Evaluation of Frost Heave on Waste Transfer Lines with Shallow Depths in DST Farms

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Abstract: The purpose of this document is to evaluate the effect of frost heave on waste transfer lines with shallow depths in DST farms.
Because of the insulation, and well compacted sandy material around waste transfer lines, the type of sandy and gravel soil, and relatively low precipitation at Hanford site, it is concluded that waste transfer lines with one foot of soil covers (sandy cushion material, and insulation) are not expected to undergo frost heave damaging effects.

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1. PURPOSE

The purpose of this report is to evaluate the effect of frost heave on waste transfer lines with shallow depths in DST farms. This concern was raised in RPP-18652, Rev. 1, *Buried Piping Analysis for DST System Integrity Assessment*. The recommendation on page 59 of 318 in this report states, "- -- due to shallowness of some of the transfer lines mentioned in this document, it is recommended that an analysis or evaluation of frost heave and its effects is in order to determine the corrective action needed. Inspections and/or testing of identified pipes might also be in order, if it is determined that frost heave is a concern and that its damaging effects could have occurred in the past." Furthermore, this document, on the same pg, states the following:

"PER No. 2004-5678 which was written against this document indicated that the soil cover for SN-631 of Tank Farm AZ should be much greater as indicated by drawing H-14-102671 Sht 1. The increase in soil cover was credited to a berm. Upon further investigation, the height of the berm was still not conclusive. Berms on other transfer lines, in other tank farms, called out on numerous related drawings are simply stated as "as required". This is not definitive enough to be included in this evaluation. Thus, as previously recommended, inspections on suspected shallow transfer lines are in order. This should provide a more accurate assessment of the soil cover above the suspect transfer line."

This report will address the impact of frost heave on shallow transfer lines, and will determine if berms on some of these lines need to be relied upon for safeguarding against frost heave.

2.0 BACKGROUND

A typical waste transfer line in tank farms is a 2" or 4" pipe encased within a 3" or 6" pipe respectively, as shown in Figure 2. The sketch in Figure 2 has been developed using information from Detail II, Dwg H-2-70550 and Sect 02200, Spec B-120-C7. The Detail II on Dwg H-2-70550 shows a minimum soil cover of 2'-9" from the top of pipe to the elevation of sub grade. But, on a further study of RPP-18652 document, it became apparent that there were a significant number of waste transfer lines which did not meet this minimum soil cover requirement. The approximate frost depth of soil covers, according to Figure 2-1, pg 2 -2, Engineering Manual, EM 1110-1-1905 in Eastern Washington state is between 1 foot to 2 feet. Therefore, the soil covers on waste transfer lines in tank farms, with less than 2 feet, will be considered as shallow covers. To give an idea of shallow soil covers in tank farms, a list of waste transfer pipe lines with soil covers less than two feet, has been developed (as shown in Table 1, Attachment A), using data from RPP-18652. These are the pipe lines which may be subject to frost heave due to their shallow burial depths.

The primary risk associated with frost heave is the damage to the pipes which may occur due to loss of soil strength. The heaving or lifting of soil occurs due to fluctuating freezing or thawing conditions of affected soils during ensuing thaw period. Frost heave in certain soils in contact with water and under freezing temperatures can result in loss of soil compaction and uneven settlement, thus altering the bearing capacity of soil to support piping.

Soil covers are provided for underground piping to safeguard against vehicular traffic, and for frost heave protection. The soil covers for waste transfer lines have been evaluated for vehicular traffic in RPP-25074. The scope of this report is limited to evaluate the effects of frost heave on waste transfer lines with shallow soil covers.

3.0 CONCEPT OF FROST HEAVE PHENOMENON

Frost heave is an upward movement of the soil resulting from the expansion of accumulated soil moisture as it freezes. Soil freezing results from the combination of cold air and soil moisture. This phenomenon is caused by crystallization of ice within the larger soil voids, and then progressing to formation of ice lenses, layers, or other ice masses. The ice lenses grow in the direction of heat transfer until freezing conditions at the freezing interface stop further crystallization. As the ice lens grow, the overlying soil heaves up. Charles Smith, horticulturist and educator in Great Barrington, Massachusetts, while responding to an enquiry about frost heave in Fine Gardening Magazine responds it best with the following statement:

"Frost heave happens when a fine-textured soil, such as a silty loam that has plentiful soil moisture, is subjected to freezing temperatures. - - - - For a frost heave to occur, cold air must migrate through the soil layers where there is an area of warmer soil deep beneath the surface and plenty of moisture in the soil. As the cold air sinks into the ground, it freezes the water in the soil into ice particles. The particles come together to form a layer of ice, called an ice lens, along the leading edge of the freezing zone. Additional moisture is also drawn upward from deeper soil layers, desiccating the soil below. This rising moisture freezes, expanding the ice lens even further while creating great pressure, both upward and downward. The downward pressure damages the soil by compacting it while the upward pressure creates the frost heave - - - - . Frost heave most often occurs in the early spring and sometimes in late fall, when cold temperatures and abundant soil moisture are most often present. Heaves can happen in any type of soil, but some are prone to heaving more than others. Coarse, sandy soils drain so well that the moisture needed to produce heaves is rarely present. Soils that are moisture retentive, such as silt, loam, and clay, are much more prone to heaving."

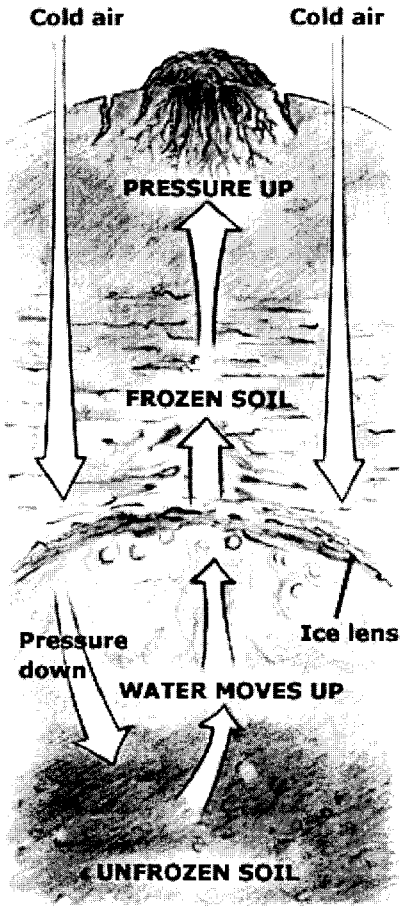

Figure 1

Cross Section of Frost Heave

4.0 FACTORS CAUSING FROST HEAVE

Design Guide for Frost-Protected Shallow Foundations, by National Association of Home Builders (see Attachment C) states "Frost heave can only occur when all the following three conditions are present: 1) the soil is frost susceptible, 2) sufficient moisture is available (soil is above approximately 80% saturation) and 3) subfreezing temperatures are penetrating the soil. Removing one of these factors will negate the possibility of frost damage." The occurrences of these three conditions, causing frost heave, are discussed below.

4.1 Soil Susceptible to Frost: The hydraulic conductivity of a soil is related to its pore size. The particles of sandy and clayey soils have larger pores as compared to silty soils, resulting in high hydraulic conductivity. Moisture retentive soils, such as silt, and loam are much more prone to heaving as compared to coarse sandy soils which drain the moisture needed to produce heaves. Common frost susceptible soils include silts, silty sands, and low plasticity clays. Soils most susceptible to frost action are low cohesive materials containing a high percentage of silt sized particles. Well-draining soils, like coarse sand, rarely if ever suffer from frost heaving issues.

4.2 Moisture in Soil: In order for the frost heave to occur, a source of water must be available within the zone of freezing. If the water to the freezing zone is restricted due to low soil permeability, water will be drawn from the voids of the soil adjacent to the growing ice crystals.

4.3 Subfreezing Temperatures in Soil: The penetration of freezing or thawing temperatures into soil depends on the magnitude and duration of the temperature differential at the air-ground surface.

5.0 FROST HEAVE FACTORS AT TANK FARMS

5.1 Soil: The geotechnical testing report for one of the latest projects, Integrated Disposal Site (IDF), near tank farms, RPP-RPT-26713, Section 3.2.2.2, describes the characteristics of soil formation at Hanford as follows:

"In general, the Hanford formation consists of poorly sorted, pebble to cobble gravel and fine- to coarse-grained sand, with lesser amounts of interstitial and interbedded silt and clay. In previous studies of the IDF site, the Hanford formation was described as consisting of three units: an upper and lower gravelle facies and a sandy facies between the two gravelly units. The silt-dominated, slack water facies (touchet beds) or interbedded sand- and silt-dominant facies is not present."

The soil samples on IDF site also showed the fines ranging from 17.5 % to 28 %, passing No. 200 series (.075 mm) from a depth of 2 to 3 feet (See pg 7, RPP-RPT-26713).

The soil at Hanford, in general, consists of sandy gravel. Furthermore, the top surfaces of tank farms containing waste transfer lines have been mostly stabilized with gravel.

5.2 Moisture: Normal annual precipitation at the Hanford Meteorological station according to Section 4.1, PNNL-14616 is 6.98", while the winter period from November to February provides 3.64"of precipitation. The maximum measurable precipitation ever recorded at Hanford was 2.7" during the period between November 28 to January 7, 2004 (Section 4.6, PNNL-14616). The average annual precipitation at the site is equivalent to only 2.4%, resulting in moisture level from 3% to 4%, according to pg 4, WHC-SD-WM-SOIL-001. The tank farms at Hanford are located in a near desert climate, and in general, there is little water near the ground surface. Even if the little water on the ground surface of waste transfer lines freezes, the associated heave in the soil will be negligible.

5.3 Temperature: Monthly average temperatures recorded at Hanford for the worst cold month in January are 36.3 F^0 and 42.7 F^0 at 15" and 36" depths of soil respectively (Table 3.15, PNNL-14616). Lowest monthly average temperatures ever recorded at Hanford, were 25.5 F^0 (in 1979) and 33.5 F^0 (in 1957) at 15" and 36" depths of soil respectively (Table 3.15, PNNL-14616).

6.0 SAFEGUARDS IN TANK FARMS AGAINST FROST HEAVE FACTORS

6.1 Insulation: The waste transfer lines at the tank farms have been enclosed within polyurethane insulation (typically rigid sprayed urethane foam), prior to backfilling (see, Figure 2, and Table 1, Attachment A), thus minimizing the chances of ice lens or frost heave formation. Insulation protects pipes from freezing and frost heave by creating a temperature barrier between pipes and frozen ground. The insulation around the piping prevents the infiltration of moisture from its top surface, and the formation of ice lens from its bottom surface. According to Design Guide for Frost-Protected Shallow Foundations, by National Association of Home Builders (see pg C-4, Attachment C), insulation will prevent underlying soil from freezing, e.g., an inch of polystyrene insulation, R4.5, has an equivalent R-Value of about 4 feet of soil on average. The frost line in soil rises because of insulation. As shown by the analysis in Attachment E, the depth of frost penetration in soil will reduce from approximately 16" to 4" if 3" insulation over the buried piping is taken into account. Thus, 3" insulation provided around the buried transfer lines will inhibit frost heave formation, because the low frost penetration depth (due to the presence of insulation) is not expected to reach the piping surface.

6.2 Sand Cushion Backfilling: The waste transfer lines along with insulation around them have been laid with sand bedding, and backfilled with granular material (sand) on their vertical sides and top surfaces, as described in Attachment A, Table 1, and shown in Figure 2. The backfill around the pipe lines consists of sandy cushion material up to one foot above pipe, and compacted with 95% of the maximum density, as evident from the following construction specifications:

- B-120-C7, Section 02200, Paragraph 3.02E (AW Tank Farm)
- B-130-C7, Section 02200, Paragraph 3.02E (AN Tank Farm)
- B-133-C1, Section 02200, Paragraph 3.02E (AW Tank Farm)
- B-621-C1, Section 02200, Paragraph 3.2.2 (AW Tank Farm)
- W-314-C4, Section 02200, Paragraph 3.4 (AZ Tank Farm & SY Tank Farm)

Application of the overlying backfill restrains the upward movement of the pipelines in case of frost heave.

Combination of backfilling with granular and insulation material has even been used in remedying the upheaval effects on the Trans-Alaska Pipeline System (TAPS). Canadian Geotechnical Journal (pg 321-322, Can Geotech. Journal), published on the NRC Research Press site at http://cgj.nrc.ca, describes this remedial effect as the following:

"On the Tran-Alaska Pipeline System (TAPS) fuel gas line, upheaval has taken place on several occasions while the pipeline was in service. Remediation was successfully carried out by excavating alongside the upheaval, laying the pipeline down in the excavation and covering it with granular and insulating material."

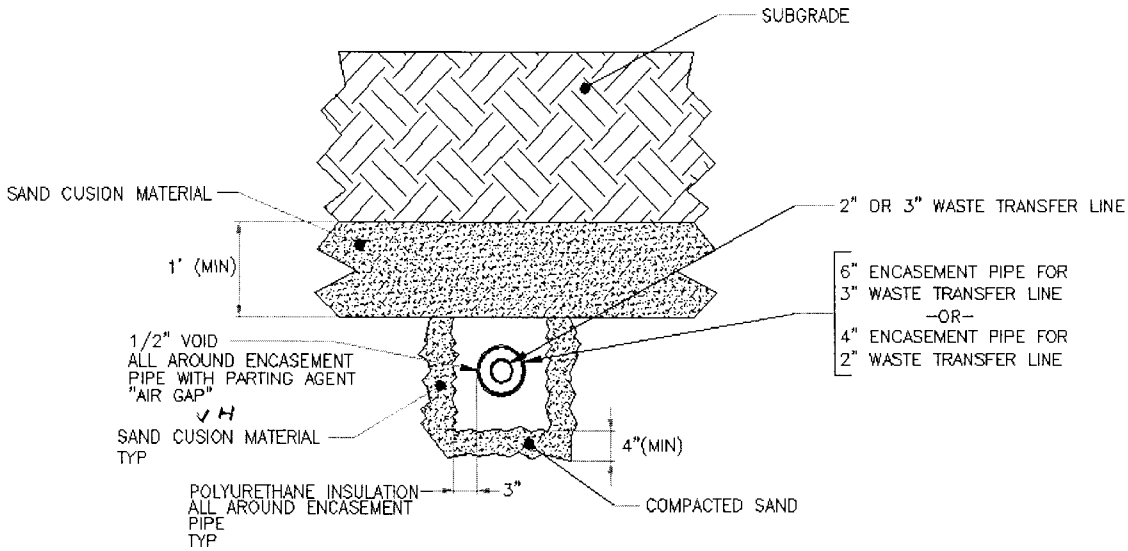

FIGURE 2 – WASTE TRANSFER LINE DETAIL

TYPICAL ARRANGEMENT OF PIPE ENCASEMENT INSULATION AND BACKFILLING WITH SAND

7.0 Conclusion

The waste transfer lines in the tank farms were specified to be laid with at least 3" of insulation wrapped around them. Furthermore, this insulation was enclosed with at least 4" of compacted sand on its sides and bottom, and with one foot of soil cover (sand) above its top surface. The insulation wrapped around the waste transfer lines, with well compacted sandy backfill material around the insulation, is strongly expected to prevent the formation of ice lens, thus inhibiting frost heave. The insulation around the buried piping plays a major role in reducing the frost line depth in the soil. As shown by the analysis in Attachment E, the depth of frost penetration in soil will reduce from approximately 16" to 4" if 3" insulation over the buried piping is taken into account. The type of sandy and gravel soil, and relatively low precipitation at Hanford site further helps in mitigating frost heave effects on waste transfer lines. Therefore, it is concluded that waste transfer lines with 3" insulation wrapped around them, and with sandy cushion material around the insulation, are not expected to undergo frost heave damaging effects in tank farms.

According to Attachment A, Table 1, the waste transfer line, with the shallowest soil cover of approximately one foot, is SN-631. PER-2004-5678 had been written to stipulate that soil cover for this pipe line was actually greater than one foot, if the berm would have been included to the soil cover. But, exact depth of the berm is not known. If there is only one foot of soil cover on this waste line, it must be consisting of insulation and sandy cushion backfilled material (in compliance with design and specification). The presence of insulation, and sandy

cushion material, as one foot minimum soil cover, safeguards against the frost heave formation, and thus negates the reliance on berm for frost protection.

8.0 REFERENCES:

1. Can. Geotech. Journal 42, *Discussion of "Frost Heave and Pipeline Upheaval Buckling"* by James M. Oswell, Darren Skibinsky, and Cavanagh, Paper published in Canadian Geotechnical Journal, Vol 42, 2005. See Attachment D.
2. Engineering Manual No. 1110-1-11905, Oct 1992, *Engineering and design – Bearing Capacity of Soils*, US Army Core of Engineers.
3. *Design Guide for Frost Protection Shallow Foundations*, National Association of Home Builders, 1995, prepared for U.S. Department of Housing and Urban Development. See Attachment C.
4. Fine Gardening Magazine (http://www.taunton.com/finegardening/pages/g00244.asp). See Attachment B.
5. RPP-18652, Rev. 1, *Buried Piping Analysis for DST System Integrity Assessment,* G. Lisle, Los Alamos Technical Associates, Inc., Richland, Washington.
6. RPP-25074, Rev. 1, *Vehicle & Equipment Access over Buried Ducts/ Pipes*, CH2M Hill, Hanford Group, Inc., Richland, Washington.
7. RPP-RPT-26713, *IDF Test Pit Excavation – Sample Analysis and Data Formation,* M. Reimbold, CH2M Hill, Hanford Group, Inc., Richland, Washington.
8. PNNL-14616, *Hanford Site Climatological Data Summary 2003 with Historical Data* (http://www.pnl.gov/main/publications/external/technical_reports/PNNL-14616.pdf).
9. PER- 2004-5678, Correction to Soil Cover for SN-631 Pipe, Tank Farm AZ.

ATTACHMENT A

(Table 1, Summary of Waste Transfer Pipe Lines, Susceptible to Frost Heave)

TABLE 1, SUMMARY OF WASTE TRANSFER PIPE LINES, SUSCEPTIBLE TO FROST HEAVE

Farm No.	Piping Design-ation	Pipe Size (in)	Encasement Pipe Size (in)	Minimum Soil Cover to Centerline of pipe (ft)	Approx. Year of Installation	Heat Trace/ Insulation	Sand Cushion & Sand around the Pipe Line (Const. Spec. /Pipe Code Ref.)	Applicable Drawings
AN	SL-167	2 Sch 40	4 Sch 40	2.03	1978	Heat Trace & Insulation Ref. Note 5, H-2-71986, Sh 1, Rev. 10	Sect 02200, Para 3.01, C1 & 3.02, E4, B-130-C7/M25/M26a	H-2-71907, Rev. 1 H-2-71986, Rev. 9 H-2-71990, Rev. 4 H-2-71998, Sh 1, Rev.9 H-2-72039, Sh 1, Rev.8
		Ref. Pg 5 0f 318 (RPP-18652)					Ref. Pg 31 0f 318 (RPP-18652)	
"	SL-168	2 Sch 40	4 Sch 40	2.03	1978	"	Sect 02200, Para 3.01, C1 & 3.02, E4, B-130-C7/M25/M26a	H-2-71907, Rev. 1 H-2-71986, Rev. 9 H-2-71989, Rev. 4
"	SN-267	3 Sch 40	6 Sch 40	1.65	1978	"	Sect 02200, Para 3.01, C1 & 3.02, E4, B-130-C7/M25/M26a	H-2-71907, Rev. 1 H-2-71986, Rev. 9 H-2-71990, Rev. 4 H-2-71998, Sh 1, Rev.9 H-2-72039, Sh 1, Rev.8
		Ref. Pg 6 0f 318 (RPP-18652)					Ref. Pg 32 0f 318 (RPP-18652)	
"	SN-268	3 Sch 40	6 Sch 40	1.65	1978	"	Sect 02200, Para 3.01, C1 & 3.02, E4, B-130-C7/M25/M26a	H-2-71907, Rev. 1 H-2-71986, Rev. 9 H-2-71989, Rev. 4
AW	SL-167	2 Sch 40	4 Sch 40	1.86	1977	Heat Trace & Insulation Ref. Note 5, H-2-70398, Sh 1, Rev. 6	Sect 02200, Para 3.01, C1 & 3.02, E4, B-120-C7/M25/M26a	H-2-79267, Rev. 6 H-2-70307, Rev. 1 H-2-70398, Sh 1, Rev.6 H-2-70398, Sh 2, Rev.0 H-2-70399, Rev. 11 H-2-70402, Rev. 5
		Ref. Pg 17 0f 318 (RPP-18652)					Ref. Pg 45 0f 318 (RPP-18652)	

Table 1, Continued

Farm	Pipe Number	Pipe Size (in)	Encasement Pipe Size (in)	Minimum Soil Cover to Centerline of pipe (ft)	Approx Year of Installation	Heat Trace/ Insulation	Sand Cushion & Sand around the Pipe Line (Const. Spec. /Pipe Code Ref.)	Applicable Drawings
AW	SL-168	2 Sch 40	4 Sch 40	1.86	1977	Heat Trace & Insulation Ref. Note 5, H-2-70398, Rev. 6	Sect 02200, Para 3.01, C1 & 3.02, E4, B-120-C7/M25/M26a	H-2-79267, Rev. 6 H-2-70307, Rev. 1 H-2-70398, Sh 1, Rev. 6 H-2-70398, Sh 2, Rev. 0 H-2-70399, Rev. 11 H-2-70402, Rev. 5
		Ref. Pg 17 0f 318 (RPP-18652)					Ref. Pg 45 0f 318 (RPP-18652)	
"	SL-169	2 Sch 40	4 Sch 40	1.86	1977	"	Sect 02200, Para 3.01, C1 & 3.02, E4, B-120-C7/M25/M26a	H-2-70307, Rev. 1 H-2-70398, Sh 1, Rev. 6 H-2-70401, Rev. 7 H-2-70402, Rev. 5
		Ref. Pg 17 0f 318 (RPP-18652)					Ref. Pg 45 0f 318 (RPP-18652)	
"	SN-267	3 Sch 40	6 Sch 40	1.77	1977	"	Sect 02200, Para 3.01, C1 & 3.02, E4, B-120-C7/M25/M26a	H-2-70307, Rev. 1 H-2-70398, Sh 1, Rev. 6 H-2-70399, Rev. 11 H-2-70402, Rev. 5 H-2-70411, Sh 1, Rev. 5
		Ref. Pg 18 0f 318 (RPP-18652)					Ref. Pg 47 0f 318 (RPP-18652)	
"	SN-220	3 Sch 40	6 Sch 40	1.94	1977	Heat Trace & Insulation Ref. Note 5, H-2-70398, Rev. 6	Sect 02200, Para 3.01, C1 & 3.02, E4, B-120C7/M25/M26a	H-2-69189, Rev. 2 H-2-69194, Rev. 2 H-2-70307, Rev. 1 H-2-70398, Sh 1, Rev. 6 H-2-70398, Sh 2, Rev. 0 H-2-70399, Rev. 11 H-2-70402, Rev. 5 H-2-70465, Rev. 2
		Ref. Pg 17 0f 318 (RPP-18652)					Ref. Pg 46 0f 318 (RPP-18652)	

Table 1, Continued

Farm	Pipe Number	Pipe Size (in)	Encasement Pipe Size (in)	Minimum Soil Cover to Centerline of pipe (ft)	Approx. Year of Installation	Heat Trace/ Insulation	Sand Cushion & Sand around the Pipe Line (Const. Spec. /Pipe Code Ref.)	Applicable Drawings
"	SN-268	Same as SN-267						
"	SN-271	3 Sch 40	6 Sch 40	1.77	1977	Heat Trace & Insulation Ref. Note 5, H-2-70398, Rev. 6	Sect 02200, Para 3.01, C1 & 3.02, E4, B-120-C7/M25/M26a	H-2-70398, Sh 1, Rev. 6 H-2-70401, Rev. 7 H-2-70402, Rev.5
		Ref. Pg 19 0f 318 (RPP-18652)					Ref. Pg 47 0f 318 (RPP-18652)	
"	SN-274	"	"	"	"	Heat Trace & Insulation Ref. Sect. D, H-2-77108, Sh1, Rev. 3	Sect. 02200, Para 3.2.3, B-621-C1/M9/M26a	H-2-70307, Rev. 1 H-2-70399, Rev. 11 H-2-77108, Rev. 2 H-2-77109, Rev. 1
		Ref. Pg 19 0f 318 (RPP-18652)					Ref. Pg 47 0f 318 (RPP-18652)	
AW	LIQW-702	3 Sch 40	6 Sch 40	1.71	1077 Mod. 2003	Insulation per Sect C-C, H-2-70706, Sh 1, Rev. 1	Section 02200, Para 3.01C & 3.02E, B-133-C1/M8/M26a E-525-C04/M8/M26a	H-14-105781, Sh 1-3, Rev. 1 H-2-69194, Rev. 2 H-2-70682, Rev. 2 H-2-70706, Rev. 1 H-2-90448, Sh 1, Rev. 1
		Ref. Pg 19 0f 318 (RPP-18652)					Ref. Pg 48 0f 318 (RPP-18652)	
AZ	SN-631	3 Sch 40S	6 Std	1.26	2000	Insulation Piping Plan, H-14-102671, Sh 1, Rev. 1 & W-314-P11 *Heat Trace	Sect. 02220, Para 2.1.4 & 3.4, W-314-C4, W-314-P11/M9/M26a	H-14-102710, Sh 1, Rev. 3
		Ref. Pg 23 0f 318 (RPP-18652)					Ref. Pg 52 0f 318 (RPP-18652)	

Table 1, Continued

Farm	Pipe Number	Pipe Size (in)	Encasement Pipe Size (in)	Minimum Soil Cover to Centerline of pipe (ft)	Approx. Year of Installation	Heat Trace/ Insulation	Sand Cushion & Sand around the Pipe Line (Const. Spec. /Pipe Code Ref.)	Applicable Drawings
SY	SLL-3160	3 Sch 40S	6 Sch 40 Mod. 6 Std. Wt.	1.85	1998 MOD 1999	Insulated Detail 1, H-2-71994, Sh 3, Rev. 0 *Heat trace	W-058-C2/M9/ M26 W-314-C5/M9/ M26a	H-14-103335, Sh 2, Rev. 5 H-2-37706, Rev. 2 H-2-71994, Sh 1, Rev. 12 H-2-71994, Sh 3, Rev. 0 H-2-822210, Rev. 3 H-2-822211, Rev. 3 H-2-822301, Sh 1, Rev. 2
SY	SNL-3150	3 Sch 40S	6 Sch 40 Mod. 6 Std. Wt.	1.96	1998 MOD 1999	Insulated, Detail 1, H-2-71994, Sh 3, Rev. 0 *Heat trace	W-058-C2/M9/M26 W-314-C5/M9/M26	H-2-37706, Rev. 2 H-14-103267, Sh 1,Rev.1 H-14-103267, Sh14, Rev.1 H-2-82210, Sh 1, Rev. 3 H-2-82211, Sh 2, Rev. 3 H-2-822291, Sh 1, Rev. 2
		Ref. Pg 28 0f 318 (RPP-18652)					Ref. Pg 58 0f 318 (RPP-18652)	

* Heat trace does not exist; it has either been discontinued or there is no readily available documentation for heat tracing.

ATTACHMENT B

(Protection against Frost Heave, Article by Fine Gardening Magazine)

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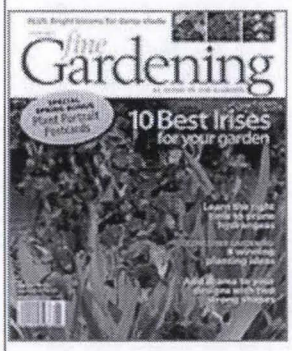

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***Fine Gardening* magazine**

Protecting against Frost Heave

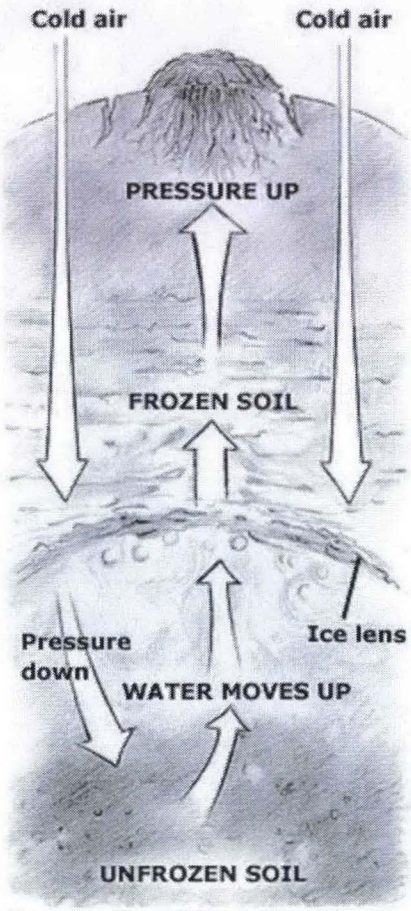
How alternating freezing and thawing wreaks havoc with plants, and what you can do about it

by Charles Smith

I believe that my garden is falling victim to frost heave. What, exactly, is frost heave and why does it happen? How do evergreen boughs protect plants from this?
— Christopher Eanes, Blairstown, Pennsylvania

Charles Smith responds: Frost heave happens when a fine-textured soil, such as a silty loam that has plentiful soil moisture, is subjected to freezing temperatures. The pressure created from alternating freezing and thawing lifts the soil, including the plants, up out of the ground. The result looks like a miniature earthquake has hit the garden, causing damage to both the plants and the soil.

For a frost heave to occur, cold air must migrate through the soil layers where there is an area of warmer soil deep beneath the surface and plenty of moisture in the soil. As the cold air sinks into the ground, it freezes the water in the soil into ice particles. The particles come together to form a layer of ice, called an ice lens, along the leading edge of the freezing zone. Additional moisture is also drawn upward from deeper soil layers, desiccating the soil below. This rising moisture freezes, expanding the ice lens even further while creating great pressure, both upward



Cross section of frost-heaved soil.

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Events

and downward.

The downward pressure damages the soil by compacting it while the upward pressure creates the frost heave that we see in the garden, thus damaging the soil structure by breaking down soil bonds, reducing soil aeration, and creating poor drainage. The soil around the heave often has deep cracks that expose a plant's roots to the killing cold. All of this causes trouble for plants, but the worst damage occurs when plant roots are lifted, or heaved, out of the soil. Without the protection of the soil, the exposed roots quickly dry out and die in the frigid air.

Frost heave most often occurs in the early spring and sometimes in late fall, when cold temperatures and abundant soil moisture are most often present. Heaves can happen in any type of soil, but some are prone to heaving more than others. Coarse, sandy soils drain so well that the moisture needed to produce heaves is rarely present. Soils that are moisture retentive, such as silt, loam, and clay, are much more prone to heaving.

An effective method to stop frost heave is to insulate the soil. That's where the evergreen boughs become useful. Placing evergreen boughs over the garden after the ground has frozen in fall will limit heaving by moderating temperature fluctuations and reducing the depth of frost penetration into the soil. Other types of mulches, such as pine bark or wood chips, help manage frost heaves but not as effectively or reliably as evergreen boughs and snow. As a general rule, a foot of snow on top of the ground reduces the depth of frost penetration into the soil by the same amount.

A little known tip about frost heaves is that heaving tends to start in depressions in the soil because they hold more moisture. So the first step is to rake out any low spots in the garden bed. Amending the soil with compost, which improves drainage in most soils, also helps reduce the chance of heaving.

Charles Smith, horticulturist and educator in Great Barrington, Massachusetts, is the author of *The Weather Resilient Garden.*

Drawing: Carol Ruzicka

From *Fine Gardening* #100, pp. 30-31
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ATTACHMENT C

(Excerpt from Design Guide for Frost Protection Shallow Foundations by National Association of Home Builders)

RPP-RPT-39400, REV. 0

HTML converted (roughly by John Cropper 19-apr-1996) from original located at "huduser.org:73" named Design Guide for Frost-Protected Shallow Foundations.

more information available from http://www.nahb.org/search.aspx?txtkeyword=frost

a better version of this current document in PDF is available HERE

U.S. Department of Housing and Urban Development

Office of Policy Development and Research

DESIGN GUIDE

FOR FROST-PROTECTED

SHALLOW FOUNDATIONS

DESIGN GUIDE FOR FROST-PROTECTED

RPP-RPT-39400, REV. 0

SHALLOW FOUNDATIONS

Prepared for:

U.S. Department of Housing and Urban Development

Office of Policy Development and Research

Prepared by:

NAHB Research Center

Upper Marlboro, MD

Instrument No. DU100K000005897

June 1994

Notice

The U.S. Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

The contents of this report are the views of the contractor and do not necessarily reflect the views or policies of the U.S. Department of Housing and Urban Development or the U.S. Government.

ACKNOWLEDGEMENTS

This report was prepared by the NAHB Research Center for the U.S. Department of Housing and Urban Development. Special appreciation is extended to NAHB members Bill Eich, Gerald Eid, Tim Duff, Jess Hall and their staffs, for constructing the five demonstration homes; Richard Morris, National Association of Home Builders, for initiating the technology transfer into the United States; Peter Steurer, National Oceanic and Atmospheric Administration, for providing and verifying proper methods of estimating long-term air-freezing indexes; Dow Chemical Company, Mid-America Molders, U.C. Industries, Inc., and Amoco Foam Products, for donation of insulation; and William Freeborne, U.S. Department of Housing and Urban Development, for guidance and review throughout the demonstration, testing, and development of this design guide for frost protection of shallow foundations.

In addition, the NAHB Research Center gives special recognition to The Society of the Plastics Industry, Inc., for several years of support that has helped to re-introduce this technology to the United States. Their sponsorship has promoted activities such as technology transfer from Europe, finite element computer modelling of heat transfer through foundations, development of design procedures for frost protection of foundations, formulation of important U.S. climate data for use in the design procedure, and initiating an interest in this technology at the level of the major U.S. building codes. These previous activities have contributed tremendously to this design

RPP-RPT-39400, REV. 0

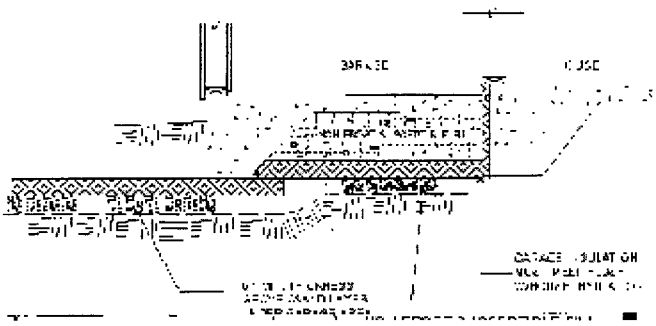

Figure 16. Insulation detail for a large unheated area (e.g. attached garage).

Common Questions and Answers

About Frost-Protected Shallow Foundations

A number of questions have been posed by building officials, builders, engineers, and others about frost-protected shallow foundations (FPSF). The most common questions and their answers are provided here to benefit those interested in this technology.

Question No. 1: How does insulation stop frost heave from occurring?

Frost heave can only occur when all of the following three conditions are present: 1) the soil is frost susceptible (large silt fraction), 2) sufficient moisture is available (soil is above approximately 80 percent saturation), and 3) sub-freezing temperatures are penetrating the soil. Removing one of these factors will negate the possibility of frost damage. Insulation as required in this design guide will prevent underlying soil from freezing (an inch of polystyrene insulation, R4.5, has an equivalent R-Value of about 4 feet of soil on average). The use of insulation is particularly effective on a building foundation for several reasons. First, heat loss is minimized while storing and directing heat into the foundation soil -- not out through the vertical face of the foundation wall. Second, horizontal insulation projecting outward will shed moisture away from the foundation further minimizing the risk of frost damage. Finally, because of the insulation, the frost line will rise as it approaches the foundation. Since frost heave forces act perpendicular to the frost line, heave forces, if present, will act in a horizontal direction and not upwards.

Question No. 2: Does the soil type or ground cover (e.g., snow) affect the amount of insulation required?

By design, the proposed insulation requirements are based on the worst-case ground condition of no snow or organic cover on the soil. Likewise, the recommended insulation will effectively prevent freezing of all frost-susceptible soils. Because of the heat absorbed (latent heat) during the freezing of water (phase change), increased amounts of soil water will tend to moderate the frost penetration or temperature change of the soil-water mass. Since soil water increases the heat capacity of the soil, it further increases the resistance to freezing by increasing the soil's "thermal

ATTACHMENT D

(Excerpt from Paper, "Discussion of Frost Heave and Pipeline Upheaval Buckling", Published in Canadian Geotechnical Journal, Vol 42, 2005)

RPP-RPT-39400 REV. 0

DISCUSSION / DISCUSSION

Discussion of "Frost heave and pipeline upheaval buckling"[1]

J.F. (Derick) Nixon and Åke L. Vebo

The Palmer and Williams paper addresses an important aspect of the design of northern pipelines, namely pipe stability with respect to uplift buckling. In a frost heaving environment, pipe stability with respect to uplift buckling can be dependent upon the vertical pipe displacements induced by frost heave and the stabilizing effect of the soil–pipe interaction. Palmer and Williams present a simplified criterion for the prediction of upheaval instability that helps to illustrate the issue but is overly conservative and should not, in general, be used for practical applications.

As correctly identified by Palmer and Williams, the driving axial forces causing upward displacement are dependent upon internal pressure and the temperature differential in the pipe wall. The Palmer and Williams analysis incorporates the following three major simplifications, however:

(1) The formulation of the differential equation assumes no axial movement and ignores the presence of the substantial axial force mobilized in the pipeline by that movement. Movement at a bend is acceptable as long as the movement is constrained by the soil. The axial force has a significant, stabilizing effect on the upheaval buckling behavior. It is initially due to the tangential soil–pipe interface friction (skin friction) mobilized along the pipe surface as the pipeline is displaced axially towards the potential upheaval location. Experience has shown that axial shear forces along the surface of a buried pipeline develop at quite small axial displacements. Additionally, the transverse upheaval displacement is generally large relative to the distance along the pipeline over which this displacement takes place, i.e., catenary or cable tension effect. The pipeline is therefore also subjected to large displacement extensions at the upheaval location, which contribute further to the stabilizing axial force mobilized in the pipeline with progressive upheaval displacement.

(2) A further simplification was introduced with the assumption that the upheaval deflection profile can be idealized as an arc of a circle with a constant curvature. The flexural rigidity of the pipeline was therefore ignored in the formulation of the instability criterion. The pipe is not bent to a uniform curvature for any significant length along the deflection profile. The varying curvature along the pipe mobilizes significant flexural forces due to the stiffness of the pipe segment, and these forces resist upward displacement.

(3) The instability criterion is presented in a closed form expression based on the assumption that the pipeline remains elastic for the upheaval displacement. It is well known that displacements of a pipeline subjected to upheaval buckling may be governed by strain criteria, and that the axial strains may typically extend into the nonlinear, plastic range. A criterion based on elastic behavior may therefore result in a severely restrictive limitation on the allowable displacement due to upheaval buckling.

The following example is presented to show that these points must all be taken into account for a realistic assessment of the potential for upheaval displacements. An insulated NPS 20 oil pipeline (diameter D = 508 mm, wall thickness t = 9.52 mm, and 25 mm insulation) was installed with a minimum cover depth of 1.2 m and backfilled with soil with a unit weight of 17.3 kN/m^3. It was designed for an internal pressure of 9930 kPa and has operated safely with a temperature differential of 65 °C for the past 12 years. It was installed using conventional construction practice with field overbends having a bend radius of 40D, i.e., a bend radius of 20.32 m, in compliance with the requirements of Canadian Standards Association (CSA) Z662. Recently, to establish the safe limit for a proposed increase of the operating temperature, overbend stability analyses similar to the numerical analysis described by Nixon and Burgess (1999) were carried out using CSA Z662 recommended limit states factors and strain-based design criteria. The results of the analyses showed that the overbends for this pipeline will remain stable for the combined loading from the specified design pressure and a temperature differential of 78 °C. For comparison, the stability of these overbends can also be assessed using the criterion proposed by Palmer and Williams. Substitution of the relevant values for this pipeline in eq. [14] shows that upheaval instability is predicted to occur for a curvature of 0.033 m^{-1}, which corresponds to a bend radius of 30.2 m, or 59D.

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[1]Appears in Canadian Geotechnical Journal, **40**: 1033–1038.
[2]Corresponding author (e-mail: derickn@nucleus.com).

 doi: 10.1139/T04-032 ATTACHD PG D-2 © 2005 NRC Canada

As noted previously, this pipeline has operated for the past 12 years under conditions that the Palmer and Williams model predicts pipe instability with respect to uplift buckling. The overly conservative nature of the proposed criterion is even more apparent when it is noted that the contribution to upheaval displacement from internal pressure is significantly less than that from the positive temperature differential for the aforementioned pipeline. Equation [14] assumes that the differential temperature is zero. Many buried pipelines operating in Canada do not satisfy the Palmer and Williams criterion for uplift stability.

It is noteworthy that the destabilizing forces have very different relative magnitudes for a small, relatively low pressure oil pipeline and a larger high pressure gas pipeline. For the smaller (0.324 m) diameter oil line, the axial forces due to temperature differential are significantly greater than the force due to a normal range of internal operating pressures. The reverse is true for a larger gas pipeline operating at higher pressures.

Two additional points should also be considered in assessing the stability of a pipeline with respect to uplift buckling. In the general case for cross-country pipelines, the terrain is undulating and pipelines include many overbends and sidebends. A more rigorous analysis of the uplift buckling phenomenon would recognize that many of the overbends and sagbends have the effect of relieving the axial load on the pipe within the virtual anchor length of those bends. Palmer and Williams conclude that "frost heave and upheaval can in some circumstances interact to threaten the integrity of Arctic pipelines." We note that loss of pipe stability with respect to upheaval (*i*) is not only an Arctic pipeline issue, (*ii*) does not depend on frost heave to initiate the loss of stability, and (*iii*) does not normally result in pipeline failure. On the Trans-Alaska Pipeline System (TAPS) fuel gas line, upheaval has taken place on several occasions while the pipeline was in service. Remediation was successfully carried out by excavating alongside the upheaval, laying the pipeline down in the excavation and covering it with granular and insulating material. The Norman Wells pipeline has also been successfully remediated by covering the KP 5.2 uplifted section with granular material. In no reported case of upheaval of an Arctic pipeline in North America has there been a loss of containment or an interruption of service.

With regard to the Norman Wells pipeline at KP 5.2, Palmer and Williams neglect to acknowledge a previous explanation of the same phenomenon by Nixon and Burgess (1999). In their referenced paper, previously published in this journal, Nixon and Burgess presented detailed results from the well-documented case history of an uplift event. Nixon and Burgess presented results of a more rigorous numerical analysis that indicates conditions under which differential frost heave might provide the initiating conditions for the loss of pipe stability from uplift buckling. The Nixon and Burgess paper is a previously documented analysis of the frost heave induced uplift buckling phenomenon that should have been reviewed by the authors.

References

Nixon, J., and Burgess, M. 1999. Norman Wells pipeline settlement and uplift movements. Canadian Geotechnical Journal, **36**: 119–135.

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ATTACHMENT E

(Analytical Calculations to determine Depth of Frost Penetration over the Buried Piping)

ANALYTICAL CALCULATIONS

Title: Determine Depth of Frost Penetration in Soil with Insulation over the Buried Piping
Originator: M. A. Haq Date: 5/11/09
Checker: Mark Scott Date: 5/11/09
Organizational Manager: M. A. Roberts Date: 5/11/09

1.0 Objective/Purpose:

The purpose of this calculation is to detemine the effect of frost penetration on soil in tank farms if the polyurethane foam insulation wrapped around the buried piping is take into account. The depth of frost penetration in soil with insulation over buried piping will be determined, and compared with the depth of frost penetration in soil if no insulation would have been present.

2.0 Results/Conclusions:

Depth of frost penetration in soil reduces from approximately 16" to almost 4", if 3" insulation over the buried piping is taken into account.

3.0 Input data:

See the body of the calculations.

4.0 Assumptions:

a). Density of soil in tank farms is assumed as 110 $\frac{lbf}{ft^3}$.

b). Latent heat of water of 144 BTU/lb, per Design Example 12-9c TM 5-852-5, Vol. 5, (Attach. G) has been used in the calculation. This is a conservative assumption, since the buried transfer line contains waste liquid which should have higher latent heat than water.

5. Method of Analysis:

The frost penetration depth, taking into account the 3 " insulation over the buried piping, and the frost penetration depth of soil without the insulation over buried piping, will be determined using the Stefan equation (Equation 12-6) from Technical Manual TM 5-852-5, Vol. 5 (Attach. H).

Design Example 12-9c, along with Tables 12-2 and 12-3 from the same manual, will be used to compuate the estimated depth of frost penetration.

Depth of Frost Penetration in Soil due to Insulation:

$\gamma_{soil} := 110$ — Density of soil or dry unit weight of soil in $\frac{lbf}{ft^3}$

$mc := .035$ — Moisture content (mc) in soil is 3 to 4% (see page 4, WHC-SD-WM-SOIL-001). Take this value as 3.5%

$K_2 := 0.8$ — Thermal conductivity of sand and gravel, with dry unit weight of soil as $110 \cdot \frac{lbf}{ft^3}$, and misture content as 3.5%, using Fig 2-2, TM 5-852-6,(Attach. H)

$K_1 := 0.014$ — Thermal conductivity of polyurethane foam insulation, Table 12-2

ANALYTICAL CALCULATIONS

Title: Determine Depth of Frost Penetration in Soil with Insulation over the Buried Piping
Originator: M. A. Haq Date: 5/11/09
Checker: Mark Scott Date: 5/11/09
Organizational Manager: M. A. Roberts Date: 5/11/09

$d_1 := 0.25$ Thickness of insulation (3") in feet

$I_a := 693$ Air freezing index for Richland, closest to Hanford site, per National Climatic Data Center (Attach. F)

$n := 0.9$ Factor for correlation of air temperature with surface temperature for sand and gravel per Table 12-3

$I_g := n \cdot I_a$ Ground surface freezing index per equation 12-10

$L_0 := 144$ Latent heat of water is 144 BTU/lb (Attach. G)

$L_2 := L_0 \cdot mc \cdot \gamma_{soil}$ Latent heat of soil

$L_2 = 554.4$

$$X_{Insulation} := \left[\sqrt{\left(\frac{K_2}{K_1} \cdot d_1\right)^2 + \frac{2 \cdot K_2 \cdot I_g}{L_2}} - \left(\frac{K_2}{K_1} - 1\right) \cdot d_1\right] \cdot ft$$

Depth of frost penetration, considering 3" insulation over piping

$X_{Insulation} = 3.754\,in$

Depth of Frost Penetration in Soil if there is no Insulation

$$X_{Soil} := \sqrt{\frac{2 \cdot K_2 \cdot I_g}{L_2}} \cdot ft$$

$X_{Soil} = 16.1\,in$

Depth of frost penetration in soil reduces from approximately 16" to almost 4" if 3" insulation over the buried piping is taken into account.

6.0 References:

1.0 NOAA, National Climatic Data Center (see Attach. F)
2.0 Technical Manual, TM 5-852-5/AFR 88-19, Joint Departments of the Army and
3.0 Air Forc USA, Arctic and Subarctic Construction Utilities (see Attach. G)
Technical Manual, TM 5-852-6/AFR 88-19, Joint Departments of the Army and Air Forc USA, Arctic and Subarctic Construction-Calculation Methods for Determination of Depths of Freeze and Thaw in Soils (see Attach. H)

Calculation Review Checklist.

Calculation Reviewed: Depth of Frost Penetration in soil with Insulation over the Buried Piping
Scope of Review: Entire Calculations
(e.g., document section or portion of calculation)
Engineer/Analyst: M. A. Haq Date: 5/11/09
Organizational Manager: M. A. Roberts Date: 5/11/09

This document consists of 4 pages and the following attachments (if applicable):
ATTACH. H: Excerpt from Technical Manual TM-852/6, Volume 6

Yes	No	NA*		
[x]	[ ]	[ ]	1.	Analytical and technical approaches and results are reasonable and appropriate.
[x]	[ ]	[ ]	2.	Necessary assumptions are reasonable, explicitly stated, and supported.
[x]	[ ]	[]	3.	Ensure calculations that use software include a paper printout, microfiche, CD-ROM, or other electronic file of the input data and identification to the computer codes and versions used, or provide alternate documentation to uniquely and clearly identify the exact coding and execution process.
[x]	[ ]	[ ]	4.	Input data were checked for consistency with original source information.
[x]	[ ]	[ ]	5.	Key input data (e.g., dimensions, performance characteristics) that may affect equipment design is identified.
[x]	[ ]	[ ]	6.	For both qualitative and quantitative data, uncertainties are recognized and discussed and the data is presented in a manner to minimize design interpretations.
[x]	[ ]	[ ]	7.	Mathematical derivations were checked, including dimensional consistency of results.
[x]	[ ]	[ ]	8.	Calculations are sufficiently detailed such that a technically qualified person can understand the analysis without requiring outside information.
[x]	[ ]	[]	9.	Software verification and validation are addressed adequately.
[x]	[ ]	[ ]	10.	Limits/criteria/guidelines applied to the analysis results are appropriate and referenced. Limits/criteria/guidelines were checked against references.
[x]	[ ]	[ ]	11.	Conclusions are consistent with analytical results and applicable limits.
[x]	[ ]	[ ]	12.	Results and conclusions address all points in the purpose.
[x]	[ ]	[ ]	13.	Referenced documents are retrievable or otherwise available.
[x]	[ ]	[ ]	14.	The version or revision of each reference is cited.
[x]	[ ]	[ ]	15.	The document was prepared in accordance with Attachment A, "Calculation Format and Preparation Instructions."
[]	[ ]	[x]	16.	Impacts on requirements have been assessed and change documentation initiated to incorporate revisions to affected documents, as appropriate.
[x]	[ ]	[ ]	17.	All checker comments have been dispositioned and the design media matches the calculations.

MA Scott 05/11/09
Checker (printed name and signature) Date

* If No or NA is chosen, an explanation must be provided on or attached to this form.

Item 16: No impact to requirements and no change documentation is required.

ATTACHMENT F

(Air Freezing Index Winter Season Values, Prepared by NOAA-National Climate Data Center)

RPP-RPT-37400
Rev0

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)

National Climatic Data Center
U.S. Department of Commerce

NCDC computer systems will be unavailable on Saturday, February 7, 2009 for building power upgrades. Please plan for this temporary outage.

DOC > NOAA > NESDIS > NCDC

Search Field: Search NCDC

Climatic Data for Frost Protected Shallow Foundations

Publications and Data

The 100-year return period of the Air Freezing Index (AFI) is available for 3,110 cities in the continental United States, Alaska, Hawaii, and Puerto Rico. These data can be interpolated from an AFI analyzed map or obtained from data tables (457K or 676K). The data table publication contains a listing of cities with the specific 100-year return period value located in the far right column. Other columns in the table contain lesser return periods and are listed for comparison purposes or other applications. Only the 100-year return period in this publication should be used for FPSF.

Another publication provides the 29 winter season values that were used to compute the 100-year return period of the AFI. Data tables (490K or 1622K) contain the AFI value for each of the 29 winter seasons from the 1951-80 period for 3,110 cities. These data are used for applications other than FPSF.

Finding a station: To find a station in the publications use the "Find" capability (binocular icon in PDF files; in Excel files, Click Edit and then Find) and enter a city or place name.

All cities do not have Air Freezing Index values located in these files. If your city is not available, you can locate a nearby city by using a station locator system called Web Cliserv.

1) Once in Web Cliserv first select the city you want but could not find like Cleveland.
2) Then choose one of the Cleveland stations, possibly Burke Lakefront.
3) Then under the station name Cleveland Burke Lakefront you will see other options such as:
   a) List stations in Cuyahoga County
   b) Surrounding Stations (+/-30 minutes)
4) Choose a and/or b to find nearby stations
5) See if one of these nearby stations has AFI values

Cautionary Note when using Air Freezing Index values: Topographic variability, proximity to bodies of water, and urban heat effects should be considered when using these data. For those locations or if the planned construction site is not located nearby a station that has AFI data, using a combination of the AFI map and the most representative city(s) AFI value(s) is advisable.

Air Freezing Index - Return Periods & Associated Probabilities
Air Freezing Index - Seasonal Data

ATTACH F, PG F-1

Air Freezing Index Winter Season Values - USA Method (Base 32 ^{0} Fahrenheit)

State and Station Name	Station Number	1951 -52	1952 -53	1953 -54	1954 -55	1955 -56	1956 -57	1957 -58	1958 -59	1959 -60	1960 -61	1961 -62	1962 -63	1963 -64	1964 -65	1965 -66	1966 -67	1967 -68	1968 -69	1969 -70	1970 71	1971 -72	1972 -73	1973 -74	1974 75	1975 76	1976 -77	1977 -78	1978 -79	1979 -80
Washington																														
NORTHPORT	455946	606	91	247	326	636	928	70	423	651	161	680	396	324	403	219	92	345	739	221	425	618	504	317	389	262	370	447	1032	333
OAKVILLE	456011	43	7	19	9	59	76	1	32	2	1	33	40	2	35	3	0	20	83	6	11	76	123	89	3	6	20	15	122	60
ODESSA	456039	505	90	252	211	556	627	7	115	319	166	268	272	128	327	98	28	135	652	236	267	493	397	375	399	263	600	265	1164	422
OLGA 2 SE	456096	35	0	48	21	58	79	0	36	9	0	28	29	0	51	1	0	15	136	1	15	67	68	12	8	9	2	10	56	31
OMAK 2 NW	456123	1000	144	393	576	1361	1029	77	537	702	316	664	374	579	533	486	72	439	1235	484	997	996	661	335	779	361	584	474	1303	576
OTHELLO 6 ESE	456215	540	120	249	160	560	624	42	106	376	170	180	280	109	348	85	23	122	899	157	176	379	359	399	172	108	370	198	944	430
PALMER 3 ESE	456295	61	1	52	21	98	102	0	57	22	0	57	56	0	72	6	0	21	172	15	31	81	135	84	20	13	20	26	131	68
POMEROY	456610	223	103	96	49	295	443	25	96	352	131	185	298	75	121	51	2	105	448	93	57	227	313	328	72	39	181	135	664	191
PORT ANGELES	456624	15	0	23	15	52	41	0	31	3	0	20	16	0	35	0	0	8	92	0	4	38	39	5	2	2	0	15	51	26
PROSSER 4 NE	456768	362	91	200	56	472	516	25	114	331	157	141	239	78	214	49	1	83	559	135	129	226	311	331	99	47	335	175	765	356
PULLMAN 2 NW	456789	403	77	149	325	532	631	40	91	321	123	305	327	113	242	149	15	159	598	159	198	375	410	365	296	92	298	174	1033	303
PUYALLUP 2 W EXP STA	456803	38	14	27	12	78	83	1	36	3	7	55	40	2	36	7	0	13	65	7	32	102	85	53	2	5	25	14	103	44
QUILCENE 2 SW	456846	21	11	28	16	68	91	2	39	8	3	32	27	3	39	7	1	18	125	5	12	72	89	56	2	6	26	22	118	38
QUINCY 1 S	456880	840	143	337	343	1122	979	72	219	448	252	337	328	333	484	357	19	240	980	277	594	620	386	356	394	199	364	183	949	474
RAINIER PARADISE RS //	456898	1053	371	657	856	1279	637	241	650	715	241	767	334	607	688	777	723	538	1198	649	1024	1119	871	982	1061	786	303	630	1281	677
REPUBLIC	456974	1023	362	629	1015	1639	1475	365	923	1193	626	1181	578	816	861	602	218	762	1394	792	993	1215	912	709	888	712	922	876	1600	773
RICHLAND	457015	213	65	128	14	247	423	8	76	238	61	109	181	40	168	23	0	79	367	55	86	205	267	279	55	23	169	120	693	180
RITZVILLE 1 SSE	457059	568	140	282	313	702	780	60	136	408	181	340	364	167	356	132	21	161	734	228	328	513	406	380	345	117	487	213	1112	386
ROSALIA	457180	580	115	219	280	670	663	68	91	334	167	345	392	122	243	109	14	187	794	290	279	466	367	377	387	75	380	222	1227	359
SEATTLE-TACOMA WSO	457473	43	12	35	21	78	71	0	31	4	2	33	39	0	42	0	0	2	77	0	9	62	62	30	3	5	2	5	51	34
SEATTLE U OF W	457478	21	0	17	9	56	40	0	21	4	0	25	23	0	41	0	0	4	75	0	7	59	58	17	0	2	2	4	47	28
SEDRO WOOLLEY	457507	59	15	67	22	79	146	0	36	13	2	44	56	2	48	6	0	19	148	1	27	89	95	40	7	7	8	12	110	38
SEQUIM	457538	24	0	24	9	71	33	0	34	6	0	16	23	0	36	1	0	11	101	0	6	51	54	15	1	4	1	18	97	36
SHELTON	457584	32	0	23	3	59	55	0	34	3	1	39	35	0	32	0	1	11	75	3	13	84	80	61	2	2	13	7	89	37
SNOQUALMIE FALLS	457773	53	19	40	23	80	109	2	36	7	3	46	36	5	51	9	0	16	110	0	25	75	96	67	5	11	32	17	70	41
SPOKANE WSO //	457938	642	157	260	412	769	779	79	185	616	241	570	456	350	474	221	43	291	960	320	311	623	391	394	558	256	463	381	1339	393
SPRAGUE	457956	605	136	284	268	670	701	60	88	332	187	381	330	135	254	167	33	229	796	234	259	573	351	372	491	225	540	223	1248	468
STAMPEDE PASS WSO //	458009	980	501	677	965	1372	890	293	662	865	564	731	429	602	740	699	350	495	1202	551	831	812	755	816	644	580	268	659	1146	810
STARTUP 1 E	458034	30	2	32	20	76	92	0	38	6	1	41	38	2	52	2	0	13	81	0	16	81	88	53	3	7	16	15	59	41
STEHEKIN 3 NW	458059	446	31	179	177	394	303	18	91	83	72	179	235	27	317	229	28	155	706	157	287	350	371	226	164	156	220	249	842	388
SUNNYSIDE	458207	273	70	156	32	377	477	11	103	279	147	135	250	63	276	45	4	68	448	109	119	206	278	327	57	27	250	143	700	298
TACOMA CITY HALL	458286	24	3	14	8	55	40	0	25	0	0	22	27	0	35	1	0	7	64	0	7	46	61	19	0	0	5	2	57	22
VANCOUVER 4 NNE	458773	38	5	12	0	56	119	0	32	9	2	41	41	0	53	4	0	14	68	6	22	70	138	125	4	8	52	17	208	63
WALLA-WALLA FAA AP	458928	212	103	126	44	302	446	42	99	280	113	169	215	62	108	31	3	97	427	63	50	266	331	351	84	37	223	142	548	155
WALLA WALLA WSO	458931	186	90	122	39	285	415	34	95	246	89	145	191	52	114	32	2	82	373	57	42	234	298	294	73	31	202	143	598	156
WAPATO	458959	387	74	171	26	467	479	7	91	269	148	125	234	69	264	53	14	74	453	91	133	213	260	311	58	27	225	138	673	291
WATERVILLE	459012	1003	376	437	723	1466	1144	176	682	576	549	789	471	669	724	646	43	486	1277	597	689	981	720	526	616	575	680	640	1353	692
WENATCHEE	459074	663	50	287	125	806	639	23	123	253	181	307	255	69	304	245	4	113	744	146	340	511	285	252	125	49	178	131	662	326
WILBUR	459238	530	102	243	420	839	937	63	277	415	161	513	359	335	398	318	92	308	1036	297	524	823	524	350	621	325	607	447	1314	548
WILLAPA HARBOR	459291	14	1	6	1	43	32	0	19	0	0	21	18	0	25	1	0	2	47	0	4	26	79	37	0	0	7	9	44	22
WILSON CREEK	459327	637	101	280	188	683	778	46	149	397	213	375	335	164	372	181	25	205	788	172	392	611	360	345	292	221	422	230	1123	412
WINTHROP 1 WSW	459376	1338	416	750	1147	1826	1560	443	1078	989	912	1111	583	941	983	1074	334	850	1687	962	1197	1359	1078	872	974	874	822	779	1584	966
YAKIMA WSO //	459465	558	83	255	109	811	629	35	117	356	220	178	293	104	361	188	21	101	709	133	226	348	324	361	133	38	341	160	857	385
West Virginia																														
ATHENS CONCORD COLLEGE	460355	64	36	52	164	163	99	371	167	306	278	148	379	287	120	322	89	301	230	360	274	74	107	66	49	116	537	543	319	190
BAYARD	460527	177	98	238	538	500	247	662	552	575	754	361	832	665	319	472	455	889	772	631	537	279	271	132	255	403	1074	1081	720	480
BECKLEY V A HOSPITAL	460580	85	34	73	210	263	121	379	304	344	406	166	502	371	140	347	154	419	274	427	315	103	137	80	77	226	858	744	468	260
BLUESTONE DAM	460939	57	22	54	138	164	88	300	205	226	337	127	443	278	130	275	108	343	215	284	225	70	95	61	43	146	627	571	349	197

Footnote:

Winter season based upon the August 1 through July 31 period

Prepared by NOAA - National Climatic Data Center

ATTACH F, PG F-2

RPP-RPT-39400 Rev0

ATTACHMENT G

(Excerpts from Technical Manual, TM-852/5, Volume 5,
Pertaining to Computing Frost Penetration)

RPP-RPT-39400, R0

Table 12-2. Thermal conductivities of common materials

Material	Unit Weight (dry) lb/ft³	Specific Heat Capacity	BTU/ft·h·°F
Air, no convection (32°)		0.24	0.014
Air film, outside, 15 miles·hr wind (per air film)			0.50
Air film, outside (per air film)			0.14
Polyurethane foam	2	0.4	0.014
Polystyrene foam	1.9	0.3	0.020
Rock wool, glass wool	3.4	0.2	0.023
Snow, new, loose	5.3	0.5	0.05
Snow, on ground	19	0.5	0.13
Snow, drifted and compacted	31	0.5	0.4
Ice at -40°F	56	0.5	1.54
Ice at 32°F	56	0.5	1.28
Water at 32°F	62.4	1.0	0.34
Peat, dry	16	0.5	0.04
Peat, thawed, 80% moisture	16	0.32	0.08
Peat, frozen, 80% ice	16	0.22	1.0
Peat, pressed, moist	71	0.4	0.40
Clay, dry	106	0.22	0.5
Clay, thawed, saturated (20%)	106	0.42	1.0
Clay, frozen, saturated (20%)	106	0.32	1.2
Sand, dry	125	0.19	0.06
Sand, thawed, saturated (10%)	125	0.29	1.9
Sand, frozen, saturated (10%)	125	0.24	2.4
Rock typical	156	0.20	1.3
Wood, plywood, dry	37	0.65	0.10
Wood, fir or pine, dry	31	0.6	0.07
Wood, maple or oak, dry	44	0.5	0.10
Insulating concrete (varies)	12 to 94		0.04 to 0.35
Concrete	156	0.16	1.0
Asphalt	156		0.42
Polyethelene, high density	59	0.54	0.21
PVC	87	0.25	0.11
Asbestos cement	119		0.38
Wood stave (varies)	—		0.15
Steel	486	0.12	25
Ductile iron	468		30
Aluminum	169	0.21	115
Copper	550	0.1	220

(1) Values are representative of materials but most materials have variable properties.

ATTACH G, PG G-2

RPP-RPT-39400, R0

solutions, such as assuming a step change in surface temperature or neglecting the soil temperature changes, they generally overestimate the maximum freezing isotherm depths for the given conditions and are, therefore, conservative for engineering applications. They are generally Neumann or Stefan-based solutions which have the basic form:

$$X = m(I_g)^{1/2} \qquad \text{(eq 12-3)}$$

where

X = depth of freezing or thawing, feet

m = coefficient of proportionality

I_g = ground surface freezing (I_f) or thawing (I_t) index, °F•hr

The following equations incorporate various assumptions, and are useful for specific conditions:

$$X = \left(\frac{2k \cdot I_g}{L} \right)^{1/2} \qquad \text{(eq 12-4)}$$

$$X = \left(\frac{2k \cdot I_g}{L + C\left(T_m - T_o + \frac{I_g}{2_t} \right)} \right)^{1/2} \qquad \text{(eq 12-5)}$$

$$X = \left(\left(\frac{k_2}{k_1} d_1 \right)^2 + \frac{2k_2 \cdot I_g - \frac{d_1^2 \cdot L_1}{2k_1}}{L_2} \right)^{1/2} - \left(\frac{K_2 - 1}{K_1} \right) (d_1) \qquad \text{(eq 12-6)}$$

$$X = \left(\frac{2k \cdot I_g}{L} \right)^{1/2} \left(1 - \frac{C \cdot I_g}{8L \cdot t} \right) \qquad \text{(eq 12-7)}$$

$$X = \lambda \left(\frac{2k \cdot I_g}{L} \right)^{1/2} \qquad \text{(eq 12-8)}$$

where

k = thermal conductivity of the material above the freezing isotherm, k_f for frost penetration and k_t for thawing calculations, BTU/hr•ft•°F.

L = volumetric latent heat of the material undergoing phase change, BTU/cf (for water L = [(144 BTU/lb) (62.4 pcf)] = 8986 BTU/cf)

C = volumetric heat capacity of the material above the freezing isotherm, C_f or C_1. For thawed soil: $C_t = \gamma\ [\ C_s + C_w (w/100)\ ]$ and for frozen soil: $C_f = \gamma[\ C_s + C_i(w/100)]$

γ = dry unit weight of soil, pcf

C_s = mass heat capacity of mineral matter in soil; assume a value of 0.2 BTU/lb

C_w = mass heat capacity of water = 1.0 BTU/lb

C_i = mass heat capacity of ice, assumed value of 0.5 BTU/lb

w = moisture content of soil, %

T_m = mean annual site temperature, °F

t = freezing or thawing period, consistent units

T_o = freezing point, 32°F for water

d = thickness of layer of material, feet

λ = a correction coefficient which takes into consideration the effect of temperature change in the soil, and primarily accounts for the volumetric specific heat effects. It is a function of two parameters. the thermal ratio (a) and the fusion parameter (μ), and is determined from figure 12-11:

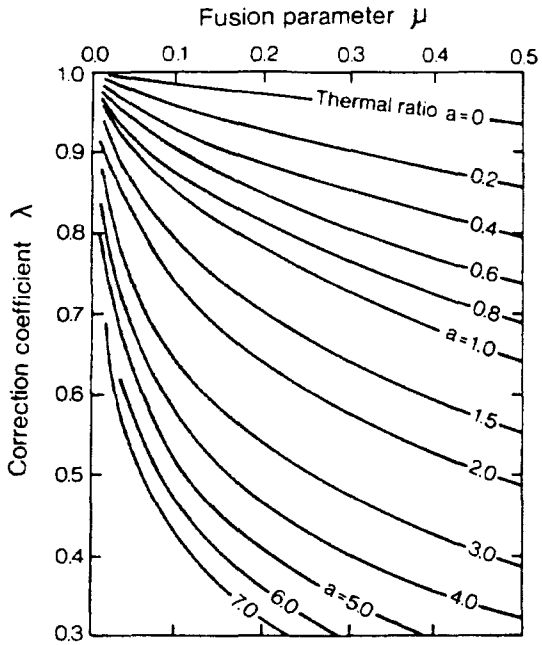
$$a = \frac{(T_m - T_o)}{T_m} = \frac{(T_m - T_o) \cdot t}{I_g}$$

$$\mu = \frac{C \cdot I_g}{L \cdot t}$$

T_s = I_g/t, surface freezing or thawing index divided by the time period t, °F.

Subscripts f and t refer to freezing and thawing, and subscripts 1 and 2 refer to the surface layer and the underlying material (all symbols are also defined in table 12-1).

ATTACH G, PG G-3



U.S. Army Corps of Engineers

Figure 12-11. Correction coefficient λ, for use in Berggren equation.

(1) Equation 12-4 is the Stefan solution for a homogeneous material with a step change in surface temperature (see example 12-9a). This is modified in equation 12-5 to account for the temperature change in the freezing or thawing soil. Equation 12-6 is a two-layer solution of the Stefan equation that is useful for calculations involving snow cover, a gravel pad or a board of thermal insulation, in which the surface layer has no latent heat and the equation is simplified (see para 12-9*b* and *c*). Equation 12-7 is a close approximation of the Neumann solution when the ground temperatures are near freezing. Equation 12-8, the modified Berggren equation, is perhaps the most commonly used approach for determining thermal responses of soils. When the soil has a high moisture content the *X* coefficient approaches unity, and the equation is identical to the Stefan approach (equation 12-4). In climates where the mean annual temperature is near or below freezing, the thermal ratio approaches zero and the *[A]* coefficient is greater than 0.9. In very dry soils, the soil warming or cooling can be significant and should be included. Multilayered soil systems can be solved by determining that portion of the surface freezing or thawing index required to penetrate each layer. The sum of the thicknesses of the frozen or thawed layers whose indices equal the total index is equal to the depth of freeze or thaw. The partial freezing or thawing index to penetrate the nth layer is

$$I_n = \frac{L_n \cdot d_n}{\lambda^2} \sum_{1}^{n-1} R + \frac{R_n}{2} \qquad \text{(eq 12-9)}$$

where

I_n = the partial freezing or thawing index required to penetrate the nth layer, °F•hr

L_n = volumetric latent heat in the nth layer, BTU/ft^3

d^n = thickness of the nth layer, ft

λ = the coefficient based on the weighted average values for μ down to and including the nth layer (see figure 12-13)

$\sum_{1}^{n-1} R + \frac{R_n}{2}$ = **the sum of the thermal resistances of the layers above the nth layer**

R_n = d_n/k_n, the thermal resistance to the nth layer, hr • ft • °F/BTU.

(2) The solution for multi-layered systems is facilitated by tabular arrangement of the intermediate values. The penetration into the last layer must be solved by trial and error to match the total freezing or thawing index at the site. It is necessary to determine the temperature condition at the ground surface to determine subsurface thermal effects, including the depth of freezing and thawing. Since air temperatures are readily available, but surface temperatures are not, a correlation factor which combines the effects of radiation, and convective and conductive heat exchange at the air-ground surface is used:

$$I_g = n \cdot I_a \qquad \text{(eq 12-10)}$$

where

I_g = ground surface freezing or thawing index, °F • hr

I_a = air freezing or thawing index, °F • hr

n = n-factor, ratio of the surface and air temperature indices.

The n-factor is very significant in analytical ground thermal considerations. It is highly variable and is usually estimated from published observations such as the values listed in Table 12-3.

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Table 12-3. Typical values of the n-factor for correlation of air temperature with surface temperature of various materials (see eq 12-10).

Surface	n-factors Thawing	n-factors Freezing	
Snow	.....	1.0	General application
Pavement free of snow and ice	.....	0.9	General application
Sand and gravel	2.0	0.9	General application
Turf	1.0	0.5	General application
Spruce	0.35 to 0.53	0.55 to 0.9	Thompson, Manitoba
Spruce trees, brush	0.37 to 0.41	0.28	Fairbanks, Alaska
Above site, cleared, moss surface	0.73 to 0.78	0.25	Fairbanks, Alaska
Stripped, mineral soil surface	1.72 to 1.26	0.33	Fairbanks, Alaska
Spruce	0.76	.....	Inuvik, NWT
Willows	0.82	.....	Inuvik, NWT
Weeds	0.86	.....	Inuvik, NWT
Gravel fill slope	1.38	0.7	Fairbanks, Alaska
Gravel road	1.99	.....	Fairbanks, Alaska
Concrete road	2.03	.....	Fairbanks, Alaska
Asphalt road	1.74 to 2.70	.....	Fairbanks, Alaska
White painted surface	0.76 to 1.25	.....	Fairbanks, Alaska
Peat bales on road	1.44 to 2.28	.....	Fairbanks, Alaska
Dark gravel	1.15 to 1.73	.....	Fairbanks, Alaska

(3) Ice thickness on water bodies can be estimated from the previous depth of freezing equations or from equations 12-3 with the m values in table 12-4 (see example 12-9a). Snow cover has a significant insulting effect and can significantly reduce the maximum ice thickness (see example 12-9b). The ice formation can be greater than calculted if the weight of snow or the lowering of the water level causes cracks in the ice and water overflows onto the surface. This water is drawn into the snow and the mixture refreezes and bonds to the original ice.

Table 12-4. m-factors for ice thickness estimation

m-factor inch [°F·d] $^{1/2}$	Conditions
0.9 - 0.95	Practical maximum for ice not covered with snow
0.8	Windy lakes with no snow
0.7 - 0.8	Medium-sized lakes with moderate snow cover
0.6 - 0.65	Rivers with moderate flow
0.4 - 0.5	River with snow
0.2 - 0.4	Small river with rapid flow

12-9. Design examples.

Eight typical examples are given below to illustrate the utilization of the calculation procedures described above.

a. Estimate the practical maximum ice thickness on a water reservoir with no snow cover when the annual air freezing index (I_g) is 3000 °F • d. Use equation 12-3:

$$x = m(I_g)^{1/2}$$

—From table 12-4, m = 0.95 inch/(°F)½(d)½

$$x = (0.95)(3000)^{1/2}$$
$$= 52 \text{ inches}$$
$$= 4.33 \text{ feet.}$$

—The Stefan equation (equation 12-4) can also be used:

$$x = \left(\frac{(2k)(I_g)}{L} \right)^{1/2}$$

where

k = thermal conductivity of material above the freezing isotherm, ice in this case, so from table 12-2:

$$k_{ice} = 1.28 \text{ BTU/ft} \cdot \text{hr} \cdot {}^\circ\text{F}$$

L = volumetric latent heat of material undergoing phase change, in this case water, so:
Latent heat of water at 32 °F = 144 BTU/lb
Density of water at 32 °F = 62.4 lb/ft^3

L = (144 BTU/lb)(62.4 lb/ft^3) = 8985.6 BTU/ft^3

I_g = (3000 °F • d)(24 hr/day) = 72,000 °F • hr

$$X = \left[\frac{(2)(1.28 \text{ BTU/ft} \cdot \text{hr} \cdot {}^\circ\text{F} \cdot \text{hr})(72{,}000\ {}^\circ\text{F} \cdot \text{hr})}{8986 \text{ BTU/ft}^3} \right]^{1/2}$$

$$= 4.5 \text{ ft.}$$

ATTACH G, PG. G-5

b. Estimate the ice thickness on the reservoir when there is an 8-inch snow cover on top of the ice and $I_g = 3000$ °F • d.

—From equation 12-3, and Table 12-4:

$$\begin{aligned} X &= m(Ig)^{1/2} \\ &= 0.7(3000)^{1/2} \\ &= 38 \text{ inches} \\ &= 3.2 \text{ ft.} \end{aligned}$$

—Or, use the Stefan equation (equation 12-6) for a two-layer system:

$$X = \left[\left(\frac{k_2}{k_1} d_1\right)^2 + \frac{(2k_2)(I_g) - \frac{(d_1)^2(L_1)}{2k_1}}{L_2} \right]^{1/2} - \left(\frac{k_2}{k_1} - 1\right)(d_1)$$

—The first layer is snow, $d_1 = 8$ inches = 0.667 feet, assumed to be drifted and compact. From table 12-2, $k_1 = 0.4$ BTU/ft • hr • °F. Since no phase change occurs in the snow, $L_1 = 0$.

—Ice: $k_2 = 1.28$ BTU/ft • hr • °F

$L_2 = (144)(62.4) = 8986$ BTU/ft^3

$$X = \left[\left[\left(\frac{1.28}{0.4}\right)(0.667)\right]^2 + \frac{2(1.28)\cdot(3000)(24)}{8986} \right]^{1/2} - \left(\frac{1.28}{0.4} - 1\right)(0.667)$$

$$= \sqrt{4.55+20.5} - 1.47$$

= 3.5 ft (includes the 8 in. of snow).

c. The Stefan equation (equation 12-6) can also be used to estimate the depth of frost penetration beneath a gravel pad or an insulation board. The L_1 in either case would be zero. The L_2 in this example would be the latent heat of fusion for the soil and would be dependent on the moisture content in the soil.

—Assume: sandy soil, dry density 125 pcf, moisture content 6% and a freezing index (I_g) = 3000 °F • d

—Find depth of frost penetration under 3-inch-thick polystyrene board. From table 12-2:
$k_1 = 0.020$ BTU/ft • °F • hr (for polystyrene),
$k_2 = 1.0$ BTU/ft • °F • hr (for sand) and thus
$d_1 = 3/12 = 0.25$ feet. The moisture content in the soil = (0.06)(125 pcf) = 7.5 lb water/ft^3 soil.

Latent heat of water = 144 BTU/lb

L_2 = (144 BTU/lb)(7.5 lb/ft^3) = 1080 BTU/ft^3 of soil

$L_1 = 0$

$$X = \left[\left(\frac{k_2}{k_1} d_1\right)^2 + \frac{2k_2 I_g}{L_2} \right]^{1/2} - \left(\frac{k_2}{k_1} - 1\right)(d_1)$$

$$X = \left[\left[\left(\frac{1.00}{0.020}\right)(0.25)\right]^2 + \frac{(2)(1.00)(3000)(24)}{1080} \right]^{1/2} - \left(\frac{1.00}{0.020} - 1\right)(0.25).$$

$$= \sqrt{156+133} - 12.25$$

= 4.75 ft.

—The depth of frost penetration would be 11.5 feet in the same soil, under the same conditions, if the insulation board were not in place.

d. Determine the rate of heat loss per linear foot of above-ground pipe from a 5-inch-ID (wall thickness ½ inch) plastic pipe encased in a 2-inch thickness of polyurethane insulation. Water inside the pipe is maintained at 40°F, ambient air temperature is -40°F, and wind speed is 15 mph. Thermal conductivity of pipe material is 0.208BTU/°F • ft • hr and thermal conductivity q of the insulation material is 0.0133 BTU/°F • ft • hr.

— Use equations a and b from figure 12-4:

Thermal resistance of pipe $R_p = \dfrac{\ln(r_{out}/r_{in})}{(2)(\pi)(k_p)}$

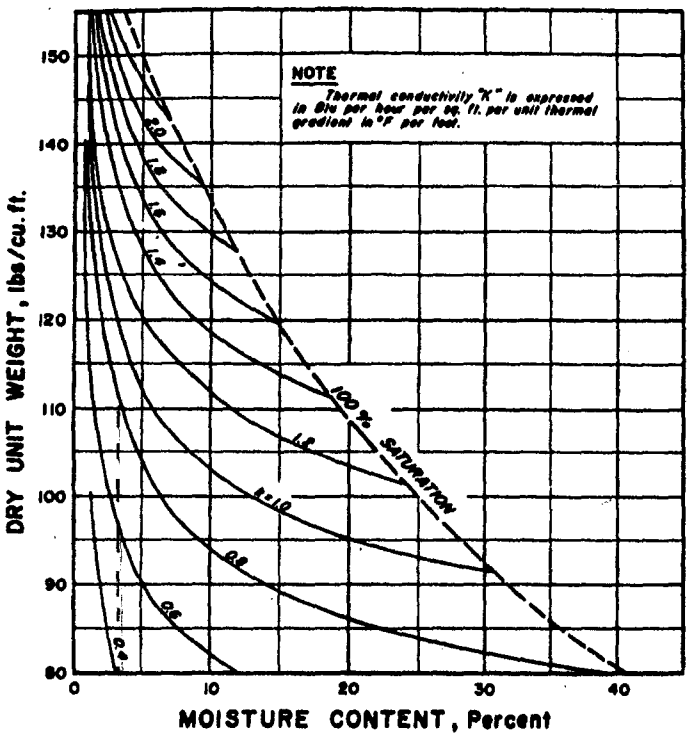
Inside radius = r_{in} = 2.5 inch

Outside radius = r_{out} = 2.5 + 0.5 = 3.0 inch

ATTACHMENT H

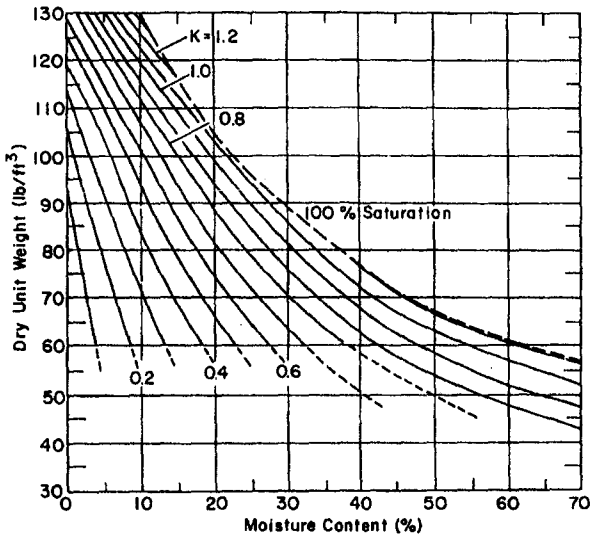
(Excerpt from Technical Manual, TM-852/6, Volume 6,
Thermal Conductivity of Sandy and Gravel Soil)

RDP-RPT-39400, R0



(U.S. Army Corps of Engineers)

Figure 2-2. Average thermal conductivity for sands and gravels, unfrozen.



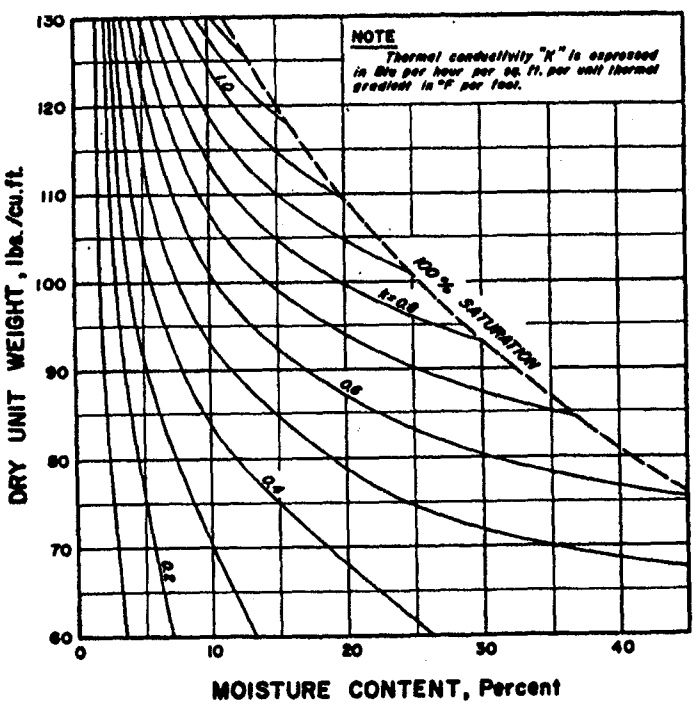
γ_d	w 90	w 120	w 100% saturated
50	N/A	N/A	1.20
40	1.00	N/A	1.23
30		0.98	1.26
20		0.61	1.26
pure ice			1.26

Thermal conductivity K is expressed in Btu per hour per square foot per unit thermal gradient in °F per foot.

Dashed line represents extrapolation.

(U.S. Army Corps of Engineers)

Figure 2-3. Average thermal conductivity for silt and clay soils, frozen.



(U.S. Army Corps of Engineers)

Figure 2-4. Average thermal conductivity for silt and clay soils, unfrozen.

ATTACH H, PG. H-2