter insulation extents outside of the building.

3.6.2 Recommendations

Check for the absence of permafrost below the specific building site. Avoid using an FPSF system when permafrost exists below the building. If permafrost exists below the building, expect thaw strain (ground settling) from permafrost degradation (melting) due to FPSF system directing building heat into the ground below the building. At one of my test-sites, I explored and discarded using an FPSF system due to the discovered permafrost below. I remain concerned about long-term thaw strain (i.e., long-term thaw settlement) from degrading the permafrost. If considering a FPSF system where permafrost exists below the building, include a thaw strain analysis for that specific site for the duration of the anticipated life span of that building. Generally, an FPSF system does not apply to permafrost areas.

Exclude unheated buildings from FPSF systems for the colder Alaska AFIs included in this study. Where the mean annual soils temperature is well above freezing, ASCE (2001) provides for additional insulation below the foundation to trap geothermal heat in warmer climates. Here, in the colder interior regions of my investigation, the ground temperatures are within 0.8 °C (1.5 °F) of the freezing point. Expect building heat to be required for keeping the footing zone above freezing. Do not expect above freezing foundation soils simply from trapping geothermal heat.

For frost-protected shallow foundations in the colder Interior Alaska zone, provide the increased insulation amounts prescribed in this dissertation. If using the prescribed insulation amounts from the lower design guide AFI limit of 2 500 °C·d (4 500 °F·d), expect the freezing isotherm to penetrate well below the footing. These lesser insulation amounts do not provide a sufficient thermal envelope to keep the freezing isotherm outside of the footing zone. I discourage designers from using 50 mm (2 in) thick vertically applied perimeter insulation, with 50 mm (2 in) thick horizontal insulation extending out from the building 0.6 m (2 ft) all around, because of increased risk of foundation frost heave, especially in the presence of both fine-grained (wicking) soils and moisture. If wicking soils and water later become present over the life of the structure, even for just one winter, foundation heaving may still occur. Wicking soils may become present, for example, from the topsoil added for flower gardens. Water may become present by being perched on top of seasonally frozen soils, like during spring thaw.

Provide structural restraint for the rotated basal pressures and for overturning moments. Consider how best to resist these almost-horizontal basal forces. One way, assumed here, is via the connected FPSF floor system. In addition, consider structural restraint for overturning moments. For high wind or seismic loads, restraint from deep footings may be required to resist the overturning moments.

Consider accessory structures and site improvements just outside of the building thaw zone from the FPSF system. This research shows full-depth seasonal frost away from the building thaw zone. Design methods prescribe about 45 cm (18 in) of NFS material below the footing. However, design recommendations vary outside of the footing zone. This research highlights the deep frost penetration in these zones, and frost susceptible soils away from the foundation may still heave. Consider seasonal heaving concerns for driveway pavements, sidewalks, and entry steps adjacent to the FPSF systems.

From these observations, and as a measure of conservatism, I recommend designers (A) consider the foundation zone as having no snow, and (B) consider the soils as being wet, especially in spring. All six sites investigated had pedestrian or vehicle traffic next to the building. All six had eave overhangs. All six sites had snow cleared from portions around the building. Therefore, my observations show "no-snow" conditions as a default condition for FPSF designs. From the spring thaw observations, I also conservatively treat the foundation system as wet from perched water table above the not-yet-thawed seasonal frost areas below.

3.6.3 Summary, frost-protected shallow foundations for non-permafrost sites in cold climate.

This research shows that using manufactured thermal insulation alters the thermal regime of soils below heated buildings and provides additional foundation methods for arctic buildings almost 80% colder than included in current design guides. For thawed sites, perimeter insulation serves to direct restricted heat flow into the soils immediately below the building and enhance the thermal thaw bulb below the building. With warming climate conditions, design methods prescribed in this dissertation are conservative. With cooling climate conditions, either consider providing additional interior building heat or consider providing additional perimeter thermal insulation. I have outlined several cautions and limitations.

PART B. PERMAFROST PROTECTION – BY RESTRICTING SUMMER HEAT GAIN

Chapter 4 Insulation Methods for Permafrost Zone

4.1 Introduction and Literature Review

The hypothesis remains the same for both parts of this research, namely, "Using manufactured thermal insulation alters the thermal regime of soils below heated buildings and provides additional foundation methods for arctic buildings." For permafrost zones, the corollary becomes, "Where climate warming threatens to compromise the structural integrity of existing building pile foundations, seasonal insulation methods provide an additional permafrost protection alternative."

4.1.1 Building distress concerns with warmer climates.

Several studies have documented current building distress and failures and related it to warming permafrost. Recent professional publications have already increased public awareness about the dangers and cost impacts that may result from warmer climate. Thermal changes in the geotechnical soils parameters potentially have significant bearing capacity losses as well as tangential frost heaving forces. Previous studies have warned that temperature increases of 0.1 °C to 3.3 °C (0.18 °F to 5.9 °F) may occur by mid-twenty-first century in western Siberia (Grebenets, Kislov, & Shmelev, 2012; Vyalov, Gerasimov, Zolotar, & Fotiev, 1993b). Similar climactic regions, elsewhere on the globe, may anticipate equivalent warming.

Quantitative simulations indicated structural bearing capacity losses may well exceed 5 % to 8 % and reach as high as 20 % to 25 %. Similarly, deeper active layers (the surface zone of seasonal freezing and thawing) were expected. With deeper active layer thaw depths due to warmer climate, the frost heaving forces were expected to increase. Simulations showed these increased frost heaving forces might be as much as 30 % to 100 % (Osterkamp, 2003; Grebenets et al., 2012).

Vyalov et al. (1993b) have performed extensive computer finite element analyses simulations. The warming of permafrost soils had been attributed to climate warming. They investigated four climatic zones. Zone I had the warmest permafrost, closest to the freezing point, and has a current active layer thaw depth of about 1.27 m (4.2 ft). In Zone I, the permafrost table might be lowered by 4.5

m to 7.9 m (14.7 ft to 25.9 ft); and, with taliks (a layer of year-round unfrozen ground within permafrost) present, the thaw depth could increase as high as 9.2 m (30.2 ft).

Zone II had a thaw depth of about 1.12 m (3.7 ft). Zone III had a thaw depth of about 0.79 m (2.6 ft). Using climate warming simulations, Vyalov et al. (1993a) reported that Zone III active layer thaw depths could increase by almost 1 m (3.3 ft).

Zone IV had the coldest permafrost, with an active layer (thaw) depth of about 0.59 m (1.9 ft). Vyalov's calculations showed that the coldest (most northern) permafrost zone (Zone IV) should anticipate strength drops of 3 % to 16 %.

For the southern permafrost zone (Zone I), Vyalov et al. (1993a) predicted significant bearing strength changes. With the highest calculated air temperature increases, complete thawing of the soils might occur. The bearing strength decrease could be from 50% to 100% (i.e., complete loss of bearing strength). Both Fairbanks and Kotzebue are located in this warmest region with the potential for the most serious negative impacts from climate warming.

Grebenets et al. (2012) reported that as the soils temperature increased, there was an accompanying increase of unfrozen water content. Increased unfrozen water content led both to a loss in adfreeze bond strength, and to a loss in overall pile bearing capacity. Serious deformations had occurred in many structures from this decreased-adfreeze bond mechanism.

Slurry-pile installation-methods include pre-auguring an oversized hole, into permafrost. The size and depth of the hole needed depends upon soils, thermal, and load characteristics. Heavier loads, in weaker soils and warmer temperatures need larger and deeper holes. After the pile is placed in the hole, the annular space between the pile and the edge of the hole is filled with a sand-and-water slurry. Slurry piles depend upon freeze back of the soils to create a frozen bond (called adfreeze bond) between soils and the pile surface. According to Holubec (2008), literally hundreds of buildings in Russia and in Nunavut Territory, Canada are experiencing problems from climate warming weakening this frozen bond. He also predicted that similar experiences would occur elsewhere with warming permafrost.

Streletskiy and Shiklomanov (2013) concluded that the structural foundation (i.e., gravity downward) support was not the only strength decrease with thawing permafrost. In thawing soils, the structural uplift resistance (i.e., for frost heave forces) was also weaker. Ultimate changes generated deeper active layers. When these deeper active layers refreeze the following winter, the (upward) frost heaving forces are greater. The higher uplift forces increased the potential for foundational frost heave distress.

4.1.2 Temperature dependent adfreeze bond may be unrepairable if broken.

A main strength characteristic determining the bearing capacity of a pile is the adfreeze bond strength. This bond strength is the maximum resistance of frozen soil to shear along a solid surface (i.e., a foundation pile). The adfreeze bond is the mechanical adhesive connection obtained between the soils and the foundation. The bond forms as the soils initially freeze against the foundation support structure. Adfreeze bond strength is analogous to glue-strength between dissimilar materials. Colder soils have higher values of adfreeze bond strengths. As the ground temperature warms, the adfreeze bond weakens and its long-term rupture-strength decreases. With the same load, the weaker bond may promote foundation strain (i.e., slow moving creep) into the warmer (now thawing) permafrost soils below (Vyalov, 1973a).

For structures designed for frozen soils, the ground temperature is a significant and salient feature for determining likely pile-capacities for resisting structural loads. This adfreeze bond strength is a key design-factor used for determining the size and depth needed for pile foundation members to support a given design load. Khrustalev (2001) reported concern that climate warming will degrade the permafrost and weaken the adfreeze bond capacity within the warmer soils. In Russia, many foundation-designs may have safety-factors of only 1.56 or less. If warming soils reduces the adfreeze bond strength by 64 % to 95 %, those foundations are at high risk of failure.

As an example, soils at -2 °C (28.4 °F) have about triple the adfreeze bond strength as soils at -0.5 °C (31.1 °F) (Vyalov, 1973b). Even small permafrost warming may have significant strength-reduction impacts, especially in warm permafrost. Research into this bond strength can be dated back to the 1930s by Tsytovich and Vologdina (Sadovskiy, 1973). One common pile design method in permafrost areas is to attribute the entire pile support capacity to the adfreeze bond strength.

Permafrost degradation has been predicted in the continuous permafrost zone. In the warmer, discontinuous zones, even complete disappearance has been predicted. Without implementing specific mitigation measures, nearly complete loss of bearing capacity is predicted within Zone I. Here, the current average annual warm soil temperatures range from 0^{o}C to -0.6^{o}C (32 °F to 30.9 °F). From 40 % to 100 % strength loss is predicted in the Zone I (Fairbanks & Kotzebue) thermal regions (Vyalov, Gerasimov, & Fotiev, 1998).

Foundation system load capacity in frozen soils depends upon maintaining the adfreeze bond strength at or below its design cold temperature. Breaking the adfreeze bond leaves much weaker residual bond strengths. Preserving existing infrastructure (especially existing buildings on pile foundations in permafrost) means preserving both, (A) the cold soils temperature, and (B) the adfreeze bond. One structurally sound approach involves protecting the frozen soils from any warming at all, and not permitting even the smallest settlement.

Even small strains may break an adfreeze bond. Under soils tests at -2 °C (28.4 °F), this adfreeze bond is essentially brittle (Ladanyi & Theriault, 1990). Strains less than 1 cm (1/4 in) have been found sufficient to break the adfreeze bond (Anderson & Anderson, 1978; UFC, 2004b; Nidowicz & Shur, 1998). Once broken, the adfreeze bond does not readily reform, and the remaining strength is called 'residual bond strength.' This residual bond strength is significantly weaker.

One proposed repair method for ruptured adfreeze-bonds refreezes the warmed soils to a cooler state. The thawing of frozen ground is likely to be spatially non-uniform, with variable mechanical characteristics. Mechanically cooling the soils with refrigeration tubes (aka. heat pipes or thermo-siphons) is one way of cooling the soils, thereby neutralizing the warming effects of climate change. Three-dimensional models have been developed to help determine the amount of refreezing that may be needed to repair and stabilize damaged adfreeze bonds (Dubina, Chernyakov, & Teslenko, 2003; Vyalov et al., 1998).

United States military literature reported as little as one-half or less of the adfreeze bond strength may remain after refreezing (UFC, 2004b). The residual bond strength may even be lower, perhaps several times less than the long-term adfreeze bond strength (Nidowicz & Shur, 1998). Sadovskiy measured the residual strength both for steel piles and for concrete piles. The friction strength alone (without adfreeze bond) was four times lower than with the adfreeze bond strength in place (Sadovskiy, 1973). Monitoring the soils temperature at specific sites permits identifying changes in the soils thermal-profile, for comparison against the initial design parameters (Grebenets et al., 2012; Streletskiy & Shiklomanov, 2013; Vyalov et al., 1993a). The climate warming projections warrant validation from actual site-specific soil temperature measurements over time. The amount of mitigation methods predicted may not be justified (Vyalov et al., 1993b).

Under some specialized conditions (A) with high lateral soil pressure (acting perpendicular to the pile), combined with (B) higher unfrozen water content, the adfreeze bond may partially recover (heal).

However, with warmer permafrost, low normal-forces, and drier soils, adfreeze bond healing may not occur at all, falling to zero (Ladanyi & Theriault, 1990).

Nidowicz and Shur (1998) explained the relationship between freezing-index (accumulated winter cooling), thawing index (accumulated summer thawing), and the resulting pavement surface temperature changes. With climate warming, the winter air freezing-index decreases, and the summer-thawing index increases. With warmer climate, the ratio decreases between freezing-index to thawing-index. With less net winter cooling, the pavement surface temperature increases. Depending upon the pavement type, the surface temperature may more easily exceed a mean annual temperature of 0^{o}C.

4.1.3 History and insulation methods for arctic foundations.

In Russia, about 5 % of the population (about seven million) resides in arctic regions. However, that region's contribution to the country's economy is a more substantial 20 %. For exports, the contribution is higher, 22 %, reported by (Streletskiy & Shiklomanov, 2013).

The Alaska population percentage is small (less than 3/10ths of one percent of the US population). Like Russia, however, the economic contributions from Alaska are disproportionally larger. In 2010, Alaska's mining contributions alone represented 3.8 % of the gross domestic product (National Mining Association, 2012). Alaska mining, in 2007, represented almost $200 million worth of Federal, State, and local tax revenues (Alaska Miners Association, 2008).

Extending the energy resources from within the United States, includes extending oil, natural gas, and coal reserves in the arctic environment for appropriately responsible development. As an example, forecasts for natural gas include increasing production to 30 % of the country's electricity, up from 20 % in 2008 (Fahey, 2012). According to Dorgan (2002, p. 2512), "Our economic and our environmental future is directly tied to our ability to produce ample supplies of clean, reliable energy."

Pavlov (1975) studied thermal insulation impacts on soil temperature in Yakutsk, Russia, and showed that permanent insulation of unheated structures increases, not decreases, soil temperature. In his studies at a snow-covered site, the increase was relatively small (from 0.4°C to 0.6°C or 0.7°F to 1.1°F). Without snow cover, however, the increase was much greater (4.5°C or 8.1°F). Pavlov concluded: "Constant thermal insulation on the soil surface has a warming impact in areas with mean annual air temperatures below 0°C (32°F) and cooling effect in areas with mean annual air temperatures above 0°C" (Pavlov, 1975, p. 266).

Esch and Rhode (1976) described a temperature regime under the permanent insulation at the Kotzebue Airport in Alaska. They found that soil at a depth of 6 m (19 ft) under insulated sections was 1°C to 2°C (1.8°F to 3.6°F) warmer than under a control section without thermal insulation. The mean annual soil temperature distribution under insulation in this study showed that the soil temperature decreased with depth, indicating further warming of the soil below permanent insulation.

Data on permafrost temperature beneath a road with permanent thermal insulation in Inuvik, Canada were presented by Johnston (1981) and analyzed by Nidowicz and Shur (1998). A warming effect of the permanent insulation on permafrost was found. Over four years, the average temperature under an insulated road section was about -5°C (23°F) at a depth of 2.5 m (8.2 ft). Under the uninsulated control section, the average temperature was about -8°C (17.6°F).

Permanent insulation was used to prevent permafrost degradation and reduce frost heave for a railroad track about 60 km (37.3 mi) south of Fairbanks, Alaska (Trueblood, Kinney & Kleinhans, 1996). After five years, the soil temperature at the site was not lower than the soil temperature in areas without insulation. In addition, the permanent insulation had no thermal impact on permafrost deeper than 2 m (6.6 ft).

Earlier, Porkhaev (1963) developed an approach for explaining the thermal impact of permanent insulation on permafrost. Porkhaev divided the yearly thermal cycle into three periods (Figure 27). He named the first period (left side of the thermal cycle) a thawing impulse; the second period, a freezing impulse; and the third period, a cooling impulse. The length of time associated with the thawing impulse is the first period and has an air (surface) temperature above 0 °C (32 °F). The thawing impulse is equal to the Thawing Index, as it is usually used. During this first period, seasonal thawing of soil takes place, and permanent insulation reduces the depth of the active layer. The duration of the freezing impulse is equal to the thawing impulse at a site without snow, and when thermal conductivities of soil in the frozen and thawed states are equal. During this second period, permanent insulation reduces the rate of freezing of the active layer. The permafrost temperature depends on the cooling impulse, which depends on the difference between the Freezing Index and the Thawing Index, soil properties, the active layer depth, and the amount of thermal insulation. During this third period, the impact of thermal insulation on permafrost can be compared with the impact of snow on permafrost, in that thermal insulation also leads to an increase in permafrost temperature.

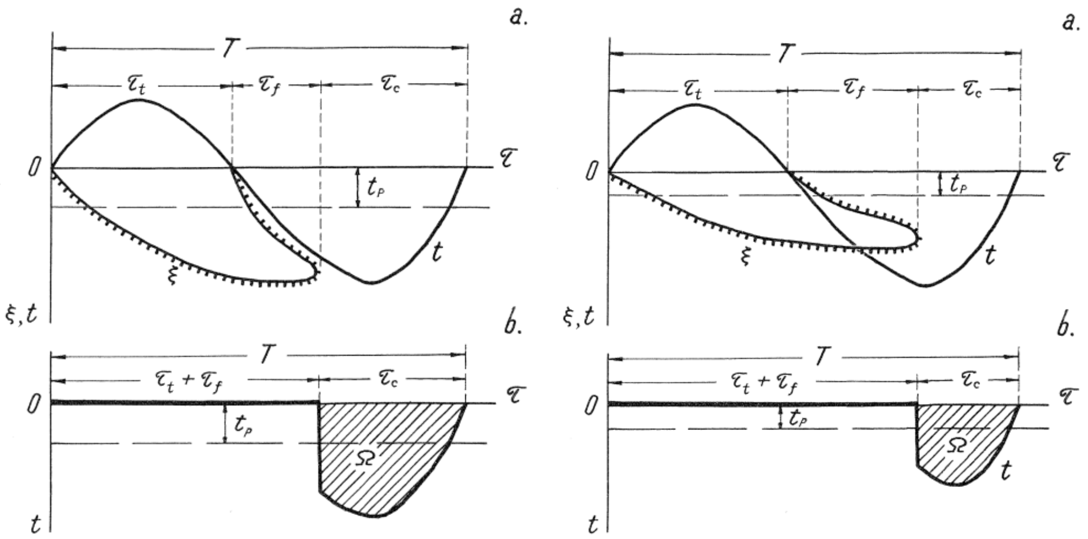

Figure 27. Porkhaev (1963) thawing, freezing, and cooling impulse effects upon the permafrost table.
The left side showed a site without permanent thermal insulation.
The right side showed a site with permanent insulation.

According to Porkhaev (1963), the mean annual temperature at the soil surface can be approximated as

$$t_0 = \frac{\Omega_c}{T}$$

where

Ω_C = surface cooling index (degree-days)

T = year's duration (365 days)

The mean annual soil temperature at the permafrost table, Ωcp, is different from the mean annual surface temperature, because the cooling impulse at the permafrost table is smaller than the cooling impulse at the soil surface. As shown in Porkhaev and Schelokov (1980), Ωcp can be found as

$$\Omega_{cp} = \Omega_c B \ ,$$

Figure 28 shows the relationship between *B* and Ψ (Porkhaev, 1970).

$$\psi = R\sqrt{C_f k_f} ,$$

Where

R = thermal resistance of insulation at the site without snow or of insulation and snow at a site with snow,

C_f = volumetric specific heat of soil of the active layer in the frozen state, and

k_f = thermal conductivity of soil of the active layer in the frozen state.

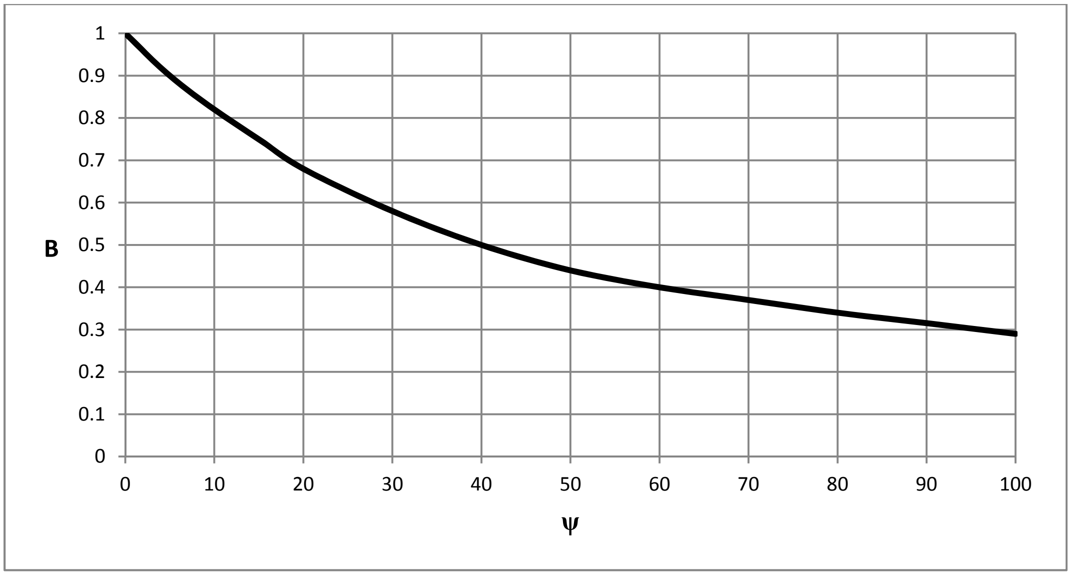

Figure 28. Porkhaev (1970) Coefficient B as a Function of ψ.

Using Porkhaev's method, we found that permanent insulation with a thermal resistance as low as 1.76 m^2 °C / W (R= 10 ft^2 hr °F/Btu) can increase permafrost temperature by 4 °C to 5 °C (7.2 °F to 9 °F) in Yakutsk, Russia. In Barrow, Alaska, the permafrost temperature increase with permanent insulation is 6 °C (10.8 °F). These findings are in agreement with observations by Pavlov (1975) and Johnston (1983).

The effect of permanent thermal insulation on permafrost under unheated structures such as roads and airfields in permafrost regions has been investigated less. There is a widespread understanding that insulation decreases permafrost temperature. For example, Doré and Zubeck (2009, p. 381) reported, "The purpose of the embankment insulation is to prevent temperature increase." Such a conclusion is not supported by field studies.

Applied seasonal thermal insulation also has history. The best-known example of seasonal insulation is snow. Snow increases the freezing impulse and decreases the cooling impulse. The deeper the snow is, the greater the freezing impulse required to return thawed soil in the active layer to a frozen state. Snow increases permafrost temperature and can cause its degradation. Kudriavtsev (1954) defined the critical depth of snow as the depth where the freezing impulse becomes equal to the Freezing Index, and mean annual temperature at the permafrost table becomes equal to 0°C. With a snow depth greater than critical, the active layer does not completely refreeze during winter. Snow deeper than critical depth leads either to formation of the residual thawed layer over permafrost or to permafrost degradation. Snow is an extremely powerful seasonal insulation. Seasonal thermal insulation has been used in winter to prevent soil freezing, to ensure soil workability, or to protect unheated or unfinished structures from frost heave.

If winter seasonal thermal insulation is so effective at protecting soil from freezing and at increasing permafrost temperature, we could expect that seasonal thermal insulation used in summer could be very effective in reducing the active layer depth and in decreasing permafrost temperature. There were a few attempts to use summer insulation to decrease the active layer thickness or to prevent permafrost degradation under buildings with ventilated crawl spaces. As described by Lukin (1946), peat insulation was heaped around piles under the external walls of a brick factory in Dudinka, Low Yenisei River, Russia in 1936 and 1937. This insulation reduced the thickness of the active layer around the piles (Lukin, 1946). Hence, Lukin recommended that insulation be installed around piles at the end of April and removed at the end of September or in October. Sanger (1969) gave an example of using seasonal insulation to protect permafrost from thawing under foundations during construction.

Bondarev (1957) described permafrost degradation under the maternity hospital in Vorkuta, Russia. The design called for insulating the crawl space in summer, using 50 cm (20 in.) of slag and removing it in winter. Insulation was installed under only one-third of the crawl space, and its thickness was 10 cm to 15 cm (4 in. to 6 in.) instead of 50 cm (20 in.). The insulation remained in place during winter and became permanent. Not surprisingly, the soil temperature under the insulated crawl space was 2 °C to 3 °C (3.6 °F to 5.4 °F) warmer than under an uninsulated area (Bondarev, 1957).

Although a few applications of seasonal thermal insulation in ventilated crawl spaces have been mentioned before, the effect of ventilated crawl spaces on permafrost has not been explored in field studies and has not been studied using analytical methods or thermal modeling. In the following discussion, we present the results of modeling the seasonal thermal insulation effect beneath a building with an open crawl space.

4.1.4 Current arctic foundation design methods.

For existing buildings, arctic foundation design includes preserving the cold soils and protecting the adfreeze bond between soils and structural members. Existing buildings have more limited technical and economic alternatives – alternatives that probably will be used from outside of the building. For existing structures, proactive and timely mitigation is of the essence. The mitigation measures need to be in place before even the smallest foundation strains (settlements or heaving) occur. Protecting the adfreeze bond is of paramount importance.

For new structures, a two-fold foundation design approach may be used. First, the design safety factors may be increased due to anticipated warmer soils. Khrustalev (2001) has outlined a risk-assessment process. A new-construction owner may select increased first-costs for a more robust initial design that includes climate-warmed soils as a basic premise. Owners may choose active cooling measures, like below-floor forced air ducts, or they may choose passive cooling via thermosyphons. Either may be more easily sequenced during the initial building construction process. An active cooling method, for example, may use open convective air-flow that permits cold air to flow under the building (McFadden, 2001). Thermosyphons are closed pressure vessels (pipes). One common type of thermosyphon uses a two-phase fluid (liquid and gas) to conduct thermal energy from the ground to the atmosphere, via evaporation and condensation of a working fluid (Holubec, 2008; Popov, Vaaz & Usachev, 2010; Zarling & Haynes, 1985).

Open crawlspaces should freely allow cold winter airflow below the entire building. Utilities, especially water and wastewater, should be enclosed in heated utilidors outside of the building crawl spaces. That way, water leaks do not flow into the permafrost zones near the building foundations. Building crawl spaces should be allowed to come as close to outside winter cold temperatures as possible (Vyalov et al., 1993b). Figure 29 shows an open crawl space below the Yuut Elitnaurviat learning center in Bethel, Alaska. Most commercial open-height crawl spaces I have observed are 1.2 m to 1.8 m (4 ft to 6 ft) tall.

Completely opening an existing crawl space that is partly closed is another way for cooling foundations below existing buildings. Allowances may need to be included for changing utility locations either to inside the thermal envelope or to heated utility ducts (called utiliducts). Figure 30 shows insulated utilities at Yuut Elitnaurviat complex.

Figure 29. People's Learning Center ("Yuut Elitnaurviat" in Yupik Eskimo).
This learning center in Bethel has an open crawl space.

Figure 30. Utilities protected from freezing by enclosure within insulated arctic pipe.

Just providing vent openings in an otherwise fully enclosed foundation system (i.e., vent openings in the crawlspace sidewalls) is not normally enough to preserve the frozen state of soils. The space below the building needs full openness (i.e., no sidewalls at all) to maximize airflow. In northern

Alaska where wind is commonly present, this author has seen a ‘venturi tube’ effect incorporated into the building shape. The curved bottom edge of the wall creates a broader transition zone around the base of the building. This rounded shape helps promote this wind-driven airflow beneath the building. This venturi effect helps keep the crawl space clearer from accumulated snow. The Yukon Kuskokwim Delta Regional Hospital (Figure 31) is one example of this curved base-of-wall shape for improved airflow under the building.

Figure 31. Improving convective airflow below a building with a curved wall-bottom shape.

For permafrost zones, the insulation methods portion of this research uses the principle of maintaining the soils in their naturally frozen state using passive methods. These methods may be increased or decreased in response to actual temperature changes at a specific location. It investigates and reports on using a lower-technology method for preserving colder soils temperatures. Presently there are a number of methods to respond to changing climate. These methods use the fundamental premise of keeping the soils below freezing either by (A) natural means, or by (B) artificial means.

The two fundamental approaches have different cost-distributions. One approach increases the first-construction-cost. Construction design includes more extreme scenarios for projected climate warming. The design is conservative and should the climate warming not occur to the extent projected, the design may be too expensive. The second approach optimizes a lower first-construction-cost with a risk management assessment of ongoing and potentially increased costs later. Opting for the second approach reduces the first cost and includes ongoing responsibilities. While providing a lower first-construction-cost, the owner must remain vigilant to site-specific thermal conditions (Khrustalev, 2001).

The evaluation and decision process for existing buildings is somewhat more cost-impacted than for new construction. New buildings, for example, may install below-grade thermo-syphon refrigeration systems more economically because the building is not-yet in place. Existing buildings, by contrast, may need to pay a premium for similar thermo siphons because the installer no longer has ready access to the spaces below the building (Khrustalev, 2001).

Cooling ducts may be installed below a building. The ducts are normally open for winter outside airflow, and may be closed during the summer. Winter airflow through the ducts may be fan-forced (forced convective airflow). Using forced convective airflow (i.e., airflow powered by fans) through below-the-building air ducts, Vyalov et al. (1993a) measured additional soil cooling at 2 °C to 4 °C colder.

In Alaska, reports of soils cooling by thermosyphons date back to the 1960s. A thermosyphon is a closed-system pressure-vessel partly below ground, and partly above ground. Thermosyphons may be installed horizontally, inclined, or vertically. Inclined thermosyphon installations occur with a minimum angle of about 3^o to 5^o from horizontal. The minimum angle permits the enclosed gas and condensate functions to work properly (Holubec, 2008). When installed as a load bearing structural member, the name “thermosyphon” changes to “thermopile” (McFadden, 2001).

The pressure-vessel contains a fluid that evaporates at temperatures below freezing. In the below-ground evaporator pipe, the fluid extracts heat from the ground and changes to vapor-form. The vapor rises to an above-ground radiator-condenser portion. In winter cold air temperatures, the vapor radiates its heat into the atmosphere. Then, as the vapor is cooled, it re-condenses into liquid form. Completing the cycle, the fluid falls by gravity down into the evaporator portion of the thermosyphon.

From the end of the 1990s, seasonal cooling devices became more commonly used as a means to keep or preserve cold permafrost below heated buildings. Keeping the permafrost cold, via mechanical means, limits the risk of ground subsidence when presented with warmer climates. One main technical solution for foundation construction is using a vented space below the building and installing the seasonal cooling devices (Popov, et al., 2010). From my own design experience, using helical rings, around the outside of the thermosyphon, allows a smaller pipe-diameter to develop higher loads than with the pipe alone. This helical ring method allows a lower installed cost than pipe piles without the helical rings.

Thermosyphons work in winter by super cooling the soils enough so summer heating does not create net heating. Cooling performance is dependent upon variables such as winter air temperatures, pressure maintenance within the tubes, and tube integrity to keep water out of the tubes. Spacing between cooling thermosyphons becomes a salient feature. Design parameters include the winter outside air temperature. With uncertainties regarding warmer climate projections, new designs may become more conservative in order to account for this uncertainty (Holubec, 2008).

A test site on Chena Hot Springs Road, near Fairbanks, Alaska, employed three different newer configurations for thermosyphons. These configurations included flat-loop, undulating, and hairpin thermosyphons. Results showed that a totally buried system, would be unobtrusive to traffic. Recommendations included increasing the size of the condenser section (Wagner, 2014; Wagner, Zarling, Yarmak & Long, 2010). For horizontal applications, installations included placing evaporator sections deeper in the ground. Insulation separated the deeper evaporator section from the closer-to-the-surface condenser section. The insulation served to separate the permafrost below from the thawing heat-source (building or outside warm air) above. Flat loop thermosyphons have an expanse of evaporator tubes that snake back and forth below the surface before being connected to a single radiator-condenser section (Holubec, 2008).

Installed vertically around the perimeter of smaller buildings, Holubec (2008) showed that thermosyphons might also create a “thermo-curtain.” He questioned if perimeter thermo-curtains alone would sufficiently protect the interior regions of larger area buildings.

Figure 32. Thermopile installation normally occurs well before building construction.
The theromopile radiator sections (tilted out from the vertical piles) are clearly visible.

Figure 32 shows conventional thermosyphons (with radiator sections above the ground) installed adjacent to the piles. This author has observed that thermosyphons are commonly installed during the construction process, before the building is erected. Installing thermosyphons below existing buildings is more complex as it must be done from outside of the building footprint. Three common alternatives include using thermal-curtains, inclined thermosyphons, or flat tubes. Flat tube installation is more suited to new construction than to retrofitting an existing structure.

Because design methods are reportedly proprietary and kept as protected intellectual property, design validation, by others, is more difficult. In addition, thermosyphons need calibration against recent ground temperature performance. The lack of clear temperature data and standards from which to design thermosyphon systems is one of the main concerns regarding long-term satisfactory thermosyphon performance. Determining the refrigeration demand comes from climate modeling. If climate warming does not occur to the extent projected, then too conservative a refrigeration system-design may result. Excess cooling capacity may have been installed at too great of a cost to the owner (Holubec, 2008).

Alaskan village indigenous life experiences abound showing that root cellars and earthen ‘refrigerators’ may keep food contents cold simply by covering the ground surface lid with grass or sod insulation. Natural vegetation serves as a protective layer, helping to insulate the soils below. Vegetation influences both summer heat-gain and winter heat-loss. In Central Yakutia, Varlamov (2003) showed that vegetation, forest litter, turf-mat, and snow were major factors influencing the soils thermal regime. Microclimatology (site-specific thermal variations due to factors like topographical depressions or ridges) also has significant thermal influence. Varlamov (2003) showed that land cover and microclimatology combined and significantly influenced near-ground temperatures relative to air temperatures as close as 2m above the surface. Vegetative insulation properties decrease the effect of summer heating on soils. Summer heat-gain into the soils is restricted when vegetation is present. In winter, vegetation's insulative properties (like snow cover) help confine the heat within the soils. The net effect of vegetation presence depends upon the annual thermal cycle. Results from Varlamov (2003) indicated that the surface temperature exhibited much greater variability than the air temperature. Vegetation may cool or warm the ground surface depending on factors like coverage and height, age and composition of tree stands, and surface moisture conditions.

When vegetation is removed (as in building zones or infrastructure), this insulation presence is reduced. Greater soil heating occurs in the summer. Greater cooling may also occur in the winter – especially in areas where the snow is also removed (e.g., for vehicular traffic or for parking zones). Grebenets et al. (2012), Nidowicz and Shur (1998), and Porkhaev and Schelokov (1980) showed the net vegetative effect as similar to permanent insulation.

Snow is also a natural insulation. Snow serves as a winter insulator – restricting the heat flow out of the ground into the cold winter atmosphere. With warmer climate, more snow is expected. With the increased snow comes increased drifting along the existing road banks. Larger snow drifts further warm the road ways; thereby, further increasing the subsidence potential (Streletskiy & Shiklomanov, 2013). Snow presence may help or hinder the soils thermal regime, depending upon desired outcome. Snow presence may be considered as an insulation cover effecting winter heat loss from the soils. If snow is present, the soils give up the contained heat more slowly.

By contrast, if snow is absent or removed, the soils lose heat more quickly to winter cold. Using the natural cold weather from winter to keep the soils cold is among the easier cooling concepts. The labor needed to perform the work may be adjusted in response to actual climate site conditions. Colder winter air temperatures in one year may mean less snow removal that year. Warmer temperatures may mean earlier and more frequent snow removal. Just removing the snow in winter allows the colder winter temperatures to penetrate more deeply into the soils. Removing the snow cover is likely to lower the natural soil temperature almost 1 °C and is often readily adaptable to existing buildings (Vyalov et al., 1993b).

4.2 Analyses Without Buildings, Permafrost Zone

4.2.1 Means and methods for testing permafrost sites without buildings.

Omitting building effects, I performed several one-dimensional analyses to determine results of changing snow conditions (no snow compared with snow covered), of varying thermal insulation amounts, and of different insulation durations. I evaluated both permanently installed insulation and seasonal insulation, installed only in the summer.

Permafrost-protection design approaches differ fundamentally from those used for frost-protected shallow foundations. FPSF system fundamentals keep the soils thawed below the footings. A permafrost-site design-approach strives to keep the soils frozen below the building. Table 5 labels this design method as the "Passive Method;" namely, keeping the frozen soils frozen and not allowing thawing.

From the literature review, permanent insulation reportedly helps preserve frozen conditions within the permafrost – helping reduce or eliminate the active layer thaw-zone above the permafrost. I want to test the validity of that presumption for our climactic conditions.

In these models, surface thermal insulation restricted heat-flow into the soils. For the one-dimensional and the two-dimensional analyses, I used a ten-year base period with no change in surface conditions. Then, I evaluated the changed conditions over a ten-year time-period. Later, when I investigated climate-warming impacts, I extended the investigative period to 25 years of changed (warmer) conditions.

The investigated durations for insulation placement varied. For the permanent insulation case, the insulation remained in place throughout the investigative period. For the seasonal insulation case, the insulation remained in place just through the warmer summer months, and was removed during the colder winter months. I analyzed each seasonally different insulation condition sequentially (i.e., a summer with insulation, followed by a winter with no insulation, then repeated). I repeated the annual sequencing for the entire investigative time-period.

I have analyzed thermal conditions for Fairbanks, Kotzebue, and Barrow. Within this main document, I included a representative sampling of the output results. See the appendices for the remainder of the output figures.

Table 5.
Alternative Design Approaches

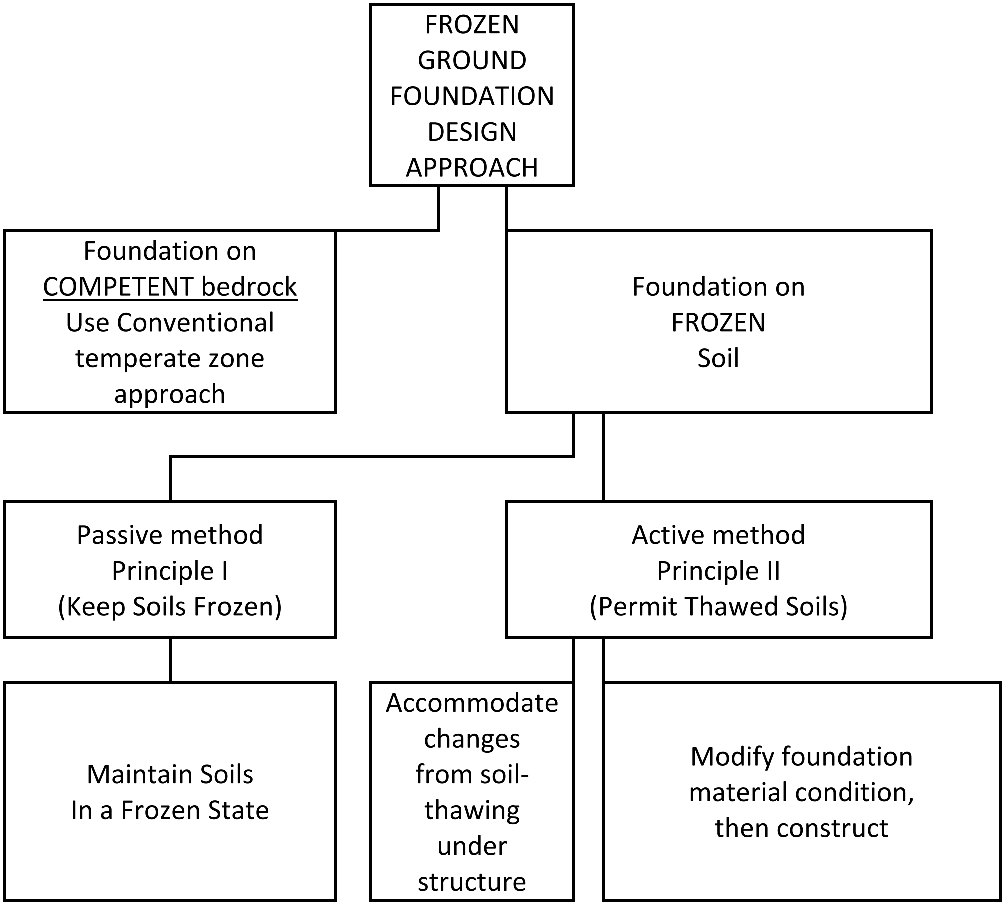

Chart adapted, by author, from Singh, Singh, and Haritashya (2011).

4.2.1.1 Finite-element thermal analyses

Initially, for the Part A frost protected shallow foundation research, I used the 2003 version of the Temp/W program. Later, the 2007 Temp/W, Version 7.14 finite element analysis program became available. I used the newer program-version for each one-dimensional and two-dimensional analysis within Part B for permafrost sites. With the newer Temp/W version’s capabilities combined with the increased computational power from a newer computer, I selected a uniform grid size. I selected the same model region for each 1-D analysis. The region measures 23.8 m (78 ft) deep below the surface, and is 30.5 m (100 ft) wide. The uniform, square, regional grid spacing was 0.61m (2 ft) squares. Also included are six surface layers at 50 mm (2 in) thick. Each surface layer represented one possible layer of 50 mm (2 in) thick rigid insulation. I took the 1-D measurements from vertical section at the 15.2 m (50-ft) point centerline of the region.

Figure 33 shows a reduced image of the region used for one-dimensional flow. See the supplemental files for a larger scale image of the region.

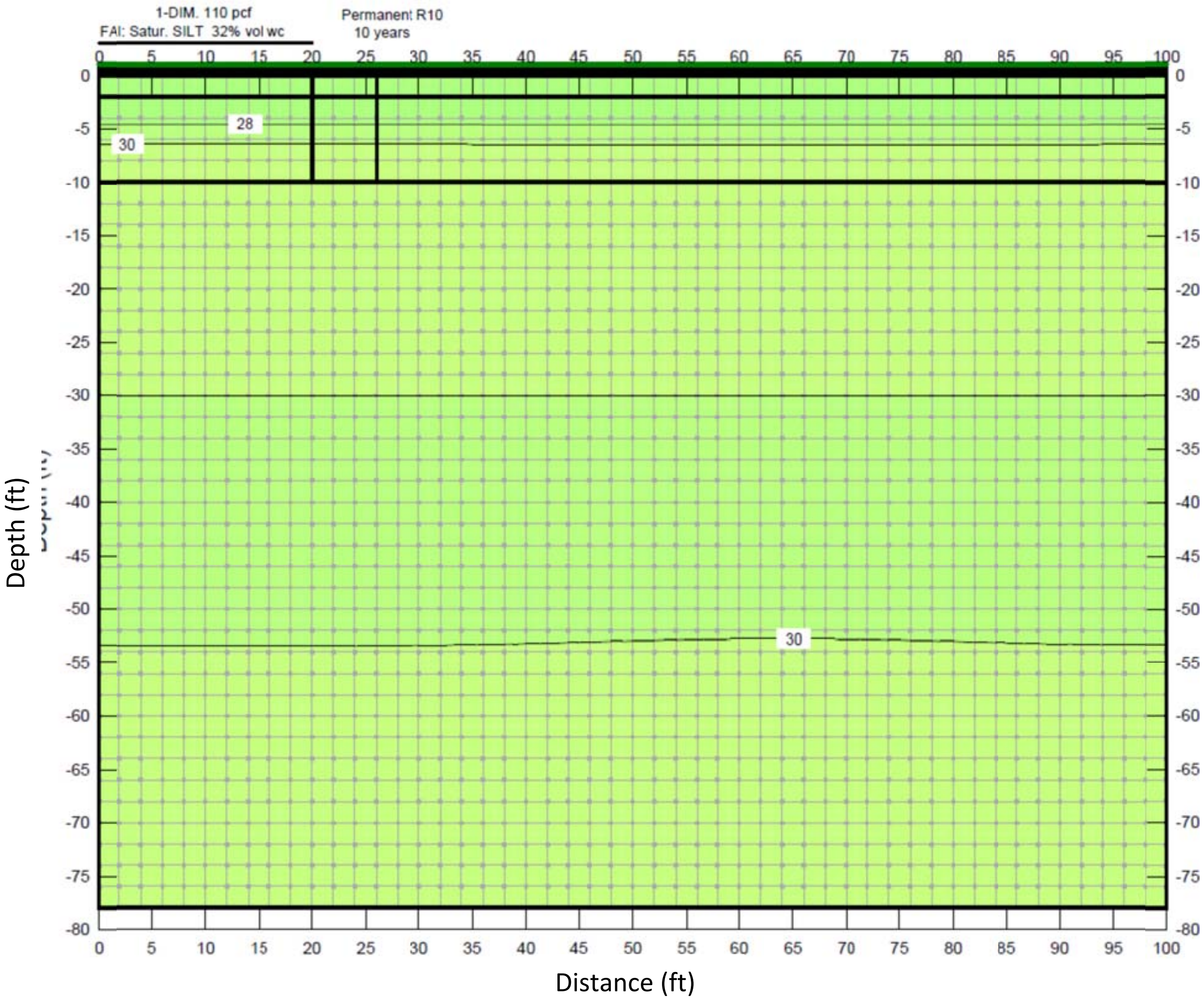

Figure 33. Temp/W print-screen. The modeling region measured 100 ft wide by 78 ft deep.

4.2.1.2 Boundary conditions.

I represented both left and right edges of each analysis-region as zero heat-flux boundaries (i.e., no heat flow out through the sides). I introduced only geothermal heat flux entering at the bottom of the region. I used a geothermal heat flux of 65 mW /m^2 (0.0206 Btu/hr-ft^2). I used climate conditions for the upper boundary.

4.2.1.3 Current climate temperature input.

Fairbanks (latitude 64.8° North) was chosen as one site. Fairbanks is in the discontinuous permafrost zone. More importantly, its frozen-soils temperatures are warmer, averaging close to -1 °C.

Because of the relatively warm permafrost, site development, alone, may lead to permafrost degradation even with current climate. Therefore, climate warming may more significantly alter the frozen ground regime. Current infrastructure, designed for frozen soils, may have higher risks of damage. Here, further warming of the soils temperatures from climate warming may change the fundamental design parameters from permanently frozen ground to seasonally frozen ground.

Kotzebue and Barrow (latitude 66.9° North and latitude 17.3° North) both have colder annual temperatures and are considered within the continuous permafrost zone. Kotzebue and Barrow may be equally at risk of permafrost degradation due to soil-salinity from their maritime locations. Saline permafrost percentages of 1.5 % or more may reduce the soils freezing point to -5 °C (23 °F) (Vyalov et al., 1993b). Soils salinity contents as low as 5 parts per 1 000 parts has been reported to reduce pile-capacities by about 50 %. Increased salinity, at 15 parts per 1 000 parts, may reduce load capacity by 90 % (Humlum, Instanes, & Sollid, 2003). The presence of saline soils, with freeze point depression, changes the effective ratio of thawing index to freezing index. That ratio-change reflects a higher sensitivity of saline soils to thermal warming. Further investigation of saline soils was outside the scope of this research.

The Alaska Climate Research Center (http://climate.gi.alaska.edu/Climate/Normals) was the source for the current mean air temperatures used in the analyses. Table 6 shows the averages from the years 1981 to 2010. Earlier thermal analysis models used similar but slightly different temperature values.

Table 6.
Monthly Mean-Air-Temperatures 1981 to 2010

Month	Fairbanks Mean Air Temp.		Kotzebue Mean Air Temp.		Barrow Mean Air Temp.	
	°C	°F	°C	°F	°C	°F
Jan	-22.2	-7.9	-19.3	-2.8	-25.2	-13.4
Feb	-18.5	-1.3	-18.2	-0.8	-25.7	-14.2
Mar	-11.4	11.4	-17.2	1.1	-24.8	-12.7
Apr	0.3	32.5	-10.4	13.3	-16.8	1.8
May	9.7	49.4	-0.1	31.9	-6.1	21.1
Jun	15.8	60.4	7.6	45.7	2.0	35.6
Jul	16.9	62.5	12.6	54.6	4.9	40.9
Aug	13.4	56.1	10.9	51.7	3.9	39
Sep	7.2	44.9	5.7	42.3	0.1	32.1
Oct	-4.3	24.2	-4.3	24.3	-8.2	17.2
Nov	-16.3	2.6	-12.7	9.1	-17.4	0.7
Dec	-20.1	-4.1	-16.5	2.3	-22.1	-7.8
Annual Average	-2.4	27.7	-5.1	22.9	-11.2	11.8

4.2.1.4 Surface temperature adjustments (“n-factors”).

Measured surface temperatures vary from air temperatures due to a variety of ground surface conditions such as snow or vegetation presence. The adjustment-factor for obtaining surface temperatures from air temperatures is the “n-factor.” The n-factor is the surface temperature divided by the air temperature for temperatures given in °C. A winter n-factor less than 1.0 means the winter surface temperatures are warmer (i.e., less negative from the 0°C freezing point) than the corresponding winter air temperatures. By contrast, a summer n-factor greater than 1.0 also means the surface temperatures are warmer (i.e., more positive from the 0 °C freezing point) than the air temperatures. I obtained n-factors from personal communication with Dr. Yuri Shur. Table 7 lists the n-factors used.

The one-dimensional analyses used different n-factors for (A) winter or summer, (B) with snow, and (C) without snow (i.e., wind-driven or plowed). Table 7 lists the n-factors used in the models. These ‘n-factors’ have been taken from Department of the Army technical manuals (UFC, 2004b; UFC, 2004c).

Surface temperature calculations are from the freezing point. Unlike calculations using Celsius degrees, surface temperature calculations for Fahrenheit degrees are from +32 °F. For Fahrenheit calculations, the numerical sign may change. Because of this sign change, simply using the arithmetic modification factor within the Temp/W program did not work for adjusting Fahrenheit air temperatures to surface temperatures. The Fahrenheit sign-change created a numerical singularity around the -17.8 °C (0 °F) soil temperature. A simple modification factor changed sign from positive infinity to negative infinity. With this limitation discovered, I changed each analysis. I calculated surface temperatures using a separate Excel spreadsheet, outside of the Temp/W program. Sample calculations follow. Table 8, below, shows example surface temperatures based upon location and season.

Table 7.
"n-factor" Surface Temperature Correction

Location	Condition	Seasonal n-factor	
		Winter	Summer
Under Building	Open	0.9	0.9
Away from Building	Snow covered	0.6	1.3
	Snow Removed	0.9	1.3

Table 8.
Applying n-factors for Surface Temperature Inputs

Month	Air Temp.		Surface Temp.							
			Under Building Open				Away From Building Snow Covered			
			Winter n=0.9		Summer n=0.9		Winter n=0.6		Summer n=1.3	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
Jan	-22.2	-7.9	-19.9	-3.9	n/a	n/a	-13.3	8.1	n/a	n/a
Jun	15.8	60.4	n/a	n/a	14.2	57.6	n/a	n/a	20.5	68.9

			Away From Building Snow Removed			
			Winter n=0.9		Summer n=1.3	
	°C	°F	°C	°F	°C	°F
Jan	-22.2	-7.9	-19.9	-3.9	n/a	n/a
Jun	15.8	60.4	n/a	n/a	20.5	68.9

A sample calculation for winter surface temperatures follows (Table 8).

Fairbanks, January air temperature, -7.9 °F.

32 °F – (-7.9 °F) = 39.9 °F

(This 39.9 °F is the total freezing impulse [amount below freezing] from the -7.9 °F air temperature.)

n-factor, away from building, snow covered: 0.6 (shows warming effect of snow)

0.6 x 39.9 = 23.9 °F below the freezing point of 32 °F.

(This 23.9 °F is the reduced freezing impulse onto the surface due to snow.)

32 – 23.9 = 8.1 °F

(I used this 8.1 °F soils surface temperature as input for the analyses.)

A sample calculation for summer surface temperatures follows (Table 8).

Fairbanks, June air temperature, 60.4 °F.

60.4 °F -32 °F = 28.4 °F

(This 28.4 °F is the total thawing impulse [amount above freezing] from the +60.4 °F air temperature.)

n-factor, away from building, summer: 1.3 (shows warming effect due to vegetation)

1.3 x 28.4 = 36.92 °F above the freezing point of 32 °F.

(This 36.92 °F is the increased thawing impulse onto the ground surface.)

32 + 36.9 = 68.9 °F

(I used this 68.9 °F soils surface temperature as input for the analyses.)

I did not use Temp/W automatic recurring sinusoidal input for temperatures, even though using this provision would have simplified the input. I wanted the analyses input-temperatures to reflect the actual data from the Alaska Climate Research Center more closely. Therefore, I input each of the surface temperatures manually.

4.2.1.5 Analyses startups and run times.

First, each analysis model was set to a steady state surface temperature that varied with location (Table 9). The steady state model included the geothermal heat flux input into the bottom of the region. I prepared the modeling runs by inputting location-specific soil surface temperature data (i.e., climatic data adjusted by n-factor to soils temperatures) and without any thermal insulation changes.

I performed the various runtimes in sequence. The steady state results became the basis for the 10-years of no change analyses. This 10-year no change condition remained constant for each analysis, both for the 1D runs with no buildings in place, and for the 2D runs with buildings in place. After the 10-year baseline run, with no insulation, each changed condition analysis with insulation, computed an additional 10-years of results, bringing the total runtime to 20 years.

The seasonal insulation analyses included thermal insulation applied only in the warmer summer months and removed in the cold winter months. Providing the required consistent units needed for the model required using consistent time-units of hours in each model. Each one-dimensional analysis start time began at zero hours and accumulated time extending through the ten years baseline, plus ten additional years of insulation influence evaluation, for a total of 20 years runtime duration.

Table 9.
Start-Up Steady-State Soils Temperatures

Fairbanks		Kotzebue		Barrow	
°C	°F	°C	°F	°C	°F
-1.7	29	-5.0	23	-8.9	16

I performed no site work using permanent insulation. The literature review provided information desired in lieu of site investigations.

I used specific insulation thermal resistance values in the modeling (Table 10). These insulation-amounts represented commonly available rigid polystyrene foam. I selected foam insulation suitable for direct-ground-contact. I varied the thermal-resistance values from RSI 1.76 m^2 °C/W at 50 mm thickness to RSI 7.0 m^2 °C/W at 200 mm thickness (R10 ft^2 ·h ·°F/Btu at 2 inches thick to R40 ft^2 ·h ·°F/Btu at 8 inches thick). Several different insulation materials could meet the thermal resistance values. I did not vary the type of insulation selected. I focused on varying the amount of thermal resistance. The insulation properties came from Andersland and Ladanyi (1994).

4.2.2 Results for permafrost sites without buildings.

I performed several one-dimensional analyses for Fairbanks, Kotzebue, and Barrow. For Barrow, the coldest location investigated, I perform additional analyses. Table 10 provides a matrix showing (A) thermal resistance, (B) duration of installation, (C) snow presence or absence, and (D) internal document links to the figure-locations. I reported output results for mean annual soils temperature (MAST) as well as for seasonal temperature variations. I showed partial results here and the remainder in the appendices.

Table 10.
One-Dimensional Analyses, R-Values, & Resulting Figures

	Thermal Insulation Properties				Snow	Temperature Results	
Location	Common Name	Thermal Resistance m^2 °C/W (ft^2 hr °F/Btu)	Thickness mm (in)	Duration	Present In Winter	Seasonal Variations	MAST
Fairbanks Table 11	None	zero	zero	n/a	Yes	Figure 34	Figure 37
	R10	1.8 (10)	51 (2)	Permanent	Yes	Figure 35	
				Seasonal	Yes	Figure 36	
Kotzebue Table 12	None	zero	zero	n/a	Yes	Figure 38	Figure 41
	R10	1.8 (10)	51 (2)	Permanent	Yes	Figure 39	
				Seasonal	Yes	Figure 40	
Barrow Table 13	None	zero	zero	n/a	No	Figure 42	Figure 48
					Yes	Figure 43	
	R10	1.8 (10)	51 (2)	Permanent	No	Figure 44	
					Yes	Figure 43	
				Seasonal	No	Figure 46	
					Yes	Figure 47	
	R20	3.5 (20)	102 (4)	Permanent	No		See Appendices
					Yes		
				Seasonal	No		
					Yes		
	R40	7.0 (40)	203 (8)	Permanent	No		See Appendices
					Yes		
				Seasonal	No		
					Yes		

4.2.2.1 Fairbanks.

Fairbanks one-dimensional analyses results showed several thermal-regime differences between the no-insulation, the permanent R10 insulation, and the seasonal R10 insulation cases. All of the Fairbanks analyses considered snow covered conditions only (Table 11).

Without any insulation (Figure 34), results showed the greatest winter-to-summer change in surface temperature. Results showed a surface-temperature-amplitude of about 29 °C (53 °F). The winter cold surface results showed -11.5 °C (11.2 °F). The summer warm surface results showed 17.7 °C (63.9 °F). The mean annual soils temperature (MAST) results showed values from the surface to 24 m (78 ft) deep. The no-insulation analyses showed an anticipated October 5 active layer thaw depth for these saturated silts of about 3.4 m (11 ft).

With permanent R10 insulation (i.e., when the insulation was left in place all winter and all summer) (Figure 35), the results changed. Results showed that the surface temperature amplitude decreased to less than 5 °C (9.0 °F). The winter cold surface results showed -1.3 °C (29.7 °F). The summer warm surface results showed 3.7 °C (38.6 °F). In spite of the decreased surface temperature amplitude, the results showed an increased active layer depth when compared to the no-insulation case. The active layer thaw-depth increased in the presence of permanent insulation to almost 4 m (13ft).

Changing to seasonal R10 insulation (Figure 36), the analyses results changed further. The presence of seasonal insulation showed a surface-temperature amplitude between the no-insulation case and the permanent-insulation case: 12.8 °C (23.1 °F). The winter cold surface results showed -13.00 °C (8.6 °F). The summer warm surface results showed -0.17 °C (31.7 °F). With seasonal R10 insulation, the active layer disappeared completely. Restated, the results showed no thawing at all below the seasonal insulation.

The mean annual soils temperature (MAST) profile also changed (Figure 37). Results showed close similarities between the no-insulation case and the permanent R10 insulation case. With permanent R10 insulation, MAST differences showed permafrost warming (not cooling) at depths below 2.4 m (8ft). By contrast, with seasonal insulation, MAST differences showed cooling at all depths shallower than 11.6 m (38 ft).

Table 11.
Fairbanks One-Dimensional Resulting Values

		Fairbanks Surface Temperatures			Active Layer	Mean Annual Soils Temp. Remarks (MAST)
Insulation Condition	Snow Condition	Amplitude °C (°F)	Winter Cold °C (°F)	Summer Warm °C (°F)	Thaw Depth m (ft)	
No-insulation	With Snow	29 (53)	-11.5 (11.2)	17.7 (63.9)	3.4 11	Initial Conditions
Permanent R10	With Snow	5 (9.0)	-1.3 (29.7)	3.7 (38.6)	4 (13)	Warmer Soils below 2.4 m (8 ft)
Seasonal R10	With Snow	12.8 (23.1)	-13 (8.6)	-0.2 (31.7)	Frozen All year	Colder Soils above 11.6 m (38 ft)

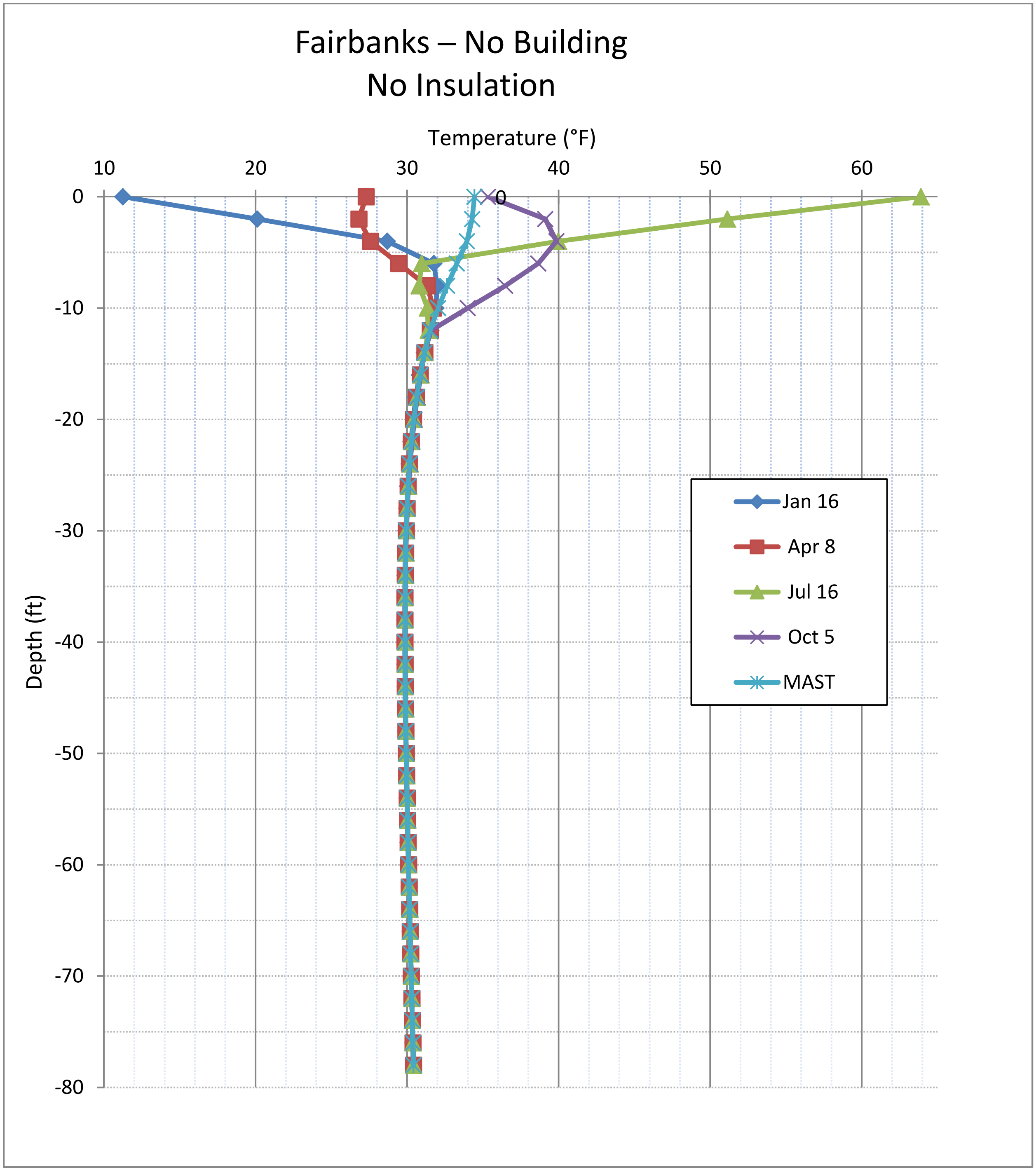

Figure 34. Fairbanks 1D, no insulation condition.
Temperature distribution with depth during the year, to evaluate initial conditions for 2D models.
Conditions included no insulation, winter snow cover, and summer bare soil surface.

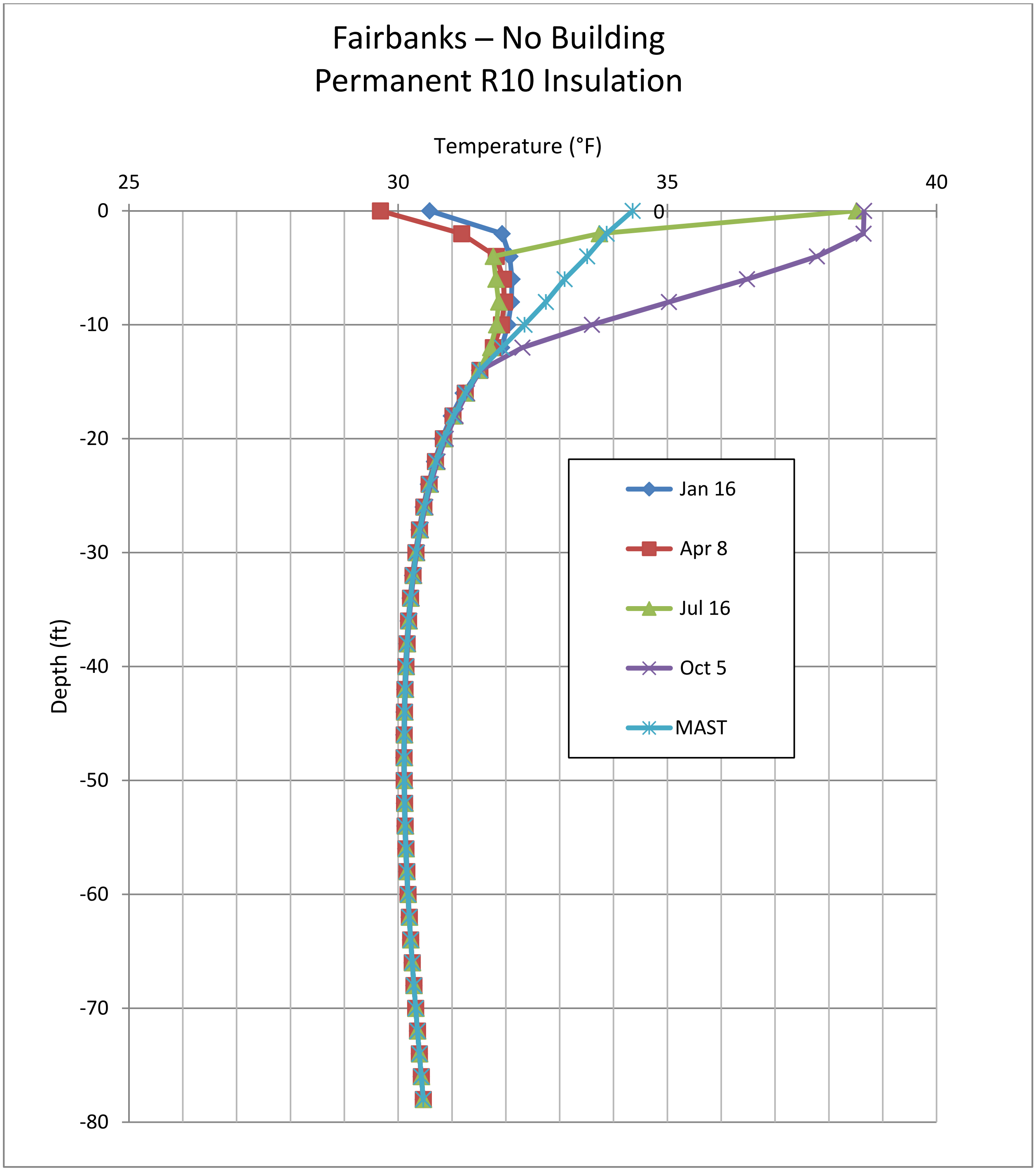

Figure 35. Fairbanks 1D, R10 permanent thermal insulation condition.
Temperature distribution with depth during the year.
Conditions included permanent insulation, winter snow cover, and summer bare soil surface.

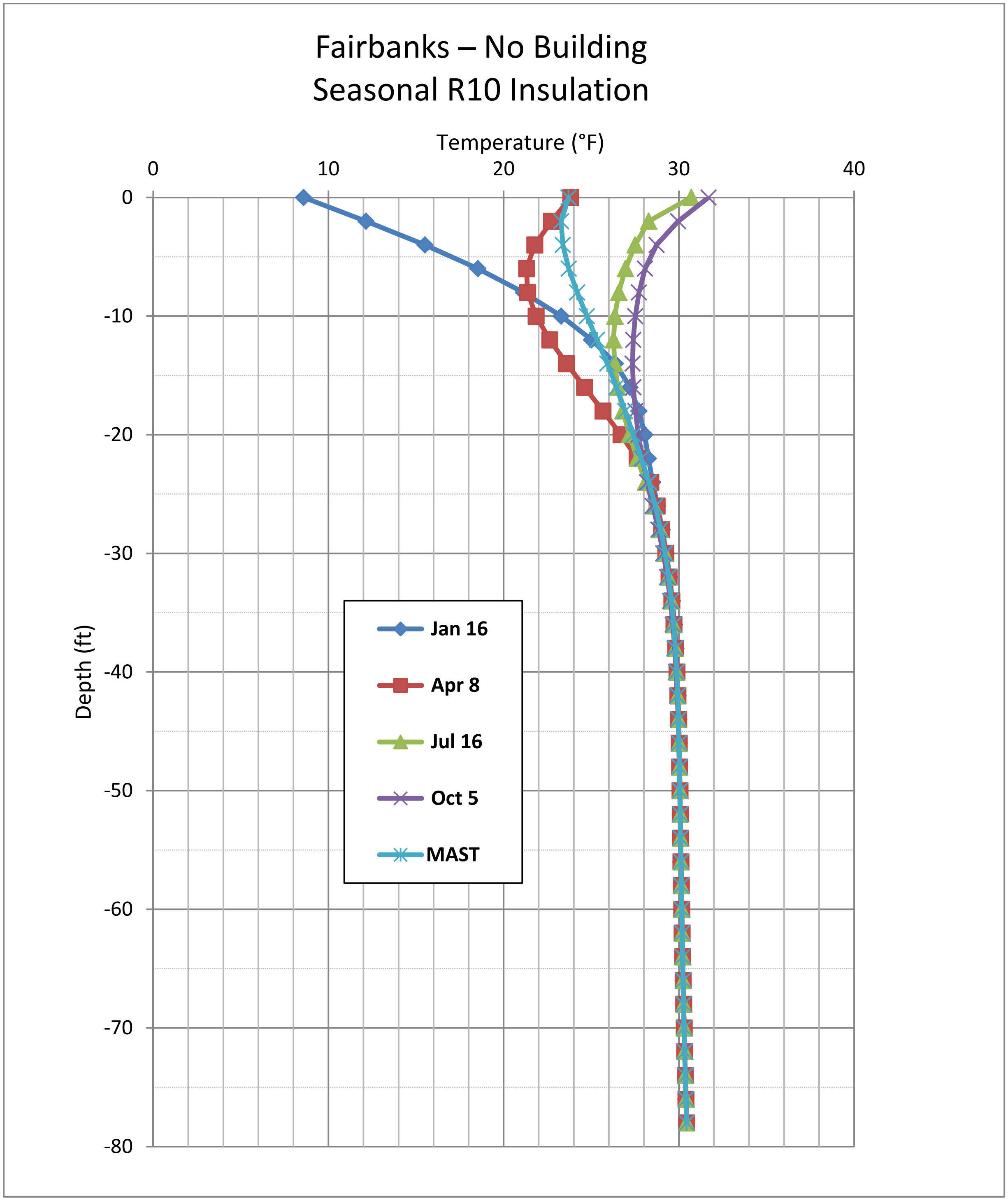

Figure 36. Fairbanks 1D, R10 seasonal thermal insulation after 10 years.
Temperature distribution with depth during the year.
Conditions included seasonal insulation, winter snow cover and bare summer soil surface.

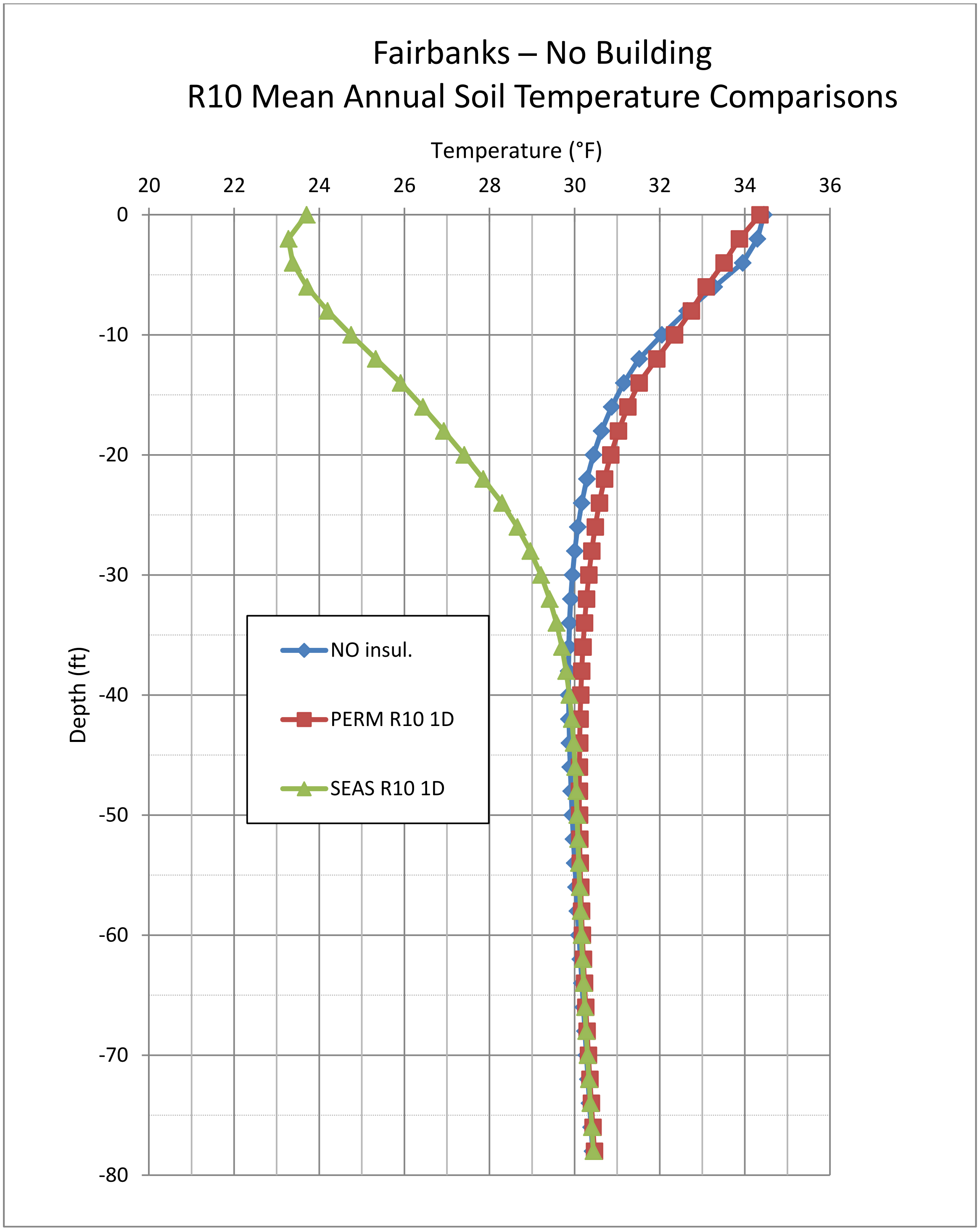

Figure 37. Fairbanks 1D, R10 thermal insulation, mean annual soil temperatures. Conditions included winter snow cover and bare soil in the summer. It contrasts 10 years using seasonal insulation (left plot) against no insulation and permanent insulation (right plots).

4.2.2.2 Kotzebue.

Kotzebue results, for one-dimensional analyses, showed similar thermal-regime changes as for Fairbanks. The no-insulation case was different from the permanent R10 insulation and different from the seasonal R10 insulation case. The Kotzebue analyses, like Fairbanks, considered snow covered conditions only (Table 12).

Without any insulation (Figure 38), Kotzebue results, like Fairbanks, showed the greatest winter-to-summer change in surface temperature. Results showed a surface-temperature-amplitude of about 18.9 °C (34 °F). The winter cold surface results showed -9.2°C (15.4 °F). The summer warm surface results showed 9.8 °C (49.7 °F). The mean annual soils temperature (MAST) results showed values from the surface to 24 m (78 ft) deep. The no-insulation analyses showed an anticipated maximum summer active layer thaw depth for these saturated silts of about 1.5 m (5 ft).

With permanent R10 insulation (i.e., the insulation remained in place all winter and all summer) (Figure 39), the Kotzebue results also changed. Results showed that the surface temperature amplitude decreased to about 4 °C (7.3 °F). The winter cold surface results showed -4.5 °C (23.8 °F). The summer warm surface results showed -0.5 °C (31.1 °F). Unlike Fairbanks, due to colder climate in Kotzebue, the Kotzebue results showed no active layer thaw depth with permanent R10 insulation.

Changing to seasonal R10 insulation (Figure 40), showed a surface-temperature amplitude between the no-insulation case and the permanent-insulation case, 9.8 °C (17.6 °F). The winter cold surface results showed -10.6 °C (13.0 °F). The summer warm surface results showed -0.8 °C (30.6 °F). In Kotzebue, with seasonal R10 insulation, just as with permanent R10, results showed that the active layer disappeared completely.

The Kotzebue mean annual soils temperature (MAST) profile also changed (Figure 41). Like Fairbanks, results for Kotzebue with permanent R10 insulation showed permafrost warming (not permafrost cooling) at all depths deeper than about 1.2 m (4 ft). Seasonal R10 insulation results showed colder MAST throughout the full soils strata depths investigated. The seasonal R10 insulation surface MAST result showed 4 °C (7.3 °F) colder mean annual soils surface temperature than with permanent R10 insulation. At 23.8 m (78 ft) deep, the seasonal R10 insulation MAST results showed permafrost cooling by as much as 1.4 °C (2.6 °F).

Table 12.
Kotzebue One-Dimensional Resulting Values

		Kotzebue Surface Temperature			Active Layer	Mean Annual Soils Temp. Remarks (MAST)
Insulation Condition	Snow Condition	Amplitude °C (°F)	Winter Cold °C (°F)	Summer Warm °C (°F)	Thaw Depth m (ft)	
No-insulation	With Snow	18.9 (34)	-9.2 (15.4)	9.8 (49.7)	1.5 (5)	Initial Conditions
Permanent R10	With Snow	4 (7.3)	-4.6 (23.8)	-0.5 (31.1)	Frozen All year	Warmer Soils below 1.2 m (4 ft)
Seasonal R10	With Snow	9.8 (17.6)	-10.6 (13.0)	-0.8 (30.6)	Frozen All year	Colder Soils Throughout The Strata

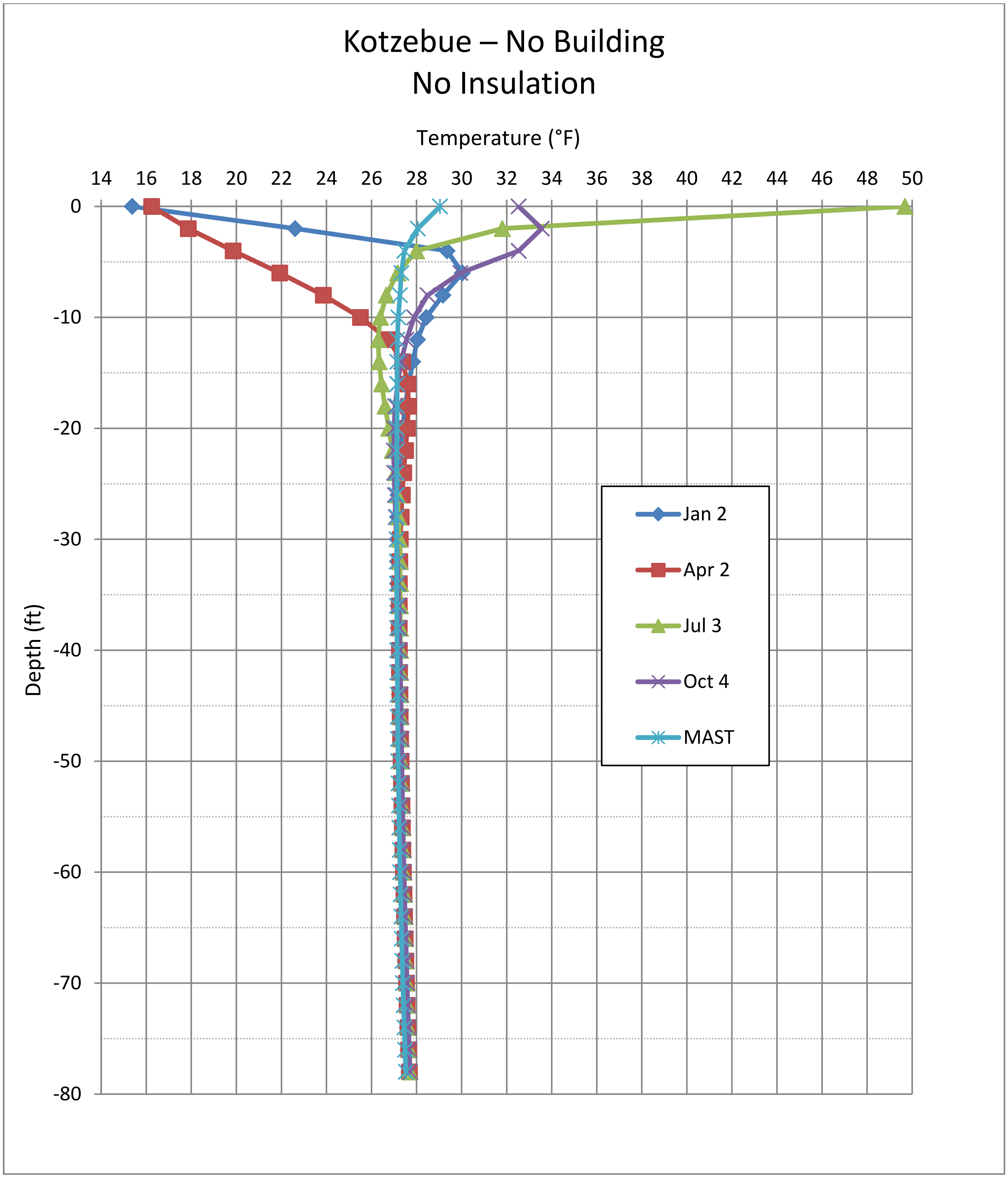

Figure 38. Kotzebue 1D, no insulation condition.
Temperature distribution with depth during the year, to evaluate initial conditions for 2D models.
Conditions included no insulation, winter snow cover, and summer bare soil surface.

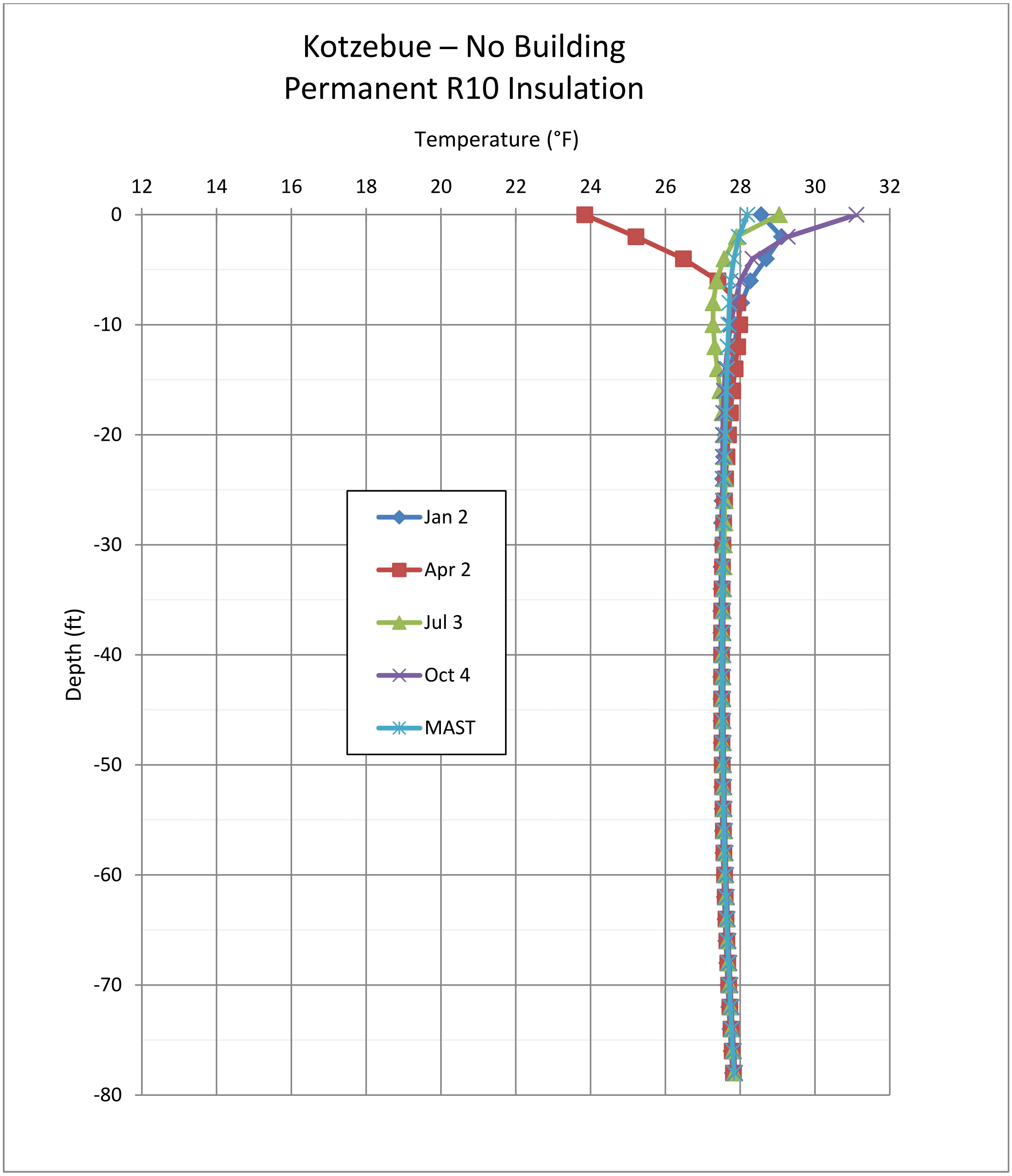

Figure 39. Kotzebue 1D, R10 permanent thermal insulation condition.
Temperature distribution with depth during the year.
Conditions included permanent insulation, winter snow cover, and summer bare soil surface.

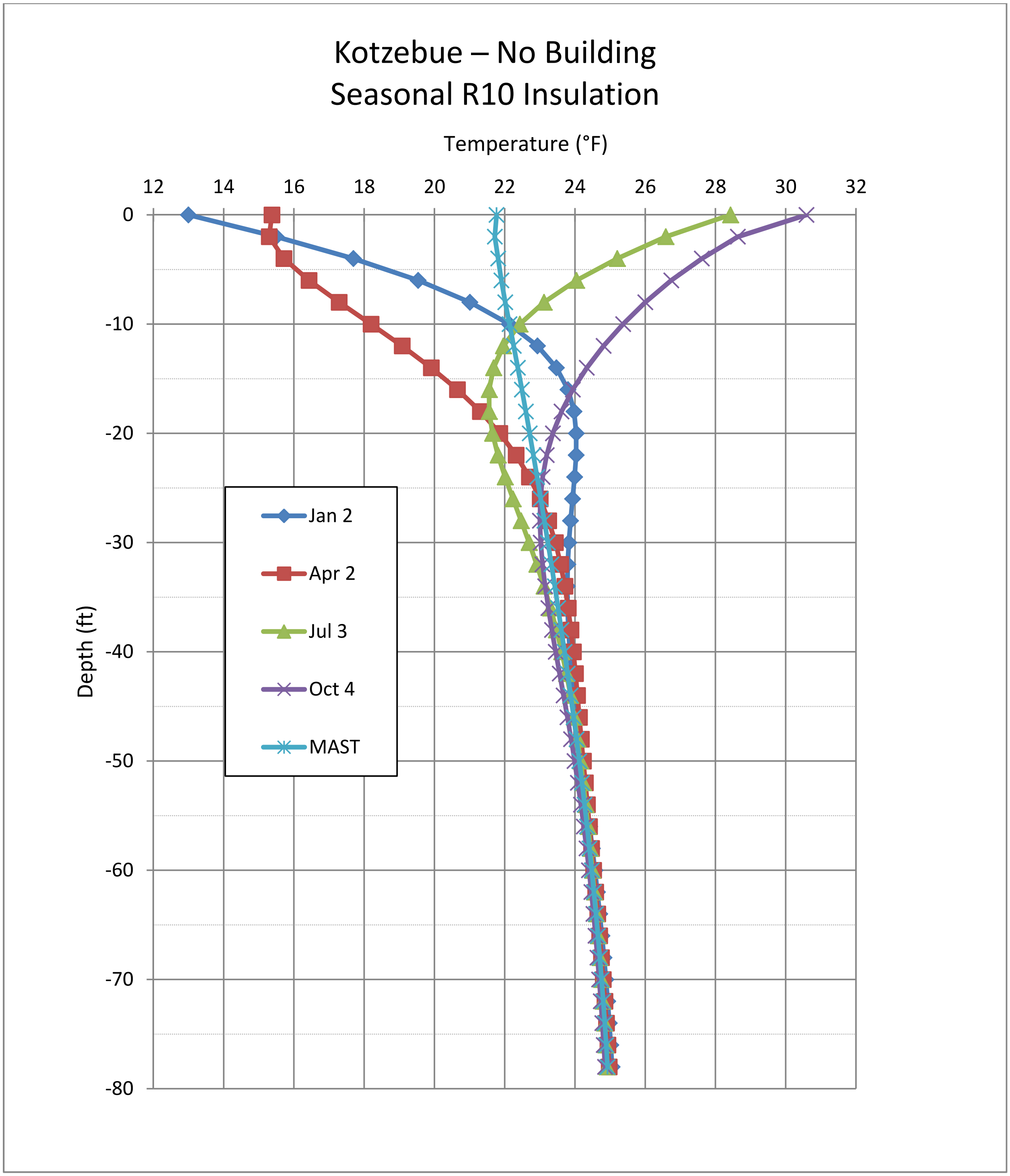

Figure 40. Kotzebue 1D, R10 seasonal thermal insulation after 10 years.
Temperature distribution with depth during the year.
Conditions included seasonal insulation, winter snow cover, and summer bare soil surface.

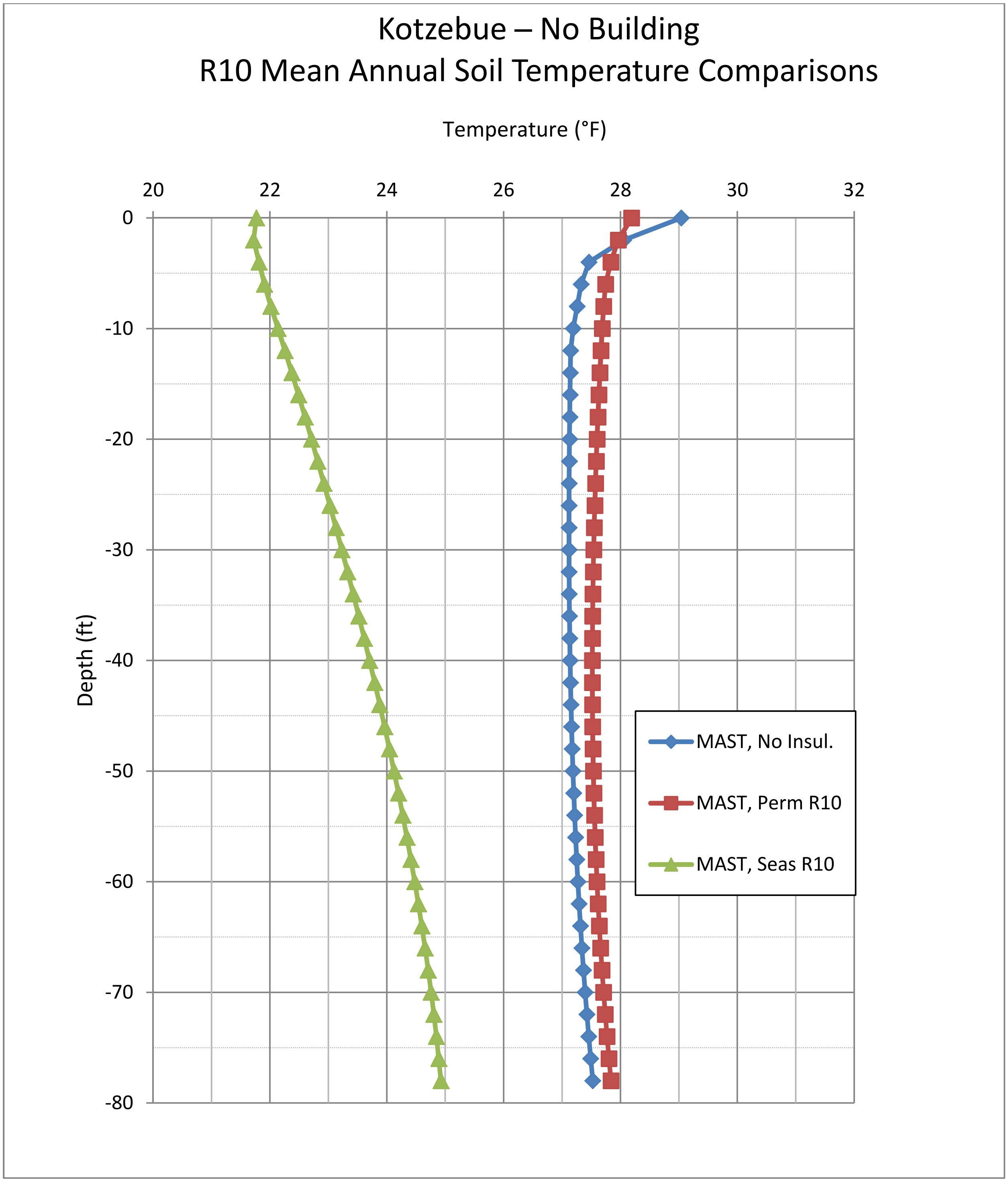

Figure 41. Kotzebue 1D, R10 thermal insulation, mean annual soil temperatures. Conditions included winter snow cover and bare soil in the summer. It contrasts 10 years usage of seasonal insulation (left plot) against no insulation and permanent insulation (right plots).

4.2.2.3 Barrow.

For Barrow, I performed several more one-dimensional analyses. For the insulation values, I included three increasing thermal resistances, R10, R20, and R40. I considered the impacts of drifting snow and of wind-driven snow. The ground surface may be bare or have snow drifted. Therefore, I also analyzed the soils thermal regime impacts from bare ground as well as snow-covered ground (Table 10).

In Table 13, I tabularized selected numerical results (A) for no insulation case, no snow and with snow cases; (B) for permanent insulation, no snow and with snow cases, and (C) for seasonal insulation, no snow and with snow cases. In addition, I presented the output-figures for Barrow in parallel-displays. For side-by-side viewing, I displayed the "no-snow" case first, followed by the "snow-covered" case. The R10 output figures, shown in the main document, displayed similar results as for R20 and R40 increased insulation amounts, shown in the appendices.

Surface thermal results displayed the largest range of temperature swing for the "no-insulation" case, both for the "no-snow" case and the "With Snow Cover" case. The with-snow case warmed the surface soils by almost 5.6 °C (10 °F). Applying permanent insulation resulted in permafrost warming (not cooling). By contrast, applying seasonal insulation resulted in permafrost cooling.

Table 13.
Barrow One-Dimensional Resulting Values

			Barrow Surface Temperatures		Active Layer	Mean Annual Soils Temp. (MAST)	
Insulation *		Surface	Winter	Summer	Thaw Depth	At Surface, & At 23.8 m (78 ft) deep °C (°F)	Permafrost Temperature Change at 6 m (20 ft) deep
Common Name	How Applied	No Snow or Snow Covered	Cold °C (°F)	Warm °C (°F)	m (ft)	°C (°F)	°C (°F)
None Page 106	None	No Snow	-23.6 (-10.5)	1.3 (34.3)	0.2 (0.7)	- 11.7 (11) -10.6 (13)	Base Line
		Snow Covered	-14.1 (6.6)	2.6 (36.6)	-17.2 (1.0)	-6.6 (20.2) -6.2 (20.8)	
R10 Page 108	Permanent	No Snow	-16.0 (3.2)	-5.8 (21.6)	Remains frozen	-10.8 (12.5) -9.7 (14.5)	+0.78 (+1.4)
		Snow Covered	-9.4 (15.0)	-2.9 (26.8)	Remains frozen	-6.2 (20.9) -5.7 (21.8)	+0.67 (+1.2)
	Seasonal	No Snow	-23.7 (-10.7)	-4.4 (24.0)	Remains frozen	-13.4 (7.9) -11.4 (11.4)	-1.3 (- 2.3)
		Snow Covered	-14.2 (6.4)	-2.2 (28.1)	Remains frozen	-7.9 (17.8) -6.8 (19.8)	-0.67 (- 1.2)
R20 See Appendices	Permanent	No Snow	14.1 (6.6)	-7.5 (18.5)	Remains frozen	-10.6 (12.9) -9.4 (15.0)	+1.0 (+1.8)
		Snow Covered	-8.4 (16.9)	-4.2 (24.4)	Remains frozen	-6.2 (20.9) -5.8 (21.6)	+0.67 (+1.2)
	Seasonal	No Snow	-23.8 (-10.8)	-6.7 (19.9)	Remains frozen	-14.2 (6.5) -12.0 (10.4)	-1.9 (-3.4)
		Snow Covered	-14.2 (6.4)	-3.9 (24.9)	Remains frozen	-8.3 (17.1) -7.0 (19.4)	-1.0 (-1.8)
R40 See Appendices	Permanent	No Snow	-12.3 (9.9)	-8.3 (17.0)	Remains frozen	-10.2 (13.6) -9.1 (15.6)	+1.4 (+2.5)
		Snow Covered	-7.6 (18.4)	-5.2 (22.6)	Remains frozen	-6.3 (20.7) -6.0 (21.2)	+0.5 (+0.9)
	Seasonal	No Snow	-23.8 (-10.9)	-7.8 (18.0)	Remains frozen	-14.8 (5.3) -12.3 (9.9)	-2.3 (-4.2)
		Snow Covered	-14.3 (6.3)	-4.7 (23.6)	Remains frozen	-8.8 (16.2) -7.3 (18.9)	-1.4 (-2.5)

* See Table 10 for thermal insulation properties.

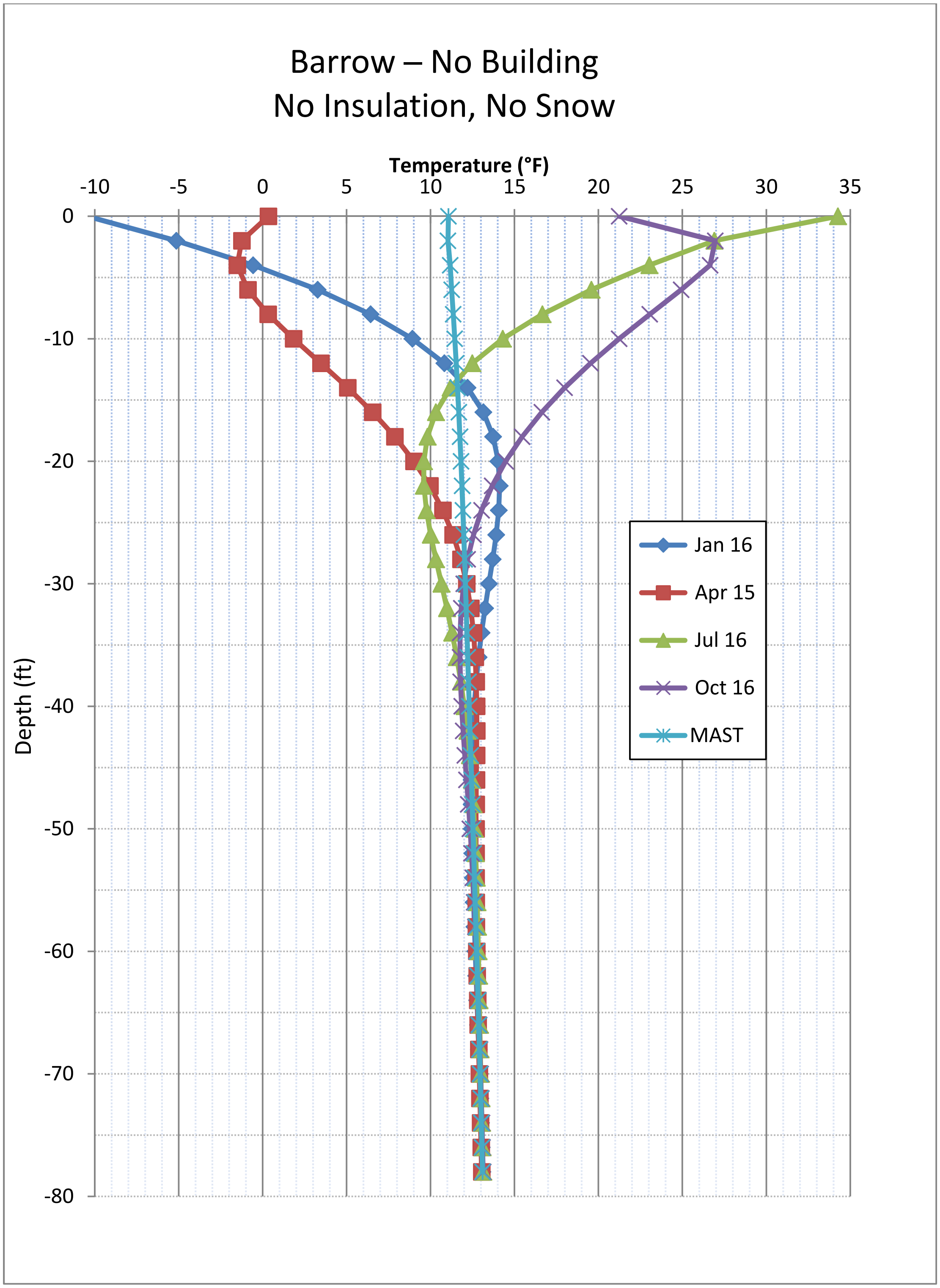

Figure 42. Barrow 1D, no insulation, no snow condition.
Temperature distribution with depth during the year, to evaluate initial conditions for 2D models.
Conditions included no insulation, bare soil surface all year.

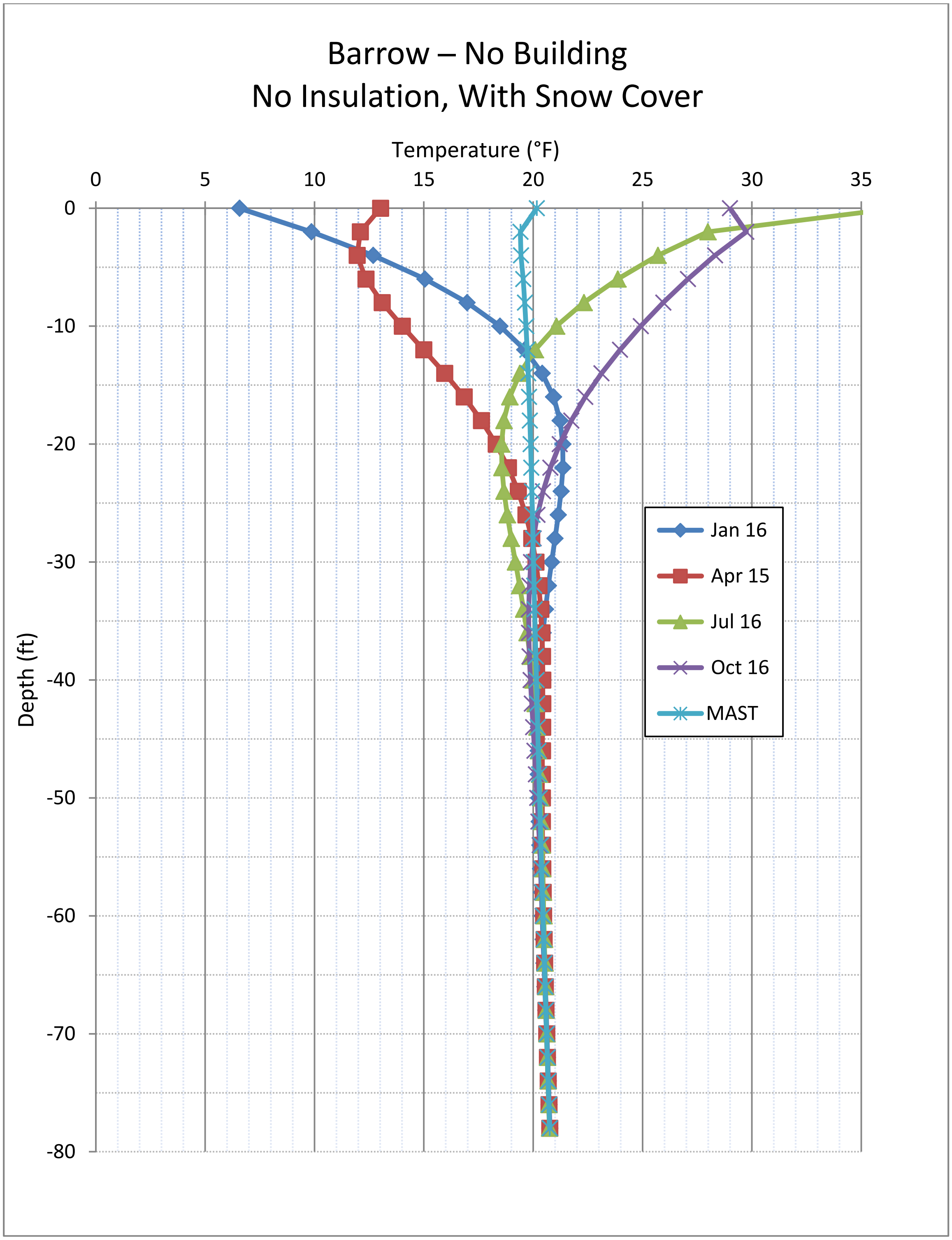

Figure 43. Barrow 1D, no insulation, snow covered condition.
Temperature distribution with depth during the year.
Conditions included no insulation, winter snow cover, and summer bare soil surface.

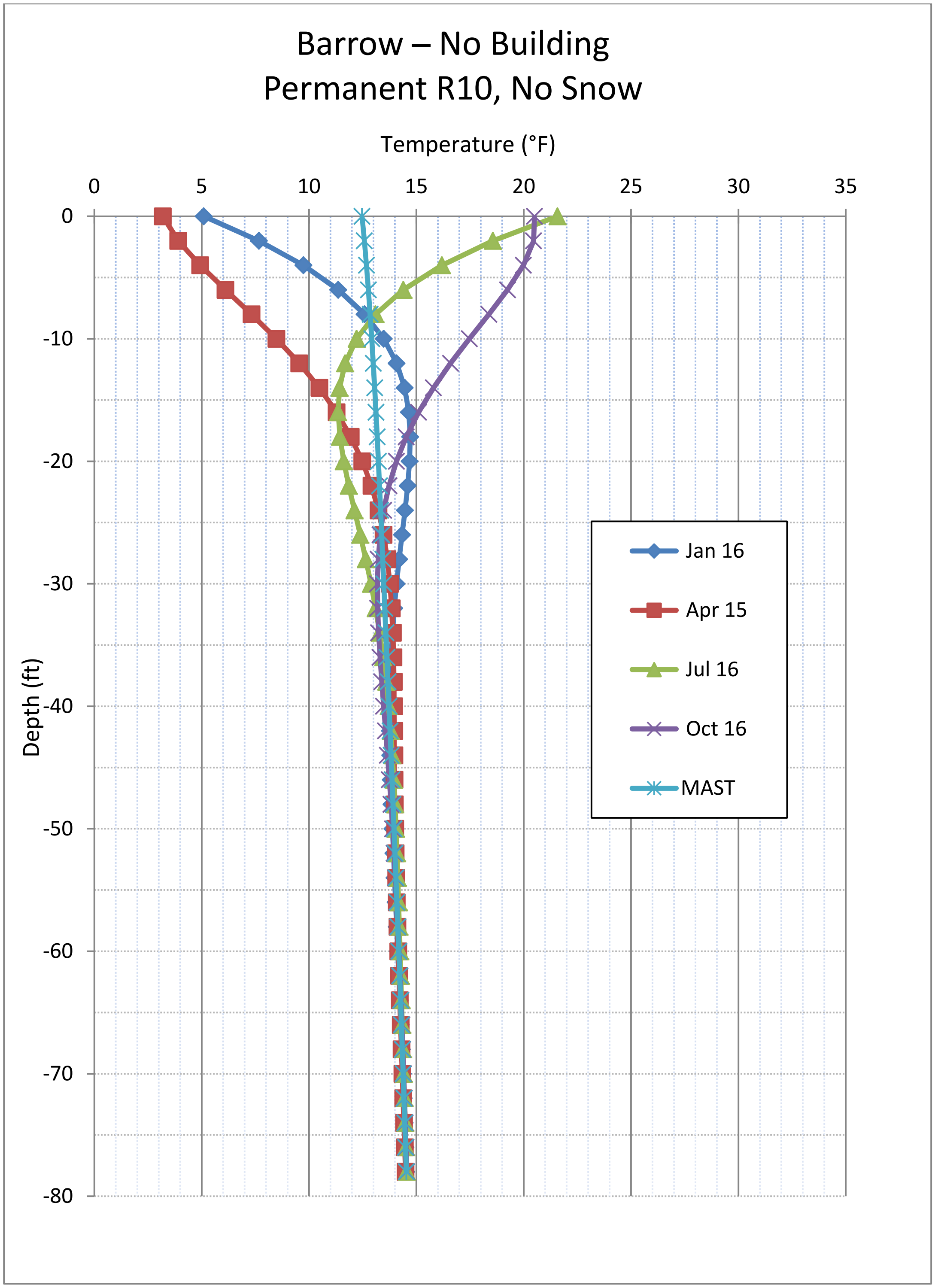

Figure 44. Barrow 1D, R10 permanent thermal insulation, no snow condition.
Temperature distribution with depth during the year.
Conditions included permanent insulation and bare soil surface all year.

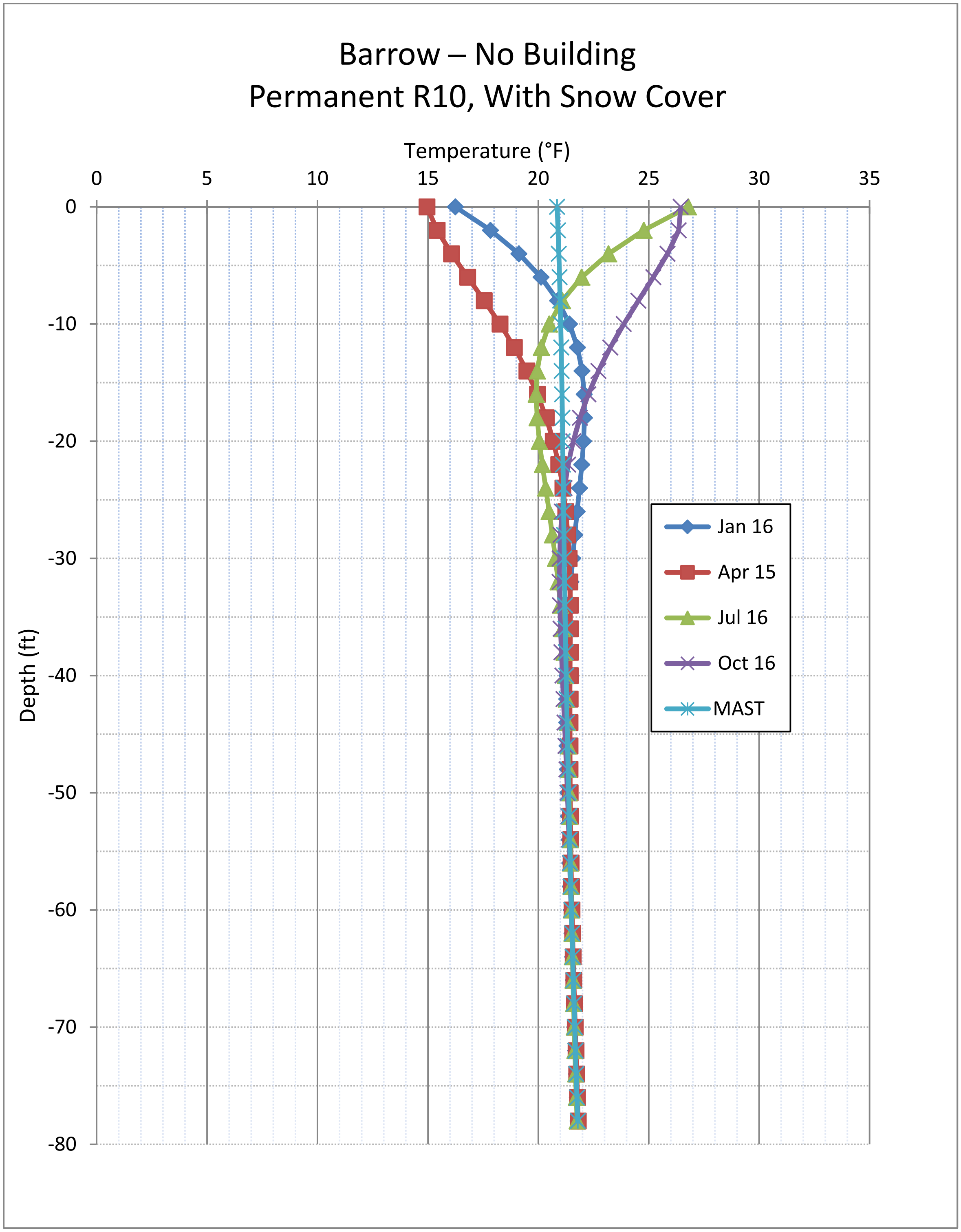

Figure 45. Barrow 1D, R10 permanent thermal insulation, snow covered condition.
Temperature distribution with depth during the year.
Conditions included permanent insulation, winter snow cover, and summer bare soil surface.

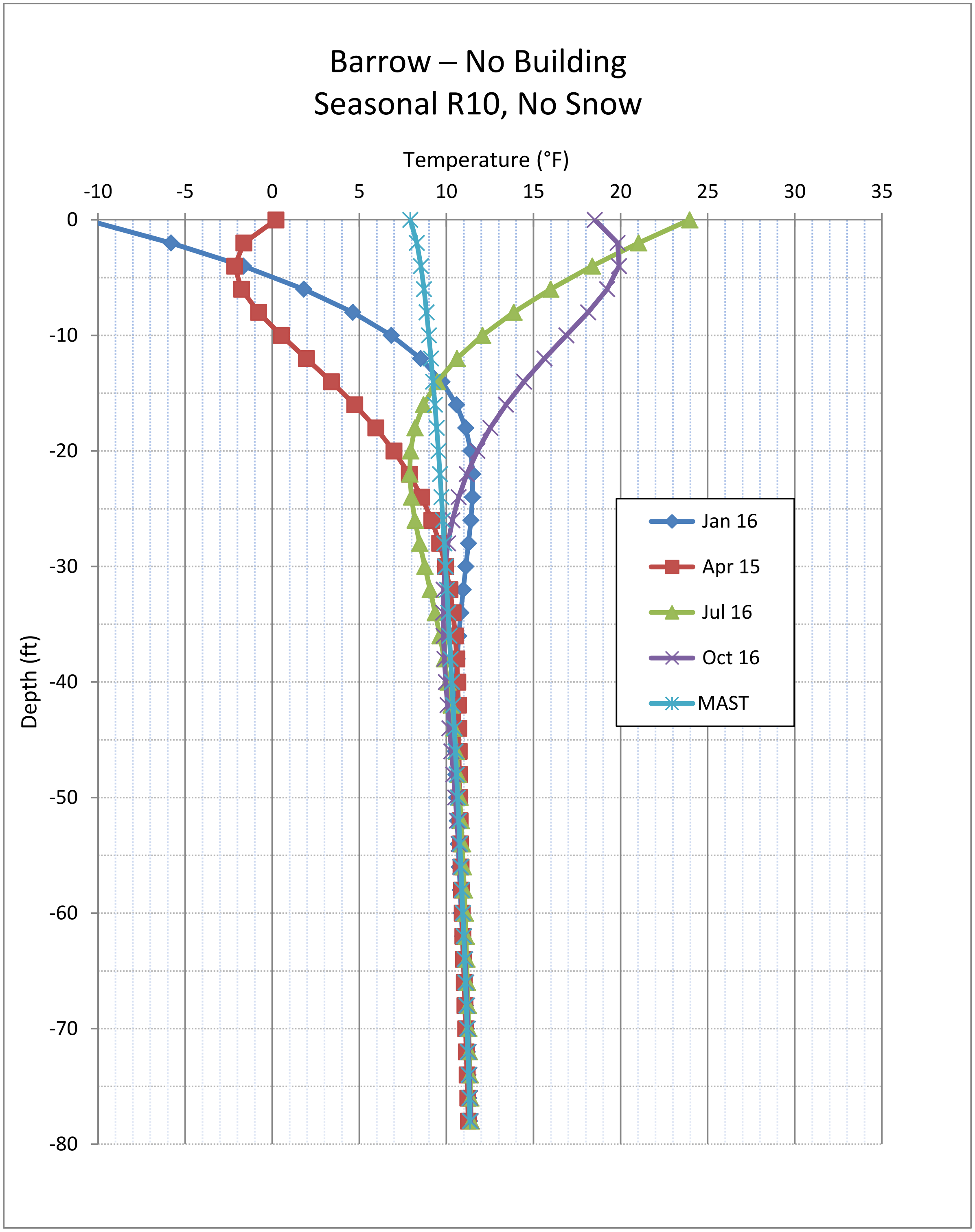

Figure 46. Barrow 1D, R10 seasonal thermal insulation after 10 years, no snow condition. Temperature distribution with depth during the year. Conditions included seasonal insulation and bare soil surface all year

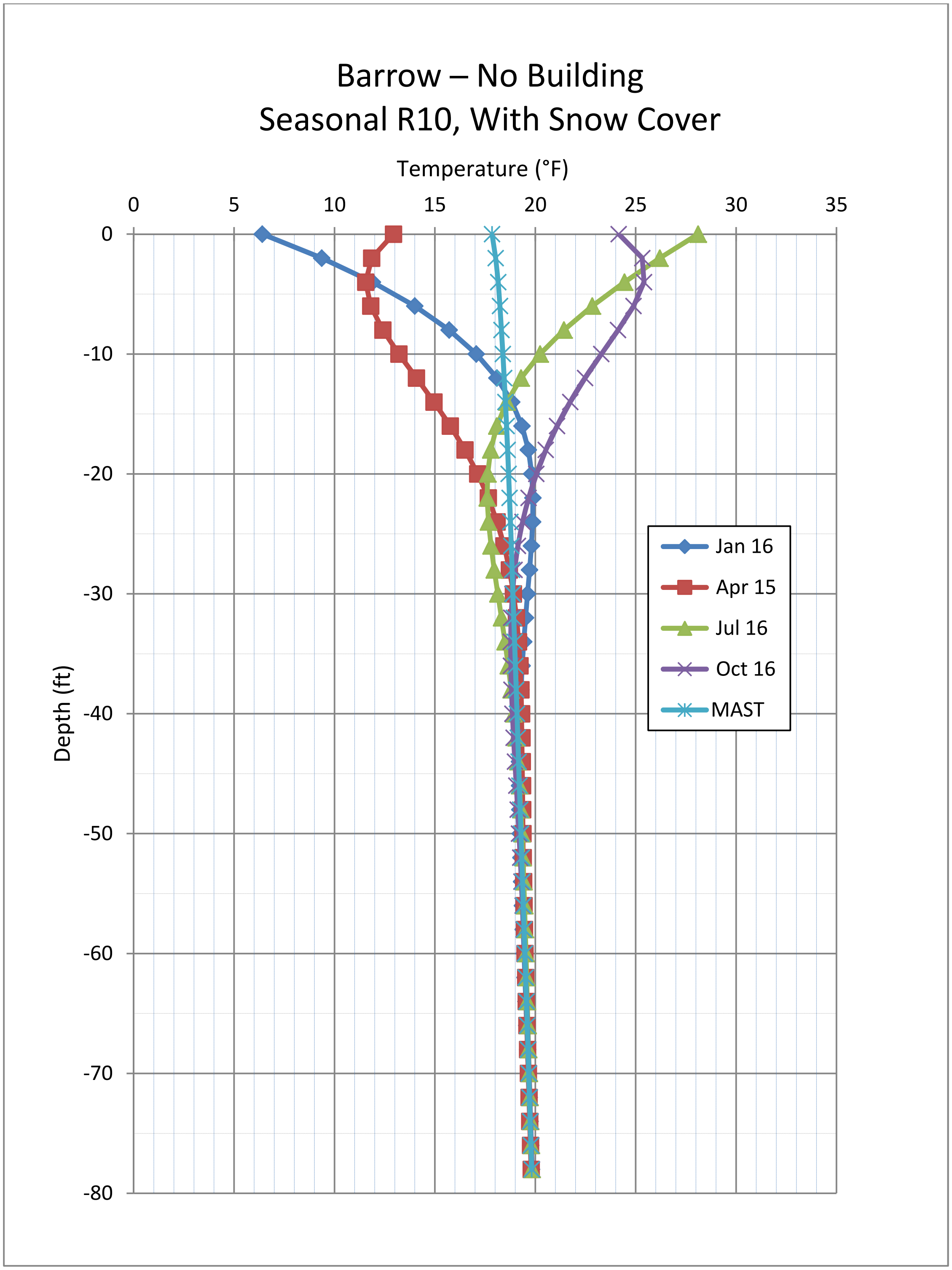

Figure 47. Barrow 1D, R10 seasonal thermal insulation after 10 years, snow covered condition.
Temperature distribution with depth during the year.
Conditions included permanent insulation, winter snow cover, and summer bare soil surface.

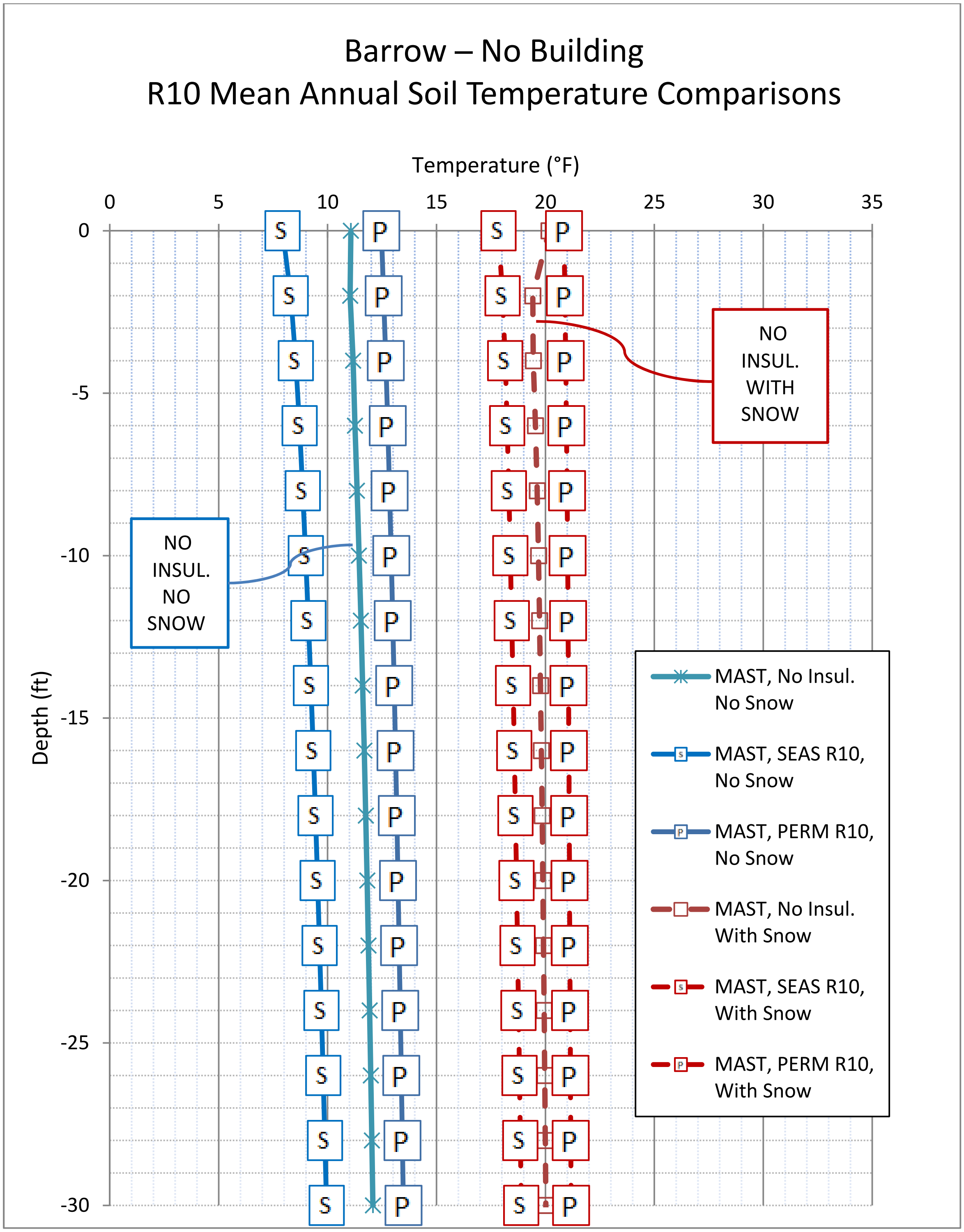

Figure 48. Barrow 1D, R10 thermal insulation, mean annual soil temperatures.
Conditions included no snow and snow cover, and bare soil in the summer. It contrasts 10 years usage of seasonal insulation (left plots) against no insulation and permanent insulation (right plots).

4.3 Analyses with Buildings in Place, Permafrost Zone

4.3.1 Means and methods for testing permafrost sites with buildings in place.

I instrumented and investigated one field site and tested the impact upon the soils from seasonally applying insulation with an R10 thermal resistance value (1.8 m^2 °C/W, 10 ft^2 hr °F/Btu).

I used many two-dimensional finite element analyses for an assumed building 12 m (40 ft) wide by long enough to approximate two-dimensional heat flow from below the building. I modeled a pile-supported building with an open crawl space below. The space below the building helps separate (decouple) the building heat from the soils thermal regime, thereby helping to preserve the permafrost in its frozen state. When not filled with owner’s stored materials, the unobstructed space provides room for convective airflow below the building.

4.3.2 Field study, one site, Willow House.

Cold Climate Housing Research Center (CCHRC) permitted me to instrument one of their “Sustainable Village” residences. Called “Willow House,” this Fairbanks building measures about 93 m^2 (1 000 ft^2) (Figure 49). Supported by a pile-foundation system, there is an open crawl space below the building. The existing ground surface had been cleared of brush but was uneven. Small stumps and brush-ends remained (Figure 50).

For the site work, I chose R10 insulation to be consistent with the finite element analyses (Table 10). I wanted to use flexible rolled insulation product similar to commercially available concrete curing blankets (e.g., similar to J.C. Smith 3/8” R5 foam core concrete curing blankets, retrieved from http://www.jcsmithinc.com/3-8-foam-core-concrete-curing-blanket-6-x-25.html?gclid=CJKNlrfIsMUCFZRgfgod304A1w). With delivery time and cost factors, I chose to use rigid 50 mm (2 in) R10 extruded foam instead. This choice meant that the rigid foam insulation conformed poorly to the uneven ground surface.

Figure 49. Willow House: Site investigation site for seasonal insulation.

Figure 50. Willow House: Founded on piles with an open crawl space below.

CCHRC provided the needed instrumentation via HOBO U12 four-channel dataloggers. The HOBOs come complete with manufactured thermistors and internal dataloggers. I assembled two thermistor strings. Each string used two HOBOs that provided eight thermistors on each string (Figure 51). I installed one string vertically down into a pre-existing hollow monitoring tube, to a depth of 6.1 m (20 ft). As in the FPSF field sites, I also filled the monitoring tube with sand to foster conductive heat transfer while reducing the likelihood of air convection currents. I laid the second string out flat on top of the ground. One end of the string was placed at the outside edge of the building. The string ran below the building inward 6.1 m (20 ft). I installed a fifth HOBO datalogger near the top of the vertical monitoring tube to capture air temperature above the insulation (Figure 52).

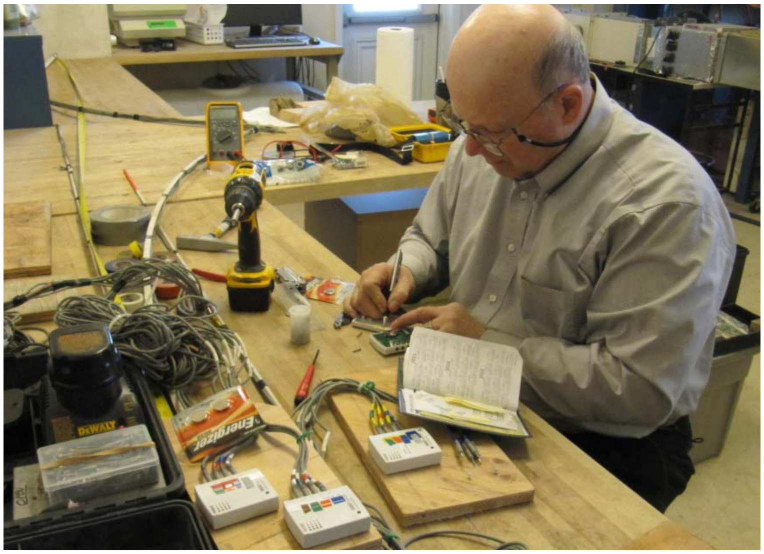

Figure 51. Willow House: The author bench-assembling and labeling HOBO dataloggers.

Figure 52. Willow House: HOBO thermistors installed, ready to place seasonal insulation.

4.3.3 Field study, results and discussion.

Results showed temperature differences between measured points. The measured points plotted below include readings taken (A) in the air, about 1 foot above the seasonal thermal insulation; and (B) at two different vertical thermistor locations (at the ground surface, and 2 ft deep). Figure 52 shows the horizontal thermistor string on top of the surface foliage, and shows the vertical grey tube with the air-temperature measuring HOBO in place.

Figure 53 shows the temperature measurements recorded near the beginning of each month for the second year of having applied seasonal insulation. Insulation covered the ground surface from May through October. Results between summer air temperatures and the surface temperatures showed the restricted surface heat available due to the insulation presence. Note the results for July and August. This warmest part of the year showed a measured seasonal thaw layer no deeper than about 0.6 m (2 ft). This reduced seasonal thaw layer, after using seasonal insulation for only two years, showed less than the 1.2 m to 1.6 m (4 ft to 6 ft) or greater thaw depths I have experienced elsewhere in the Fairbanks vicinity.

In addition, after two years of seasonal insulation use, these results showed a measured MAST, both at the surface and at 0.6 m (2 ft) below the surface of about -2.8 °C (27 °F). The comparison from air-temperatures to surface-temperatures resulted in a site-specific winter (uninsulated ground) n-factor of 0.90 to 0.94.

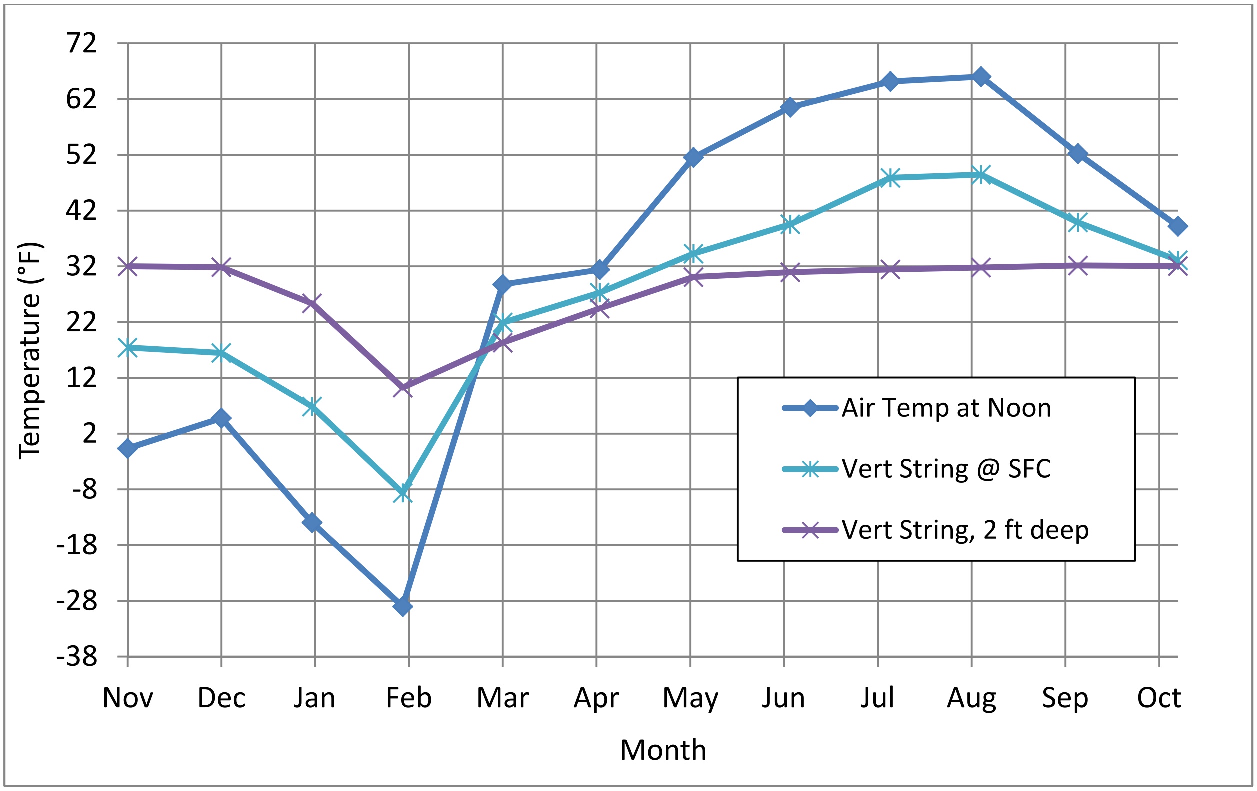

Figure 53. Willow House: Air, soil surface, and 0.6m (2 ft) deep temperature results. Temperature distribution throughout the year for the top two feet of soil.

I was especially interested in the annual maintenance time needed for the insulation work. I unitized the time in worker-hours needed per 93 m^2 (1 000 ft^2). With one helper, the first beginning-of-summer application took less than 3-hours for an untrained two-person-crew (6 worker-hours) to cut, fit, and initially install the insulation. Subsequent installations took less than 4 worker-hours per 93 m^2 (1 000 ft^2) of building area. Insulation removal, at the end of summer, took less than 3 worker-hours per 93 m^2 (1 000 ft^2) of building area. The combined annual installation plus removal time totaled less than 9 worker-hours per 93 m^2 (1 000 ft^2) of building area. For example, my field results meant that using seasonal insulation on a building about the size of the Yuut Elitnaurviat learning center in Bethel (Figure 29 and Figure 30) would likely take a two-worker crew less than two days at the beginning of summer to install the insulation. That same crew would likely need just over one day at the end of summer to remove the insulation. From my experience, this work needs physical mobility but no special skills or educational requirements.

4.3.3.1 Site work, thermistor discussion.

I deeply appreciated CCHRC's permitting me to instrument their existing building, called Willow House, here in Fairbanks. I used the existing site conditions with minimal additional preparation. I used a gasoline lawn mower to cut the smaller shrubs sticking out of the ground. However, the protruding larger shrub-stems and tree stumps remained. Therefore, the rigid foam insulation did not fit flat against the ground. I realized several points from this ground surface condition. First, I recognized the potential for convective air currents, circulating between the rough ground surface and the insulation. I am aware that this moving convective airflow influences the data output – especially for the thermistor string installed immediately below the insulation.

Part B's field operations using the HOBO U12 four-channel dataloggers were, for me, considerably easier than attempting to use the Campbell Scientific multiplexors as in Part A. For this Part B seasonal insulation investigation, I added a 10 watt light bulb inside the datalogger enclosure as a heat source. This minimal heat permitted the coin-sized CR-2032 batteries to remain warm enough to function through the winter season. I recommend providing new batteries twice per year, at the beginning of winter, and at the beginning of summer. Changing batteries only once per year was not frequently enough for my weather conditions.

As in the Part A, (FPSF) experience, filling the monitoring tube with sand (to limit convective air loops within the monitoring tube) proved problematic. After installation, the thermistor strings froze within the tube and I could not extract them for ongoing maintenance and output validation. That meant that while I checked for correct freezing point output before installation, I was not able to maintain or replace thermistors after the initial installation. I was not able to calibrate or validate suspected error-output readings. For future test sites, I recommend using a suitable-for-ground water contact fluid that will not freeze at the soils temperatures anticipated. The fluid should be non-contaminating for ground water contact if the monitoring tube develops leaks.

4.3.3.2 Site work, insulation discussion.

For installing the foam insulation, I worked with one helper. Using rigid insulation measuring 1.2 m x 2.4 m (4 ft x 8 ft) insulation had noteworthy salient features. For early summer installation, we easily slid the panels over one another to get the panels approximately in place. For final placement, we were able to cut around columns and obstructions by hand, using a hand-held sheetrock keyhole saw – without needing any electric power. Removing the panels at the end of summer went quickly. It took the two of us less than two hours per 93 m^2 (1 000 ft^2) for removal.

We were not able to lay the foam panels flat against the uneven ground. Not lying flat against the soils meant that the 50 mm (2 in) thick rigid insulation would not always support a person's weight during installation or removal. Several of the rigid insulation boards broke. Joints were not always tight between the rigid foam panels. The data-influence for the cracked or open-jointed insulation is unaccounted for in my measurements. However, by using the rough ground surface, I suspected that the results would be closer to a worst-case scenario. If seasonal insulation results were satisfactory under these conditions, then I would feel more confident in this site investigation serving as a proof of concept for using seasonal insulation on sites with more careful surface preparation.

Based on the broken rigid thermal insulation experiences, for uneven sites I recommend using flexible mat insulation similar to that used as cold-weather concrete-curing mats. Several manufacturers produce flexible mat insulation, including Grip Rite, Micro Foam, or similar concrete curing blanket manufacturers. These insulation blankets advertise in the range of R4 to R5 per blanket. Two blanket layers with overlapping seams would provide a similar thermal insulation value to the rigid XPS foam that I used. If the site may be first prepared with a leveling course of sand or gravelly sand to permit a smoother fit, then using the rigid foam also seems acceptable.

I envision accomplishing off-season insulation storage in multiple ways. First, stockpile the insulation out from under the building on the site. Choose insulation that includes ultraviolet light protection, so that covering the insulation becomes less important. A second alternative for open crawl space buildings includes supporting the insulation above its ground location, on the underside of the building above. The ground is open to winter cooling. The insulation becomes part of the building's thermal envelope. Racks or trays, much like commercial electrical wiring trays could support these lightweight panels. A third alternative, especially suited to the flexible curing blanket concept, recognizes that the concrete construction industry needs cold weather curing blankets at about the same time as the building no longer needs blanket protection from warm weather. Construction's summer time off-season storage may include spreading the blankets out below buildings and helping keep the permafrost cold.

4.3.4 Thermal analyses by finite-element program.

For a building analysis region, I used Temp/W two dimensional analysis methods. This means I assumed having a design building that was several times longer than it is wide, and symmetrical about its centerline. Therefore, I could input only half of the building into the finite element program. For this

12.2 m (40 ft) wide building, I used a half-width of 6.10 m (20ft). From my personal work with wind tunnels and turbine-spacing design, I came empirically predisposed to using an analysis region that was about five-times wider and deeper than the building half-width. Therefore, I chose a region of 30.5 m (100 ft) wide by 23.8 m (78 ft) deep. Figure 54 shows the extents of the analysis region used throughout all two-dimensional investigations.

I evaluated thermally restricting the heat flow into the soils using added insulation placed directly on top of the ground. I did not model the insulation as buried below the surface. I wanted to have equivalent insulation locations between the permanent insulation cases and the seasonal insulation cases. I evaluated the heat-flow restricting effects of thermal insulation two ways. First, I used permanently installed insulation. After a ten-year base period with undisturbed conditions, I applied permanent insulation that remained in place the duration of each analysis period. Second, I used seasonal insulation. After an identical base period, I applied seasonal insulation in the summer, then removed it in the winter. This alternating on-in-the-summer and off-in-the-winter sequencing altered the thermal regime, restricting heat gain in the summer but not in winter. Third, I tested the impact from varying the insulation amounts. I evaluated insulation values of R10, R20, and R40.

From my previous wind tunnel work, I remain sensitive to edge effects around discontinuities. My earliest analysis models showed similar edge effects at the building when I terminated the insulation exactly at the edge of the building. Therefore, I made these analyses using insulation extending out beyond the building perimeter by 1.8 m (6 ft). Each insulated analysis region extended from the building centerline, past the edge of building, at 6.1 m (20 ft), to the edge of insulation at 7.9 m (26 ft).

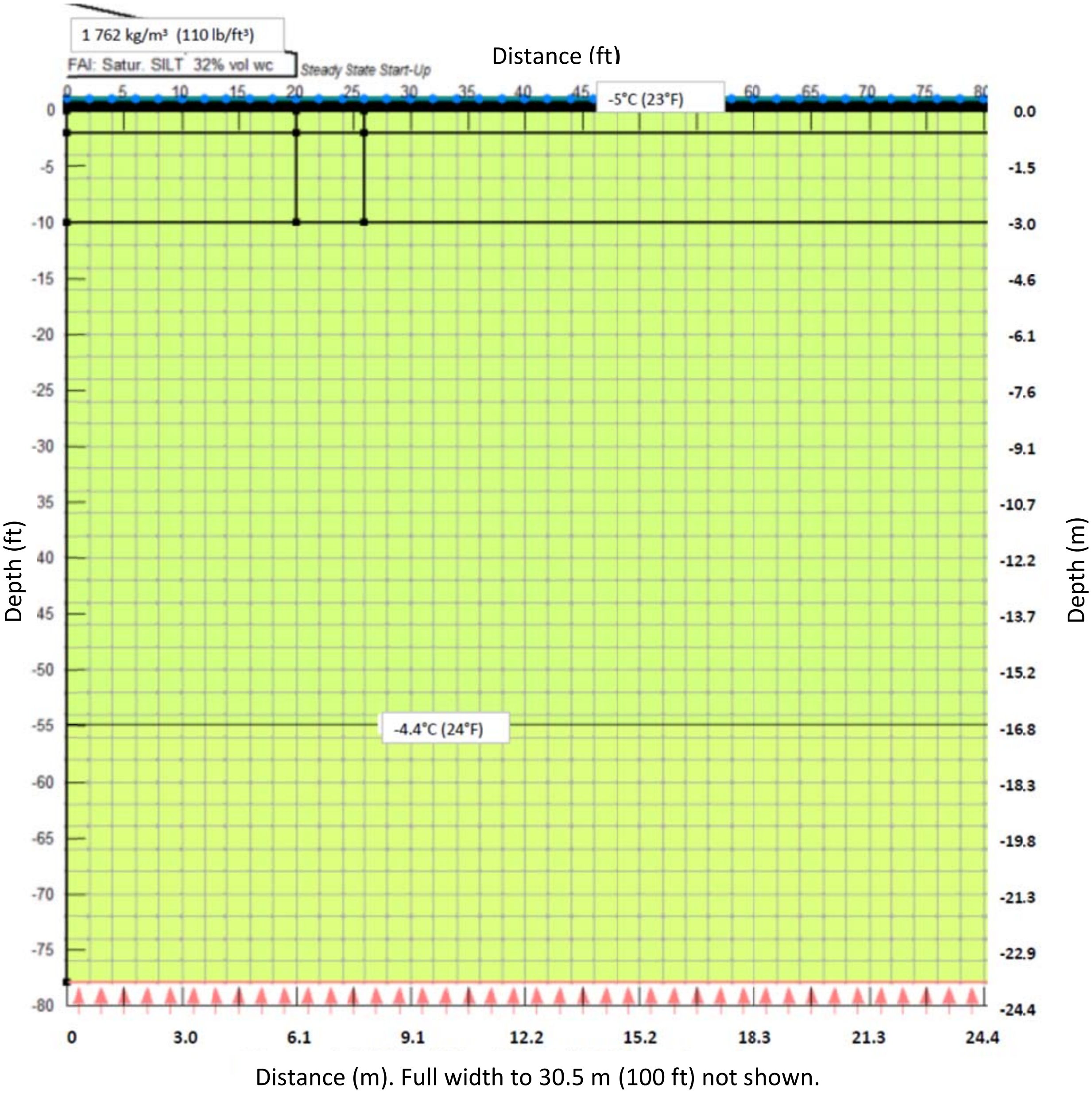

Figure 54. Temp/W print-screen showing model input analyses extents.
Finite element model-region measured 30.5 m (100 ft) wide by 23.8 m (78 ft) deep.

For temperature inputs, some may represent the variable air temperatures as successive half-sine-wave mathematical terms for the winter and summer sinusoids. Instead, I used measured mean monthly air temperatures as reported by the Alaska Climate Research Center (Table 6). I did not use the Temp/W program's modification function to apply the air-to-surface temperature adjustments (n-factors). When using °F input temperatures, I found a numerical discontinuity in the modification function around the 0 °F soil surface temperature. Therefore, I used the n-factors and reported air temperatures to calculate soil surface temperatures manually. I then input the soil surface temperatures, month by month, into the Temp/W program.

I evaluated Fairbanks saturated silts at 1762 kg/m^3 (110 lb/ft^3), and a volumetric water content of 32 % as well as the other gravel and silt properties shown in Table 4. I limit this presentation, however, to Fairbanks saturated silts as illustrative of the results found for the other soil-conditions evaluated.

As in a one-dimensional analysis, I started each two-dimensional model with the same location-dependent steady state temperature input (Table 9), followed by ten years of seasonal soils climate temperatures without any insulation installed. Third, after this ten-year baseline period of no insulation, each analysis computed an additional 10 to 25 years of results with varying insulation configurations. The seasonal insulation analyses included thermal insulation applied only in the warmer summer months and removed in the cold winter months. Analysis times started at zero hours, and accumulated through 306,600 hours at the end 35 years total elapsed time (ten years no insulation, plus up to 25 years of insulation configuration evaluations).

4.3.5 Print screen results, Fairbanks.

Here in the main text, I have displayed only a limited number of output-figures. The goal is to show the primary trends given by the results. For those interested in more details, the appendices contain additional figures for a fuller understanding of the results.

To start off, I provide two pairs of screen shots from the Temp/W program output. Each pair has a thumbnail sketch plus a close up. These output figures include snow-covered soils away from the building, and clear of snow soils below the building. Table 7 shows the n-factors used.

Results from the first pair of print-screens (Figure 55 & Figure 56) showed the amount of soils cooling below the building simply from maintaining a fully open crawlspace below the building. The ten-year base period without insulation showed at least 3.3 °C (6 °F) surface soil cooling (from 8.9 °C (48 °F) away from the building to 5.6 °C (42 °F) below the building).

The second pair of print-screens (Figure 57 & Figure 58) showed the effects from having R10 seasonal insulation in place. Note the thermal insulation edge effects between the 6.1 m and 7.9 m (20 to 26 ft) distances from building centerline. Results showed that extending the insulation outside of the building footprint created a more-uniform cooling action below the entire building footprint investigated. Further, note the results showed movement of the freezing isotherm from the no-insulation case of about 1.5 m (5 ft) deep (Figure 56) to within the surface insulation (Figure 58) for the R10 seasonal insulation case. This means, even for the lowest thermal value of insulation investigated, R10, the active layer completely disappeared with seasonally applied insulation. Results clearly showed the formerly seasonally thawed soils now remain frozen.

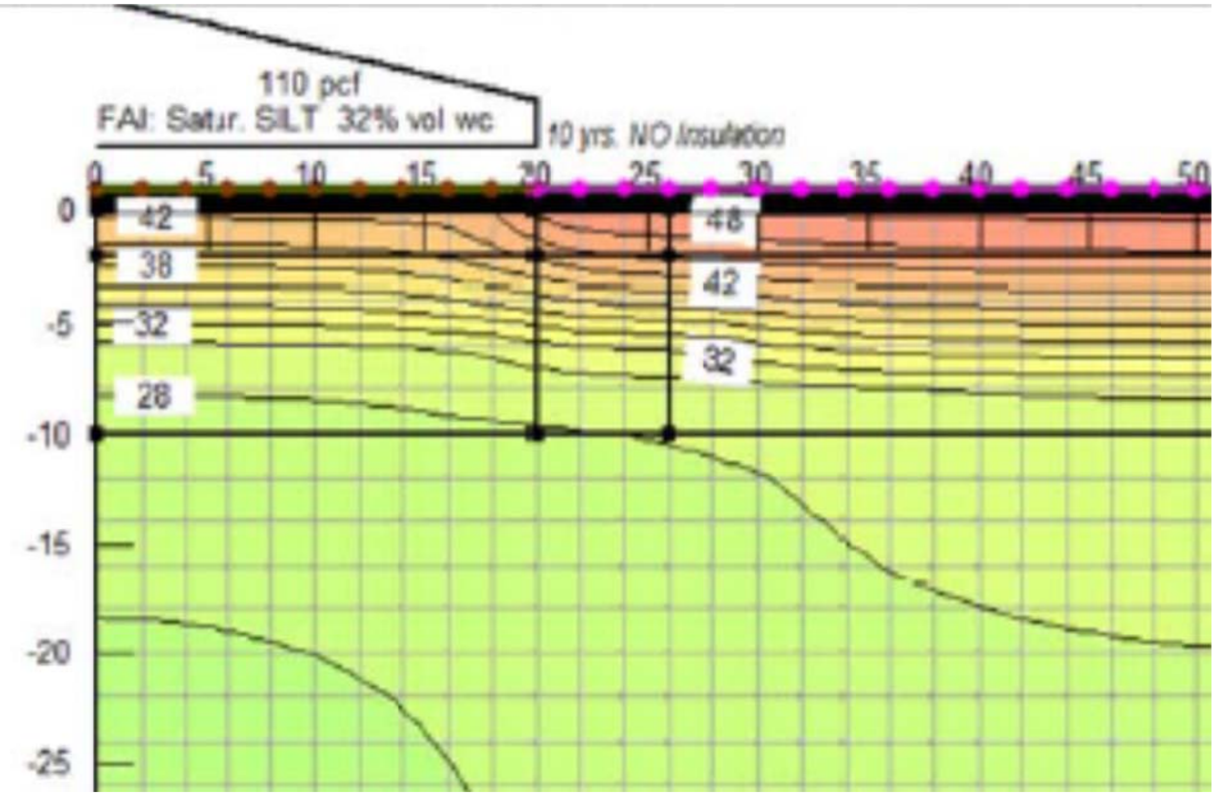

Figure 55. Temp/W print-screen: Fairbanks current climate, no insulation.
Temperature isothermal lines under natural conditions.

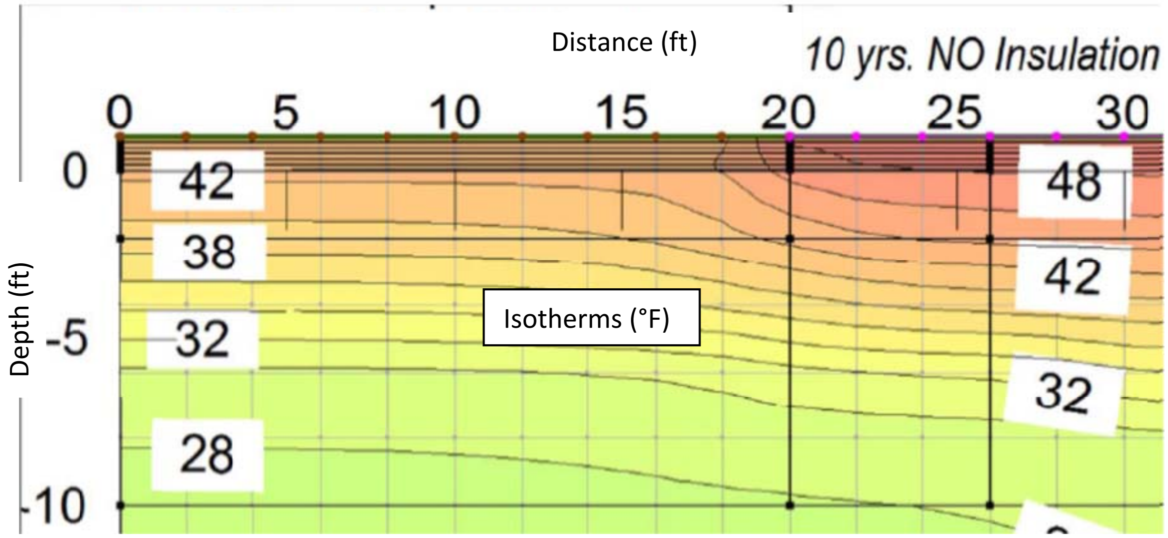

Figure 56. Temp/W print-screen, enlarged: Fairbanks current climate, no insulation.

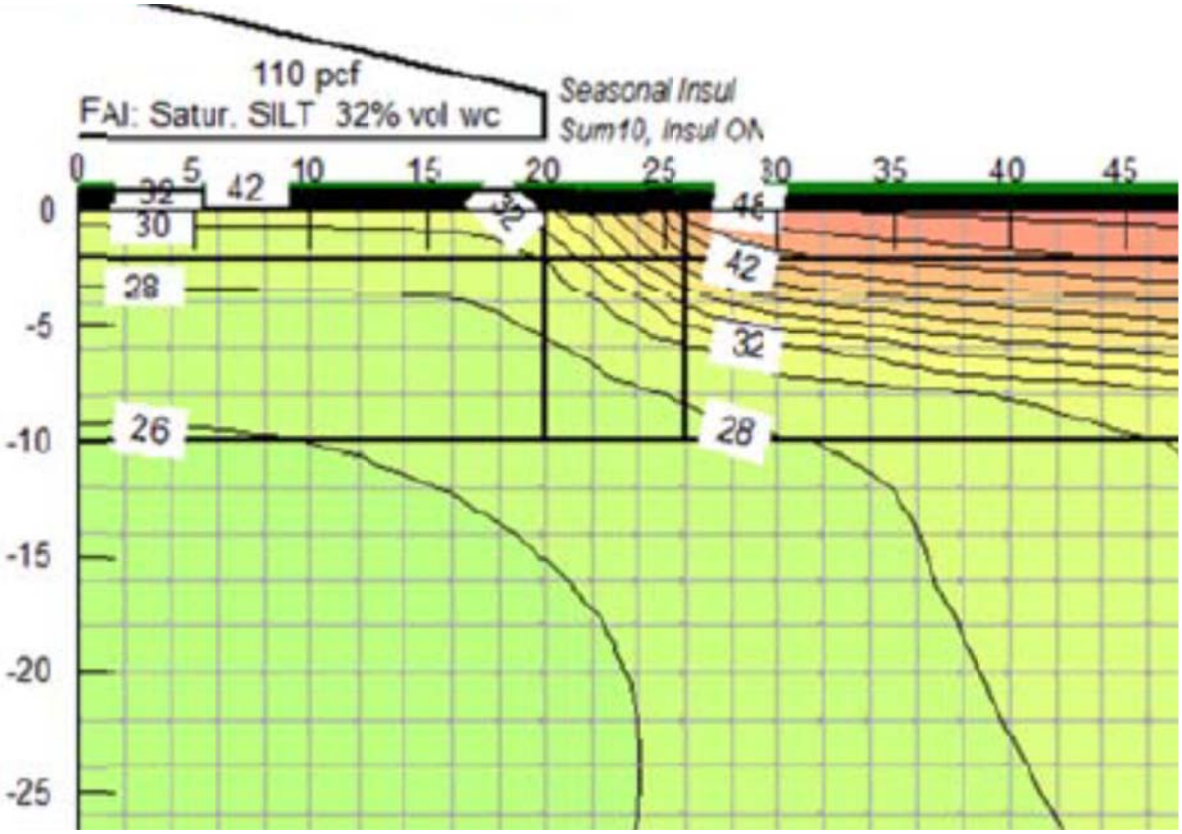

Figure 57. Temp/W print-screen: Fairbanks current climate, R10 seasonal insulation results. Temperature isothermal lines after 10 years usage of seasonal insulations.

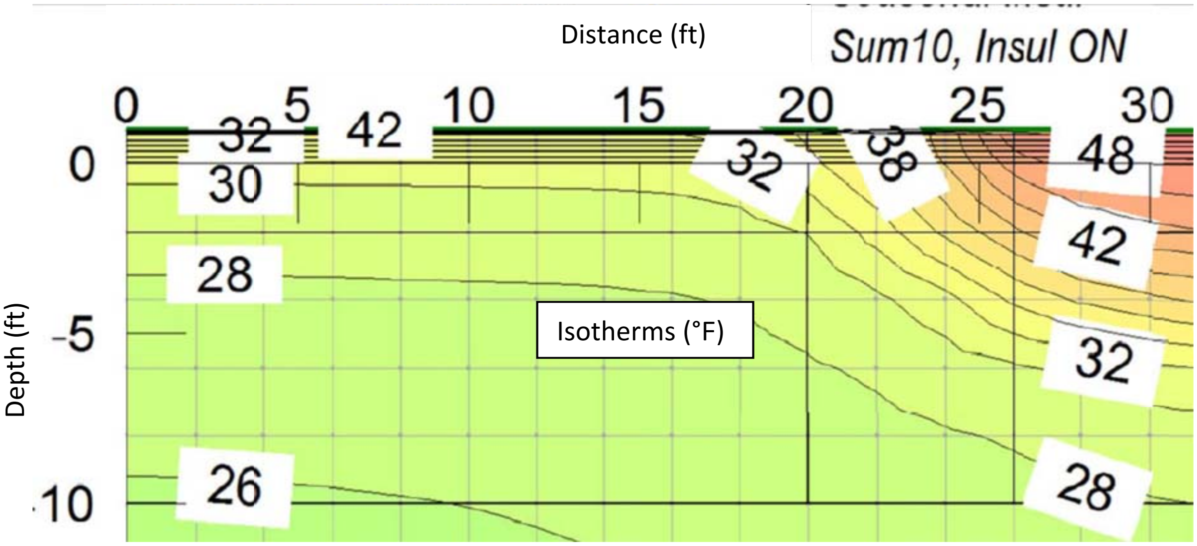

Figure 58. Temp/W print-screen, enlarged: Fairbanks current climate, R10 seasonal insulation.

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4.3.6 Graphic results and discussion for Fairbanks.

4.3.6.1 Comparative results, center of building with edge of building.

I intend viewing the following graphic results in pairs, side-by-side. First, I have shown the mean annual soils temperature comparison for the center of the building compared with the edge of the building. Next, for the same locations, I have shown the end-of-summer results for the presumed close to warmest time of year

Each MAST result showed the differences between no insulation at all and with (R10) insulation applied seasonally. Without any insulation, results for an open crawl space showed over 2.8 °C (5 °F) cooler surface MAST below the building centerline (Figure 59) than at the edge of the building (Figure 60). Then, added seasonal insulation, (i.e., insulation applied only in the warm summer months) quickly altered the active layer depth. Thermal results with as early as one year of seasonal insulation use showed about 90 % of the cooling effectiveness at the building centerline and almost 80% of the cooling effectiveness at the edge of the building. By ten years of seasonal summer insulation use, results showed 5 °C to 6.7 °C (9 °F to 12 °F) surface soil cooling (Figure 59 & Figure 60). Minimal additional cooling occurred between the 10th and the 25th year of seasonal summer insulation use.

End-of-summer considerations, at the warmest soils time of year, have particular interest to me. From my engineering experience along the Yukon River villages, I am quite sensitive to the differences in end-of-summer seasonal thawing between the building centerline and the edge of the building. The September 15 end-of-summer results both for the centerline of the building and for the edge of the building (Figure 61 & Figure 62) show these differences. Comparing these two September 15 figures showed the edge of the building over 2.2 °C (4 °F) warmer than below the center of the building. These output figures showed that only one year of seasonal insulation use resulted in complete elimination of the September 15 thaw-zone below the building centerline. In addition, after five to ten years of use, applied seasonal insulation resulted in further permafrost cooling to depths of 15.2 m (50 ft) (Figure 61). At the edge of the building, results showed that while a September 15 thaw-zone remained, it decreased from 1.8 m (6 ft) to only about 0.3 m (1 ft) (Figure 62).

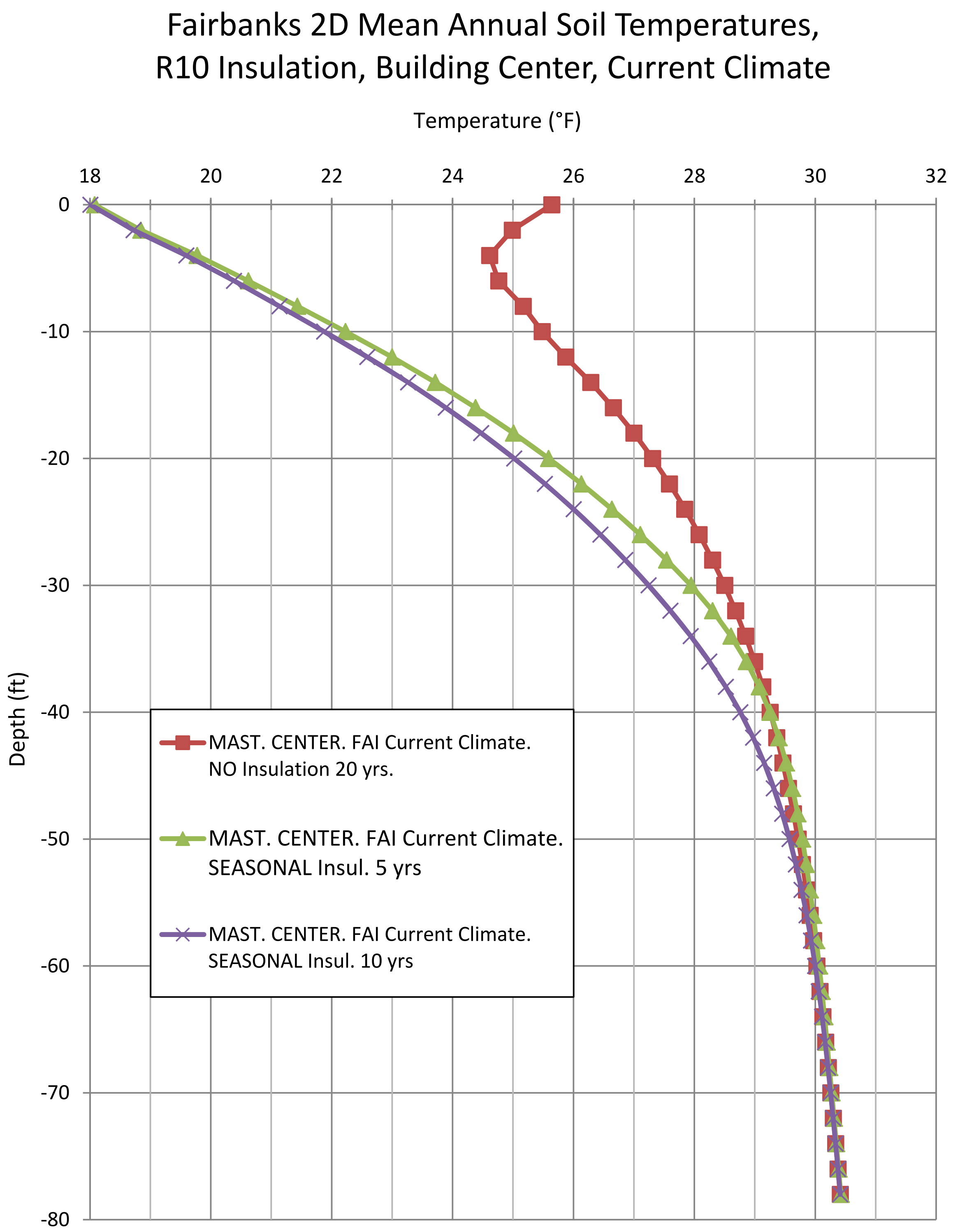

Figure 59. Fairbanks 2D, R10 seasonal insulation, building center, mean annual soil temperatures. Mean annual soil temperatures with depth, showing the effect of seasonal insulation. Conditions included R10 seasonal insulation and bare soil surface with no snow.

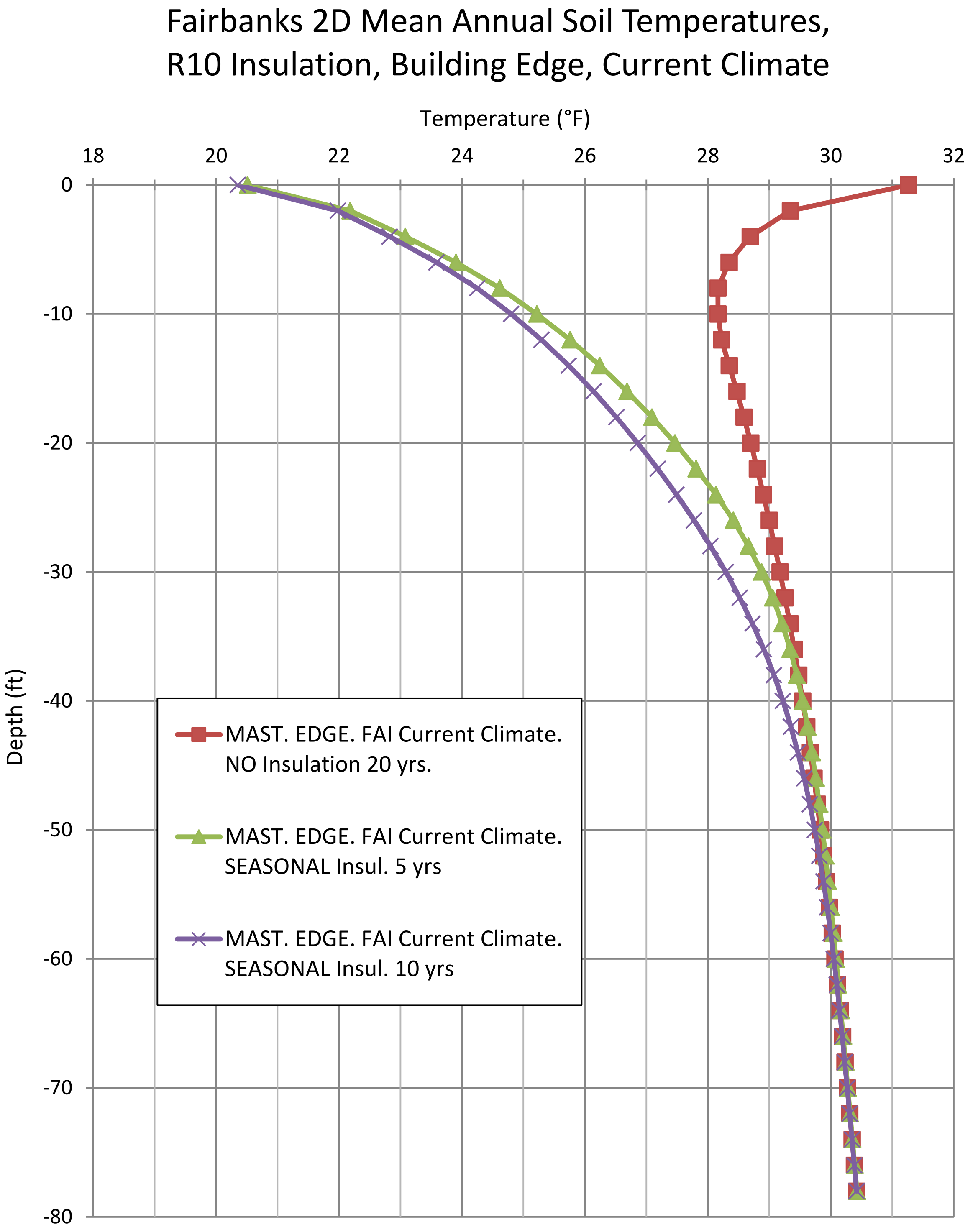

Figure 60. Fairbanks 2D, R10 seasonal insulation, building edge, mean annual soil temperatures. Mean annual soil temperatures with depth, showing the effect of seasonal insulation. Conditions included R10 seasonal insulation and bare soil surface with no snow.

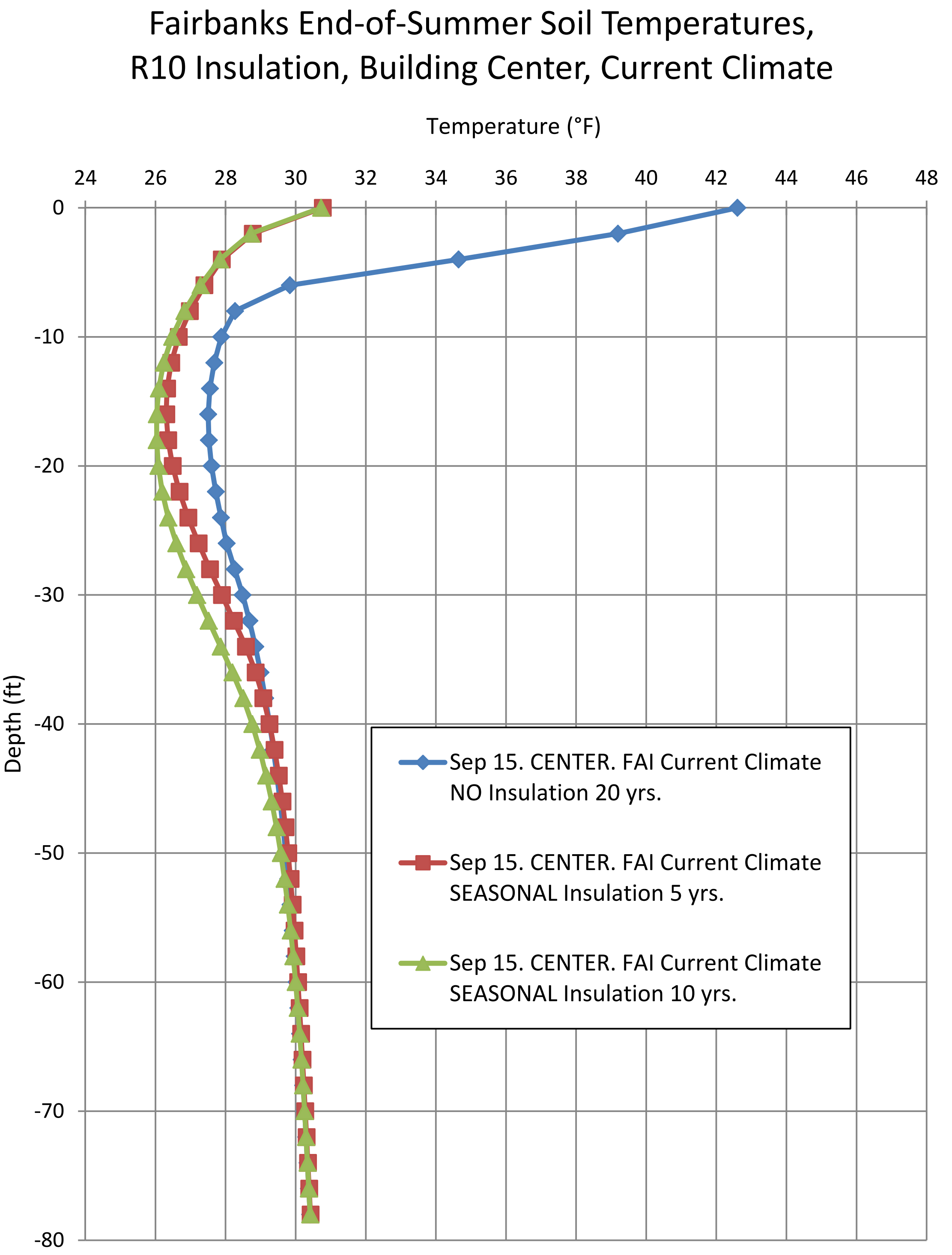

Figure 61. Fairbanks 2D, R10 seasonal insulation, building center, Sep. 15 soil temperatures. End of summer soil temperatures with depth, showing the effect of seasonal insulation. Conditions included R10 seasonal insulation and bare soil surface with no snow.

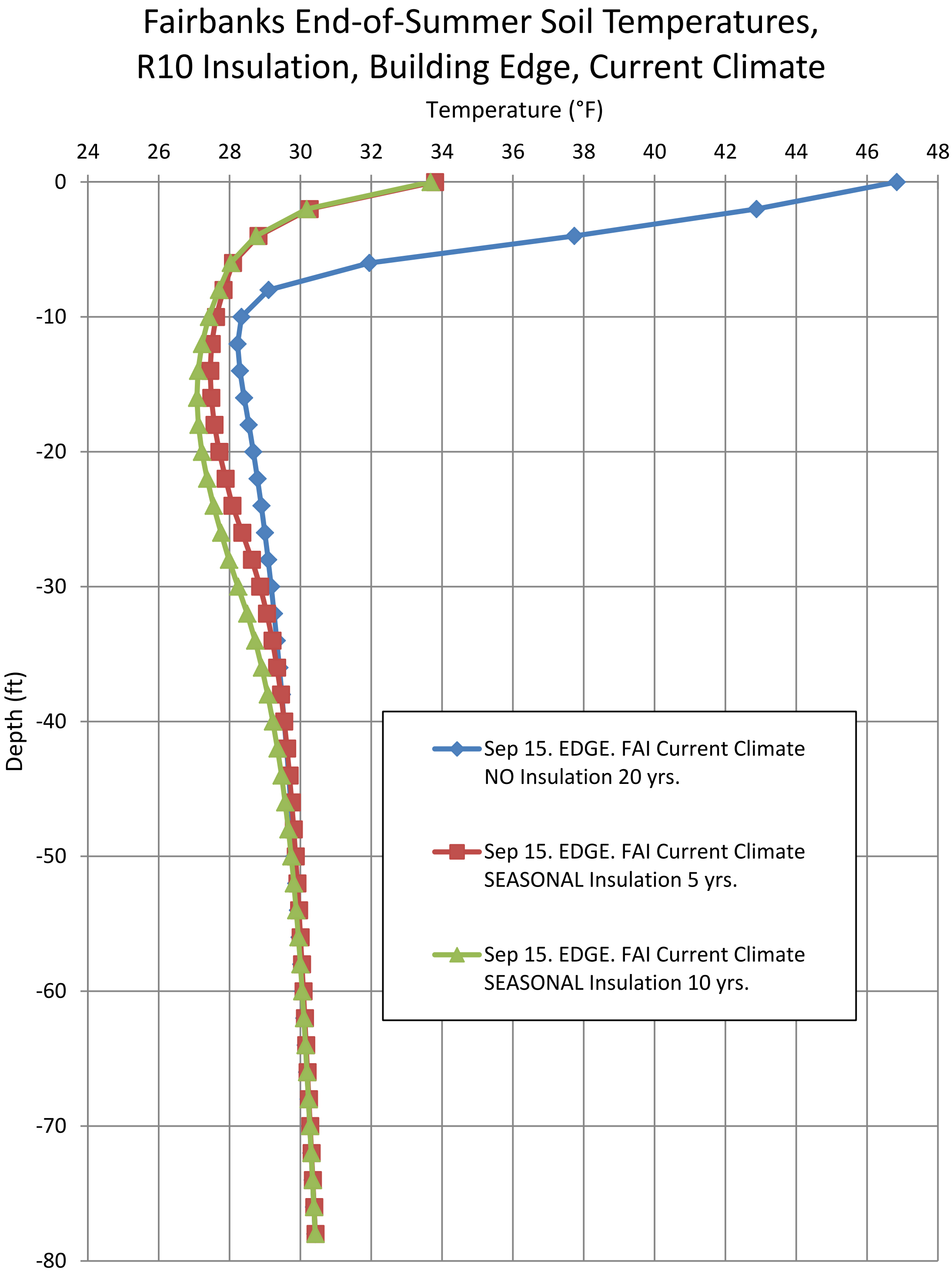

Figure 62. Fairbanks 2D, R10 seasonal insulation, building edge, Sep. 15 soil temperatures. End of summer soil temperatures with depth, showing the effect of seasonal insulation. Conditions included R10 seasonal insulation and bare soil surface with no snow

4.3.6.2 Comparative results, permanent or seasonal insulation, with or without snow.

The next output-mode presented includes selected graphs of soil strata temperatures for the different cases investigated. Results showed the differential temperatures between the center and the edge of the building. Therefore, each of these output graphs is a double graph, showing thermal results both for the center of the building and for the edge of the building. Additionally, the graphs, presented in pairs, display results for no-snow cases side-by-side with results for snow-covered cases.

Table 14 summarizes the thermal cases investigated, displays the result-figures, and serves as a hyperlink source for moving quickly to an output figure.

Table 14.
Fairbanks, Two-Dimensional Analyses, R-Values, & Resulting Figures

	Insulation				Snow	Temperature Results	
Location	Common Name	Thermal Resistance m^2 °C/W (ft^2 hr °F/Btu)	Thickness mm (in)	Duration	Present In Winter	Seasonal Variations	MAST at CL, at Edge
Fairbanks	None	zero	zero	n/a	No	Figure 63	Figure 69, Figure 70
					Yes	Figure 64	
	R10	1.8 (10)	51 (2)	Permanent	No	Figure 65	
					Yes	Figure 66	
				Seasonal	No	Figure 67	
					Yes	Figure 68	
Fairbanks See Appendices	R20	3.5 (20)	102 (4)	Permanent	No		
					Yes		
				Seasonal	No		
					Yes		
	R40	7.0 (40)	203 (8)	Permanent	No		
					Yes		
				Seasonal	No		
					Yes		

Comparing the results for no snow versus snow-covered cases without insulation (Figure 63 & Figure 64) showed almost no effect at the center of the building. By contrast, the snow-covered case showed the edge of the building warmer than the no-snow case by 4.4 °C (8 °F). In addition, both cases showed edge of building summer thawing zones to about 1.5 m (5 ft) deep.

The permanent R10 cases (Figure 65 & Figure 66) showed several effects. For both the no-snow and the snow-covered cases, the insulation presence reduced the amount of temperature change from summer to winter (thermal amplitude). For example, a -18.9 °C (-2 °F) no insulation no-snow case surface winter temperature warmed to -6.9 °C (19.5 °F) with the permanent R10 insulation present. With the snow-covered case, the winter surface temperatures warmed even more, to -4.50 °C (23.9 °F). The depth of the end of summer thawing zone also reduced to practically zero for the no snow case, and to about 0.8 m (2.5 ft) for the snow-covered case.

Results for the seasonal R10 insulation showed a hybrid of effects between the no insulation and the permanent insulation cases (Figure 67 & Figure 68). The surface temperatures in winter cooled slightly, about 1 °C (2 °F), below the no-insulation cases, both for the no-snow and for the snow-covered scenarios. In addition, the summer surface temperatures remained about as cool as in the permanent insulation cases, both for the no-snow and for the snow-covered cases. Comparing the results from all six of these output figures (Figure 63 through Figure 68) yielded that seasonal insulation resulted in maintaining the coldest temperatures of the no-insulation cases, while also reducing the active layer thawing zones like the permanent insulation cases.

Comparing the mean annual soil temperature (MAST) variations between the building center and the edge-of-building (Figure 69 & Figure 70) showed soil temperature differences. Results showed the warming effect (not cooling) with permanent insulation, and the cooling effect with seasonal insulation. Results showed the further warming effect on edge-of-building caused by snow cover.

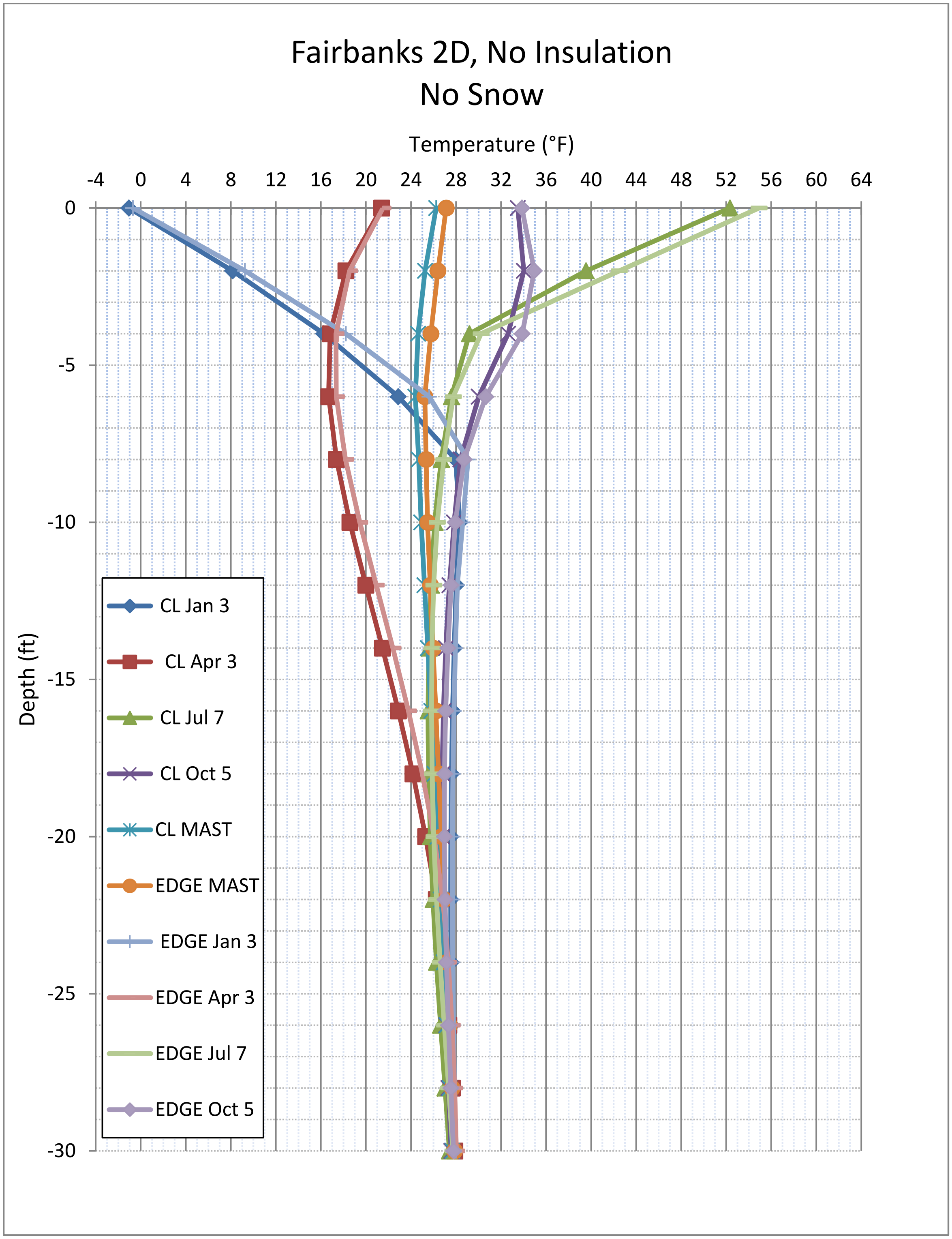

Figure 63. Fairbanks 2D, no insulation, no snow condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included no insulation, no winter snow, and summer bare soil surface.

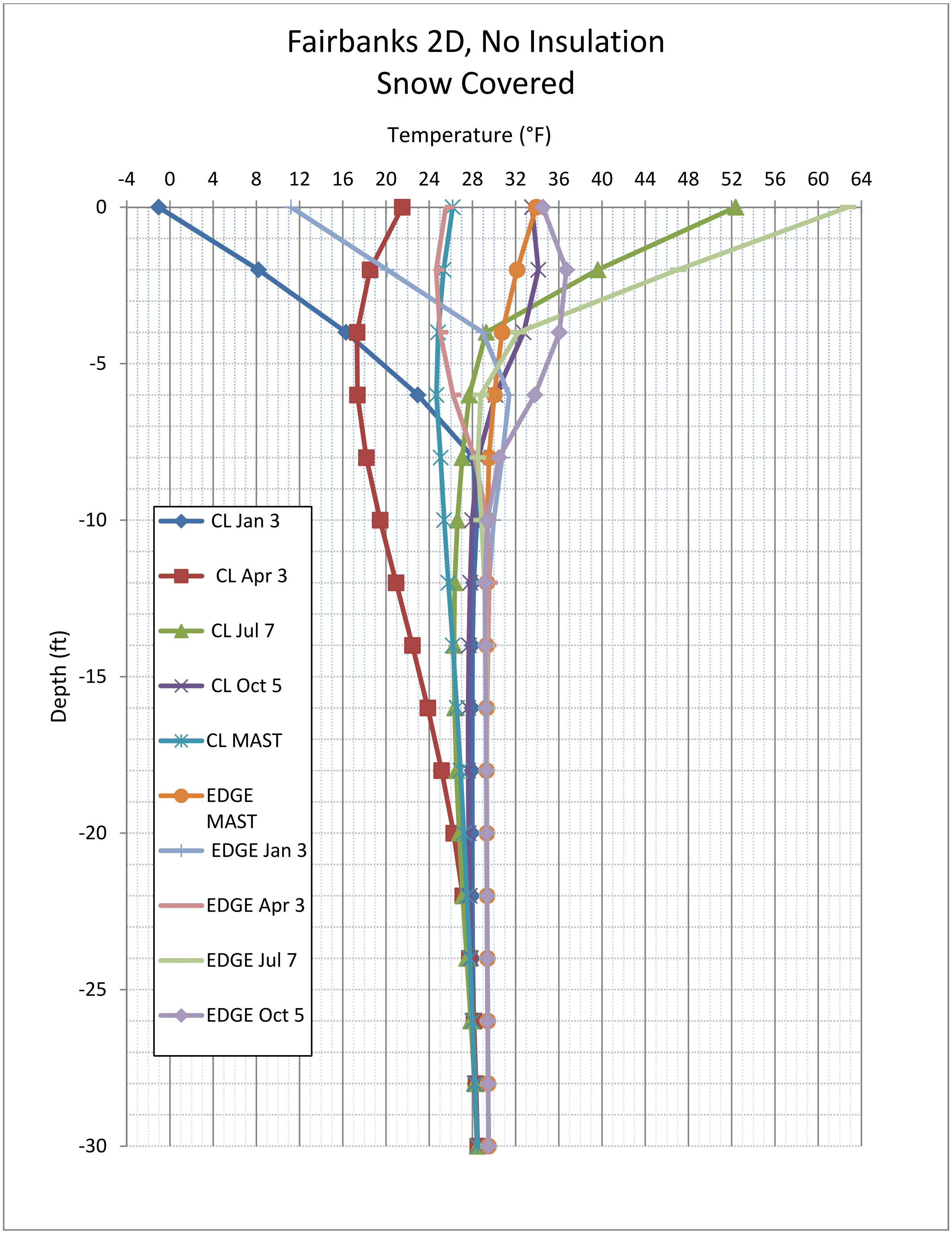

Figure 64. Fairbanks 2D, no insulation, snow covered condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included no insulation, with winter snow cover, and summer bare soil surface.

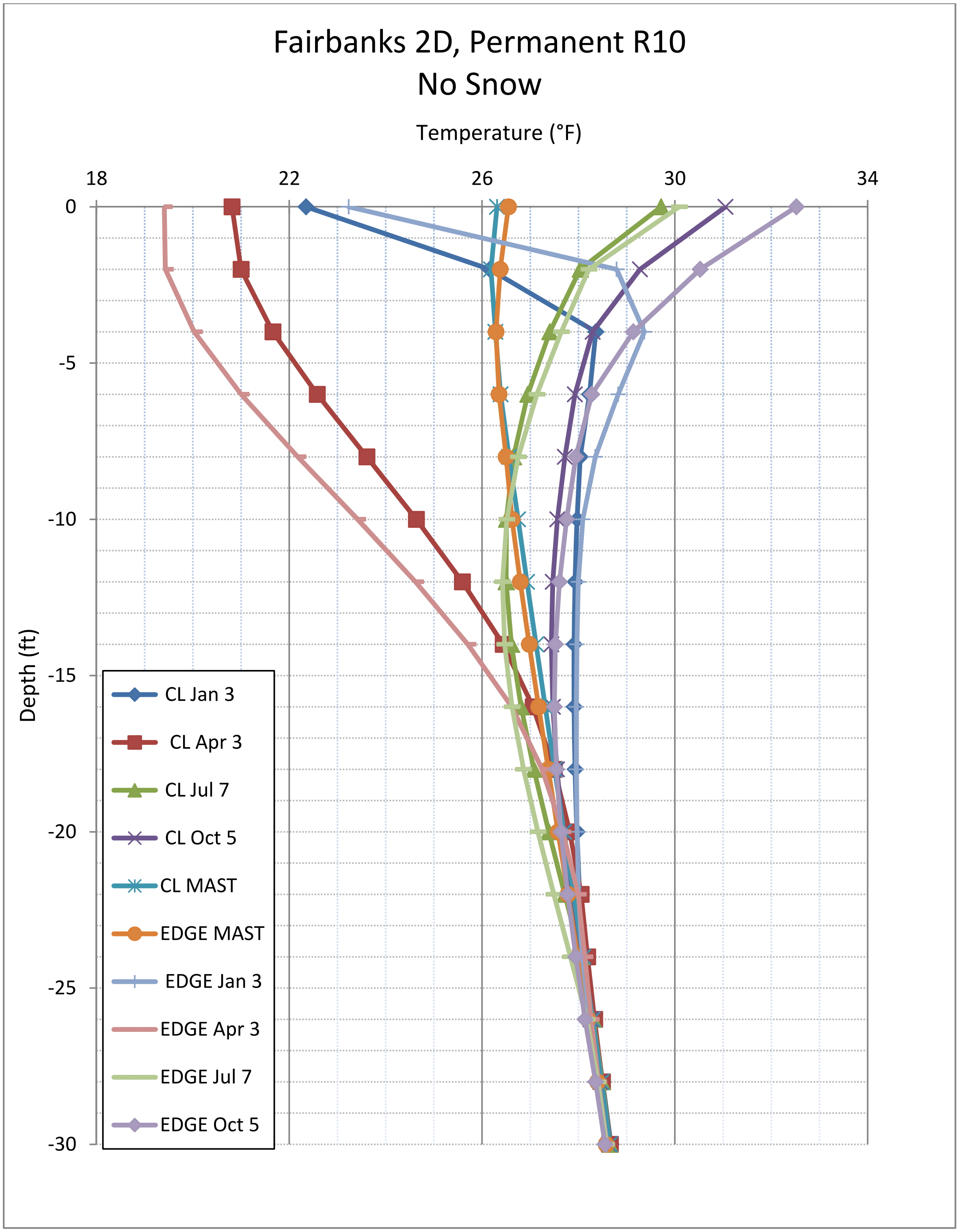

Figure 65. Fairbanks 2D, R10 permanent thermal insulation, no snow condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included permanent insulation, no winter snow, and summer bare soil surface.

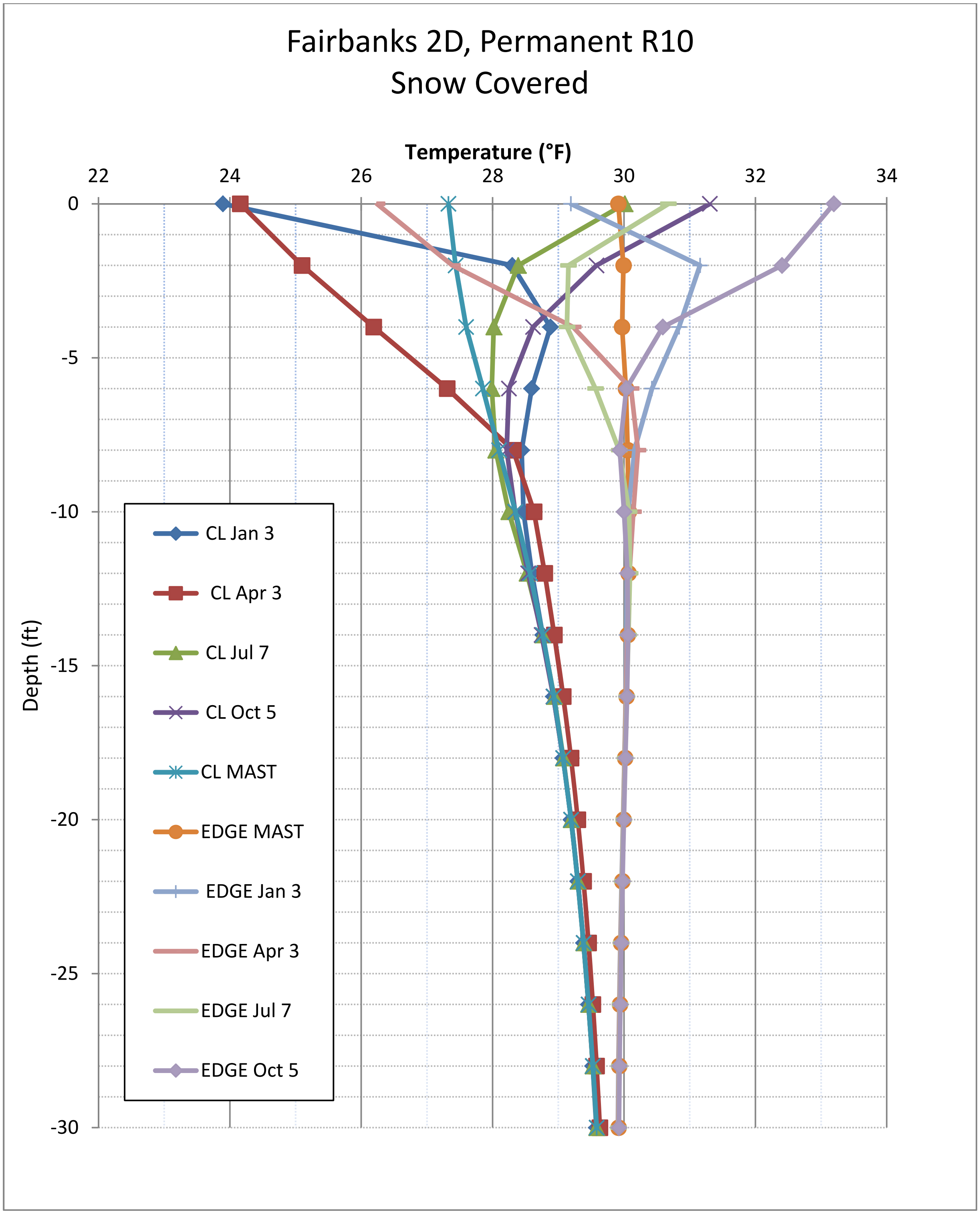

Figure 66. Fairbanks 2D, R10 permanent thermal insulation, snow covered condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included permanent insulation, with winter snow cover, and summer bare soil surface.

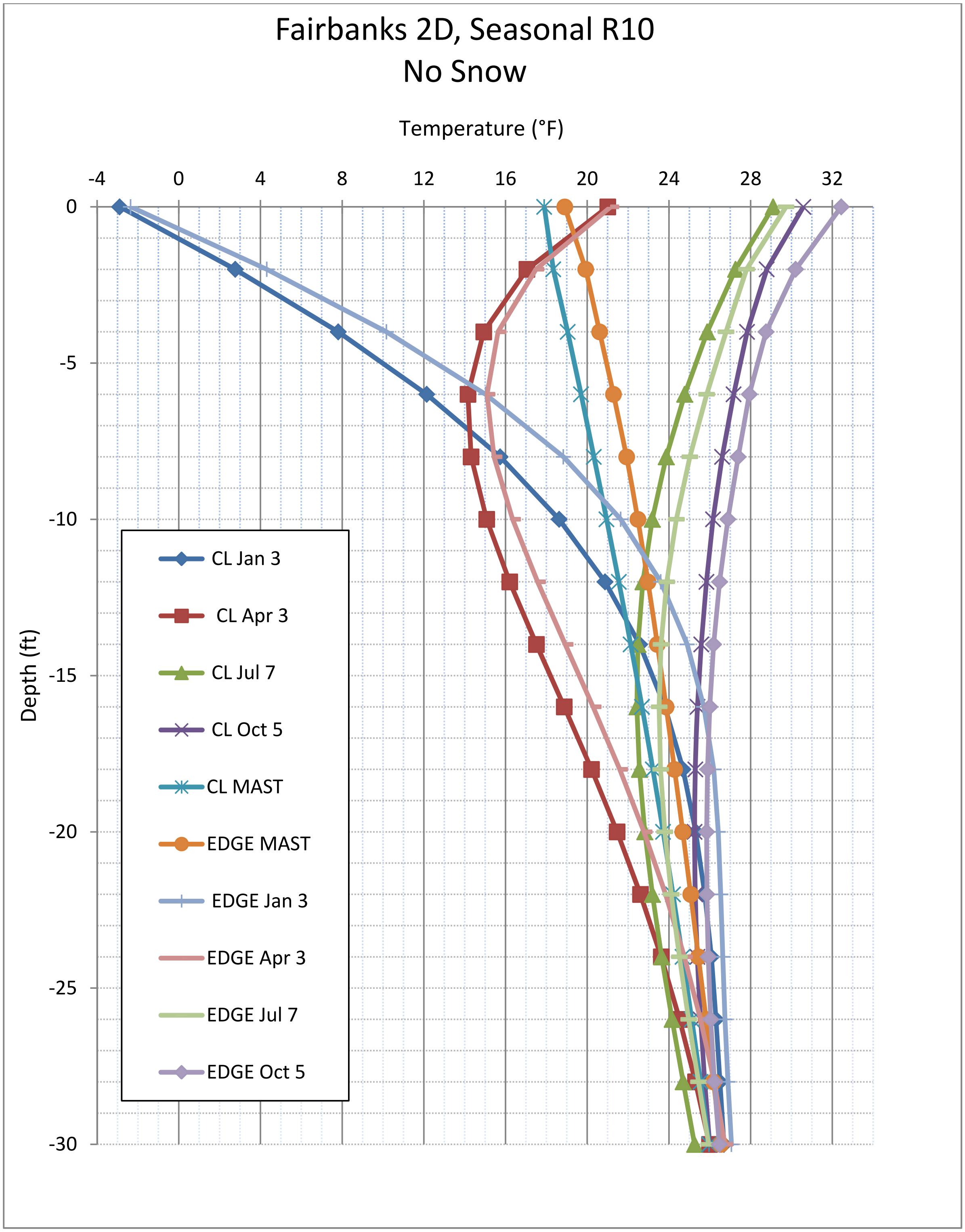

Figure 67. Fairbanks 2D, R10 seasonal thermal insulation after 10 years, no snow condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included seasonal insulation, no winter snow, and summer bare soil surface.

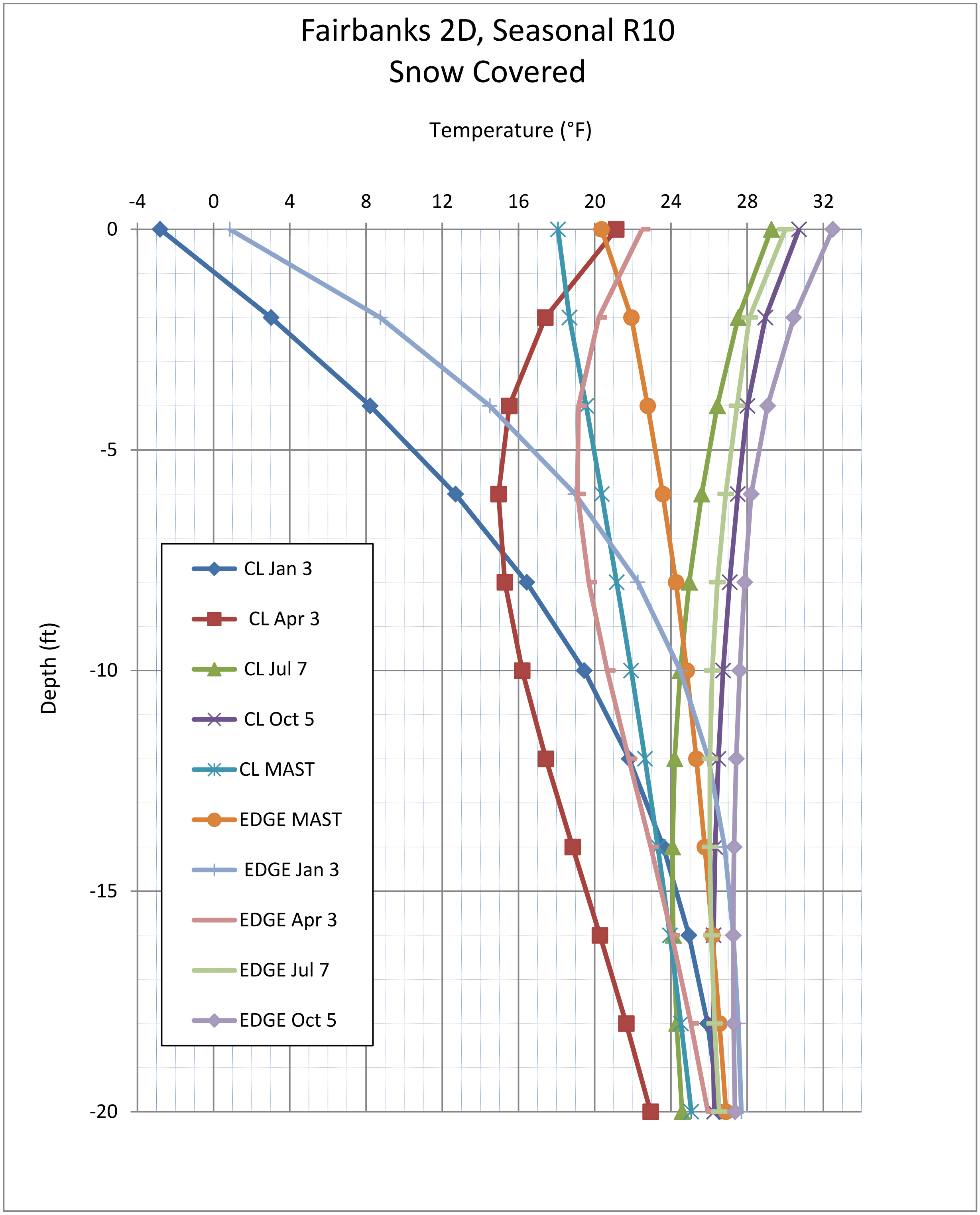

Figure 68. Fairbanks 2D, R10 seasonal thermal insulation after 10 years, snow covered condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included seasonal insulation, with winter snow cover, and summer bare soil surface.

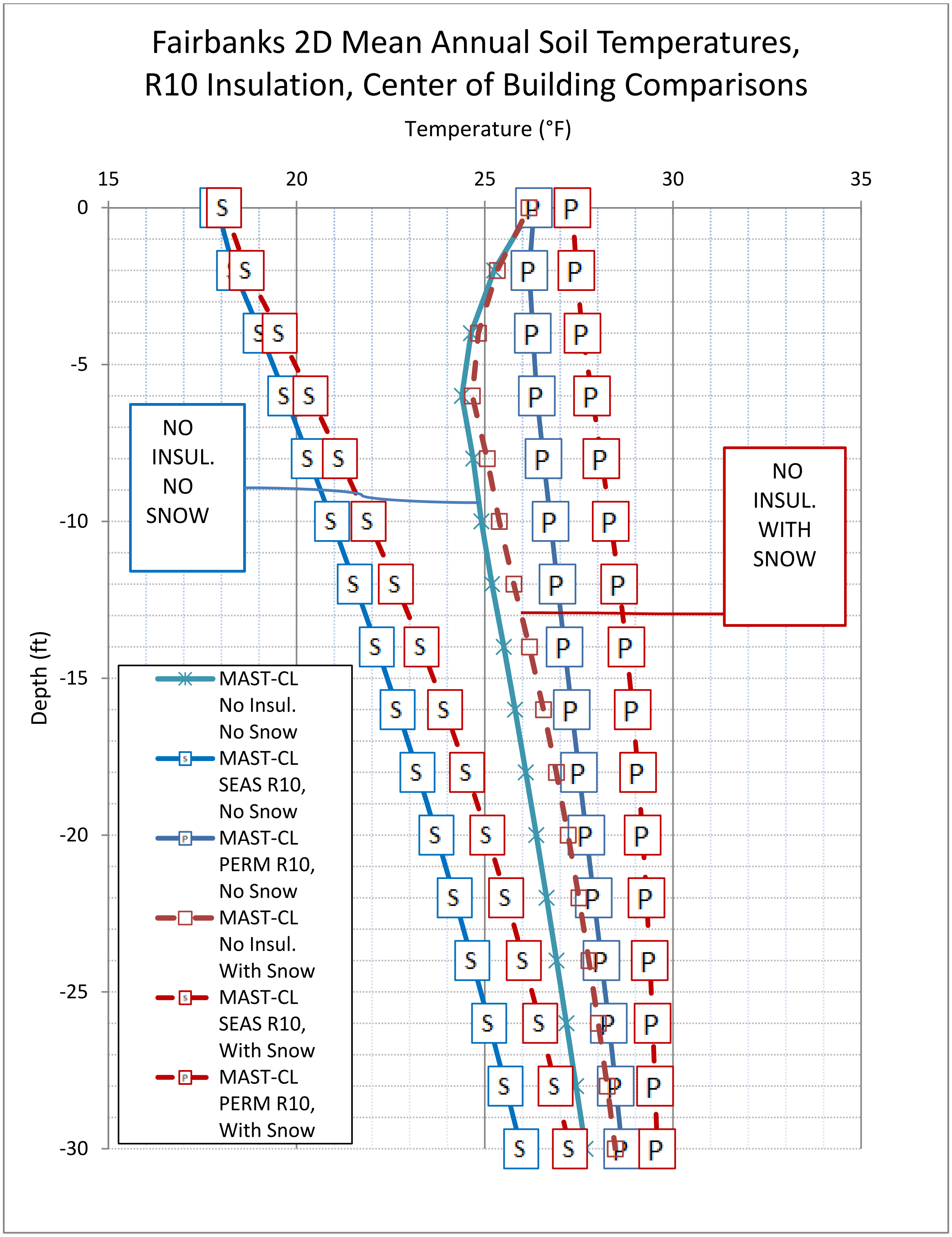

Figure 69. Fairbanks 2D, R10, building center, mean annual soil temperatures. Conditions included 10 years seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

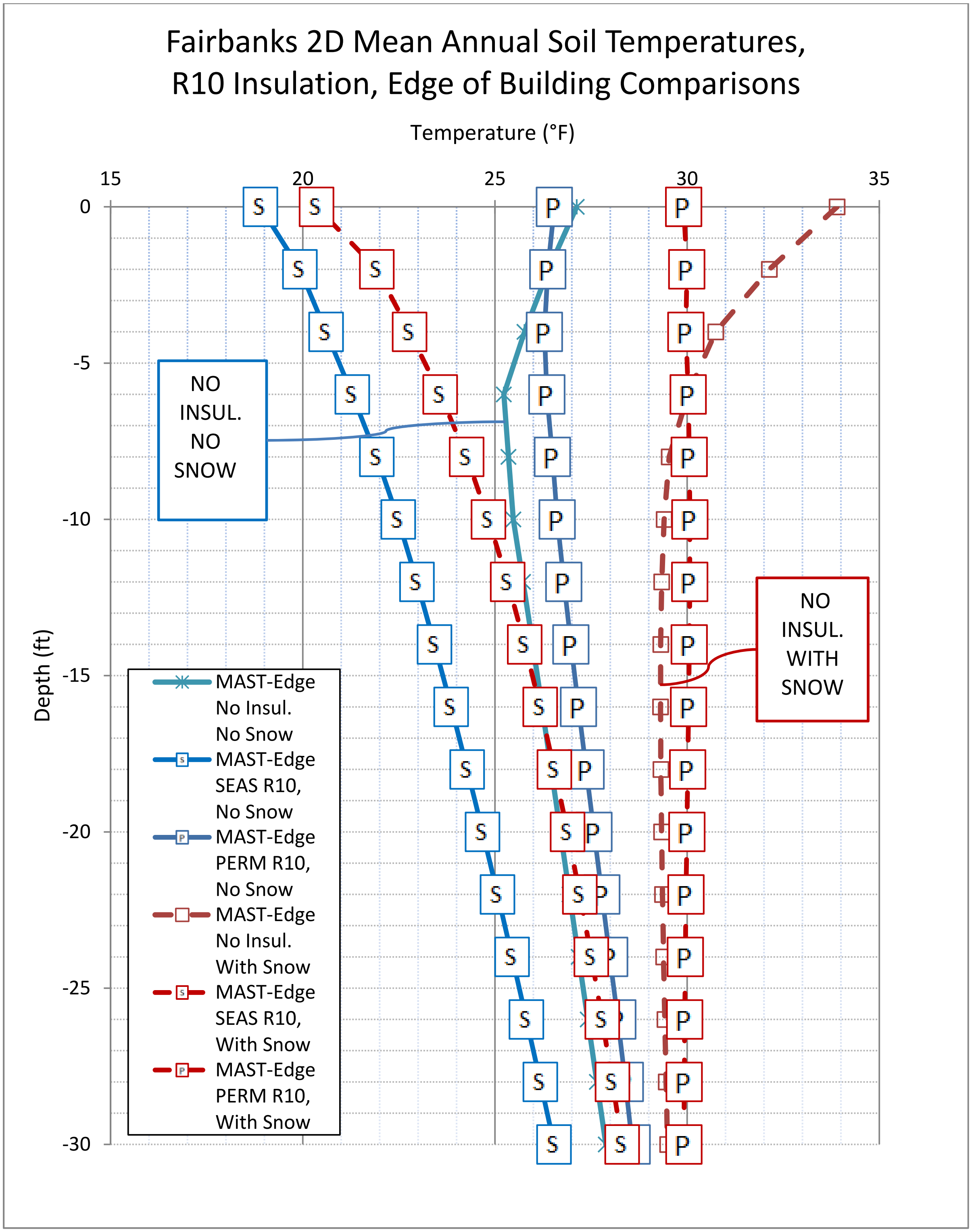

Figure 70. Fairbanks 2D, R10, building edge, mean annual soil temperatures. Conditions included 10 years seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

4.3.6.3 Fairbanks discussion.

These early results showed clear differences between the center of the building and the edge of the building. The centerline of the building trended cooler than the edge of the building for both summer and winter. Shadowing the perimeter of buildings via external decks continues as one soil cooling and permafrost protection method already used and recommended for permafrost areas (McFadden & Bennett, 1991). This same southern side shading effect was a design method I used successfully in Nulato, Alaska some years ago. This shading method greatly reduced the seasonal frost heave effects. This rapid upper level cooling is of particular importance to me because of its potential for stabilizing the effects for the seasonally thawed soils. Shallower active layers represent less adfreeze bond frost jacking stresses (less tangential stresses) within the now shallower active layer.

For Fairbanks (Figure 69 & Figure 70), finding warmer permafrost with permanent insulation is counter-intuitive to many people with whom I have spoken. This output represents a change in thinking. I also find two other items interesting. First, results showed that the center of the building remained colder than the outside edge both for permanent insulation and for seasonal insulation. In no case, did permanent insulation cool the soils over the “no insulation” base line. Snow presence, as expected, warmed the soils both with permanent insulation and with seasonal insulation.

Results showed that the presence of thermal insulation decreased the soil surface temperature thermal amplitude. For Fairbanks, compare the one-dimensional results, Figure 34 with both Figure 35 and Figure 36. The no-insulation analysis (Figure 34) resulted in a surface temperature that varies from -11 °C (11 °F) (winter) to just below 18 °C (64 °F) (summer), or a surface temperature amplitude of about 30 °C (53 °F).

Providing thermal insulation changes the surface temperature thermal dynamics. Results showed that permanent R10 insulation (Figure 35) reduced the surface temperature thermal amplitude, while allowing summer thawing (an active layer) to remain. Depending upon time of year, the surface temperature varied from just under -1 °C (30 °F) to almost 4 °C (39 °F), to only about a 5 °C (9 °F) surface temperature amplitude. Summarizing, the thermal amplitude reduced significantly from 30 °C (53 °F) for the no insulation case to about 5 °C (9 °F) for the R10 permanent insulation case.

With seasonal R10 insulation, results also showed changed the thermal dynamics, but differently than with permanent insulation. Multiple modeling results showed that the freezing isotherm is within the insulation layer or within the first 30 cm (12 in) of depth below the insulation. Almost no active layer persisted when utilizing seasonal insulation. This represents a considerable decrease in frost jacking forces during seasonal freezing-soil conditions.

4.3.7 Graphic results and discussion for Kotzebue.

Table 15.
Kotzebue Two-Dimensional Analyses, R-Values, & Resulting Figures

	Insulation				Snow	Temperature Results	
Location	Common Name	Thermal Resistance m^2 °C/W (ft^2 hr °F/Btu)	Thickness mm (in)	Duration	Present In Winter	Seasonal Variations	MAST at CL, at Edge
Kotzebue	None	zero	zero	n/a	No	Figure 71	Figure 77Figure 69, Figure 78
					Yes	Figure 72	
	R10	1.8 (10)	51 (2)	Permanent	No	Figure 73	
					Yes	Figure 74	
				Seasonal	No	Figure 75	
					Yes	Figure 76	
Kotzebue See Appendices	R20	3.5 (20)	102 (4)	Permanent	No		
					Yes		
				Seasonal	No		
					Yes		
	R40	7.0 (40)	203 (8)	Permanent	No		
					Yes		
				Seasonal	No		
					Yes		

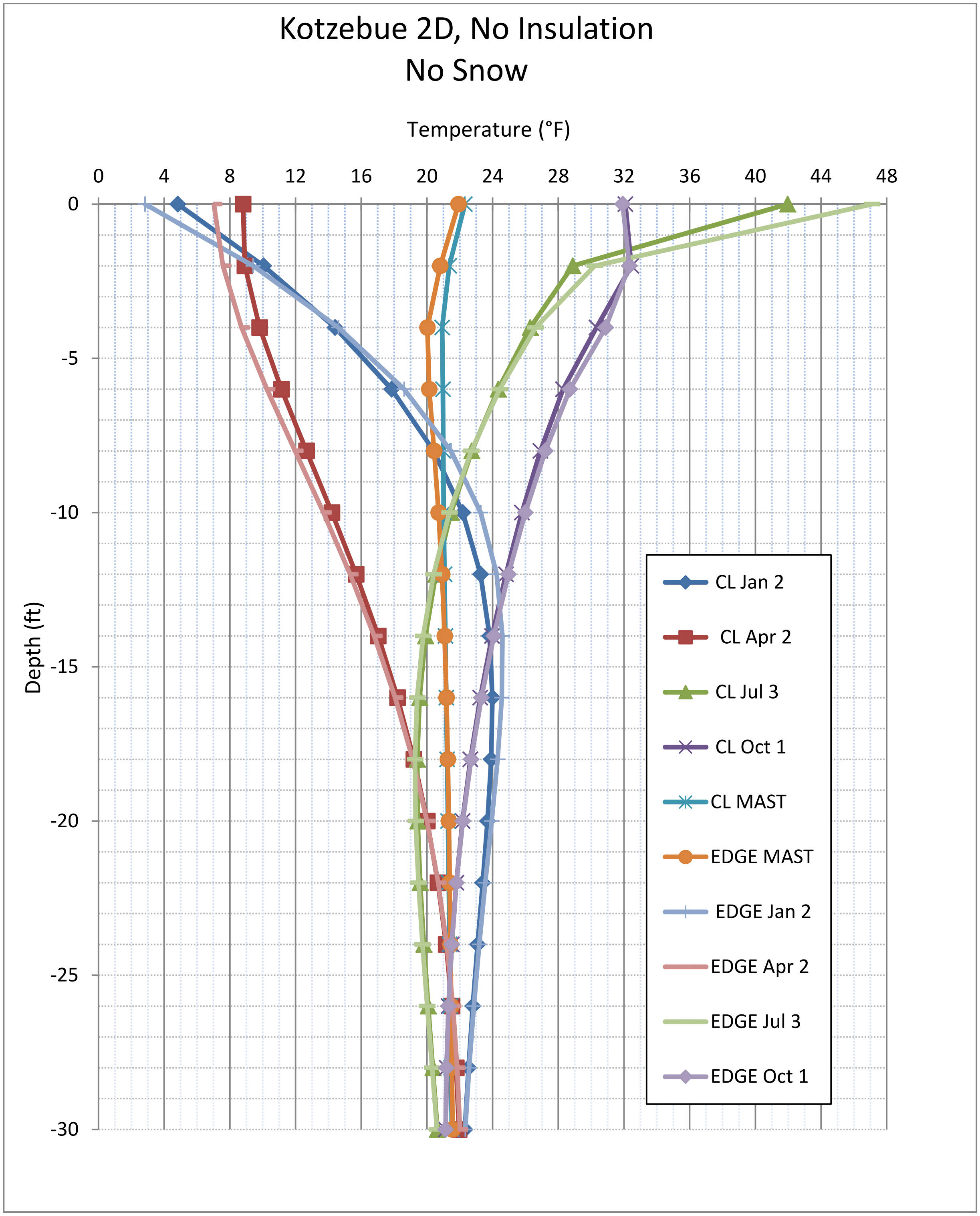

Figure 71. Kotzebue 2D, no insulation, no snow condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included no insulation, no winter snow, and summer bare soil surface.

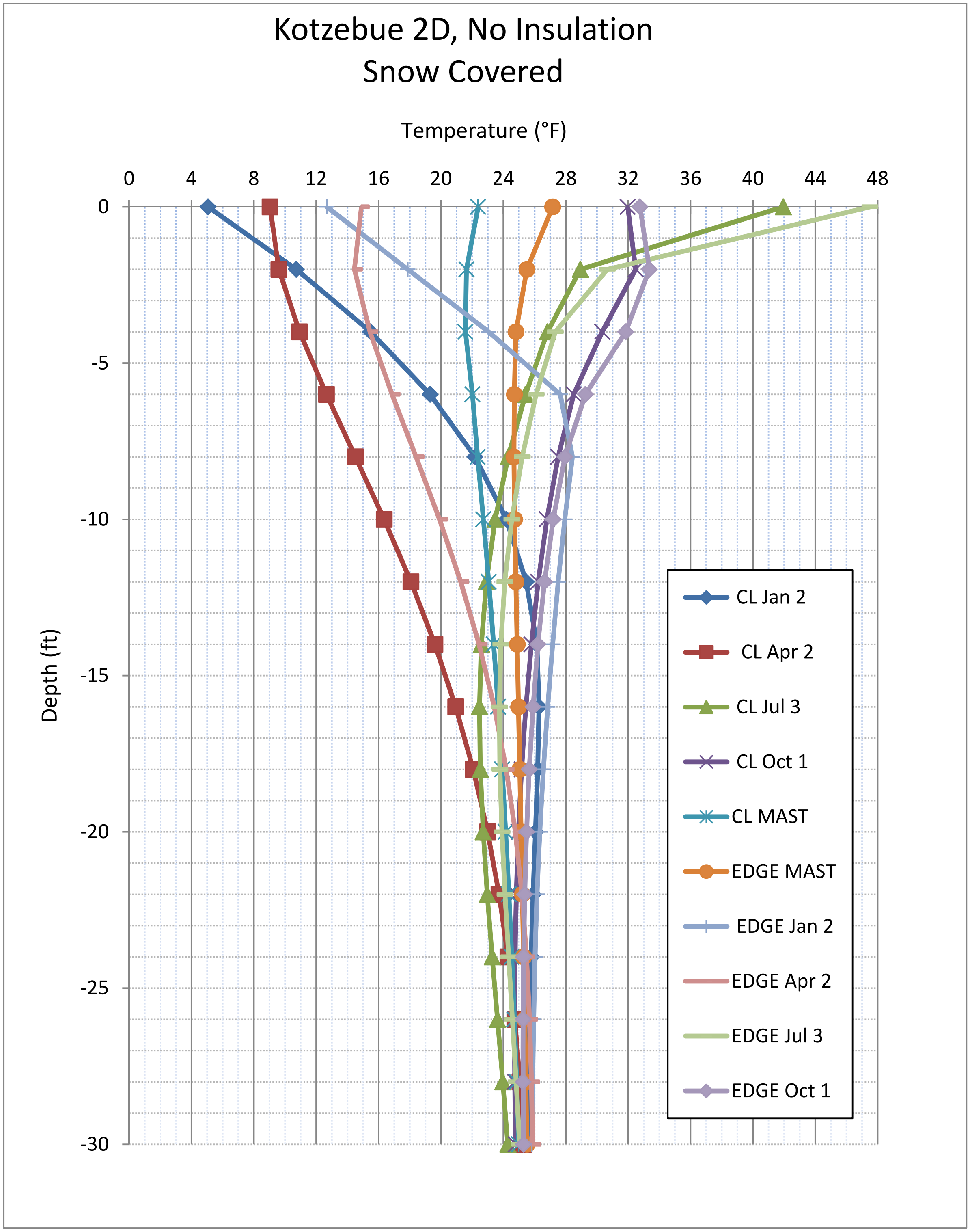

Figure 72. Kotzebue 2D, no insulation, snow covered condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included no insulation, with winter snow cover, and summer bare soil surface.

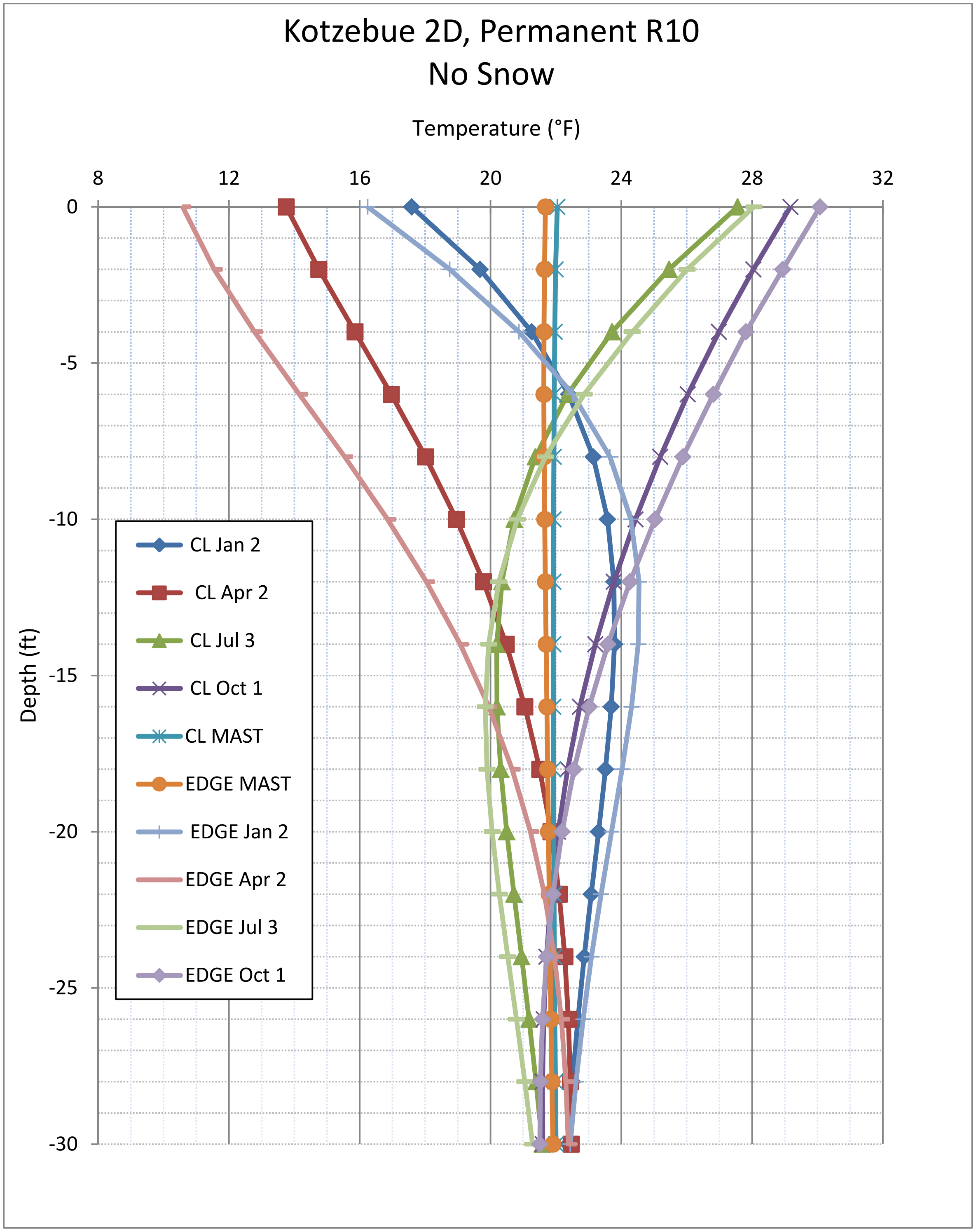

Figure 73. Kotzebue 2D, R10 permanent thermal insulation, no snow condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included permanent insulation, no winter snow, and summer bare soil surface

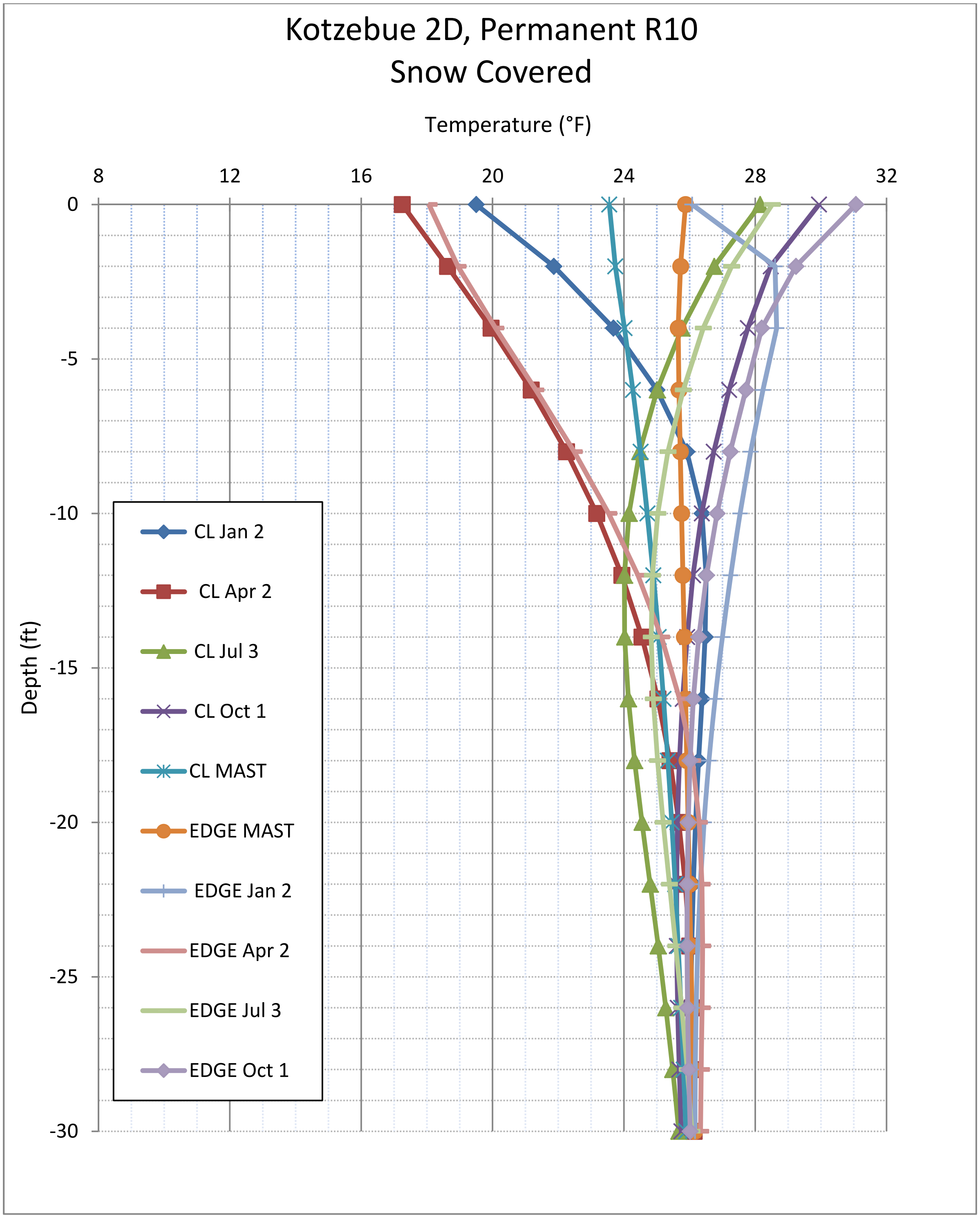

Figure 74. Kotzebue 2D, R10 permanent thermal insulation, snow covered condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included permanent insulation, with winter snow cover, and summer bare soil surface.

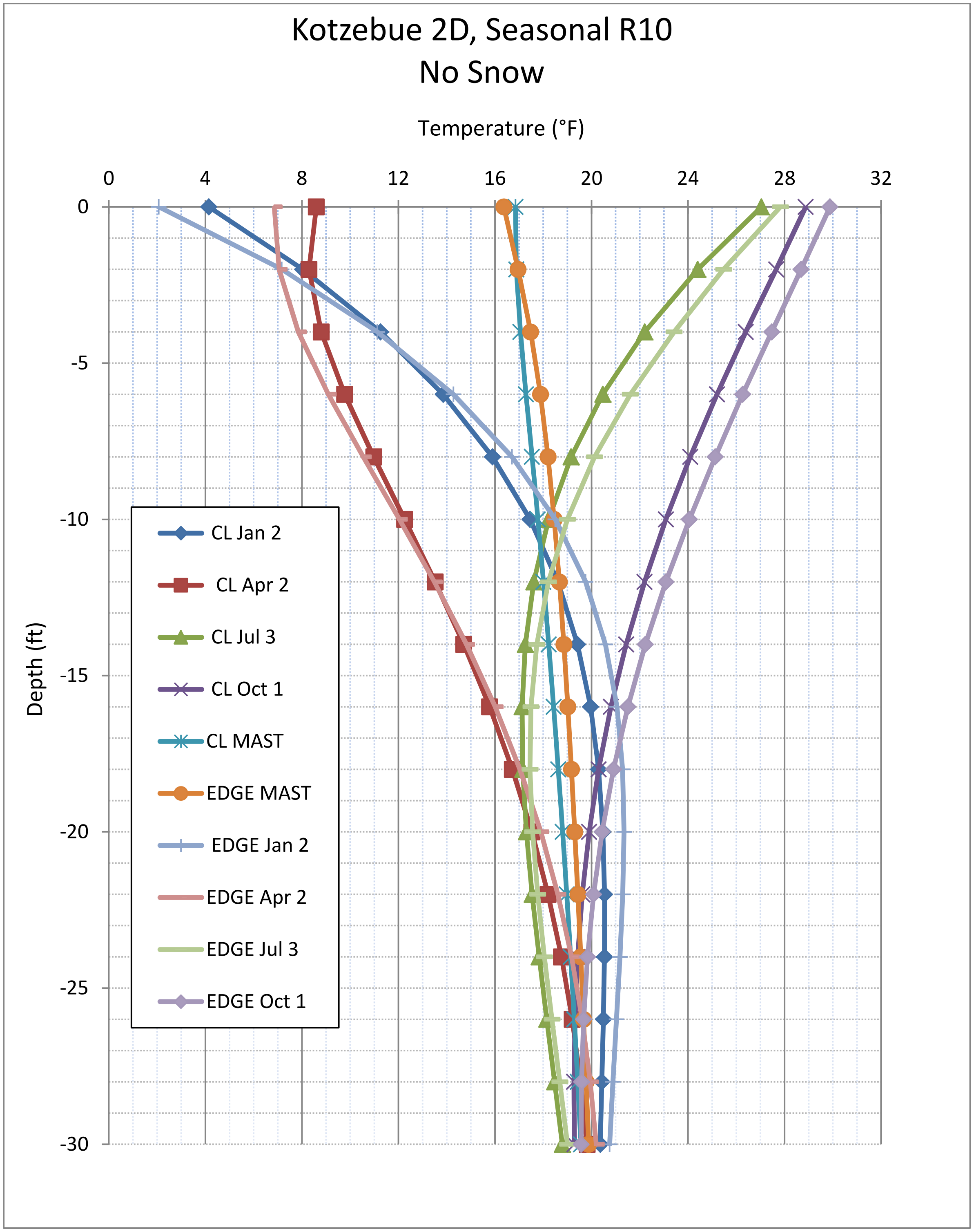

Figure 75. Kotzebue 2D, R10 seasonal thermal insulation after 10 years, no snow condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included seasonal insulation, no winter snow, and summer bare soil surface.

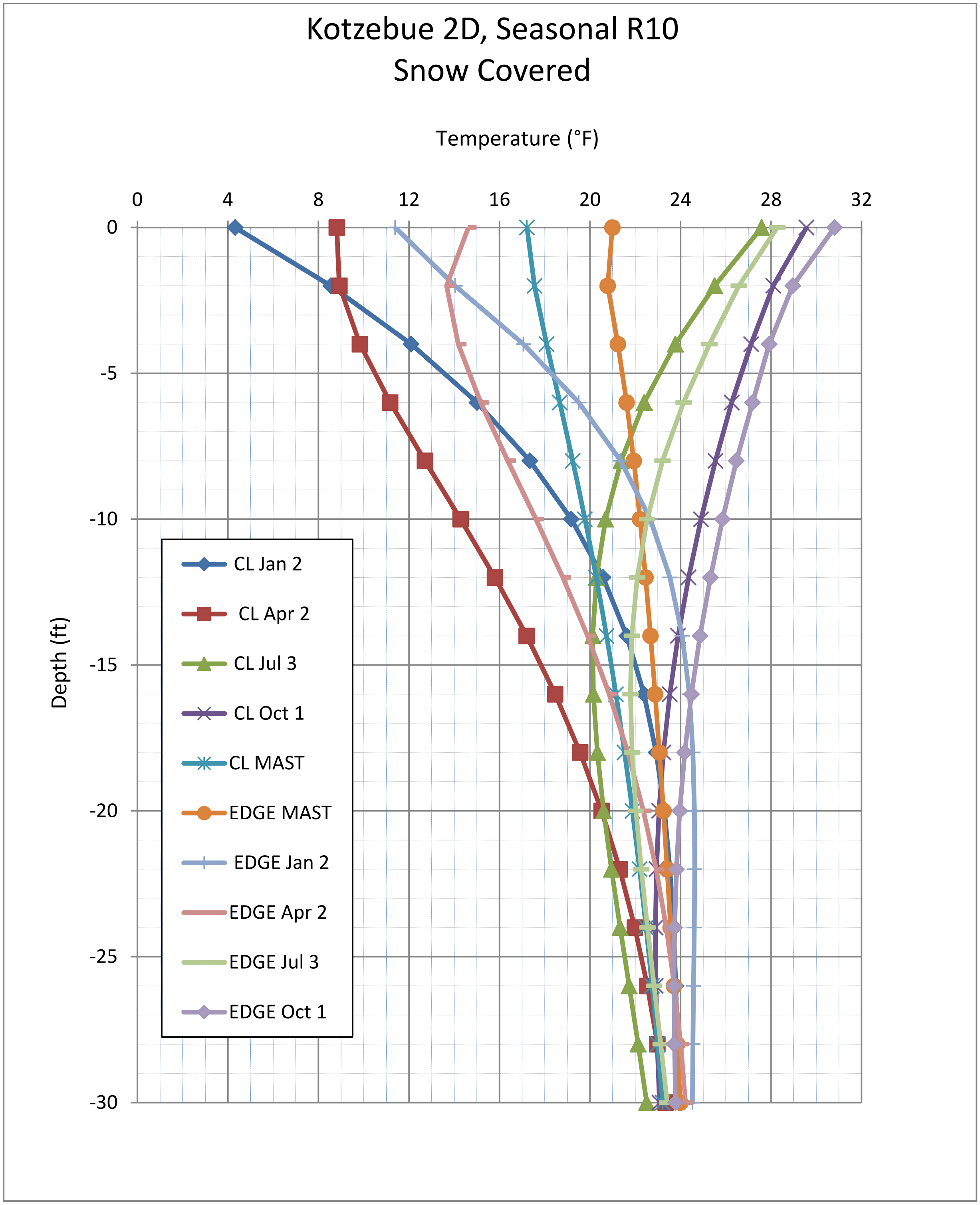

Figure 76. Kotzebue 2D, R10 seasonal thermal insulation after 10 years, snow covered condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included seasonal insulation, with winter snow cover, and summer bare soil surface

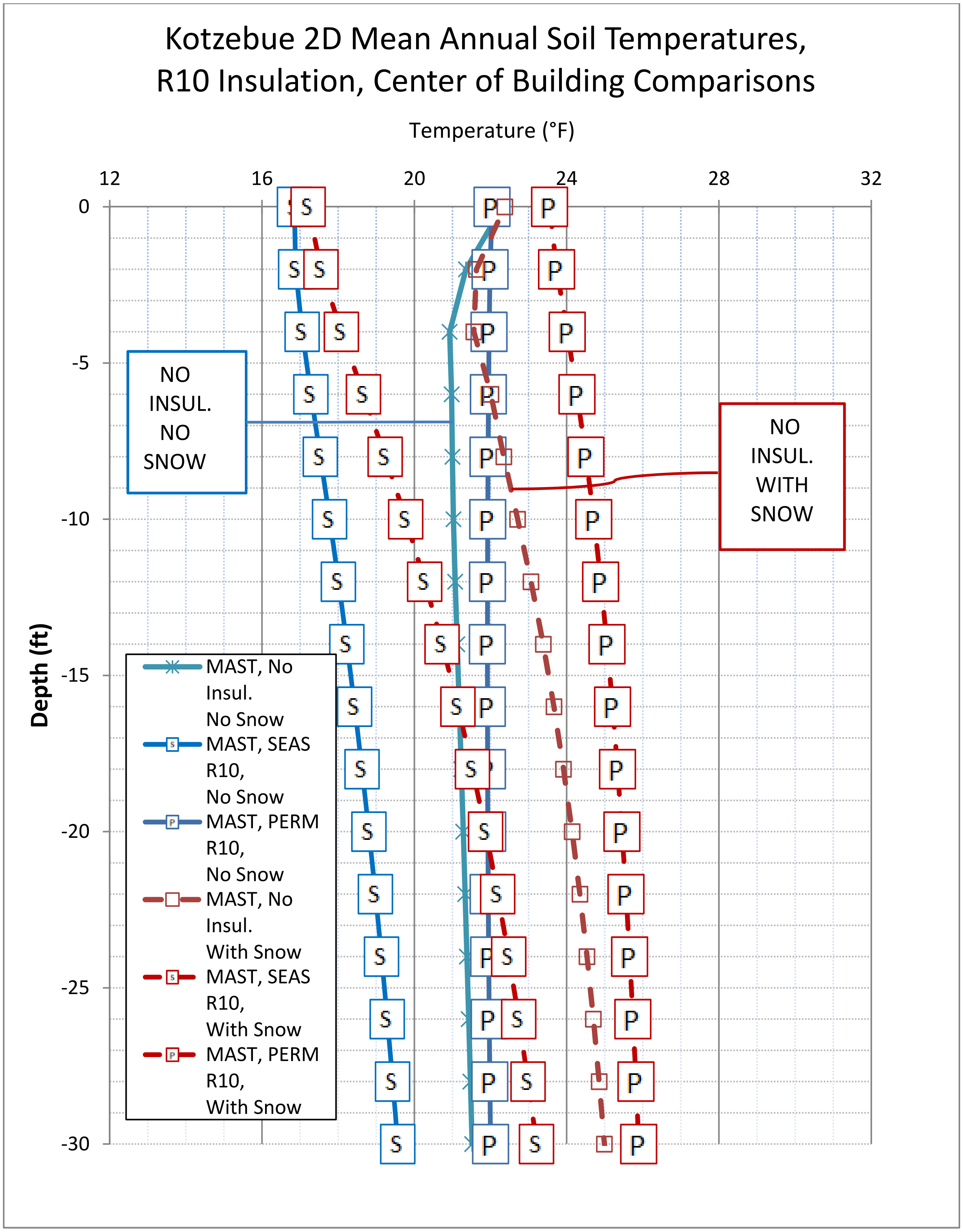

Figure 77. Kotzebue 2D, R10, building center, mean annual soil temperatures. Conditions included 10 years seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

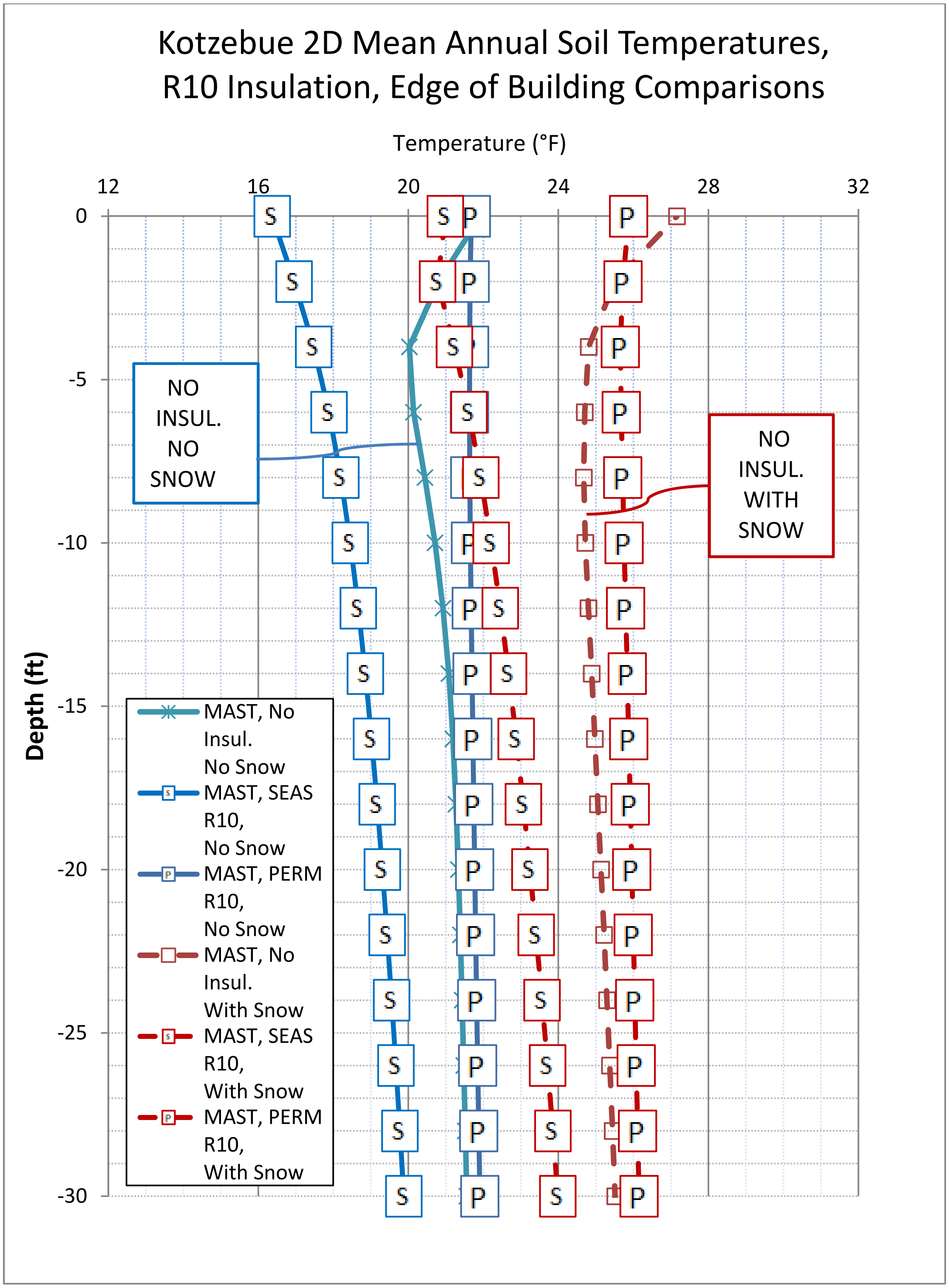

Figure 78. Kotzebue 2D, R10, building edge, mean annual soil temperatures. Conditions included 10 years seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

For Kotzebue, each insulation case investigated (Figure 73 through Figure 76) demonstrated smaller surface temperature changes (thermal amplitudes) than the “no insulation” cases (Figure 71 & Figure 72).

For Kotzebue (Figure 77 & Figure 78), as in the Fairbanks investigations, permanent insulation warmed the permafrost and seasonal insulation cooled the permafrost. The center of the building remained colder than the outside edge for both permanent insulation and for seasonal insulation. In no case I investigated did permanent insulation cool the soils over the “no insulation” base line. Snow presence, as expected, warms the soils with both permanent and seasonal insulation.

For Kotzebue, providing seasonal insulation decreased the surface temperature thermal amplitude and eliminated the active layer. Snow removal had more cooling effect on permafrost temperatures than keeping the snow-cover and applying seasonal insulation.

4.3.8 Graphic results and discussion for Barrow.

Table 16.
Barrow Two Dimensional Analyses, R-Values, & Resulting Figures

	Insulation				Snow	Temperature Results	
Location	Common Name	Thermal Resistance m^2 °C/W (ft^2 hr °F/Btu)	Thickness mm (in)	Duration	Present In Winter	Seasonal Variations	MAST at CL, at Edge
Barrow	None	zero	zero	n/a	No	Figure 79	Figure 85, Figure 86
					Yes	Figure 80	
	R10	1.8 (10)	51 (2)	Permanent	No	Figure 81	
					Yes	Figure 82	
				Seasonal	No	Figure 83	
					Yes	Figure 84	
Barrow See Appendices	R20	3.5 (20)	102 (4)	Permanent	No		
					Yes		
				Seasonal	No		
					Yes		
	R40	7.0 (40)	203 (8)	Permanent	No		
					Yes		
				Seasonal	No		
					Yes		

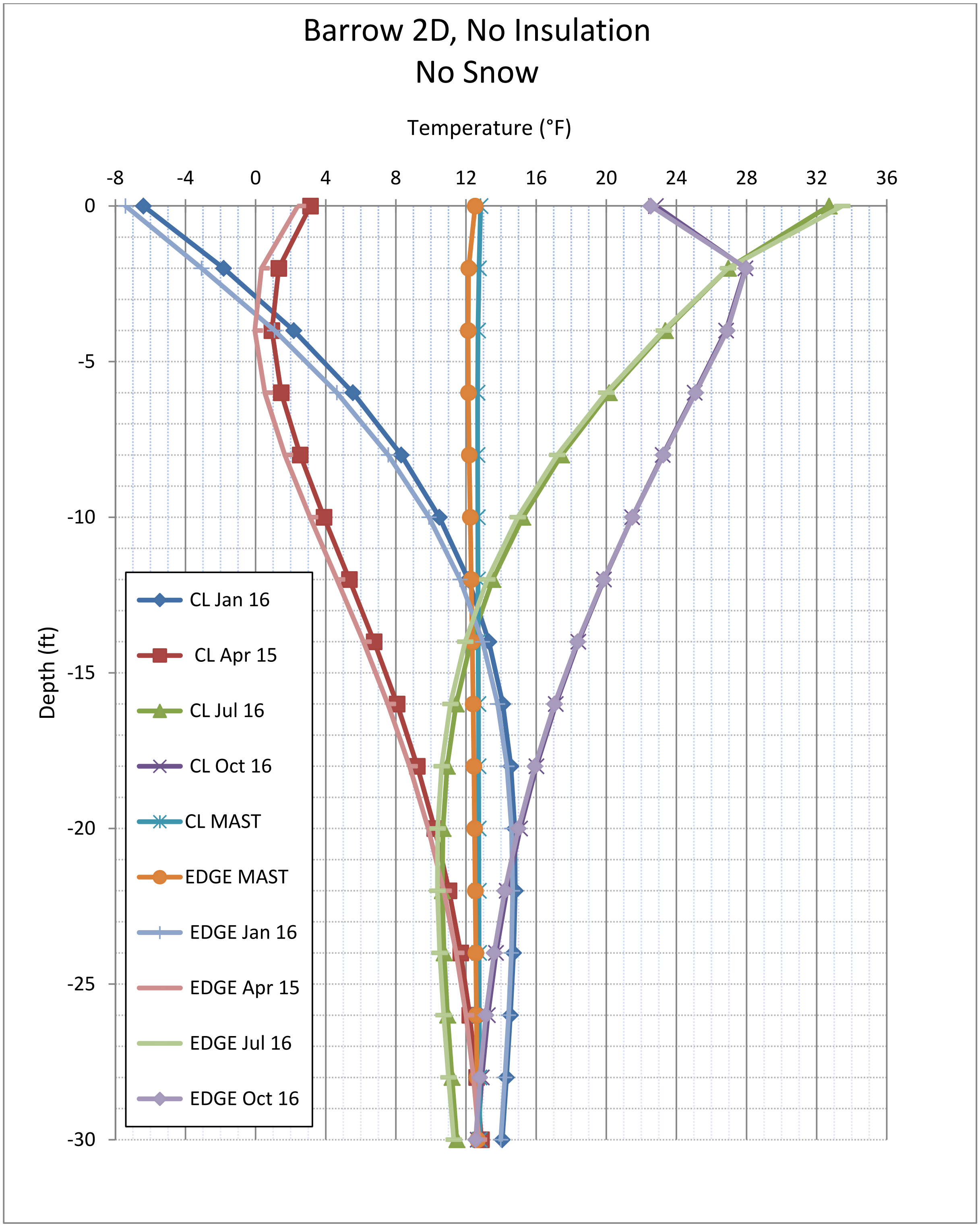

Figure 79. Barrow 2D, no insulation, no snow condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included no insulation, no snow, and summer bare soil surface.

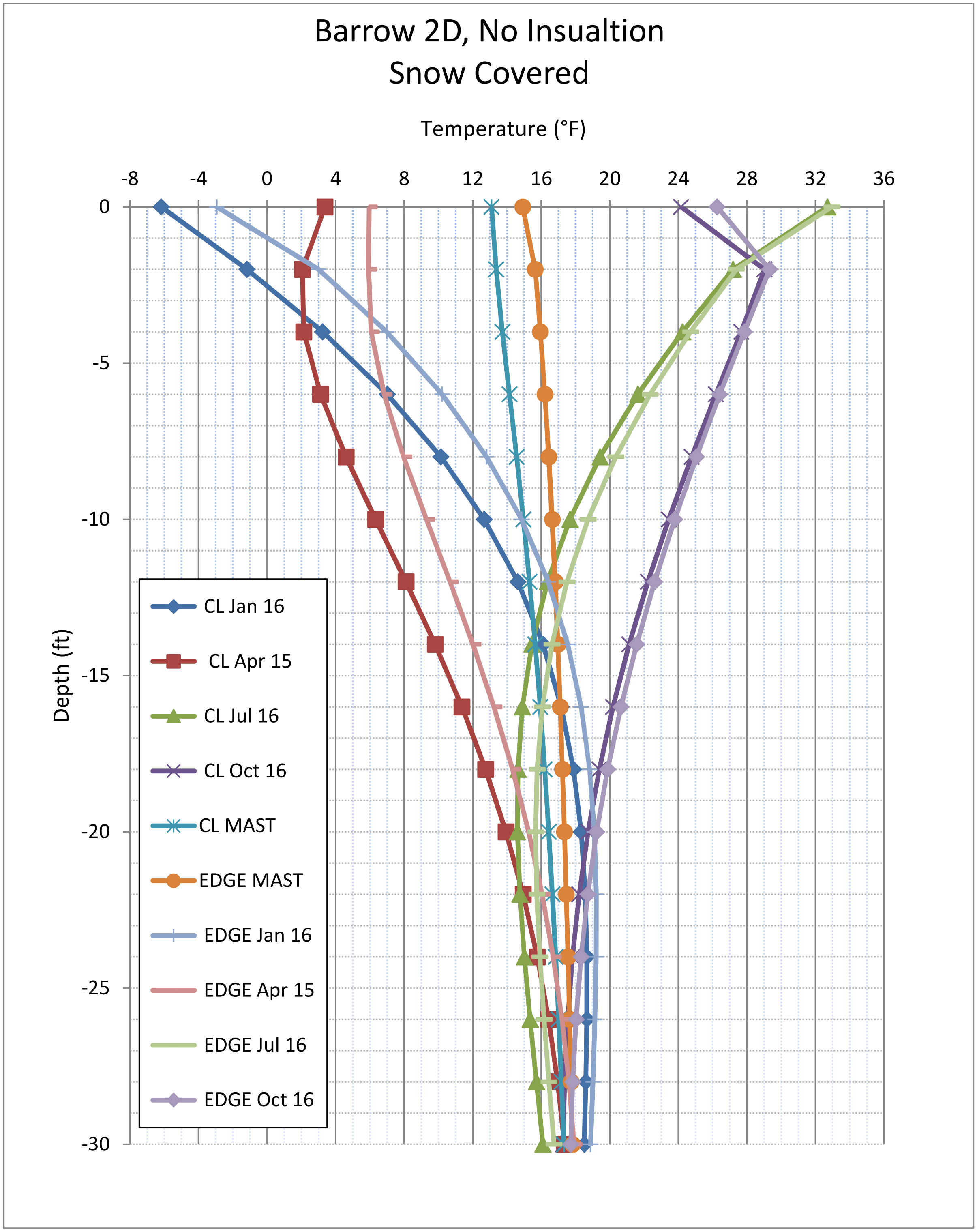

Figure 80. Barrow 2D, no insulation, snow covered condition.
Temperature distribution with depth during the year, at centerline (CL) and edge.
Conditions included no insulation, with snow cover, and summer bare soil surface.

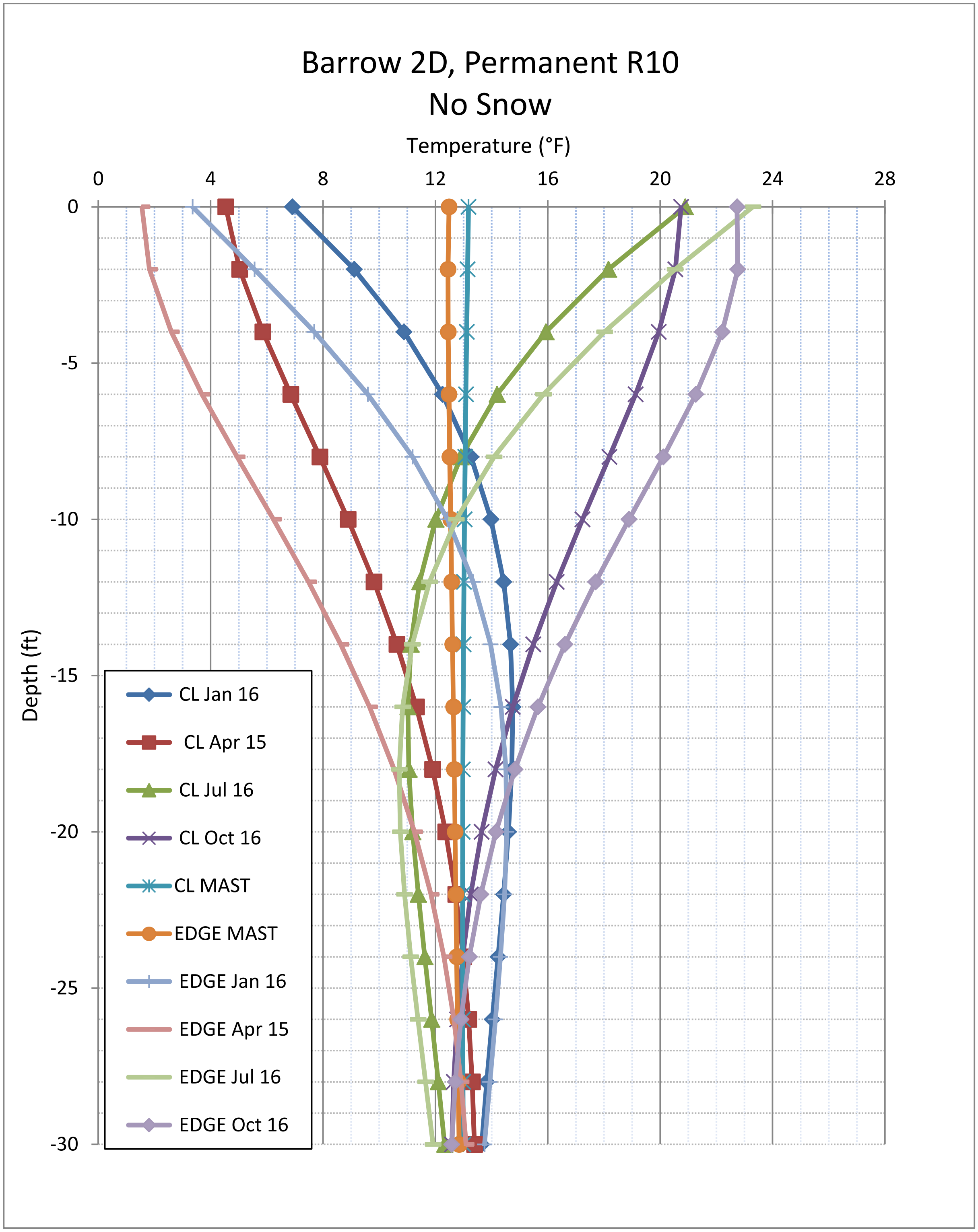

Figure 81. Barrow 2D, R10 permanent thermal insulation, no snow condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included no insulation, no snow, and summer bare soil surface.

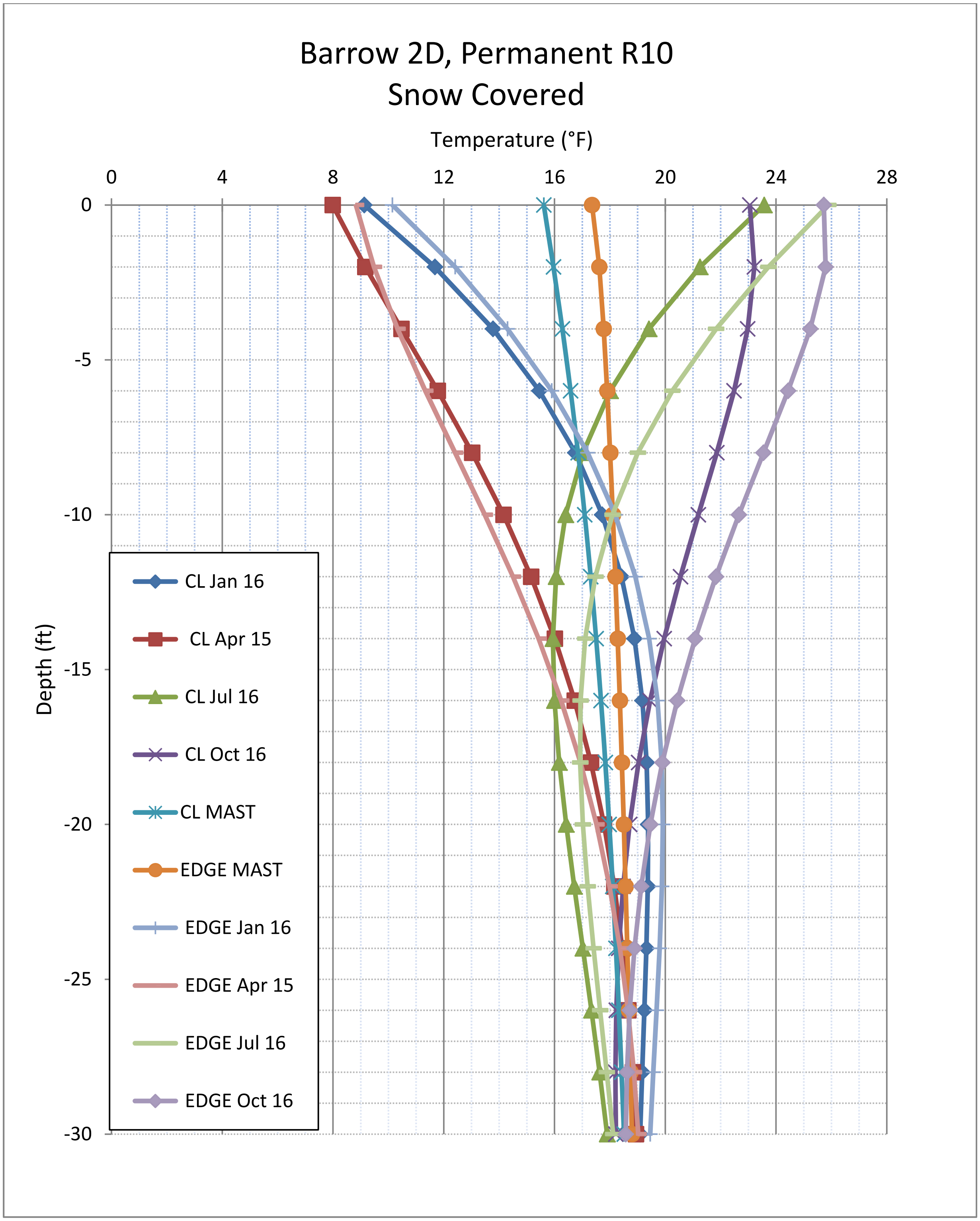

Figure 82. Barrow 2D, R10 permanent thermal insulation, snow covered condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included no insulation, with snow cover, and summer bare soil surface.

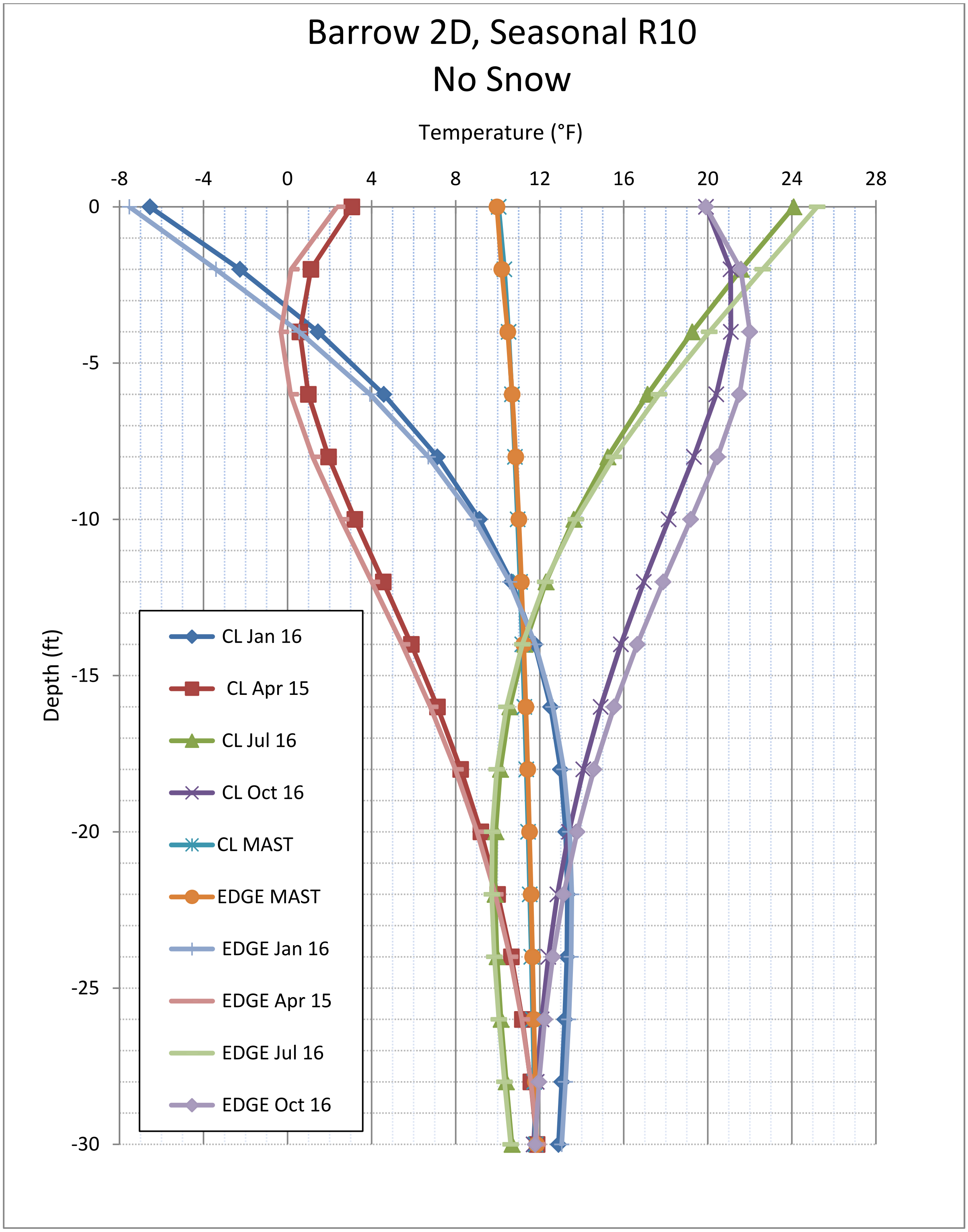

Figure 83. Barrow 2D, R10 seasonal thermal insulation, no snow condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included 10 years seasonal insulation, no snow, and summer bare soil surface.

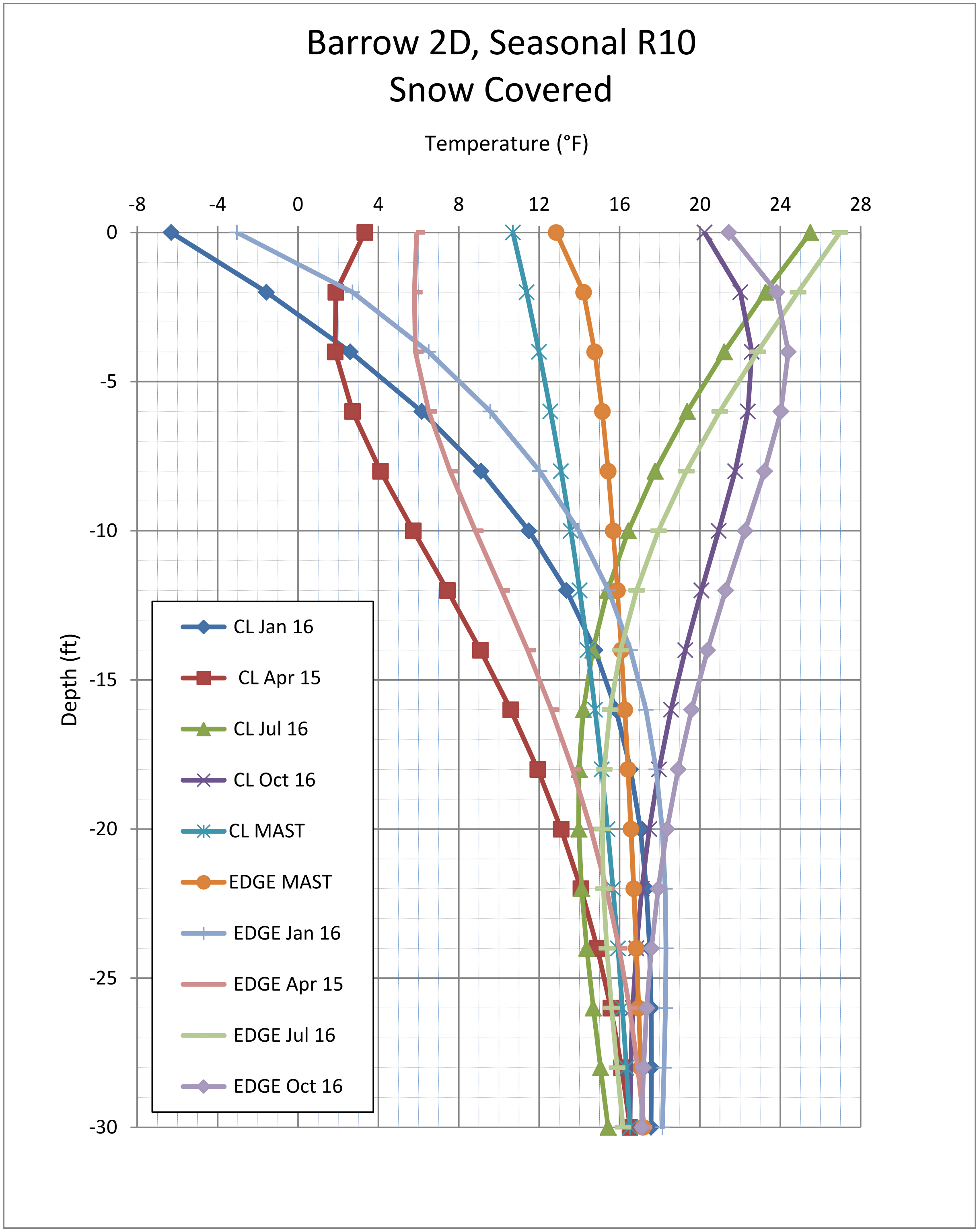

Figure 84. Barrow 2D, R10 seasonal thermal insulation, snow covered condition. Temperature distribution with depth during the year, at centerline (CL) and edge. Conditions included 10 years seasonal insulation, with snow cover, and summer bare soil surface.

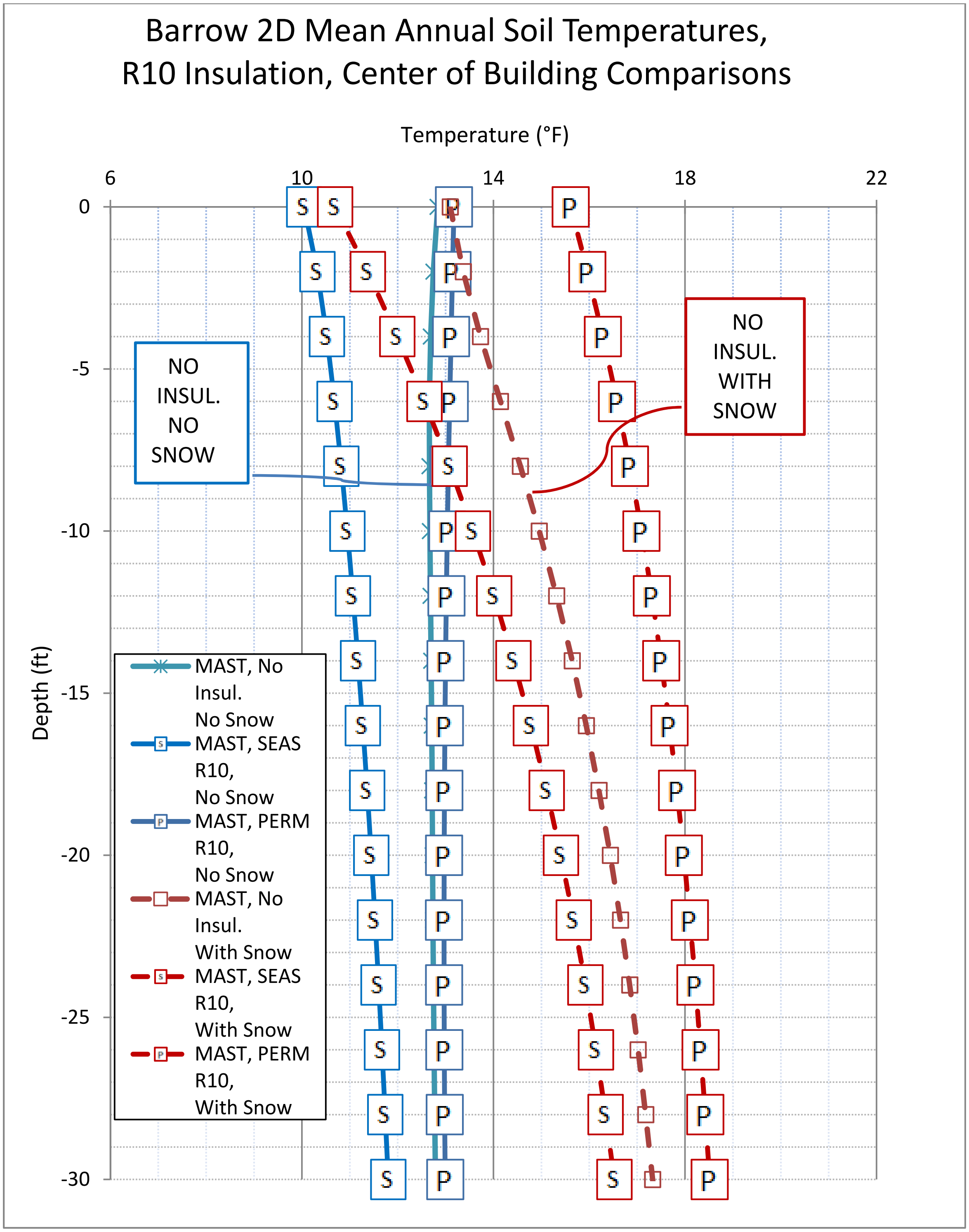

Figure 85. Barrow 2D, R10, building center, mean annual soil temperatures.
Conditions included 10 years seasonal (S) and permanent (P) insulation,
both no snow and with snow cover.

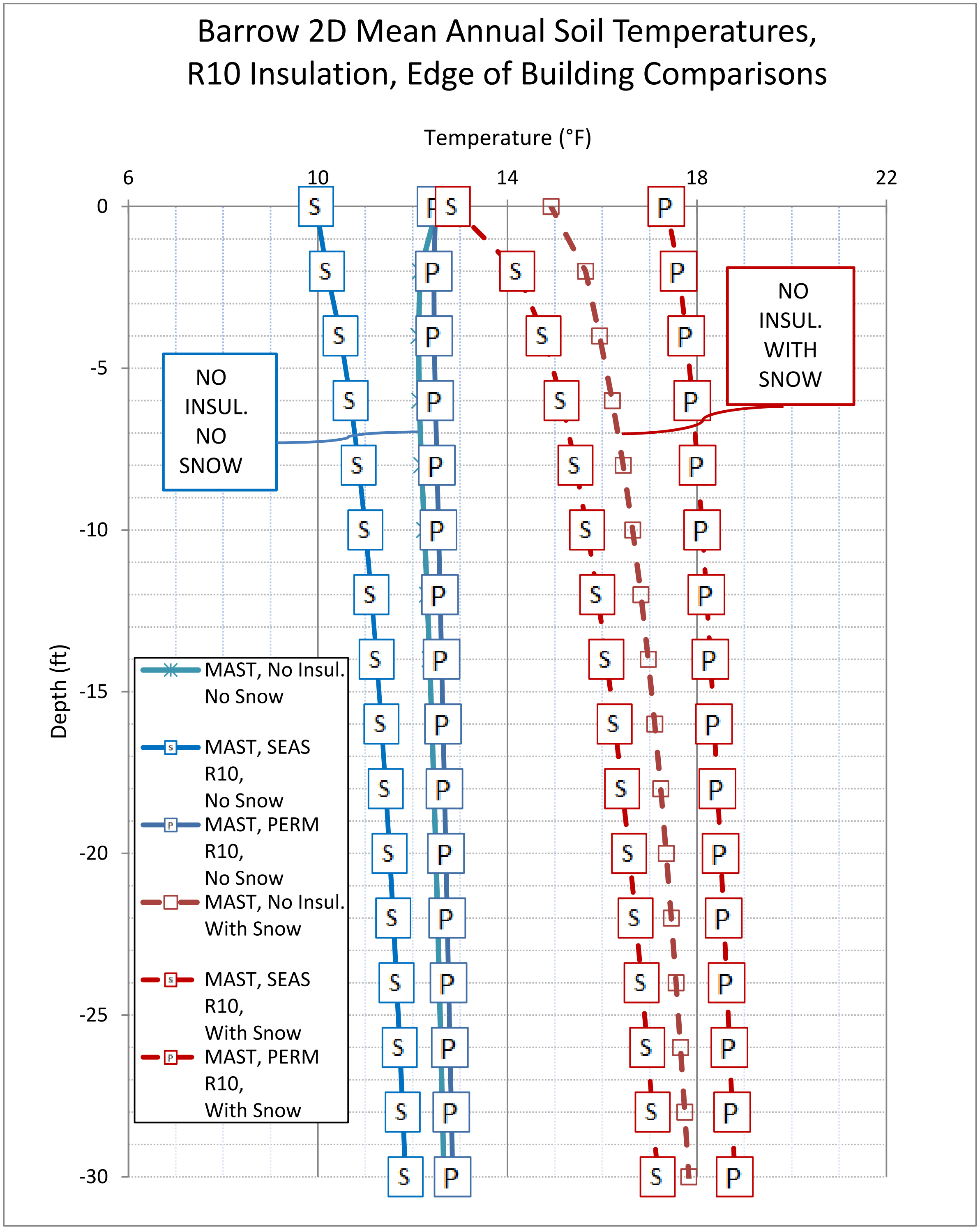

Figure 86. Barrow 2D, R10, building edge, mean annual soil temperatures. Conditions included 10 years seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

For Barrow, first compare the no snow, one-dimensional (no building) scenarios, as follows:

Compare Figure 42 (no insulation and no snow)
with Figure 44 (permanent R10 insulation and no snow)
and with Figure 46 (seasonal R10 insulation and no snow).

Both the permanent insulation scenario and the seasonal insulation scenario eliminated the active layer for the no-snow condition and provided reduced frost heaving risks.

Next, compare the snow covered, one-dimensional (no building) scenarios, as follows:

Compare Figure 43 (no insulation, with snow cover)
with Figure 45 (permanent R10 insulation, with snow cover)
and with Figure 47 (seasonal R10 insulation, with snow cover).

As in the no-snow scenarios, the snow covered scenarios produced similar results. Both the permanent insulation scenario and the seasonal insulation scenario eliminated the active layer and provided reduced frost heaving risks.

The Barrow one-dimensional (no building) mean annual soils temperature summary (Figure 48) provided additional insights. While the seasonal insulation cools the MAST for both the no snow case and for the snow covered case, permanent insulation warms the permafrost for both the no snow scenario and for the snow covered scenario. Similar results occurred for the two-dimensional (with building) evaluations. This permafrost warming with permanent insulation represented a pivotal finding.

Move forward to Barrow's two-dimensional R10 insulation results (Figure 85 & Figure 86). Permanently installed insulation warmed the permafrost at depth. However, the no-snow case with permanently installed insulation (left side of the graphs) resulted in cooler permafrost soils at depths below the active layer than did the snow-covered case (right side of the graphs). While permanently applied thermal insulation may be helpful for reducing the active layer thickness, expect permafrost warming at depth. Compare the mean annual soils temperature (MAST) results for both the center of the building and for the edge of the building. Examine the results for Fairbanks, Kotzebue, and Barrow. In every case investigated, permanently installed thermal insulation warmed the permafrost at depths.

Contrast Barrow results with the results for more thaw-sensitive permafrost temperatures, like for Fairbanks (Figure 69 & Figure 70). For warmer, more thaw sensitive soils, the cooling impact from snow removal may not overcome the warming impact, at depth, from permanently installed insulation.

Therefore, I do not recommend permanently applied thermal insulation where permafrost warming of thaw-sensitive soils may become a design constraint.

4.4 Climate Change Impacts

I have already shown that discontinuous zone permafrost, with temperatures close to the thawing point, may degrade more significantly than in the colder continuous permafrost zones. These climactic regions, with warm thaw-sensitive permafrost exhibit greater potential for infrastructure damage if the permafrost warms or thaws. Therefore, I constrained my climate warming investigation to Fairbanks-like temperature regions. From the permanent insulation soils-warming results of section 4.3 Analyses with Buildings in Place, Permafrost Zone, I investigated only seasonal insulation use, not permanent insulation. In addition, I extended the investigation time line to 25 years of seasonal insulation use in warmer climatic conditions.

4.4.1 Testing means and methods for climate change.

I used Fairbanks current monthly temperatures as a baseline (Table 6). I investigated an air temperature warming by 2.2 °C (4 °F). I used an abrupt air temperature increase, not a gradual increase over time. I also used the air temperature increase for the entire year, not just a seasonal application. I intentionally wanted conservative analyses results and hoped to provide a ‘worst-case’ scenario for climate warming by using sudden air temperature increases. I used the same soils and insulation parameters as described in Table 4, above. I used the same Temp/W analysis program, the same analyses regions, and the same bottom and side boundary conditions. I only changed the surface temperatures. For all analyses connected with climate warming, I investigated using R10 insulation with the thermal properties shown in Table 10.

The following output modes included the effects of warmer climates upon the soils thermal regime. The model included air temperature increases of 2.2 °C (4 °F). The analyses duration extended from 10-years to 25-years of seasonal-insulation-use. The thermal effects below the center of the building contrasted with the edge of building effects. I present four results plots here.

4.4.2 Results and discussion for changed climate.

First, for easier direct comparison, I duplicated Figure 59 and Figure 60, above, as Figure 87 and Figure 88, here. These first two plots, for current Fairbanks climate, compared soils temperatures with depth for ten years of no insulation. Then, the output compared one, five, and ten years of summer seasonally applied insulation (i.e., with insulation ground cover applied below the building in the summer and removed in the winter). The output results compared the center-of-building results with the edge-of-building. Results continued to show warmer soils near the edge of the building, compared with the center of the building. Note how quickly the soils cooled with just one year of applied seasonal insulation. Results also showed little additional soils cooling after five years of applied seasonal insulation.

Next, the analyses considered a warmer climate (Figure 89 & Figure 90). I extended the timeline effect of the warmer temperatures to 25 years. These next two plots provided the 25-year seasonal insulation results with air temperatures 2.2°C (4 °F) warmer. The output results compared the center-of-building results with the edge-of-building. As expected, the MAST results for warmer climate, without applied seasonal insulation, showed soils warming.

Even when warmer air temperatures increased the mean annual soil temperatures (MAST) to above freezing, results showed that one year of applied seasonal insulation reduced the MAST to below freezing again. While the surface soils cooled with seasonal insulation application, at depth, different soils results occurred than at the surface.

Influenced by the long-term warmer air temperatures, results at depth indicated increasing soils-temperatures with time. The soils temperatures below 12 m to 15 m (40 ft to 50 ft) deep warmed about 0.6 °C (1 °F) in the 25 years of seasonal insulation use.

September 15, end of summer, results provided additional information (Figure 91 & Figure 92, compared to Figure 61 & Figure 62). Without applied seasonal insulation, these climate change results showed the expected warmer surface temperature increases to about 7.8 °C to 11.1 °C (46 °F to 52 °F).

Results showed seasonally applied insulation, with a warmer climate, reduced the end-of-summer surface-zone of thawed soils. Initially, the current climate, edge of the building, results showed a thaw depth of about 2.1 m (7 ft) (Figure 62). With warmer climate, and with seasonally applied insulation, the edge of building results showed a decreased thaw depth to less than 0.6 m (2 ft) (Figure 92).

I arranged the following figures in pairs, starting on an even page number, to facilitate side-by-side viewing.

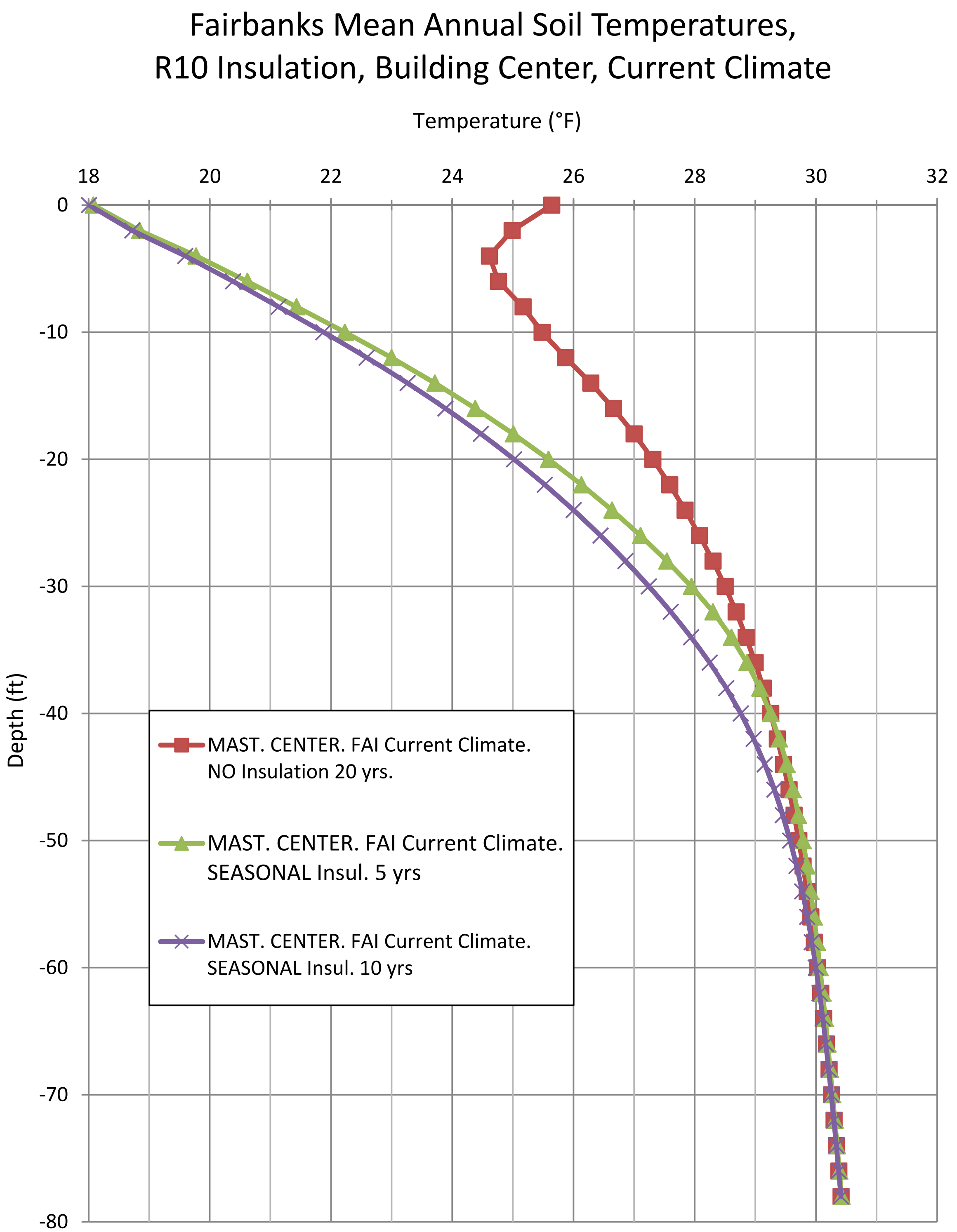

Figure 87. Fairbanks current climate, R10, building center, mean annual soil temperatures. Conditions included seasonal insulation at different durations, and bare soil surface with no snow.

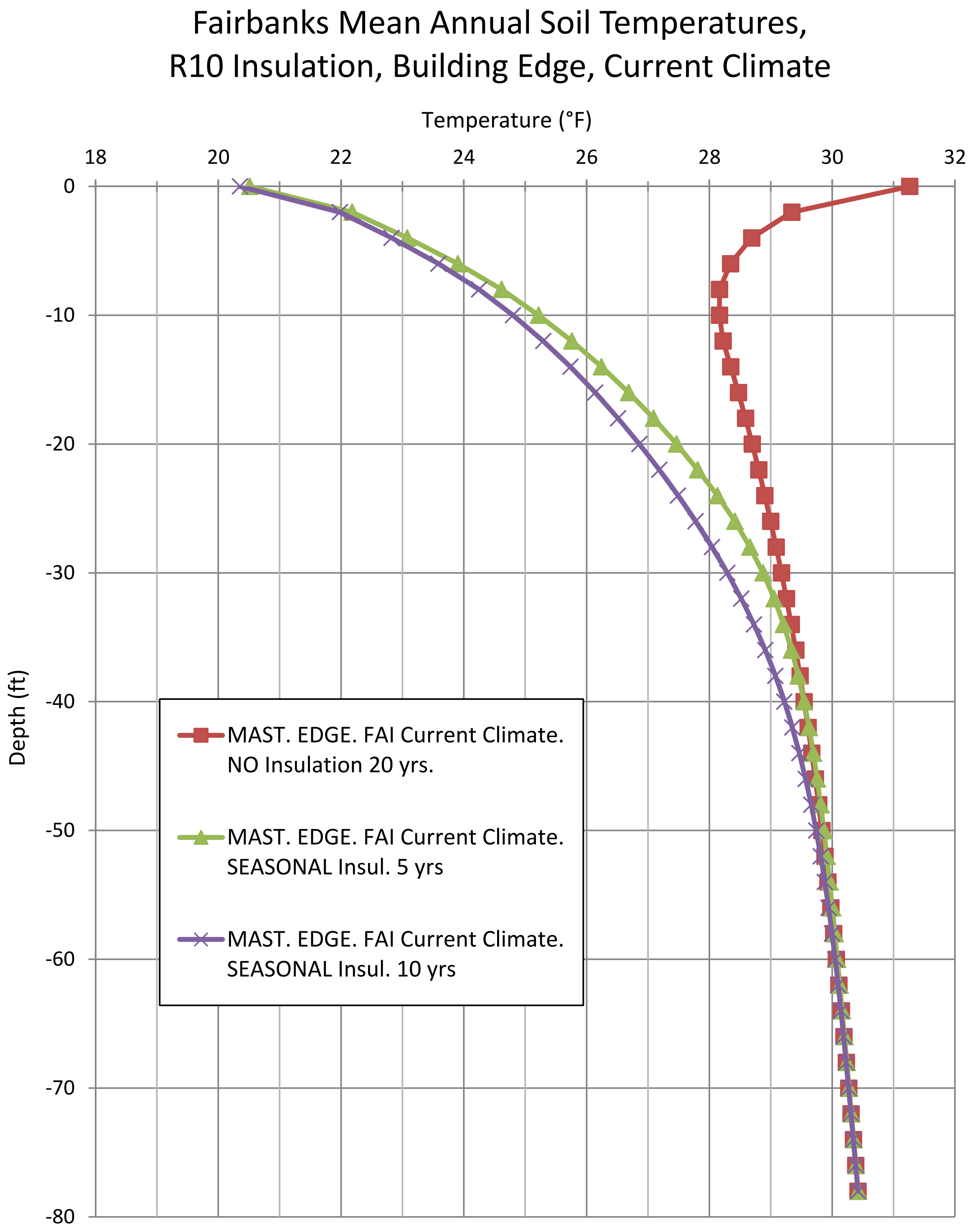

Figure 88. Fairbanks current climate, R10, building edge, mean annual soil temperatures. Conditions included seasonal insulation at different durations, and bare soil surface with no snow.

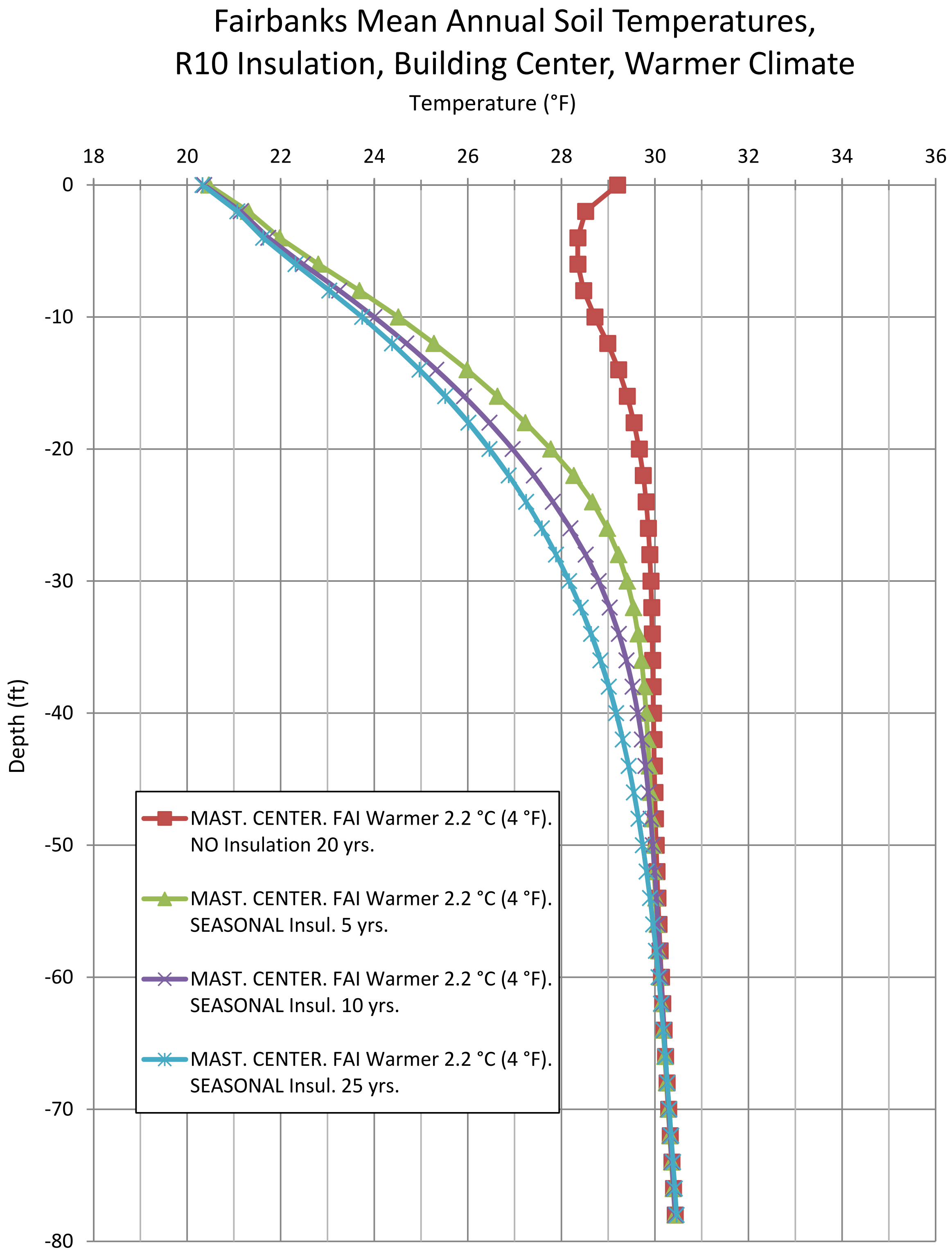

Figure 89. Fairbanks warmer climate, R10, building center, mean annual soil temperatures. Conditions included 2.2 °C (4 °F) warmer climate, seasonal insulation at different durations, and bare soil surface with no snow.

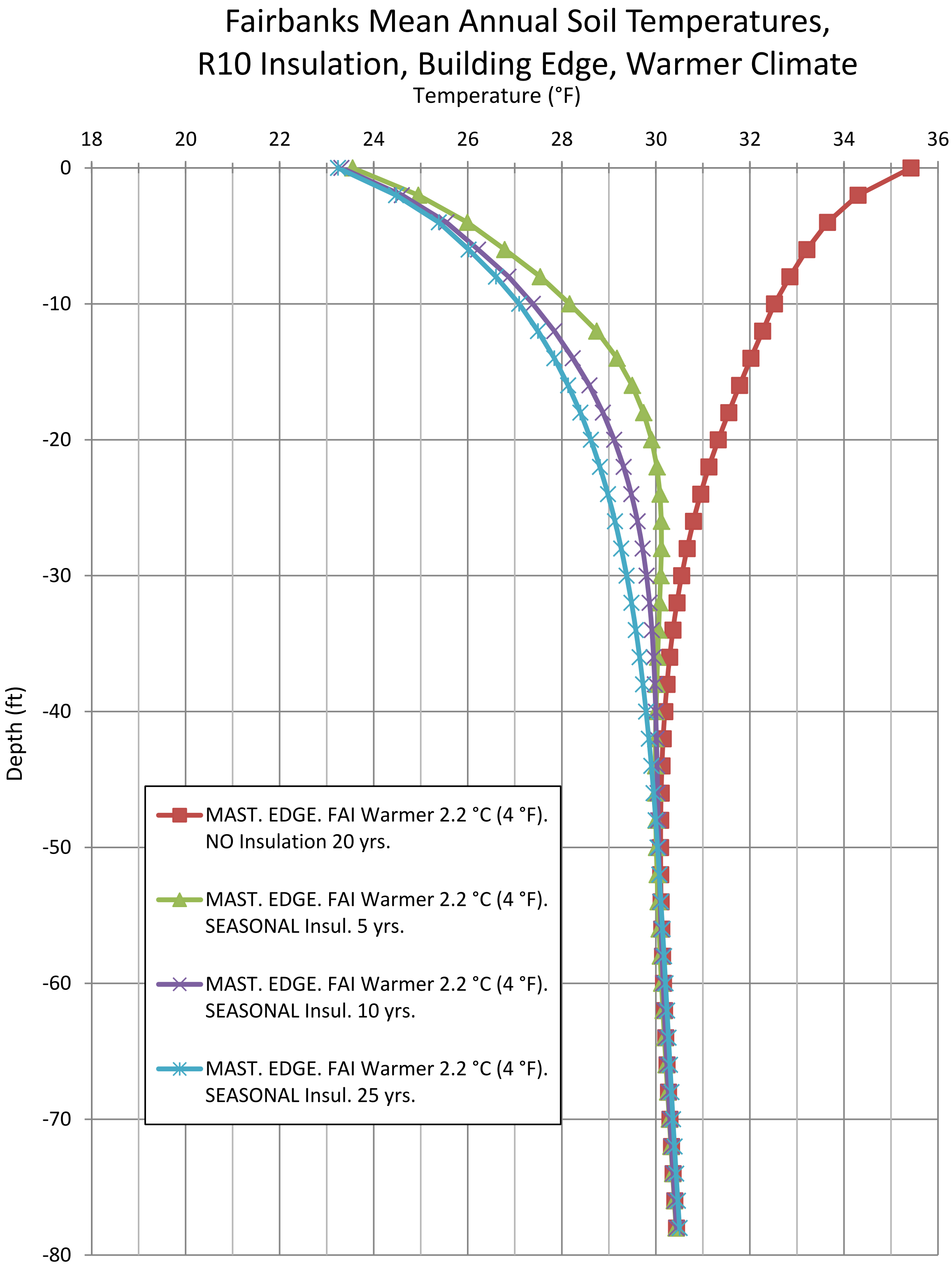

Figure 90. Fairbanks warmer climate, R10, building edge, mean annual soil temperatures. Conditions included 2.2 °C (4 °F) warmer climate, seasonal insulation at different durations, and bare soil surface with no snow.

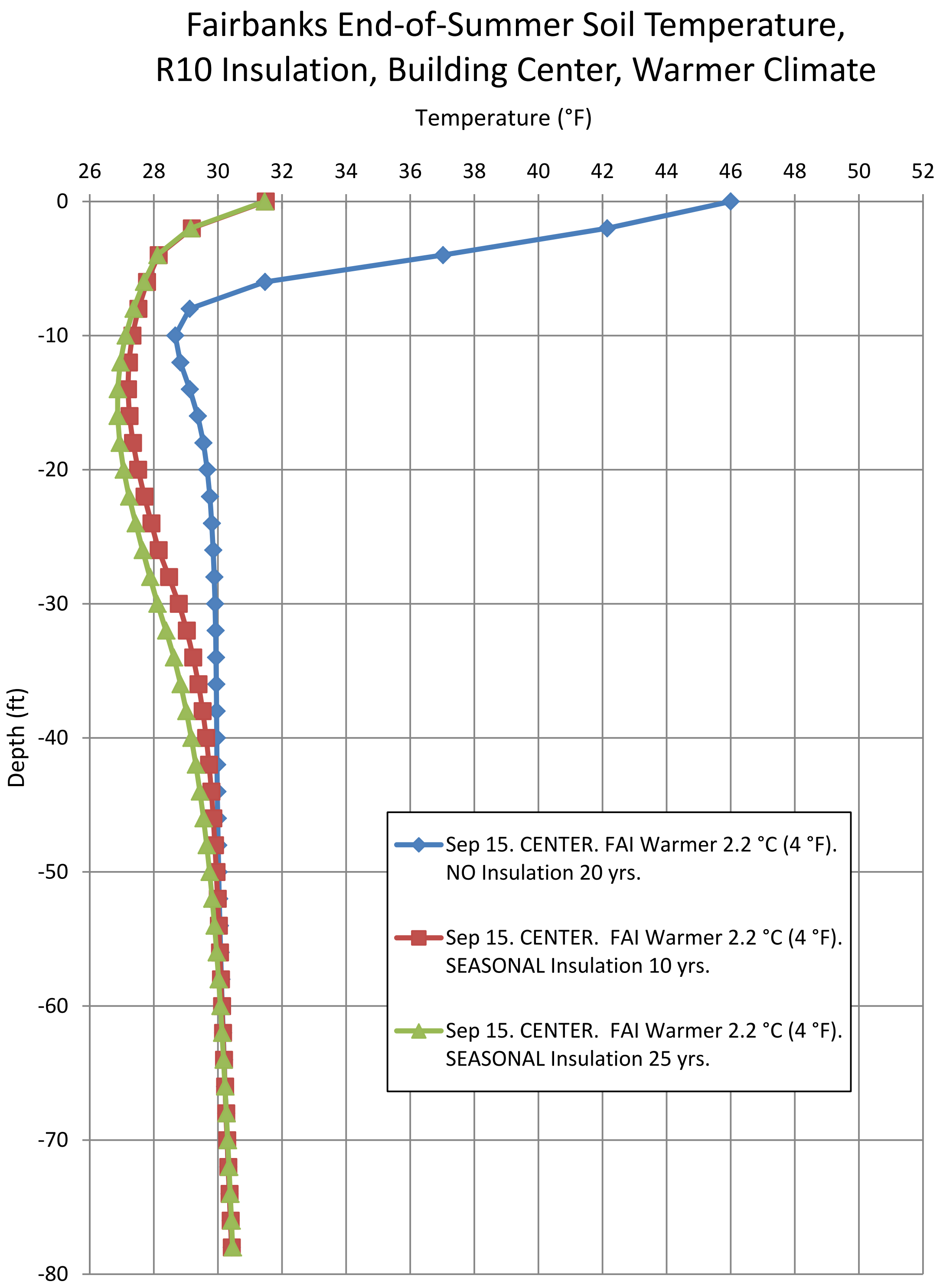

Figure 91. Fairbanks warmer climate, R10 insulation, building center, Sep. 15 soil temperatures. End of summer soil temperatures with depth; included 2.2 °C (4 °F) warmer climate, seasonal insulation at different durations, and bare soil surface with no snow.

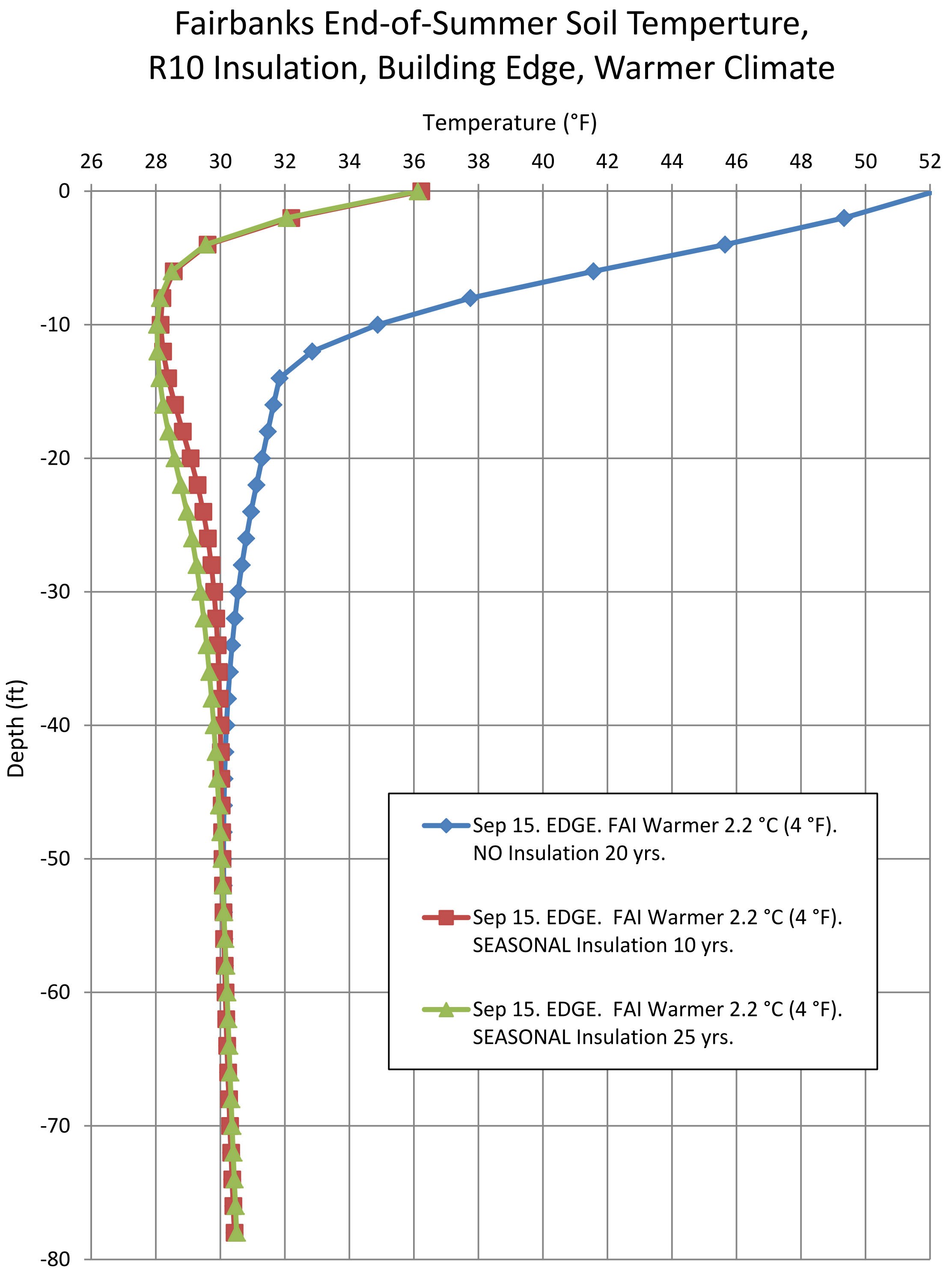

Figure 92. Fairbanks warmer climate, R10 insulation, building edge, Sep. 15 soil temperatures. End of summer soil temperatures with depth; included 2.2 °C (4 °F) warmer climate, seasonal insulation at different durations, and bare soil surface with no snow.

While seasonally applied insulation protected the building area, results for a 2.2 °C (4 °F) warmer climate showed permafrost degradation away from the building. Compare Figure 55 with Figure 93, at a distance of 15.2 m (50 ft) from the building centerline. With current climate conditions, results showed the freezing isotherm at about 2.3 m (7.5 ft) deep (Figure 55). With warmer climate conditions, at the same distance from the building centerline, results showed a deeper freezing isotherm, at almost 7.3 m (24 ft) deep (Figure 93).

These distant permafrost degradation results contrasted with results at the edge of the building. When protected with seasonal insulation, the edge of the building results at 6.1 m (20 ft) deep showed that the permafrost table rose not degraded. Current climate showed the permafrost depth at 1.8 m (6 ft) deep (Figure 55). After 25 years of warmer climate, with seasonally applied insulation, the edge-of-building permafrost table raised over 1 m (3 ft) to about 0.6 m (2 ft) below the surface (Figure 93). In addition, the center-of-the-building results showed the freezing isotherm even higher, right below or within the insulation layers.

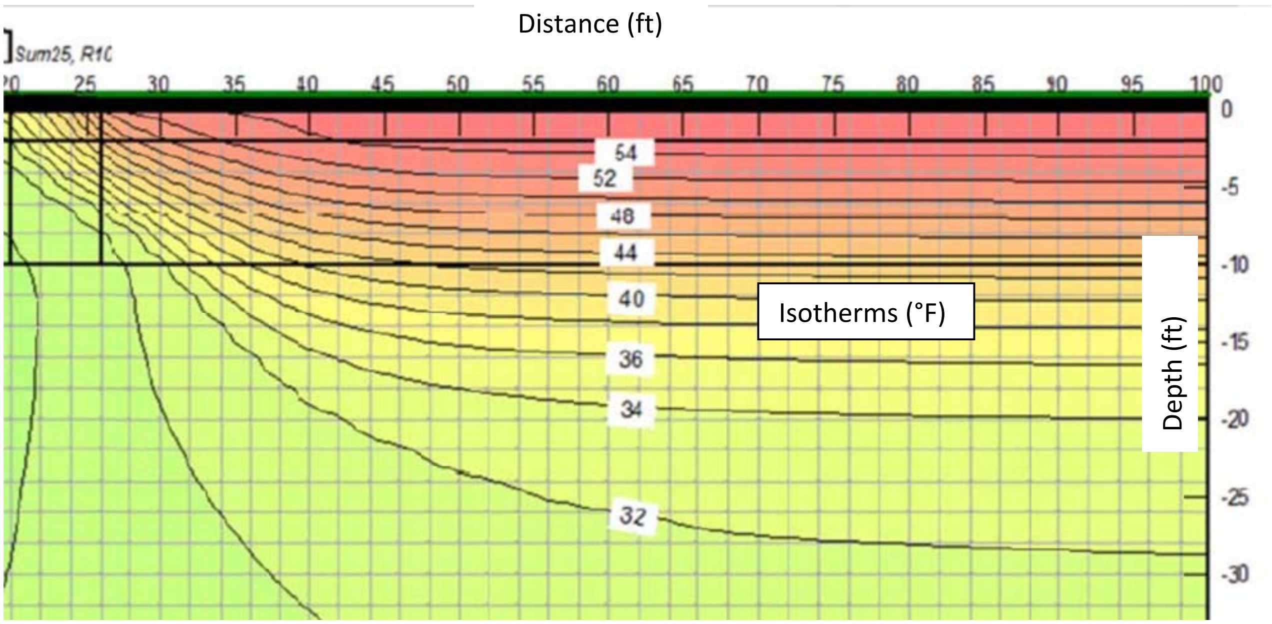

Figure 93. Temp/W print-screen: Fairbanks warmer climate, R10 seasonal insulation, with snow. End of summer (Sep 15) conditions included 2.2 °C (4 °F) warmer climate for 25 years, with snow cover (not plowed) next to building.

Warmer climate results for buildings protected with seasonally applied insulation showed results with a decreased active layer. At the center of the building, the active layer disappeared. At the edge of the building, the warmer air active layer decreased about 1.2m (4 ft) less than current air temperatures without seasonal insulation protection. Seasonal insulation served to reduce or eliminate the active layer even with warming air temperatures.

Results with a 9.1 m (30 ft) plowed parking lane adjacent to a building showed that snow removal further improved the soils cooling. For the snow-covered case, at 15.2 m (50 ft) from the center of building, and at 3 m (10 ft) deep, the soil-temperature results showed 5.6 °C (42 °F) (Figure 93). By contrast, the plowed-snow case, at the same location showed that the soil temperature results cooled to 0 °C (32 °C) (Figure 94).

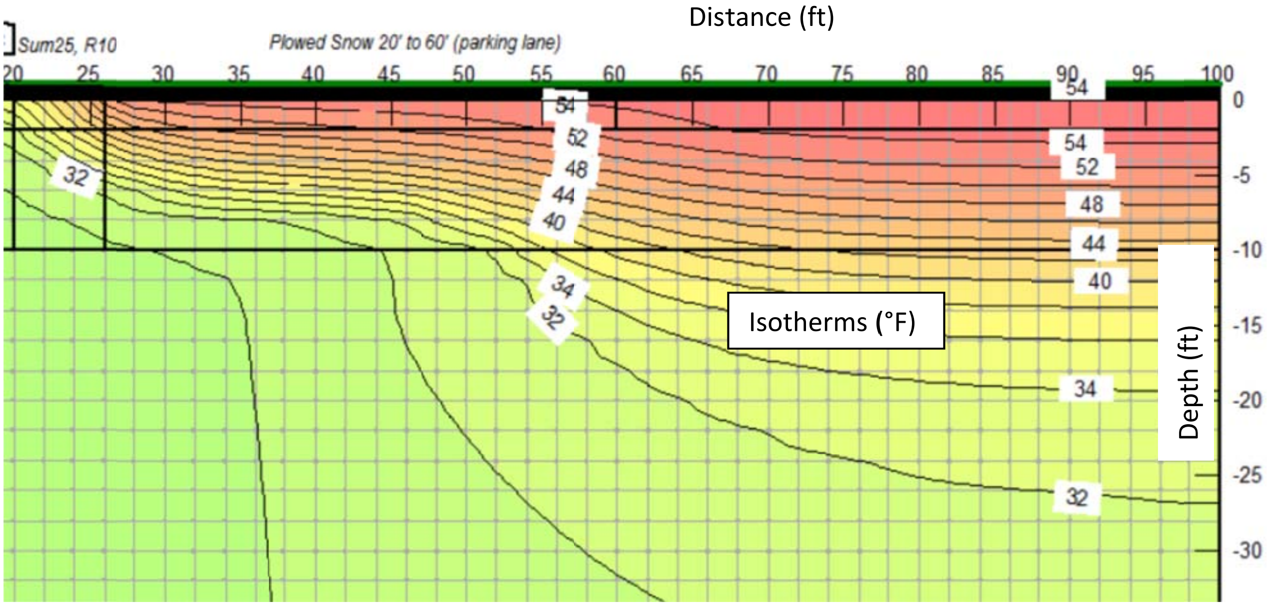

Figure 94. Temp/W print-screen: Fairbanks warmer climate, R10 seasonal insulation, plowed snow. End of summer (Sep 15) conditions included 2.2 °C (4 °F) warmer climate for 25 years, and snow plowed away from building.

4.4.3 Important caution.

I treat this section individually to stress its importance to those concerned about air temperature warming at a particular site. For existing building foundations in warm permafrost, I recommend acting now. Monitor the soils temperatures in the permafrost. Do not wait. Adopting a 'wait and see' attitude incurs higher risk. If the brittle glass-like adfreeze bond breaks (i.e., the "glue" that holds the piles in place breaks), then it is likely to be too late. Researchers have strongly warned not to expect full repair to the adfreeze bond once broken. I recommend proactively protecting the frozen state of soils. Monitor the soils temperatures at the specific site. If temperature measurements validate that permafrost soils are warming at your site, consider starting with incremental amounts of seasonal insulation and getting real-time measured thermal results as one of the alternatives for protection.

4.5 Discussion, Multiple Investigations, Permafrost Protection via Thermal Insulation.

4.5.1 Variability in n-factors not investigated.

I took the n-factors used in this study from several resources, already referenced. I agree with Doré and Zubeck (2009) who wrote about the n-factor unreliability due to (A) surface characteristics like thermal conductivity; (B) radiation balance related to cloud conditions, slope orientation, and shading; (C) convective heat transfer from close-to-the-surface boundary layer wind speed changes; and (D) large water body effects. Therefore, I recommend continued research into realistically applicable n-factors specific to building sites, especially with the wind-effects from many coastal villages.

Meanwhile, I stress overcoming these types of uncertainties by providing site-specific temperature measurements for buildings relying upon thermal insulation methods for stabilizing suitable soils thermal regimes. Owners, in my opinion, need to provide the feedback information, knowing that the seasonal insulation methods are in fact working as represented in this dissertation. Recall the need for staying interactive with the methods discussed here, relying upon real time soils temperature feedback to adjust (fine-tune) the thermal insulation application to a specific site.

4.5.2 Snow drifting not investigated.

I did not measure snow depths as part of this dissertation. Rather, I represented snow cover as a winter warming effect shown by a lower winter n-factor. Considerable variability in n-factor values exists in the references already cited. I used a subjective evaluation roughly mid-range within these widely varying bounds. My purpose included providing first results for general applications.

I did not include snowdrifts, even though most of the 50 villages within which I have worked have considerable interest in snowdrift locations and amounts. I expect, but have not verified, that lower n-factors (i.e., warmer soils) would exist below the snowdrifts. Given snowdrift presence, I would expect varying n-factors (i.e., varying soil surface temperatures for the same air temperature) around a single building.

4.5.2 Insulation reduces surface thermal amplitude and reduces active layer depth.

With insulation present, information from all three sites showed smaller surface temperature ranges (thermal amplitudes) between the minimum winter cold soil surface temperature and maximum summer warm soil surface temperature. Information from all three sites also showed a decreased or completely eliminated active layer thawing depth. This reduced or eliminated active layer means a reduced or eliminated risk of seasonal frost jacking for piles.

4.5.3 Possible additional usage for shallow footings founded on permafrost.

Shallow footings founded upon permafrost become an additional design consideration, especially when combined with seasonal thermal insulation. McFadden and Sanger both showed designs for a shallow foundation not anchored in the permafrost (McFadden, 2000, Figure 3.9; Sanger, 1969, Figure 14). For new buildings, excavate the footing pads into the permafrost about 45 cm (18 in). This shallow footing foundation represents an additional alternative, especially when used in combination with seasonal insulation. I have personally seen this method used successfully at both Nightmute and Chevak, Alaska. McFadden reports this foundation style as needing periodic leveling adjustments. At Chevak, I investigated a building with record evidence showing shallow pad footings like this on ice rich sandy-silt permafrost. After 25 years, the shallow footings around this 465 m^2 (5 000 ft^2) building had differential-movement that measured less than 2.5 cm (less than 1 in), which could easily have been within the tolerances of the original “dug by hand” construction methods.

4.5.4 Research considerations and uncertainties.

Temp/W programming experiences from this research include information regarding using U.S. Customary temperature units. As previously discussed, I found a numerical discontinuity when applying n-factors via Temp/W’s modification function. The modification function multiplies a value (i.e., a temperature) by a user-selected value, (often a simple n-factor constant). Using Temp/W's modification factor in U.S. Customary units showed a numerical discontinuity in the modification function around the 0 °F point, a discontinuity that does not occur when using temperatures in °C. For example, consider a winter with snow. Consider applying an n-factor of 0.6 (Table 7) to outside air temperatures, as follows:

Example 1. -1 °F air temperature.

Soil surface temperature. 32 – 0.6 x(32 – -1) = 32 – 19.8 = 12.2 °F surface temperature.

Temp/W modification factor. 12.2 / -1 = -12.2 (negative value)

Example 2. - 0.5 °F air temperature.

Soil surface temperature. 32 – 0.6x(32- -0.5) = 32 – 19.5 =12.5 °F surface temperature.

The Temp/W modification factor. 12.5 / -0.5 = -25 (negative value)

Example. + 0.5 °F air temperature.

Soil surface temperature. 32 – 0.6 x(32 – 0.5) = 32 -18.9 = 13.1 °F surface temperature,

Temp/W modification factor. 13.1 /0.5 = 26.2 (discontinuity to a positive value)

Example 4. +1 °F air temperature.

Soil surface temperature. 32 – 0.6x(32 – 1) =32 – 18.6 = 13.4 °F surface temperature.

Temp/W modification factor. 13.4 /1 = 13.4 (positive value)

Note the discontinuity around the 0 °F surface temperature, where the multiplication factor changes from a large negative value to a large positive value. If using US Customary units, I recommend calculating the surface temperatures manually, outside of the Temp/W program. Then, input soil temperatures into Temp/W.

Second, I also had difficulty using the Temp/W repeat function. Allegedly, I could input only one full thermal cycle and have Temp/W calculate the remaining 20 to 35 years of cyclic input. When I checked the Temp/W automatically generated long-term temperature function, I found numerous irregularities. The high and low temperature points of the automatically generated Temp/ W thermal graphs were not equal throughout the overall time duration. I was concerned that these thermal irregularities would adversely influence the results output. Therefore, I manually entered and manually checked each thermal point for the entire model duration.

With seasonally applied R10 insulation, the summer thawing zone (active layer) reduced to less than 0.3 m (1 ft). With this reduced active layer thickness, using a pad-on-permafrost foundation for buildings becomes an alternative for consideration. With permafrost remaining in its frozen state, even when faced with climate warming scenarios, the alternative pad-on-permafrost is much less disruptive to an existing building. For new construction, the overall process is easier and uses less materials and less heavy equipment time than conventional driven piles, or slurry back-filled load-bearing thermopiles.

For remediation events, my Galena post-flood repair design is one example of utilizing a pad-on-permafrost footing. At Galena, the repair included installing pads embedded into the permafrost below the existing building. Reduced construction efforts resulted because only the floor in the vicinity of the new pads needed removal to enable the excavation.

Less building disruption occurred because the excavation required only small-scale equipment, equipment used inside of the building. Excavating the soils occurred by working through floor openings. Consider, for example, that assembly area floors commonly include load-ratings up to 4 800 Pa (100 psf). A passenger-vehicle parking garage includes floor load-ratings for 2 400 Pa (50 psf) plus a concentrated load. Smaller excavators complying with the existing building floor loads may dig through floor holes down to the permafrost for retrofitting building foundations. My (unpublished) experiences at Galena, Nightmute, and Chevak support this as a possible remedial technique.

4.6 Part B – Pivotal Findings for Permafrost Sites

This portion of the dissertation (Part B) contrasts with Part A. Part A investigations had no permafrost below. Here, in Part B, the sites do have permafrost below. I investigated the same hypothesis; that is, how using manufactured thermal insulation alters the thermal regime of soils with permafrost, thereby providing foundation alternatives for arctic buildings. I studied both permanent insulation and seasonally applied insulation. Seasonal insulation applications occur in the warm, above freezing, months. I studied one permafrost field site in Fairbanks. I used finite element analyses to investigate permafrost sites without buildings (one -dimensional analyses), and to investigate permafrost sites with buildings in place (two-dimensional analyses). I evaluated thermal conditions in Fairbanks, Kotzebue, and Barrow. Both permanent insulation methods and seasonal insulation methods have noteworthy and different salient features. These salient features make either one more (or less) favorable for a particular site, depending upon the needs and goals for that particular site.

One key goal becomes keeping the owner’s existing infrastructure upgrade costs to a minimum while providing adaptability to actual site-specific climate conditions. Due-diligence warrants taking proactive steps. Preserving the adfreeze bond requires proactive and vigilant monitoring and controlling the actual permafrost temperature at a specific site, before pile-settlement begins. These methods add alternatives for reducing permafrost temperatures.

4.6.1 Results and recommendations, permafrost sites, permanent thermal insulation.

In permafrost zones, with mean annual soils temperatures below 0°C (32°F), these results and available data showed that using permanent thermal insulation accomplished the following:

(A) Decreased the surface temperature thermal amplitude (annual minimum to maximum surface temperature),

(B) Decreased the depth of the active layer, while also

(C) Concurrently warmed (not cooled) the permafrost temperature below the active layer.

This pivotal finding warrants additional discussion. Permanent insulation warms (not cools) the permafrost at depth where the mean annual soil surface temperature is below freezing. The permafrost warming impact increases with warmer mean annual soils temperatures. Compare the following:

Fairbanks (Figure 37, Figure 70, Figure 102, and Figure 103), with
Kotzebue (Figure 41, Figure 78, Figure 104, and Figure 105), and with
Barrow (Figure 47, Figure 86, Figure 108, and Figure 109).

Observe, especially, the R20 and R40 insulation values, in the appendices. Note the snow-covered results at the shallower soil depths. In the warmer sites, like Fairbanks and Kotzebue, permanent insulation does cool at shallower depths. This finding concurs with the smaller thermal amplitude of soil surface temperatures from having thermal insulation in place. By contrast, the permanent insulation warms the permafrost at greater depths. With permanent insulation, the amount of permafrost warming increases when the initial permafrost temperature is colder, particularly when the ground has snow-cover present. At shallow depths, one may conclude that permanent insulation cools the permafrost. The upper regions, especially for Fairbanks and Kotzebue, and with snow conditions, seem to support this position. To repeat, at deeper depths, permanent insulation warms the permafrost.

Consider, rather, the decreased thermal amplitude at the soil surface. Data results here showed the amount of difference in thermal amplitude (minimum to maximum annual temperature) at the soil surface occurred with permanent insulation. Compare the following:

Fairbanks Figure 64 with Figure 66, and
Kotzebue Figure 72 with Figure 74, and
Barrow Figure 80 with Figure 82.

This smaller thermal amplitude accounts for the decreased active layer and for the decreased soil temperature at shallow depths.

At deeper depths, results from this research clearly showed that permanent insulation warmed (not cooled) the permafrost. This finding represents a significant change in design-outlook with respect to using permanent insulation for permafrost temperature control. Therefore, consider using permanent thermal insulation where frost heaving due to active layer freezing is of concern because permanent insulation decreases the active layer. Also, consider using permanent thermal insulation when trying to reduce the active layer tangential frost jacking stresses on piles. Consider using permanent insulation for sites with cold permafrost temperatures, perhaps below -1 °C (below 30 °F) at a pile design depth of 3 m (10 ft). For a specific cold permafrost site, warming the permafrost may not change the original tangential adfreeze-bond design parameter.

By contrast, avoid using permanent insulation at warm permafrost sites with permafrost temperatures at or above -1 °C (30 °F) at a pile design depth of 3 m (10 ft). With permanent insulation, expect the permafrost temperature below the active layer to increase (not decrease). In warmer permafrost, others have told us to expect warming soil temperatures to decrease the adfreeze bond stress available at warm permafrost sites more appreciably than at cold permafrost sites. Expect decreased structural support available for bearing piles. At a warm permafrost site, this decrease in structural support becomes more important than at a cold permafrost site and, therefore, consider using seasonal (not permanent) thermal insulation.

4.6.2 Results and recommendations, permafrost sites, seasonal thermal insulation.

Seasonal thermal insulation methods use manufactured thermal insulation applied directly on top of the ground to restrict soils heat gain during the warmer months. The methods especially apply to buildings with open crawl spaces. The thermal insulation is in place from late spring, throughout summer, to fall. The ground remains uninsulated over the winter. Seasonal thermal insulation cools the ground surface and decreases or eliminates the depth of the active layer, while also cooling the permafrost at a pile deign depth of 3 m (10 ft).

Site work and modeling results show best results from applying seasonal thermal insulation from spring air temperatures of -6.7 °C (+20 °F), and removing the insulation at cooling fall temperatures of 0 °C (32 °F), leaving the ground surface un-insulated over the winter. Use seasonal thermal insulation methods to cool soils below both seasonal frost sites and permafrost sites.

Practical application of the summer thermal insulation requires some extra costs associated with insulation placement, removal, and storage. Not removing the seasonal insulation before winter could compromise its cooling effects upon the permafrost. As measured in this research, seasonal insulation combined effort for installation and removal required less than 7 worker-hours total per 93 m^2 (1 000 ft^2) per year. Provide space for off-season insulation storage either on-site, or by creative multiple use planning, as already discussed.

Consider using seasonal insulation both for (A) warm permafrost zones (described above, as in Fairbanks), and for (B) sites with climate warming concerns. The impact of seasonal insulation on permafrost increases with an increase in the thawing index. It is especially applicable to frozen portions within the discontinuous permafrost zone. Here, permafrost bearing capacity and adfreeze strength are sensitive to minor soil temperature changes. Seasonal summer insulation in a ventilated crawl space decreases the active layer depth and, as a result, minimizes the impact of frost heave on foundations.

Consider using seasonal thermal insulation to reduce active layer tangential pile frost jacking stresses. In many of the cases modeled, with seasonal insulation, the active layer zone of thawing remained confined within the insulation layer. Seldom did the modeling show more than 30.5 cm (12 in) of active layer thawing below the insulation-protected zone.

Consider using seasonal insulation as an alternative foundation method to installing dee0bearing piles. Seasonal insulation cools the soil, enhances the bearing capacity and augments using a pad-on-permafrost foundation system (McFadden, 2000, Figure 3.9). Even without utilizing seasonal insulation, I have seen this pad-on-permafrost foundation method used successfully in both Nightmute and Chevak, Alaska.

Avoid using seasonal thermal insulation methods for thawed ground intended to remain thawed. Do not use together with FPSF systems. Expect seasonal thermal insulation to cool the soil and perhaps promote permafrost formation. This soil cooling is contra-indicated for sites intended to remain thawed.

Avoid using seasonal insulation for cold permafrost sites, (i.e., colder than 0^{o}C to -3^{o}C; 32 °F to 26.6 °F), where the design goal is to reduce or eliminate active layer frost heave or frost jacking. For a cold permafrost site, slight permafrost warming might not alter the adfreeze bond strength sufficiently to be of concern. Minor permafrost warming could remain within the pile design parameters, especially at a cold permafrost site. The soil cooling added by using seasonal insulation may be unnecessary. Using permanent insulation in such cases avoids the annual operational expenses of installing and removing the seasonal insulation.

Use seasonal thermal insulation methods before thawing ground permits pile-creep, before the thawing breaks the adfreeze bond. Permit me to re-emphasize importance by repeating the cautions from others. Even small strains may break the adfreeze bond. Under soils tests at -2 °C (28.4 °F), the adfreeze bond is essentially brittle (Ladanyi & Theriault, 1990). Strains (pile-creep) less than 1 cm (less than 1/4 in) may be sufficient to break the adfreeze bond (Anderson & Anderson, 1978; UFC, 2004b; Nidowicz & Shur, 1998). Once broken, the adfreeze bond does not readily reform. Even if repaired, expect the residual bond strength, after repair, to be significantly weaker, several times weaker than the initial (long-term) adfreeze bond strength (Nidowicz & Shur, 1998).

Insulation materials may be stored off-season (A) below the building on raised racks immediately below the raised floor system, (B) out from under the building, covered on-site, or (C) in use for an alternative purpose. For example, I envision using soft insulation blankets, similar to concrete cold weather curing blankets. The blankets are rolled up for off-season storage and unrolled for quick installation. Owners may optimize insulation usage over a longer period by using the insulation all summer below seasonally protected buildings, and removing the insulation in time to aid concrete curing during the fall construction season.

4.6.3 Results and recommendations, permafrost concerns for warming climate.

Applying summer seasonal thermal insulation is an adaptive and flexible approach, especially in view of climate-change projection-uncertainties. These site and modeling results provided proof of concept to expect that seasonal insulation will work for changing climate, either warming or cooling.

This seasonal insulation method permits an incremental response to actual climate conditions, measured at a specific site. For a warming climate, use additional thermal insulation to restrict heat-gain during the warm months. For a cooling climate, decrease the thermal value of the insulation or discontinue its use altogether. Monitor actual site-specific soils temperatures. Adjust the amount of seasonal thermal insulation used in an interactive response to those measured site-specific soils temperatures.

4.6.4 Results and recommendations, open crawl space and snow removal.

Results showed that maintaining an open ventilated crawl space under buildings decreased the temperature in the permafrost even without including insulation methods. Evaluations of climate change impacts on permafrost under buildings should consider this fact. Snow removal contributes to soils cooling. Results showed that snow removal from around the building (e.g., from adjacent parking areas) provided considerable cooling impact. Expect snow-cleared parking areas, adjacent to a building, to help soils-cooling.

4.6.5 Summary, thermal insulation methods for permafrost sites.

This research shows that using manufactured thermal insulation alters the thermal regime of soils below heated buildings and provides additional foundation methods for arctic buildings.

Compared with no insulation methods, permanently applied insulation reduces the surface thermal amplitude (maximum-to-minimum annual surface temperature difference), decreases the active layer thaw depth, and concurrently warms (not cools) the permafrost below the active layer.

Compared with no insulation methods, seasonal insulation not only decreases the thermal amplitude at the surface, and decreases the active layer thaw depth, and does cool the permafrost temperature below the active layer.

Insulation methods provide an adaptive response to site-specific temperature changes. For warming sites, where increasing air temperatures threaten to compromise the structural integrity of existing bearing pile foundations, seasonally applied insulation, as described here, cools the permafrost and thereby provides an additional permafrost protection method. For cooling sites, with decreasing air temperatures, seasonal insulation methods respond to actual soils temperatures. Use in situ soils temperature measurements to adapt insulation methods to site-specific conditions.

Chapter 5 Conclusions

This research explores two important issues in cold region engineering. First, for areas free from permafrost, I investigate and provide results for protecting building foundation soils from freezing via using thermal insulation to contain and direct building heat. Second, for areas with permafrost below the building, I investigate and provide results for protecting that permafrost from thawing via using thermal insulation to restrict summer heat gain. In both cases, thermal insulation plays an important role.

This chapter summarizes the main findings and shares the knowledge gained during this research. Started in 2003, this research combines results from many years of direct research, plus over 30-years of personal engineering design and construction experiences in over 50 locations within Alaska. Outside of this study, I have investigated over 500 building foundations and site-conditions in Alaska's Arctic and Subarctic regions. From the beginning, I have devoted this research to providing practical applications, helping resolve cold regions engineering questions both for seasonal frost areas and for permafrost areas. Now, with the ever-present warnings about warming climate, these conclusions provide timely responses.

5.1 Frost-Protected Shallow Foundations – for Seasonal Frost Sites

For permafrost-free sites within the discontinuous permafrost zone, I investigated heat flow under buildings with shallow foundations and impacts of using thermal insulation to reduce the depth of seasonally frozen soil, and to keep the soils unfrozen beneath foundations. I evaluated possibly extending the current ASCE 32-01 standard for perimeter insulation methods of frost-protected shallow foundations to the colder Alaska interior temperatures. My field studies included six sites, and I performed mathematical analyses, and analyzed the results from several finite element models. Both field studies and thermal modeling show that FPSF methods can protect foundations from freezing, even in the colder conditions of Alaska's interior. Given winters that are colder than previously studied, frost protection requires additional insulation, as shown in this research.

On the other hand, this research shows that basal forces can develop and act upon the sides of foundations. Lateral forces result from the freezing isotherm rotation to almost vertical, i.e., parallel to the foundation sidewall. Almost horizontal frost heaving forces develop in frost susceptible soils immediately adjacent to the foundation wall. These forces press against the foundation sidewalls, with restraint coming from the exterior soils.

A summary of practical engineering recommendations follows. Provide a site-specific subsurface soils investigation (i.e., soils testing) before installing a frost protected shallow foundation system. Determine if permafrost exists below the building site before applying an FPSF system. If permafrost exists below the building, and is not otherwise preserved, expect permafrost degradation (thawing) from an FPSF system confining and directing building heat into the soils below. Investigate and expect thaw strain settlement of frozen soils.

When the soils below the building at a specific site are non-frost susceptible (i.e., dry and non-wicking) to depths below the seasonal frost penetration, my research shows using minimal or no thermal insulation does not cause visible frost heave distress. However, the owner needs to maintain the coarse-grained soils free from silt contamination.

For foundations in frost-susceptible soil, provide continuous building heat. Because of the smaller foundation depth for FPSF systems, expect seasonal freezing below the footings for unheated buildings. Expect that basal frost-heaving forces might develop, perhaps acting both vertically and laterally against the foundation system. Consider the possibility of developing frost-heaving forces acting perpendicular to the sides of the foundation.

5.2 Seasonal Frost Sites – Pivotal Findings

For unheated buildings, these results clearly indicate not to rely upon an FPSF system to preclude frost heave risks. In the higher freezing indices covered in this research, do not expect ASCE 32-01 insulation methods to confine enough geothermal heat to keep unheated building foundations above freezing. Anticipate needing to provide building heat in addition to the geothermal heat confinement; or, anticipate using other frost-heave risk mitigations. For unheated buildings, alternatives in these colder climates include (A) providing non-frost susceptible soils to depths below the maximum credible seasonal frost penetration, and (B) keeping the soils dry by directing all surface moisture and roof runoff away from the building foundation.

For buildings heated in winter, site investigations and modeling results showed that FPSF systems function satisfactorily to keep the foundation zone above freezing. Design requirements include providing additional insulation thermal values and extents, values and extents greater than currently indicated for the warmer climate-limit within ASCE 32-01. The current ASCE 32-01 design standard stops at 2 500 °C·d (60 000 °C·h) (4 500 °F·d). New results from this research extend FPSF system applications to colder regions and provide a prescriptive design method for AFIs as cold as 4 400 °C·d (8 000 °F·d). Appendix A is new information, providing a proscriptive method for determining insulation thermal values and locations that correlate with colder Alaska seasonal frost zones.

For the colder AFIs covered in this research, do not place thermal insulation directly below the footings. For these colder climates, this is different information than currently included in ASCE 32-01. The insulation-below-the-footing method may apply to certain conditions for the warmer climates as currently included in ASCE 32-01, but does not apply to the colder climates researched here. Rather, for these colder climates, maintain the unfrozen state of soil beneath foundations by not restricting the heat flow to the soils below the building. Thermally connect the warm interior space and the cooler soils directly below the footings. Omit thermal insulation below the footing. Restated, allow the base of the footing to bear directly upon the soil.

Provide extra insulation at overhead garage door areas in the same thermal value and extents as for building corners. My site investigation results showed these areas behaved in a thermal manner similar to corner zones. The soil freezing depths at the garage door openings behaved similar to corner zones. Expect the footings at these entries to be colder due to less garage door thermal resistance and due to the cold-weather door operation.

This FPSF research involves only the thermal regime of soils below heated buildings. It does not address structural restraint systems. Designers must also consider structural load-restraint systems. For example, overturning moments (particularly uplift loads from lateral wind and seismic forces) need structural restraint. One traditional design-method restrains uplift and lateral overturning-moment loads via providing deep footings. Without deep footings, an FPSF system provides a different level of uplift restraint. Structural considerations, rather than thermal provisions, may control the footing depths and sizes needed.

Consider the effects of basal stresses on the foundation sides in the structural design of buildings and retaining walls. Basal forces may act horizontally, not just vertically. The freezing isotherm becomes almost vertical, parallel to the side of foundations. Horizontal frost heaving forces, acting perpendicular to foundation sides, can develop in frost-susceptible soil. This is one of the significant new findings of this research.

Sketches accompanying warmer climate FPSF systems schematically show the freezing isotherm rotated at about a 45° angle. In the colder AFI regions I have researched, the freezing isotherm rotates to almost vertical adjacent to the foundation (Figure 26). That means the basal-stress-orientation for frost heaving becomes almost horizontal (much less inclined) with these colder climate FPSF systems. These almost-horizontal frost-heaving stresses act inward against the foundation wall and outward against the exterior soils and site work.

Local site visual investigations have shown satisfactory building performance in the field where the foundation restraint for these horizontal stresses comes from having a structural floor system integrally connected to the footings. This integral structural connection takes a three-part system. The footings on one side of the building connect through the floor slab, to the footings on the opposite side of the building. This three-part system exists in each of the sites investigated. I did not research foundations that had footings on gravel and with a gravel floor, that is , not with an integrally connected structural floor system.

By contrast, however, soils and site work (e.g., driveways and sidewalks) have exhibited spalling and damage. Structural designers need to recognize and account for the almost horizontal basal stresses acting upon both the foundation and upon the soils-system.

5.3 Permafrost Protection – Summary

For sites with permafrost below buildings, I analyzed two ways of applying surface insulation as a measure to preserve the permafrost. First, I analyzed the effects of using permanent thermal insulation. In thermal modeling, permanent insulation, once applied, remained in place over the entire 35-year duration for each analysis. Second, I analyzed the effects of using seasonal insulation, applied in the spring and removed in the autumn. Seasonal insulation restricts heat flow into the soils, while the soil cooling remains unobstructed.

In addition, I analyzed seasonal insulation applications in current climatic conditions and in climates warmer by 2.2 °C (4 °F). I varied surface conditions by including both snow-covered and bare ground scenarios. I analyzed many finite element models for climate conditions found in Fairbanks, Kotzebue, and Barrow.

A seasonal-insulation site investigation included instrumenting and recording results from one Fairbanks site at the Cold Climate Housing Research Center.

5.4 Permafrost Sites – Pivotal Findings

A pivotal finding from this research alters a commonly shared understanding, that permanent insulation cools the permafrost in all cases. This research shows that permanent thermal insulation (A) decreases the soil surface temperature-amplitude (the annual minimum to maximum surface temperature), (B) decreases the active layer depth, while concurrently (C) increasing (not cooling) the permafrost temperature below the active layer. Therefore, this research now shows that permanent insulation is contra-productive for preserving the adfreeze bond between piles and soils. This finding changes a commonly held assumption that permanent insulation cools the permafrost soils.

Seasonal insulation used in open crawl spaces, however, (A) decreases the soil surface temperature-amplitude, (B) sufficiently decreases or eliminates the active layer depth, while concurrently (C) cooling the permafrost, and as a result (D) increases the adfreeze bond strength available for bearing piles. This research shows the thermal benefits from using seasonal insulation begins almost immediately and further improves over about a 10-year period. R10 seasonal insulation, with a thermal resistance value of 1.8 m^2 °C/W, (10 ft^2 hr °F/Btu), cools the permafrost below its current non-insulated temperature value, even with air temperature increases of 2.2 °C (4 °F).

Applying seasonal insulation provides an adaptive method, in response to specific site conditions and changes. Seasonal insulation use requires some ongoing operational effort. Thermal insulation, applied in the late spring, restricts summer heat gain in to the soils. Then, when removed in the winter, normal winter heat removal from the soils continues. Total annual operational labor effort took less than 7-worker-hours per 93 m^2 (1 000 ft^2). Off-season insulation storage requires space planning. Alternative storage methods include the following: hangers attached to the underside of the raised floor system, a separate location, or creative multiple-use planning coordinated with other needs for cold-weather concrete construction.

Seasonal thermal insulation creates a new pattern of temperature distribution with depth. Thermal insulation reduces the depth of the active layer. Seasonal thermal insulation decreases permafrost temperature most effectively in the upper part of permafrost and increases the bearing capacity. This increased bearing capacity can make shallow spread foundations more attractive than piles when seasonal thermal insulation is used.

Where warming soils temperatures are of concern for an existing building, owners should act immediately. Keeping the permafrost at or above its design temperature reduces the risk of breaking the adfreeze bond. Current science includes knowledge that the adfreeze bond, once broken, does not readily reform. Therefore, action must be taken before noticeable pile-creep (settling) occurs. Conducting site-specific soil temperature monitoring can reduce climate change uncertainties. Site-specific soils temperature monitoring provides an advance notice for taking proactive soil cooling measures. Seasonal insulation provides one possible alternative for soils cooling. Costs for providing seasonal insulation seem more directly aligned with measured (not just projected) climate risk factors. The amount and timing of climate warming projections remains uncertain. The thermal resistance for the seasonal insulation may be increased or decreased in response to real-time permafrost temperatures.

Snow cover helps insulate the soil surface, restricting heat flow out from the ground. Without snow cover, the cold air temperatures have a greater influence on soils surface temperatures. Snow removal cools the soils. Research results, here, show a greater soils cooling impact from snow removal than from using thermal seasonal insulation. Therefore, for soils cooling first provide snow removal.

5.5 Future Studies

The research shows that horizontal basal frost-heaving forces can act on sides of frost-protected foundations in cold climatic conditions similar to the Alaska interior. Further evaluations should include determining the magnitude of these forces, not only on building foundations but also on retaining walls.

Applying thermal insulation for frost-protected shallow foundations assumes that the thermal properties do not deteriorate extensively with time. Future analyses should include the long-term in-situ thermal properties of both expanded and extruded polystyrene rigid foam insulation. I agree with multiple other colleagues that future investigations should include analyzing the long-term thermal properties of rigid thermal insulation in contact with soils.

These analyses do not consider freeze point depression characteristics from solutes that may be in the soil. Applying seasonal insulation over saline permafrost soils should be studied in future works.

My studies proved that seasonal insulation has sufficient effect to preserve permafrost under buildings with open crawl spaces, even with a warming climate. I recommend further field studies to validate these findings.

I recommend sharing results within the broader community, including scientific, engineering and construction industries. I have shared these results with the Cold Climate Housing Research Center, in Fairbanks Alaska. Based on this research, they are already applying seasonal insulation methods below one of their experimental buildings. I look forward to further results from more-in-depth field studies. By this research, I hope to have pointed the way toward using manufactured insulation to help alter the thermal regime of soils, thereby permitting additional foundation design-alternatives in view of future possible temperature changes.

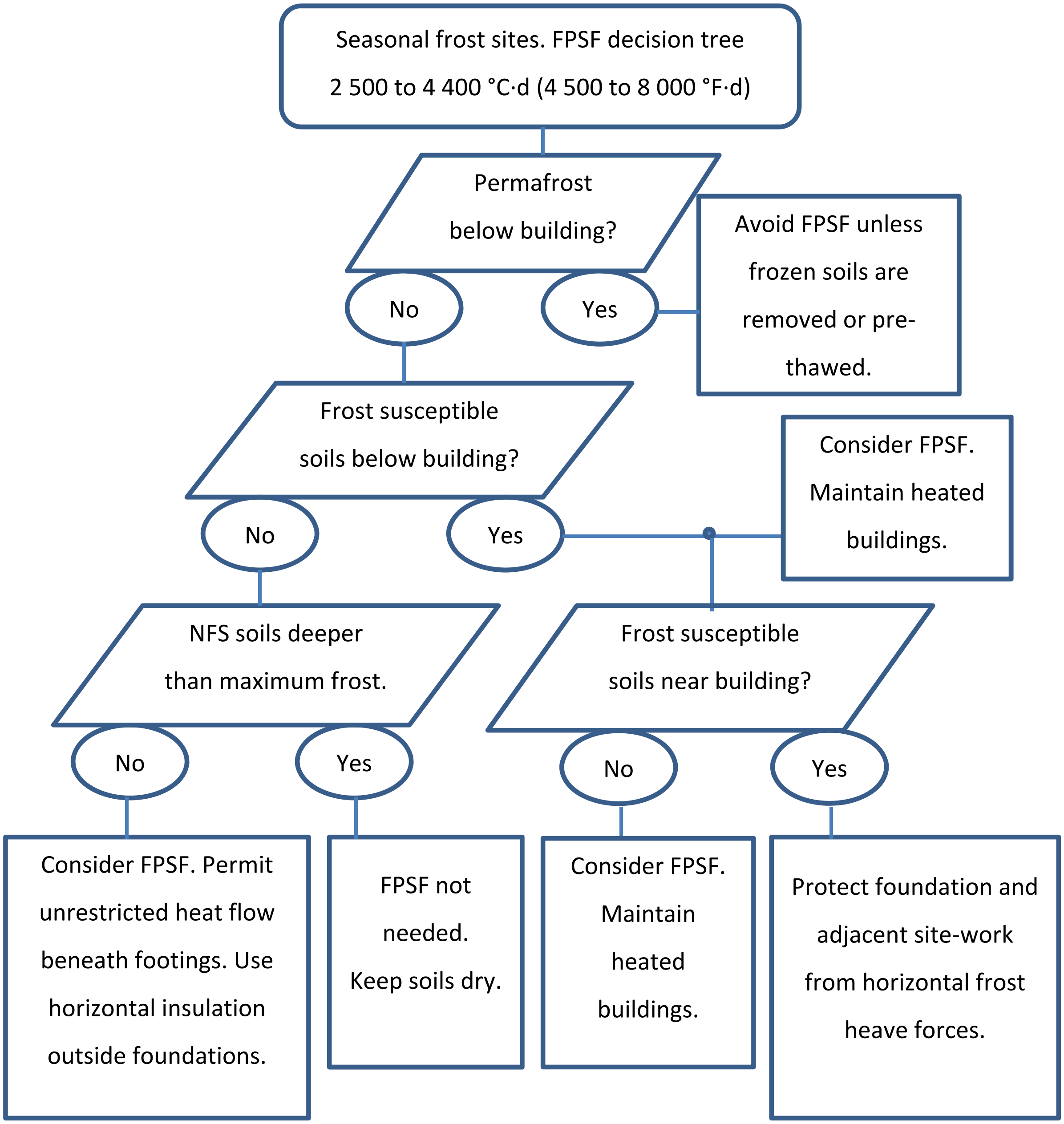

Figure 95. Summary considerations for seasonal frost sites – frost-protected shallow foundations.

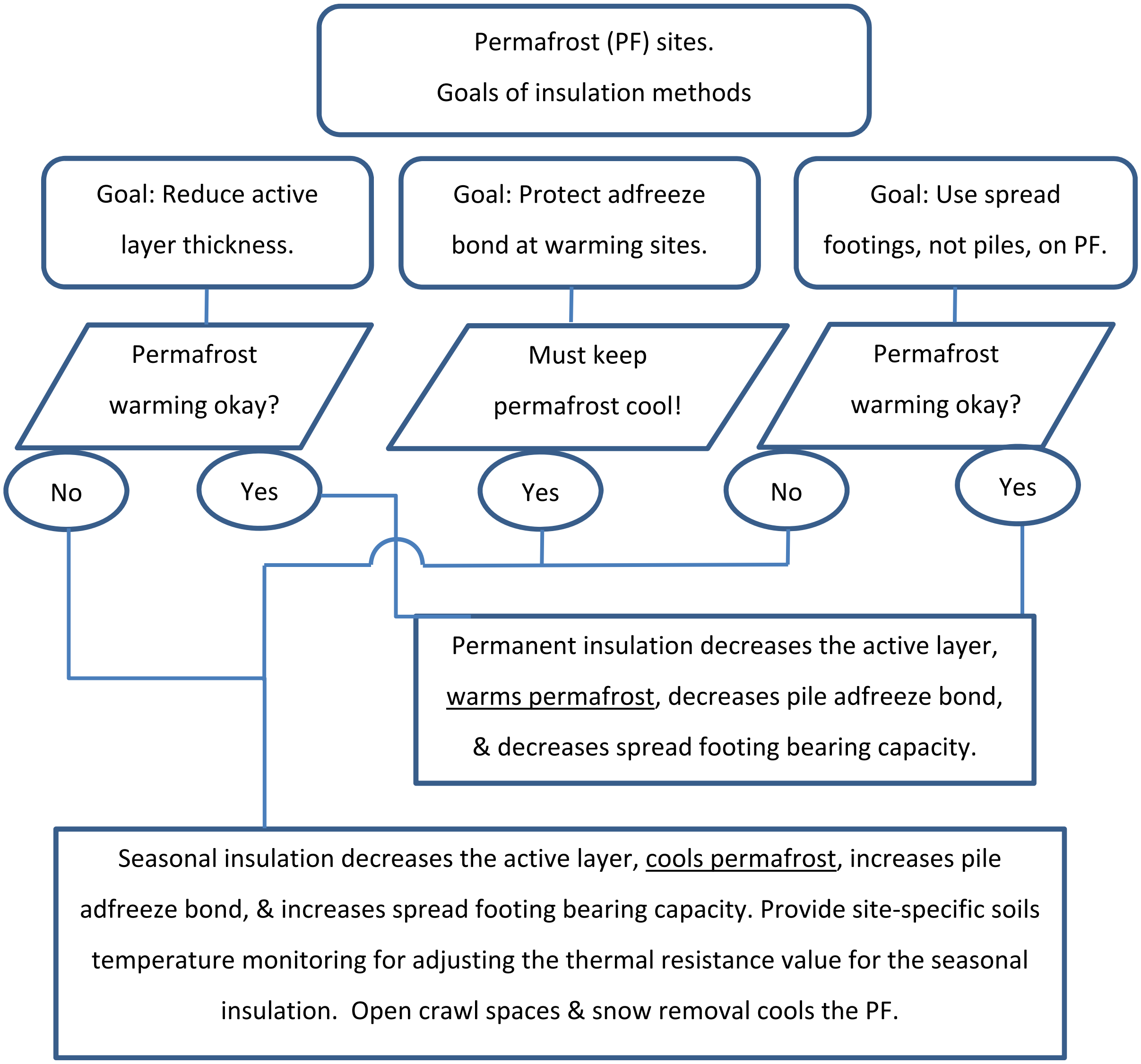

Figure 96. Summary considerations for permafrost sites – permanent or seasonal insulation.

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Appendix A.
Design Examples for Frost-Protected Shallow Foundations

Frost-Protected Shallow Foundation Design Examples

The following are recommended design tables and graphs for use in cold regions with Air Freezing Indices of 4,500 °F-Days to 8,000°F-Days. Sample calculations follow. These recommendations extend beyond the current design information available in building codes or design guides. Final review and approval for specific building projects rests with the code official having jurisdiction over the project.

The procedure is as follows:

1. Air freezing index

Determine the desired life span of the building. From that lifespan, select a design air freezing index (AFI). Data for Fairbanks, for example, suggests

30-year recurrence	6,500°F-Days AFI
100-year recurrence	7,300°F-Days AFI

2. Vertical Insulation R-value

Determine the recommended Resistance for the vertical insulation (Rv) applied around the perimeter-face of the foundation system (Figure 98).

Commentary:

The City of Fairbanks has a prescriptive requirement for R-10 minimum for Rv.

3. Horizontal Wall Insulation R-value

Along long walls (away from corners) determine the recommended Resistance for the horizontal wall insulation (Rhw) (Figure 99). This insulation will be installed horizontally out from the bottom of the foundation.

Commentary:

There are two graphs: one for poorer soils (SM or worse) and one for better soils (SP or better). The soils are evaluated using a standard Unified Soil Classification System (USC). The USC is chosen because it is widely used and is in the International Building Code. This distinction applies to the soil from the surface to about 12 feet deep. See the examples, below.

4. Horizontal Wall Insulation Projection Distance

Along long walls, determine the Distance from the wall (Dw) that the insulation will project (Figure 99).

5. Corner Zone Length

Determine the Length of the corner zone (Lc) (Figure 100).

6. Corner Zone Insulation R-value and Projection Distance

Calculate the recommended Resistance for the horizontal corner insulation (Rhc) as follows:

EITHER USE

Alternative A:
Add 30% more insulation and extend the insulation 30% further.
Do both: Rhc = 1.3 x Rhw (corner zone R-value is 30% higher than along the wall).
And Dc = 1.3 x Dw (corner insulation projects further from the foundation).

OR USE

Alternative B:
Add more 50% more corner insulation, and keep the same projection all around.
Do one: Rhc = 1.5 x Rhw (corner zone R-value is 50% higher than along the wall).
And Dc = Dw (the Dw distance applies to the corners as well).

Commentary:
Recall, corner zones are colder because heat may escape from both the adjoining cold-faces of the foundation system. Research by others (Hong), as well as my own indicates a simple multiplier is sufficient to account for the increased heat loss at corners. That multiplier adds 30% more insulation value and distance to the corners than is present along the long walls. A case study, reported from the Galena Project (Danyluk) and 2004 NAHV both show adding enough extra insulation R-value (50% more) at corners decreases the need for extending that insulation further.

7. Increasing Perimeter Insulation to Overcome Ground Insulation (e.g., Radiant Heat)

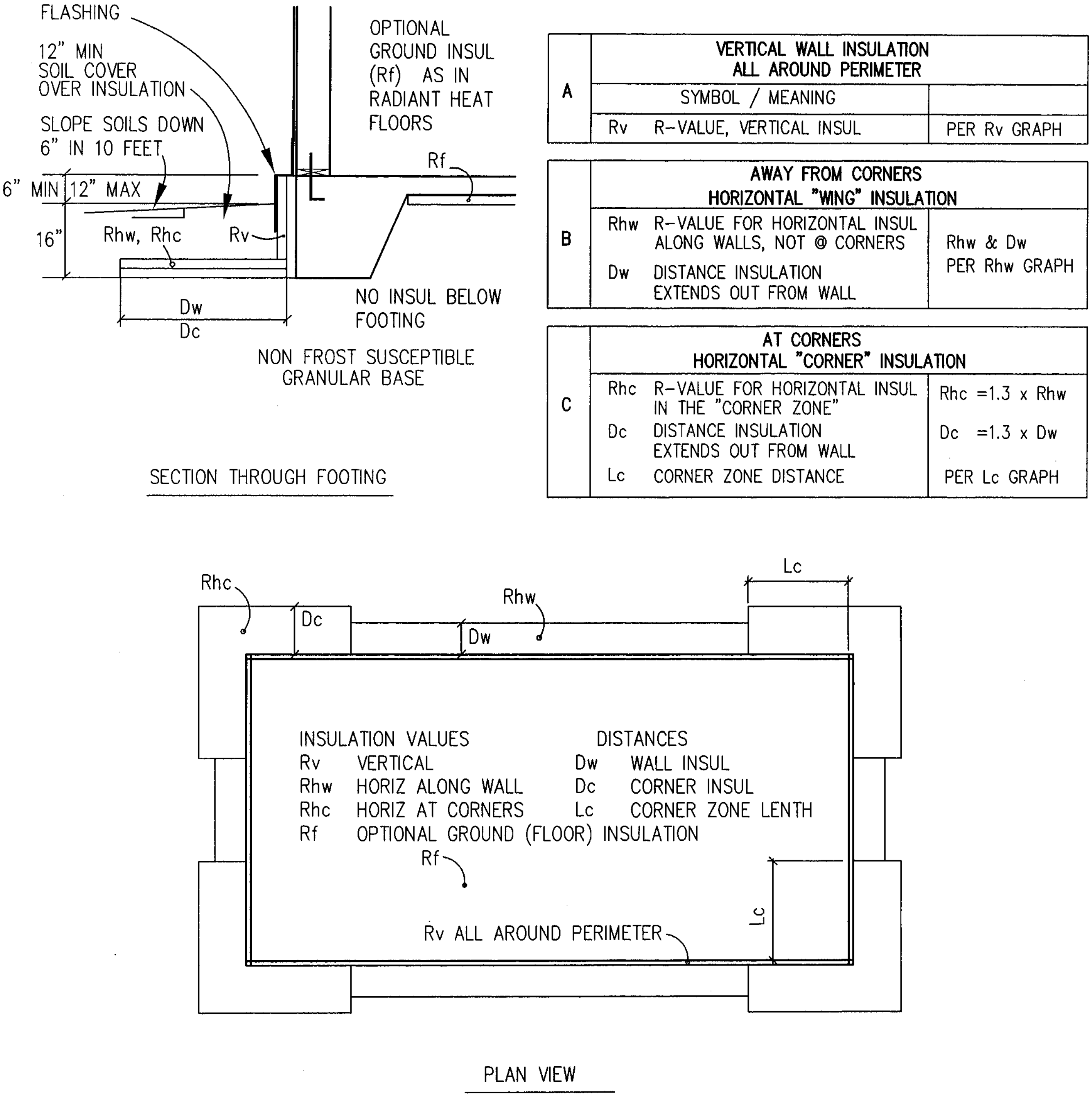
See Rv, shown in Figure 97.
(1) Add Rf to Rv. (2) Add Rf to Rhw. (3) Add Rf to Rhc.

Commentary
Ground insulation, below the slab, may be chosen in certain radiant floor heating systems. The ground insulation helps provide a means of positively anchoring the radiant floor tubing before placing the concrete slab. Two inches of EPS insulation has commonly been observed – in order to resist foot traffic loads without breaking.

However, the ground insulation retards the heat flow from the heated space into the soils below the slab. Note the comment in NAHB 1994, (Figure 4), which states, "Increasing floor insulation will decrease heat flow to the foundations and more perimeter FPSF insulation is required."

That heat flow from the building into the soils is a vital salient feature, enabling an FPSF system to keep the winter frost line (freezing isotherm) from intruding below the footings. The heat, in the soils, resists the freezing isotherm movement into the foundation zone, below the footings.

Therefore, when ground insulation (Rf) is used below the slab (e.g., for radiant floor heating) additional insulation is also needed around the perimeter of the foundation. The added perimeter insulation is provided to overcome the restricted heat flow caused by the ground insulation.



A	**VERTICAL WALL INSULATION ALL AROUND PERIMETER**		
	SYMBOL / MEANING		
	Rv	R-VALUE, VERTICAL INSUL	PER Rv GRAPH

B	**AWAY FROM CORNERS HORIZONTAL "WING" INSULATION**		
	Rhw	R-VALUE FOR HORIZONTAL INSUL ALONG WALLS, NOT @ CORNERS	Rhw & Dw PER Rhw GRAPH
	Dw	DISTANCE INSULATION EXTENDS OUT FROM WALL	

C	**AT CORNERS HORIZONTAL "CORNER" INSULATION**		
	Rhc	R-VALUE FOR HORIZONTAL INSUL IN THE "CORNER ZONE"	Rhc =1.3 x Rhw
	Dc	DISTANCE INSULATION EXTENDS OUT FROM WALL	Dc =1.3 x Dw
	Lc	CORNER ZONE DISTANCE	PER Lc GRAPH

NOTE: IF GROUND INSUL (Rf) IS USED,
THEN ADD Rf VALUE TO BOTH Rhw AND Rhc.

Figure 97. Frost-protected shallow foundations: Design parameters.

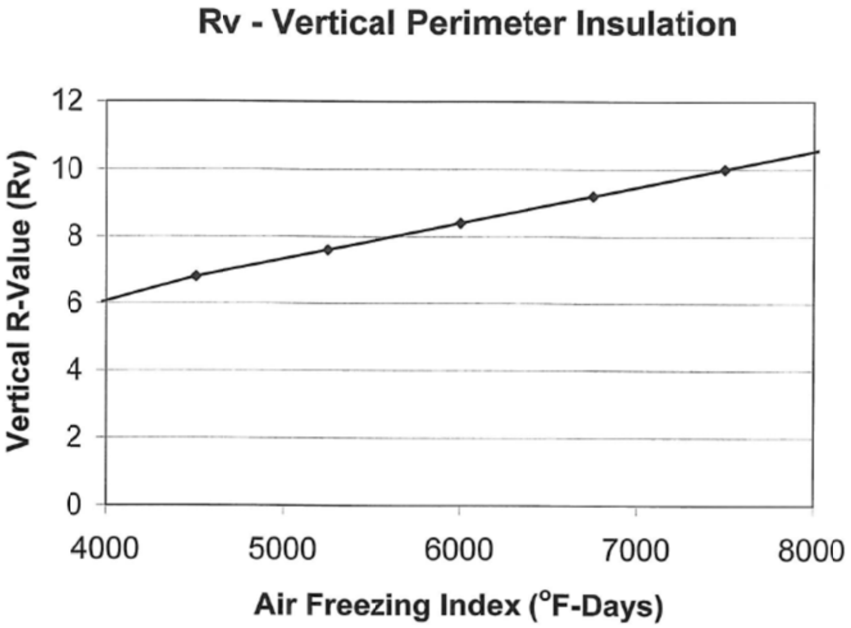


Figure 98. Frost-protected shallow foundations: R-value, vertical face of foundation perimeter.
U.S. Customary R-value units (ft^2 hr °F/Btu)

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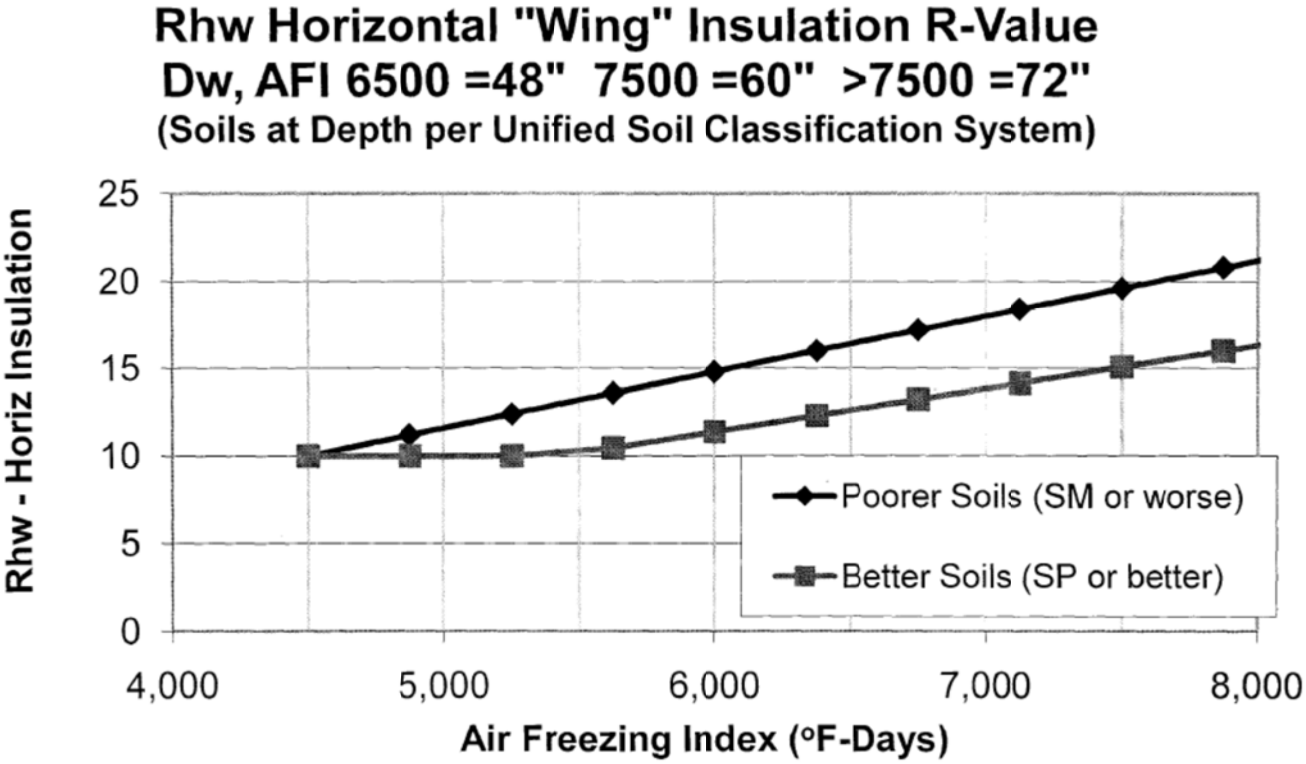

Figure 99. Frost-protected shallow foundations: R-value, horizontal wall insulation.
U.S. Customary R-value units (ft^2 hr °F/Btu)

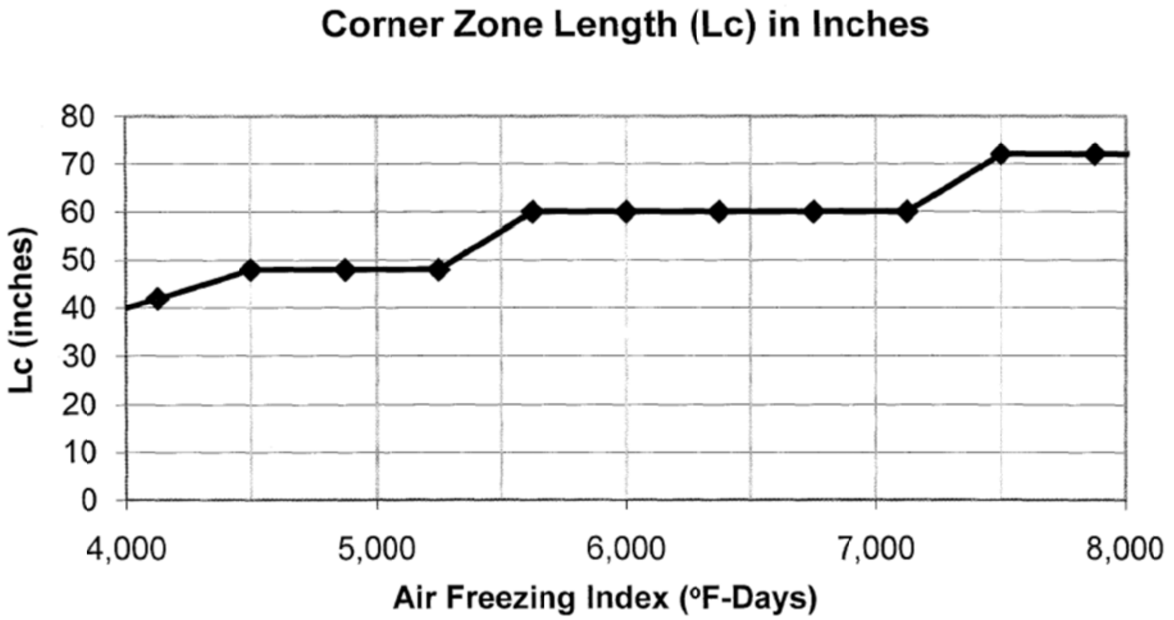

Figure 100. Frost-protected shallow foundations: corner zone length (Lc) in inches.

Design Example 1

The building is a residence with a 30 year mortgage. The soils are sandy silts. The ground floor has radiant floor heat, with 2-inches EPS Type II insulation below the slab.

Suggested Solution:

1. Air Freezing Index (AFI)

A 30-year mortgage suggests using a 30 year AFI. From weather data (Page 3), select AFI_{30yr} = 6,500^{o}F-Days

2. Vertical Insulation R-Value

From Figure 98, select Rv = 9. Note: In Fairbanks, use R-10, minimum, per Local requirements. Rv = 10

3. Horizontal Wall Insulation R-Value, away from corners.

A. Evaluate soils parameters using the Uniform Soil Classification (USC) System from ASTM D2487. The USC Classification for sandy silt is "SM."

Commentary

The USC classification system is used here because it is also used in the 2006 International Building Code, adopted for use in Alaska and in Fairbanks. Retrieved from http://www.asphaltwa.com/wapa_web/modules/04_design_factors/usc.htm shows a USC Classification table.

B. From Figure 99, with poorer soils, and with AFI=6,500, select Rhw = 16

Select insulation thickness:

Alternative insulations for R-16: EPS II @ R2.6/in = 6.15 in (say 6 in)
EPS IX @ R2.8/in =5.71 in (say 6 in)
XPS @R4.0/in = 4 in

4. Horizontal Wall Insulation Projection Distance

From Figure 99, with AFI = 6,500°F-Days, Dw = 48 inches.

5. Corner Zone Length.
From Figure 100, with AFI = 6,500°F-Days, Select Lc = 60 inches.

6. Corner Zone: Horizontal R-value and Projection Distance
Alternative A
Alternative A adds both 30% more R-value, and 30% more projection distance.
Rhc, Alternative A
Rhc = 1.3 x Rhw: 1.3 x 16. Rhc,a = 20.8
Select insulation thickness:
Alternative insulations for R-20.8: EPS II @ R2.6/in = 8 in
EPS IX @ R2.8/in =7.73 in (say 8 in)
XPS @R4.0/in =5.2 in (say 6 in)
Dc, Alternative A
Dc = 1.3 x Dw: 1.3 x 48 inches = 62.4 inches Dc,a= 60 inches.
Alternative B
Alternative B adds 50% more R-value, but does keeps one insulation projection distance all around. z1
Rhc, Alternative B
Rhc = 1.5 x Rhw: 1.5 x 16 Rhc,b = 24
Alternative insulations for R-24: EPS II @ R2.6/in = 9.23 (say 9 in
EPS IX @ R2.8/in =8.57 (say 9 in)
XPS @R4.0/in = 6 in
Dc, Alternative B
Dc is unchanged. Dc =Dw Dc,b = 48 inches.

7. Increased Perimeter Insulation due to presence of Ground Insulation
Ground insulation = 2=inches EPS-II, at R2.6/in. 2 X 2.6 = 5.2 (say R5)
Add R5.2 to vertical and horizontal insulation
Rv + 5 Rv,w/ground insul = 14
Rhw + 5 Rhw,w/grnd insul = 21
Rhc + 5 Rhc, w/ grnd insul = 26

Design Example 2

The building is a commercial building (e.g. a shop or a warehouse). The soils are silty sands with few fines. The design life is 50 years. The building is heated with overhead forced-air heating, not radiant floor heating.

Suggested Solution:

1. Air Freezing Index (AFI)
Select AFI from weather data (Page 3). AFI_{50yr} = 7,000 °F-Days

2. Vertical Insulation R-Value
From Figure 98 Rv = 10

3. Horizontal Wall Insulation R-Value, away from corners.

USC Classification for soils type SP or better

From Figure 99, with better soils, and with AFI=7,000, select Rhw = 14

Select insulation thickness:

Alternative insulations for R 14:	EPS II	@ R2.6/in	= 5.38 (Say 5 in)
	EPS IX	@ R2.8/in	= 5
	XPS	@R4.0/in	= 3.5 (say 4 in)

4. Horizontal Wall Insulation Projection Distance

From Figure 99, with AFI = 7,000°F-Days, (interpolate) Dw = 54 inches.

5. Corner Zone Length.

From Figure 100, with AFI = 7,000°F-Days, Select Lc = 60 inches.

6. Corner Zone: Horizontal R-value and Projection Distance

Alternative A

Alternative A adds both 30% more R-value, and 30% more projection distance.

Rhc, Alternative A

Rhc = 1.3 x Rhw: 1.3 x 14. Rhc,a = 18.2

Select insulation thickness:

Alternative insulations for R-18.2:	EPS II	@ R2.6/in	= 7 in
	EPS IX	@ R2.8/in	=6.5 in (say 7 in)
	XPS	@R4.0/in	=4.6 in (say 5 in)

Dc, Alternative A

Dc = 1.3 x Dw: 1.3 x 54 inches = 70.2 inches Dc,a= 72 inches.

Design Example 3

This is a government building, a school, or a hospital. It is to have a 100 Year design life. The soils are poorly graded sands or gravelly sands. The floor is insulated with two inches of XPS ground insulation. Perimeter insulation is specified as XPS only.

1. Air Freezing Index (AFI)

Select AFI from NCDC Map (Page 3). AFI_{100yr} = 8,000 °F-Days

2. Vertical Insulation R-Value

From Figure 98 Rv = 10

3. Horizontal Wall Insulation R-Value, away from corners.

USC Classification for soils type SP or better

From Figure 99, with better soils, and with AFI=7,000, select Rhw = 16

Select insulation thickness:

XPS @R4.0/in 4 inch XPS

4. Horizontal Wall Insulation Projection Distance

From Figure 99, with AFI = 8,000°F-Days, Dw = 72 inches.

5. Corner Zone Length.

From Figure 100, with AFI = 8,000°F-Days, Select Lc = 72 inches.

6. Corner Zone: Horizontal R-value and Projection Distance

Rhc, Alternative B

Rhc = 1.5 x Rhw: 1.5 x 16 Rhc,b = 24

Dc, Alternative B

Dc is unchanged. Dc =Dw Dc,b = 72 inches.

7. Increased Perimeter Insulation due to presence of Ground Insulation

Ground insulation = 2=inches XPS, at R4/in = Rf = 8

Add R8 to vertical and horizontal insulation

Rv + 8 Rv, w/grnd insul = 18

Rhw + 8 Rhw,w/grnd insul = 24

Rhc + 8 Rhc, w/ grnd insul = 32

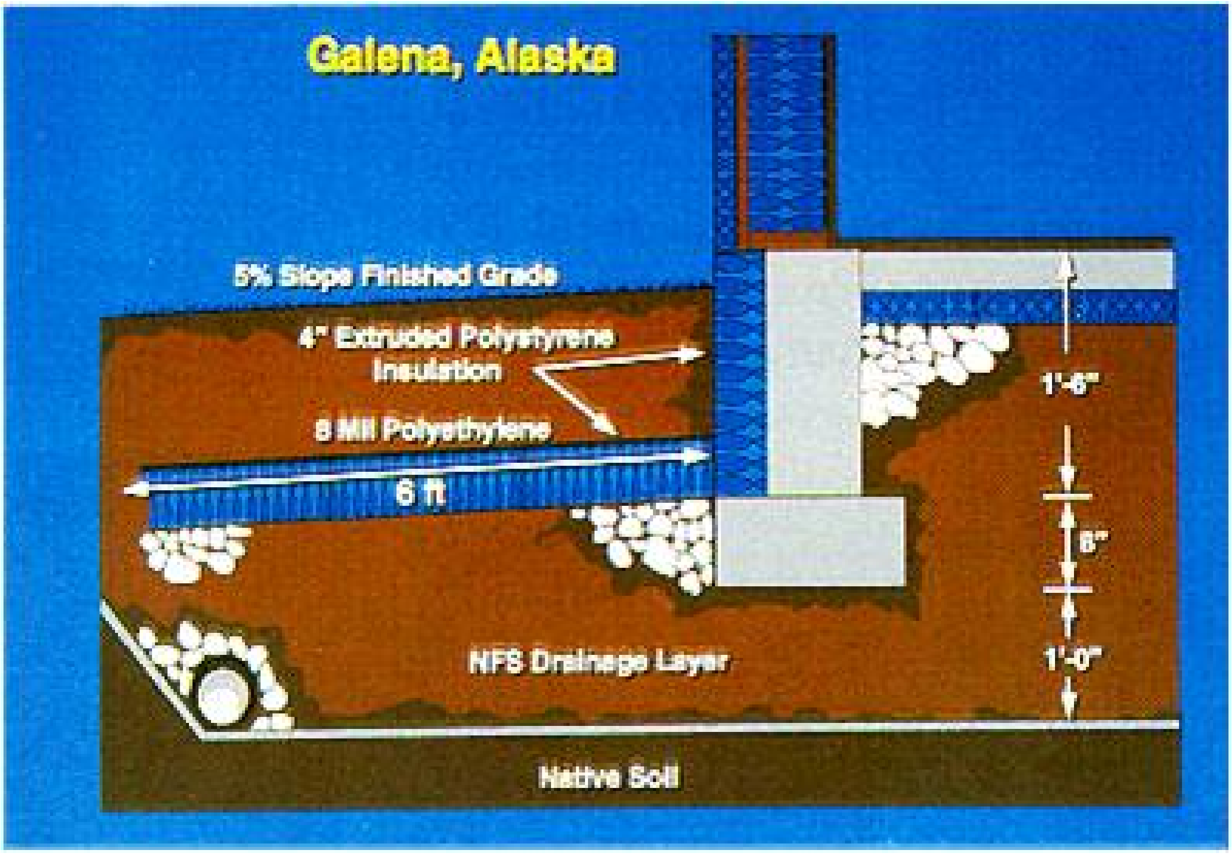

Figure 101. Frost-protected shallow foundations: Galena, Alaska, 100-year design example. (Danyluk, 1997)

Figure 101 shows an example of a CRREL designed FPSF system at Galena Alaska

(Danyluk, 1997).

Design Example 4

An initially heated building is expected to be closed down ("mothballed") and left unheated for extended periods. Frost susceptible soils are within the active frost layer that is seasonally frozen each year.

> Commentary:
> Consult an Alaskan registered design professional for a site-specific evaluation.
>
> In Interior Alaska (including the greater Fairbanks area) the average annual soils temperatures are often below freezing. Over time, expect the soils to freeze below unheated buildings. If frost susceptible soils and water are additionally present, expect frost heave. Either, change the soils or choose a different site.
>
> By contrast, if the soils are non-frost susceptible and dry throughout the seasonal frost layer, then FPSF methods may still apply. Again, consult an Alaskan registered design professional for a site-specific evaluation.

Appendix B.
Fairbanks, Results for R20 & R40 Thermal Insulation

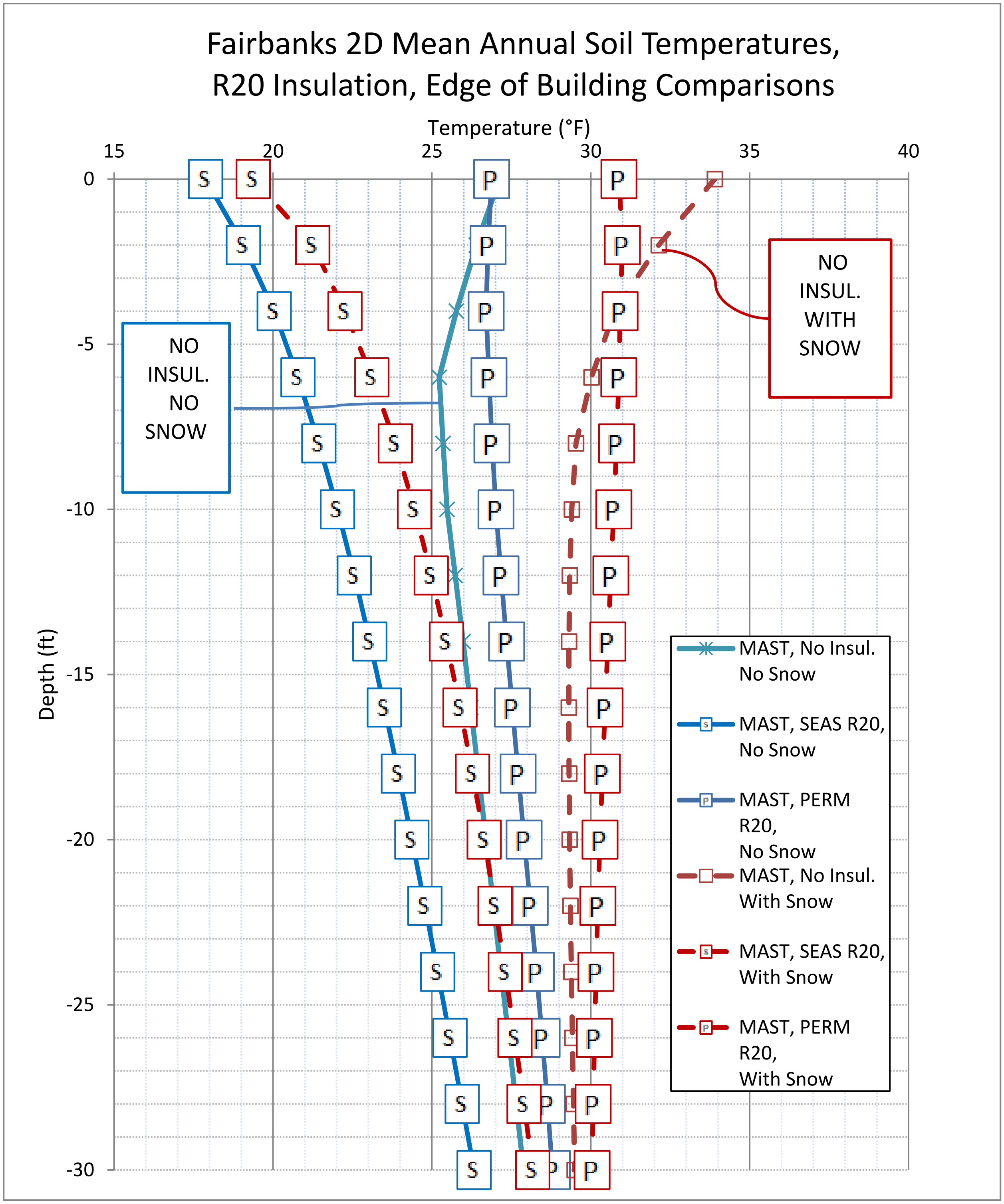

Figure 102. Fairbanks 2D, R20, building edge, mean annual soil temperature comparisons. Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

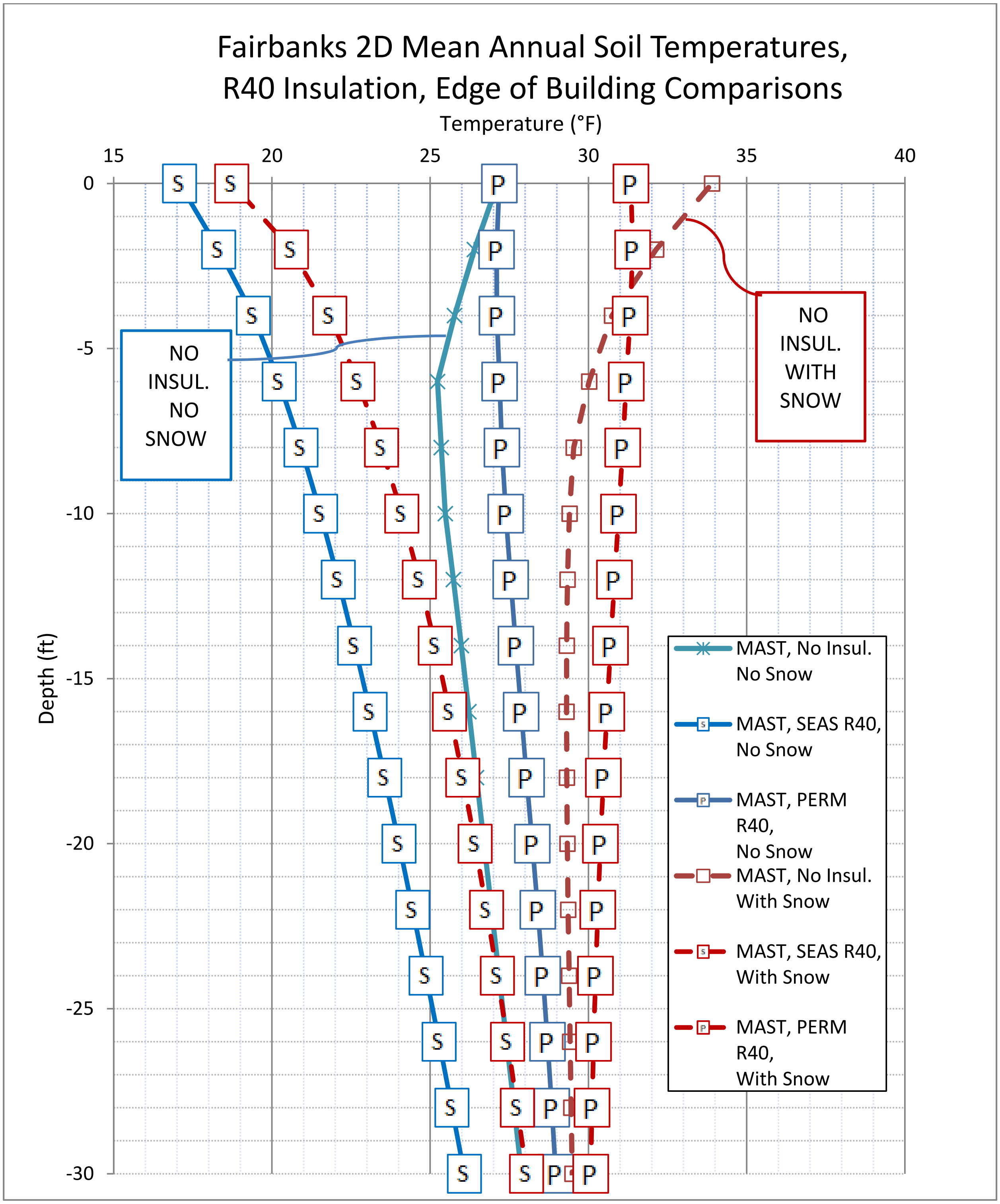

Figure 103. Fairbanks 2D, R40, building edge, mean annual soil temperature comparisons. Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

Appendix C.
Kotzebue, Results for R20 & R40 Thermal Insulation

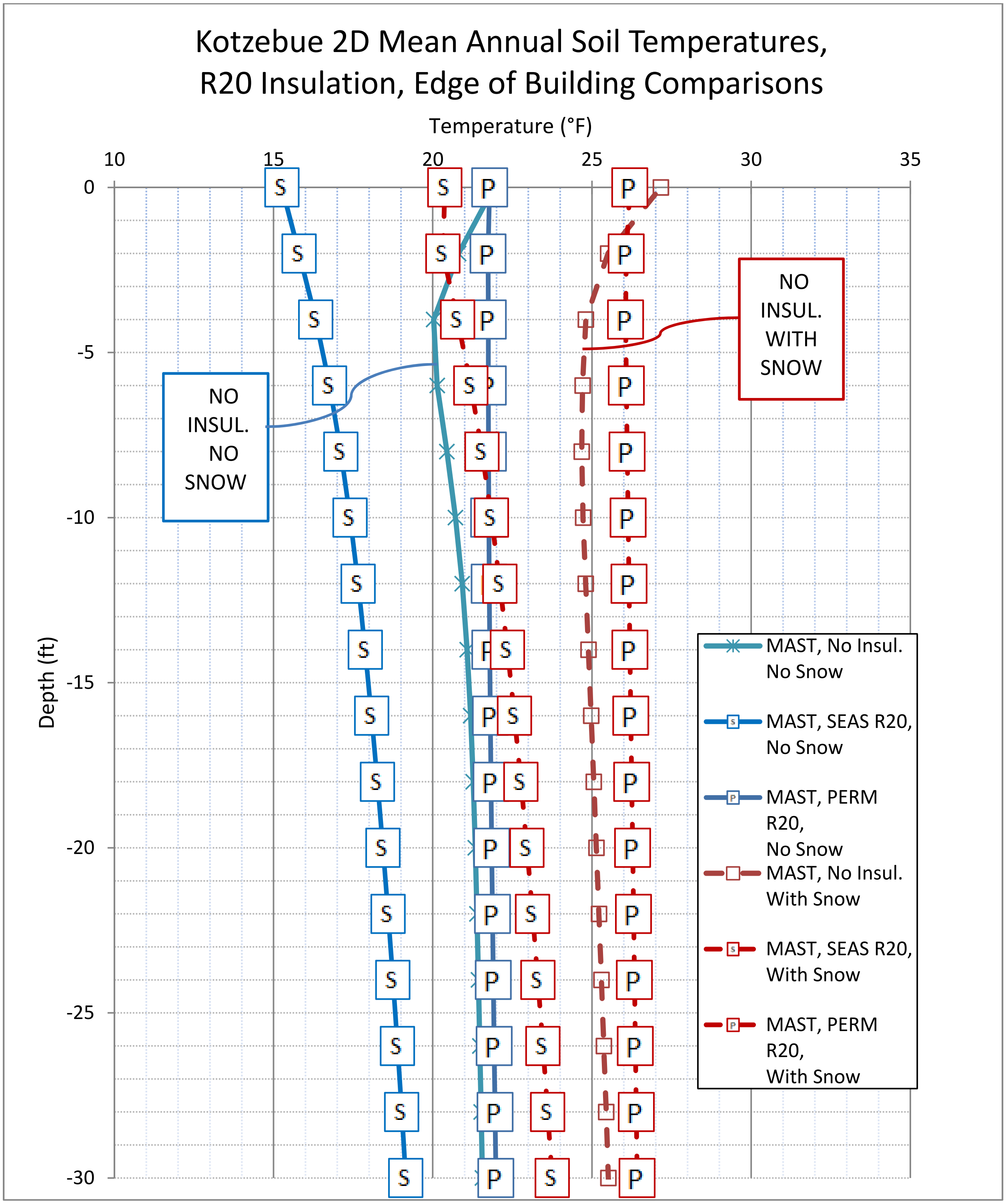

Figure 104. Kotzebue 2D, R20, building edge, mean annual soil temperature comparisons. Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

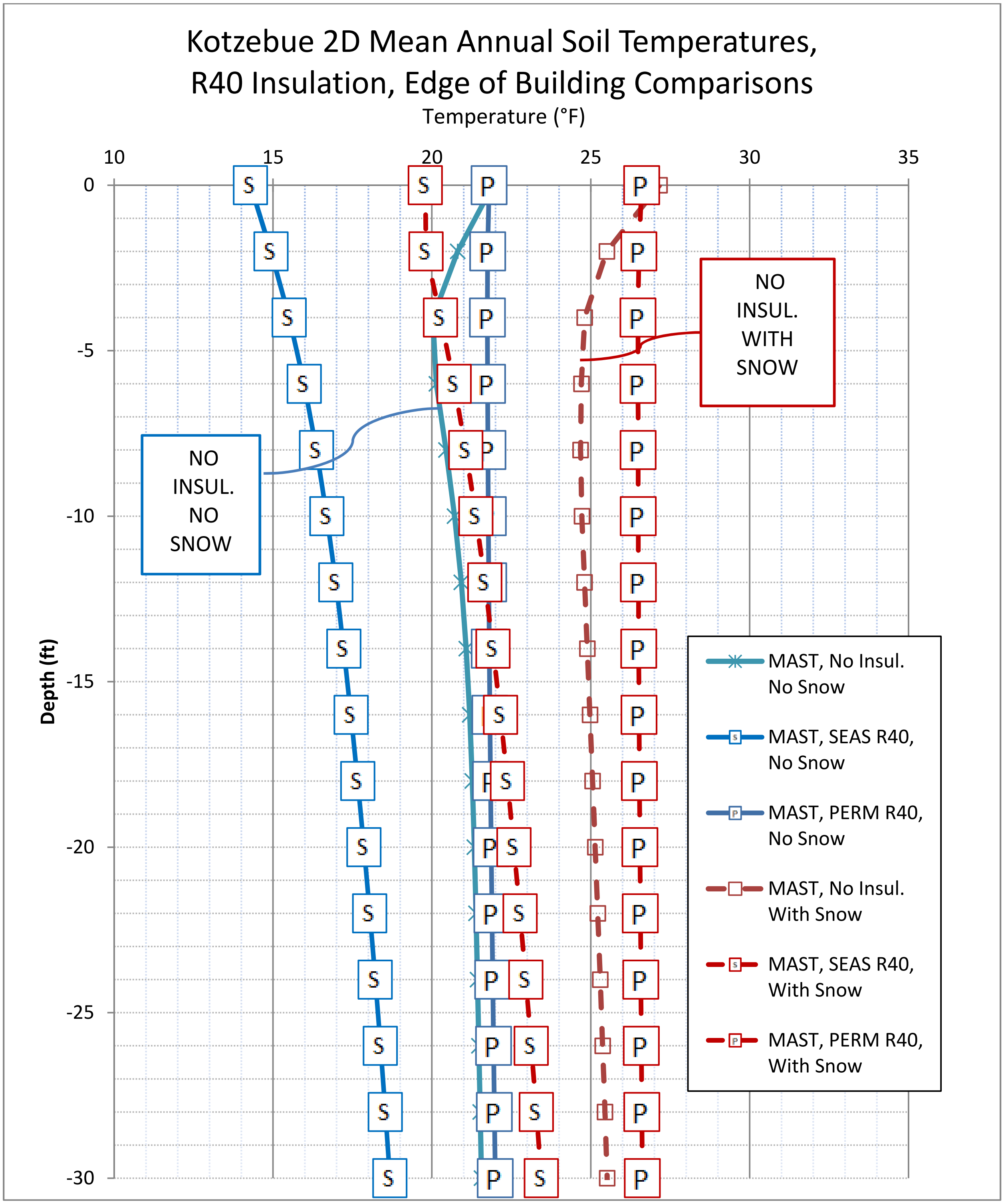

Figure 105. Kotzebue 2D, R40, building edge, mean annual soil temperature comparisons. Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

Appendix D.
Barrow, Results for R20 & R40 Thermal Insulation

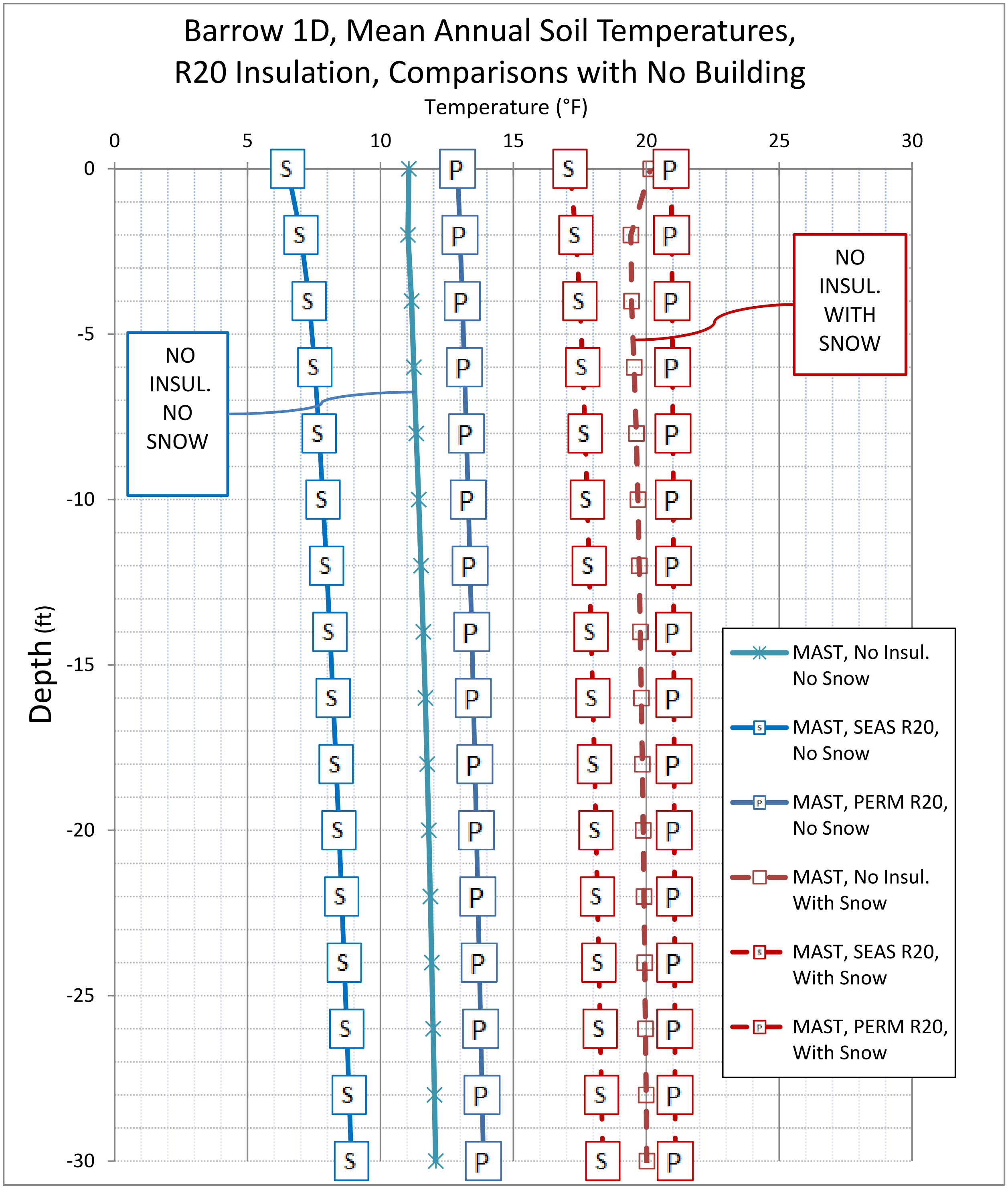

Figure 106. Barrow 1D, R20 insulation, mean annual soil temperature comparisons.
Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

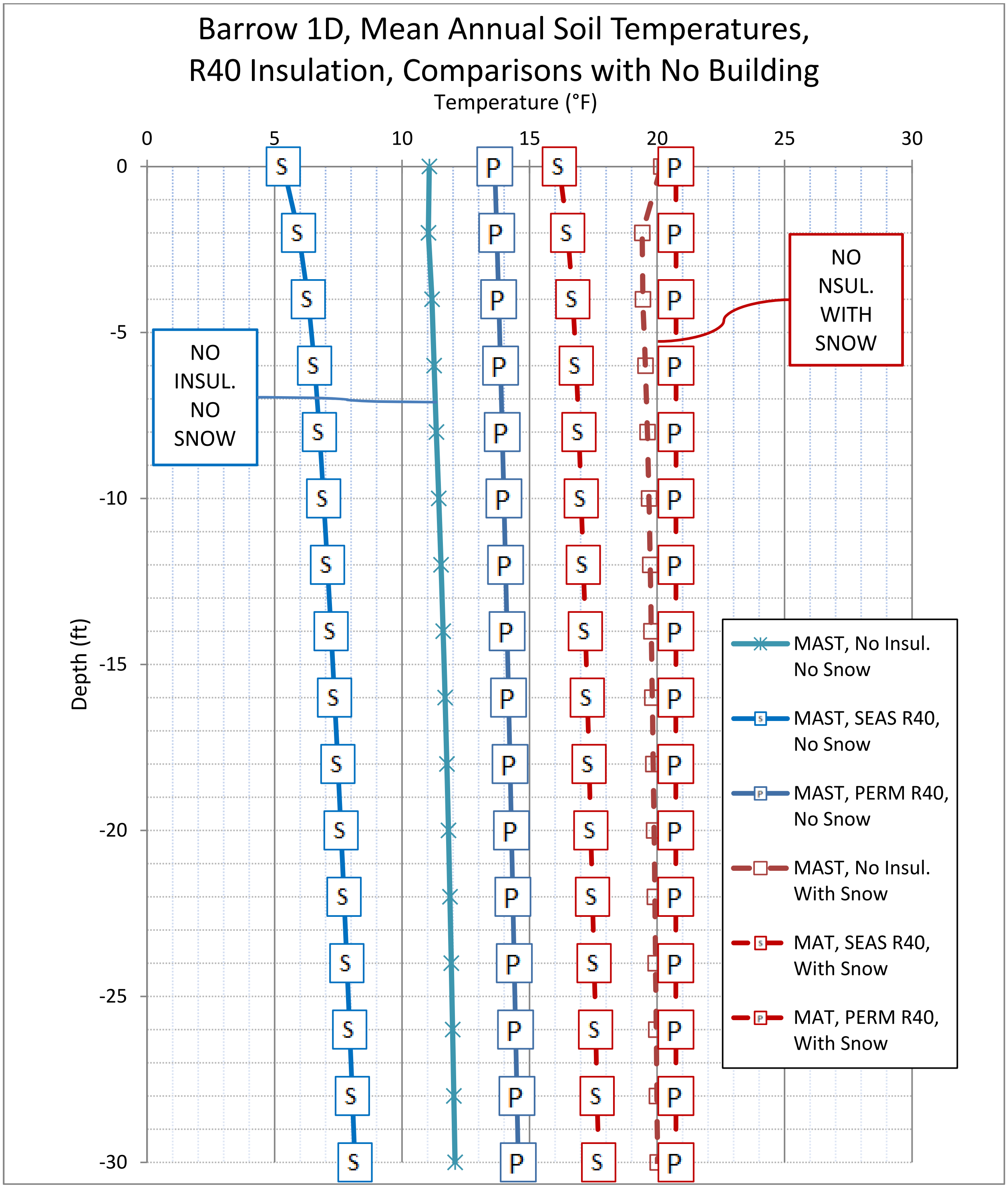

Figure 107. Barrow 1D, R20 insulation, mean annual soil temperature comparisons.
Conditions included seasonal (S) and permanent (P) insulation, both no snow and with cover.

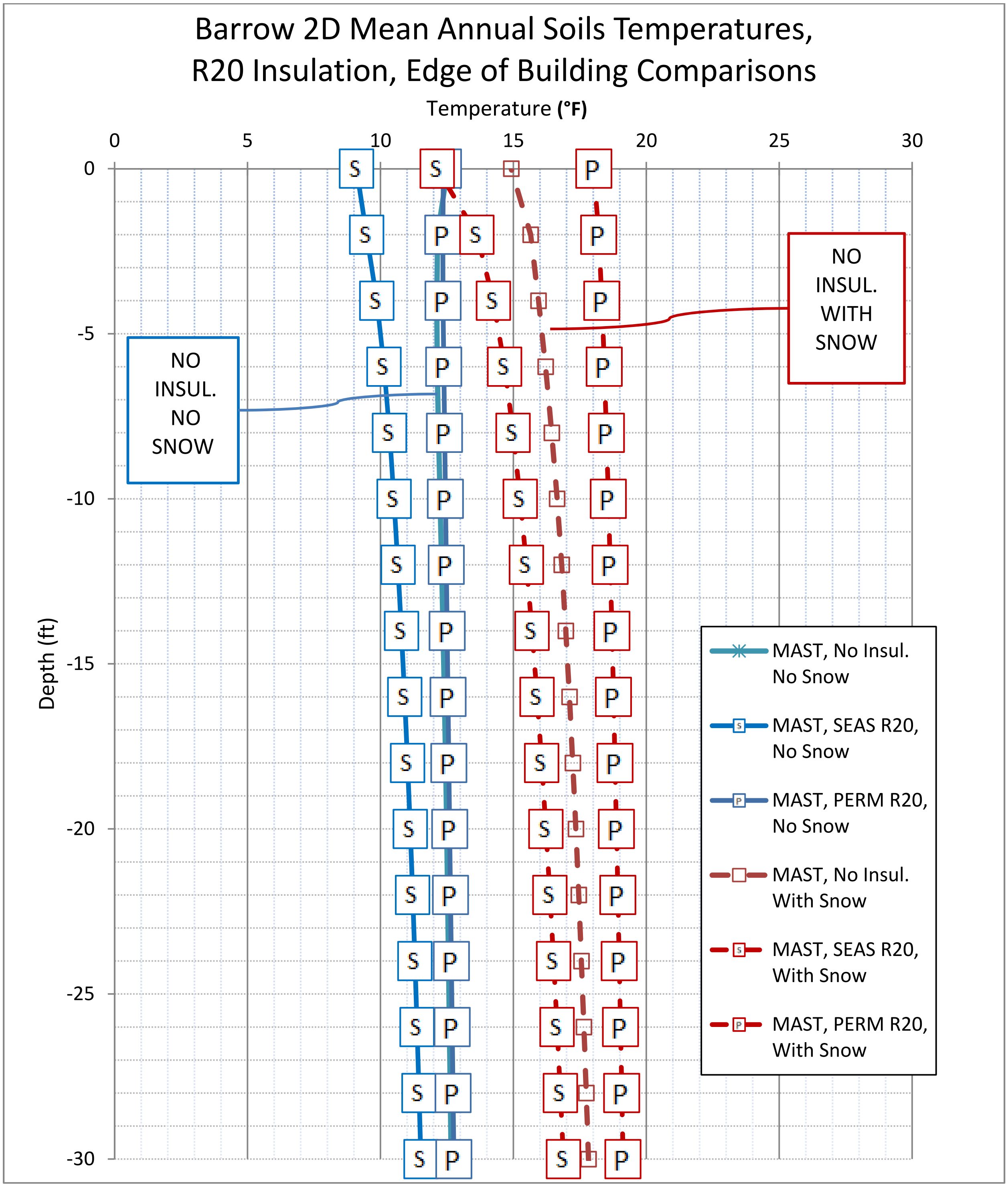

Figure 108. Barrow 2D, R20 insulation, mean annual soil temperature comparisons. Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.

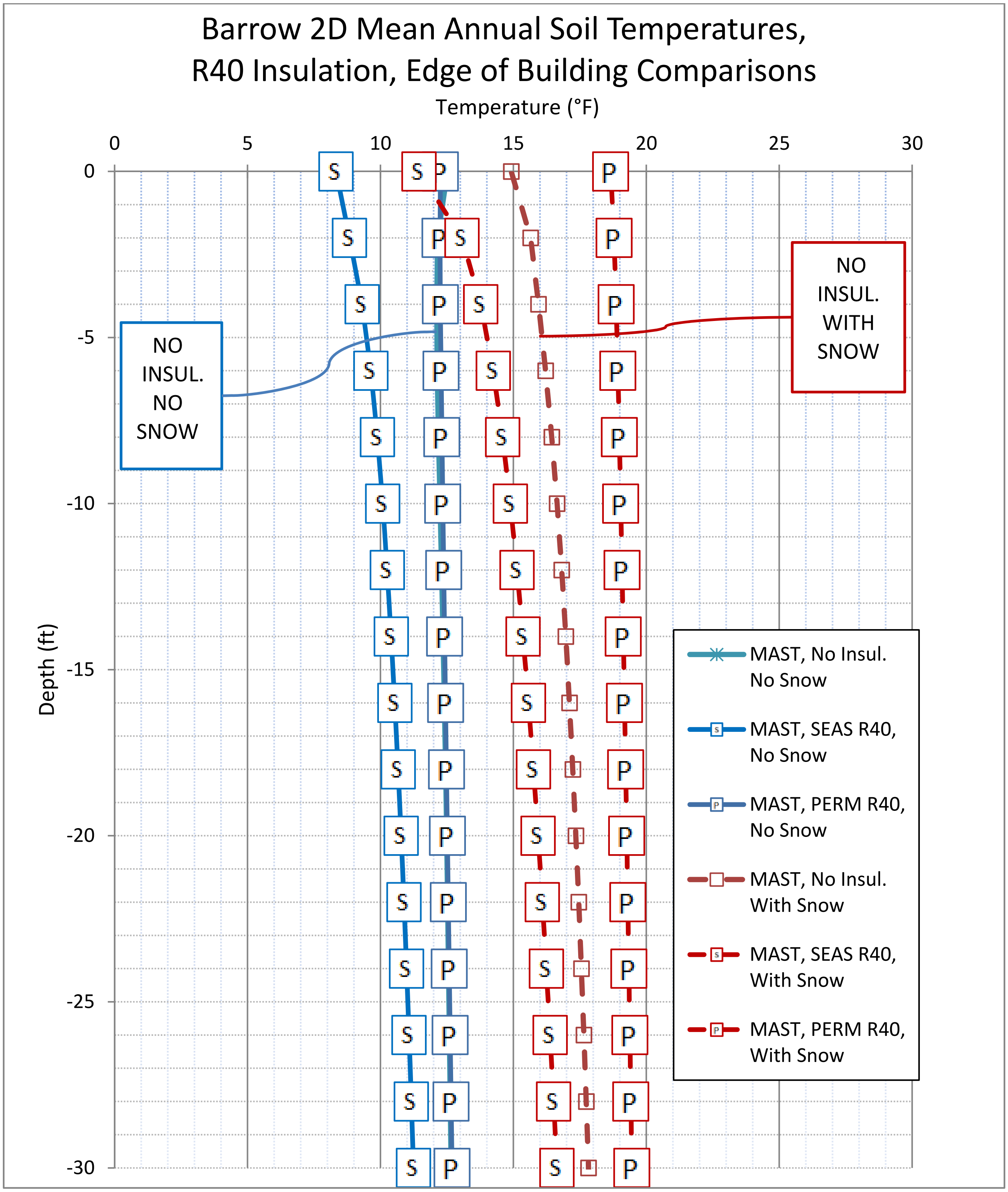

Figure 109. Barrow 2D, R40 insulation, mean annual soil temperature comparisons. Conditions included seasonal (S) and permanent (P) insulation, both no snow and with snow cover.