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THE APPLICATION OF HEAT PIPES ON THE TRANS-ALASKA PIPELINE

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The application of heat pipes on the Trans Alaska Pipeline is reviewed. The subjects addressed include the general functioning of a heat pipe, the specific heat pipe design used, the different situations where heat pipes were employed, the methods used to develop the heat pipe design, the methods used to monitor the operating heat pipes, and the performance of the heat pipes. The discussion is qualitative in nature. Quantitative information is largely omitted to allow coverage of a broad area, and because it may be considered proprietary. Nevertheless, the information presented here should give a good appreciation of the

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quality and complexity of the heat pipe design. The information should also be useful in developing heat pipes for use in other cold regions applications.

Preface

This report was prepared by Christopher E. Heuer, while on temporary duty at the U.S. Army Cold Regions Research and Engineering Laboratory, in partial fulfillment of his obligations as a 1st Lieutenant in the U.S. Army Inactive Reserve.

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FOREWORD

During design and construction of the Trans Alaska Pipeline, literally mountains of paper were generated. However, little of the technical documentation has been made available to the public. The team of engineers brought together for the pipeline has now been largely disbanded so few additional disclosures are likely. With the lack of public information, it will be difficult for lessons learned on the pipeline to be applied to other projects.

This paper was written to help engineers interested in heat pipes. It is more historical than technical and can not be used for design. Rather, it will help an engineer decide if heat pipes might be used to solve his problems, and if so, what the design effort might involve.

The paper is based on the author's experience on the pipeline. He was associated with the pipeline for approximately five years, from 1973 to 1978, with slightly more than the last two years spent in Alaska. From 1973 to 1975 he worked for Exxon Production Research Company, and from 1975 to 1978 for Alyeska Pipeline Service Company. During this time, he worked on thermal problems arising during design and construction.

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To Obtain
inch	25.4	millimeter
foot	0.3048	meter
watt/ft	3.2808	watt/meter
degrees Fahrenheit	$t_{°C} = (t_{°F}-32)/1.8$	Degrees Celsius

THE APPLICATION OF HEAT PIPES ON THE TRANS-ALASKA PIPELINE

Introduction

Because of its size and the problems solved, the Trans Alaska Pipeline is a unique project. It is really several different projects: the pipeline itself, twelve pump stations, a tanker terminal, a communications system, a network of roads and airfields, and a series of construction camps. Problems arose from several sources: the remote undeveloped location, severe weather, permafrost, earthquakes, mountainous terrain, numerous stream crossings, increased public awareness, emphasis on environmental impact, and extensive government review.

The design philosophy was to make the pipeline as close as possible to being fail-safe using the best state-of-the-art technology. This required a flexible, multi-disciplinary approach. Extensive laboratory tests, field tests, and computer simulations were conducted to develop the new technology needed. Engineers from many different disciplines including geotechnical, structural, and thermal worked closely together to develop the design.

Due to the wide variation in soil conditions, it was necessary for the engineering effort to continue until construction was completed. The different types of problems encountered were generally foreseen before construction, but it was not always possible to predict exactly where these problems would occur. During construction, site specific conditions were reviewed in the field; these conditions were compared with those originally assumed in design, and if necessary, the design was modifed. In most cases, design modifications were accomplished using previously developed procedures. Some situations did require significantly different designs. Therefore, design tools had to be readily adaptable to site specific conditions.

Where possible, soil thermal problems were avoided by judicious route selection and mode selection. Mode selection refers to the different schemes used to bury and elevate the pipeline. Where thermal problems could not be avoided, heat pipes, insulation, and mechanical refrigeration were used. Heat pipes and insulation were widely used because they are passive and simple. Refrigeration is relatively complicated and requires a power source. However, it also has greater cooling capability. Therefore refrigeration was used wherever heat pipes and insulation were not adequate.

The use of insulation and refrigeration represents relatively well established technology. But the use of heat pipes in geotechnical applications is relatively new. The application of heat pipes on the Trans Alaska Pipeline is the subject of this paper.

Heat Pipes and Radiators

About 120,000 heat pipes were installed along the Trans Alaska Pipeline. The heat pipes were used to provide additional ground cooling during the winter. The pipeline is not the first project where heat pipes have been used in this manner; however, it is by far the largest. The heat pipes used on the pipeline were specially designed for the project.

A heat pipe is a closed metal tube which transfers heat by natural convection with gas-liquid change of phase. Since natural convection is involved, heat transfer is in only one direction, and since change of phase is involved, heat transfer is efficient even at very low temperature differences. A heat pipe has no moving parts and requires no external power. It is therefore ideal for remote applications such as the pipeline.

To provide ground cooling, a heat pipe is placed vertically in the ground. The aboveground portion of the heat pipe is referred to as the condenser section and the belowground portion as the evaporator section. This terminology is based on the operating cycle described below.

During the summer, the heat pipe does not operate. Most of the working fluid is in a liquid pool at the bottom of the heat pipe. The rest of the heat pipe is filled with working fluid gas. The temperature of the liquid pool equals the local ground temperature. The pressure of the gas is the saturation pressure (the pressure at which gas and liquid phases are in equilibrium) corresponding to the temperature of the liquid. The temperature of the gas in the aboveground portion of the heat pipe is equal to the air temperature. Since the air temperature is greater than the soil temperature and greater than the saturation temperature of the gas, no condensation occurs. There is no mass transfer and no heat transfer within the heat pipe.

During the winter, the air temperature is colder than the ground temperature. As the temperature of the aboveground portion of the heat pipe falls below the saturation temperature of the gas, some of the gas condenses releasing heat to the atmosphere and forming a liquid film which flows down the pipe wall. Simultaneously, the condensation creates a vertical pressure gradient and lowers the gas pressure below the saturation pressure of the liquid pool at the bottom of the heat pipe. Some of the liquid evaporates, absorbing heat from the soil. Some of the liquid film also evaporates as it flows along the belowground portion of the heat pipe. As evaporation occurs, the gas flows upward and again condenses on the aboveground portion of the heat pipe. Thus a natural convection cycle is established which absorbs heat from the soil and rejects it to the atmosphere as long as the air temperature is colder than the soil temperature. Laboratory tests on the heat pipes used on the pipeline demonstrated that the cycle can be established in less than an hour and requires a temperature difference between the evaporator and condenser sections of only a fraction of a degree to operate.

The working fluid for a heat pipe must be carefully chosen. The range of temperatures and pressures encountered must fall within the two-phase region of the fluid so the evaporation and condensation can occur. To maximize heat transfer, the fluid should have a high latent heat of vaporization, a high liquid thermal conductivity, a high liquid density, and a low liquid viscosity. Increasing the latent heat increases the heat transfer rate for a given mass flow rate. Increasing the liquid density and conductivity and decreasing the liquid viscosity decrease the thickness and thermal resistance of the liquid film. The liquid film controls the heat transfer rate inside the heat pipe. Gas properties are not as important because the gas flow rate can easily increase to accommodate higher heat transfer rates. The fluid should also have long-term chemical stability and be non-corrosive. Ammonia and carbon dioxide are common working fluids in geotechnical applications.

The heat pipes used on the pipeline were designed to transfer a minimum of 12 watts/ft of belowground embedment for a 3°F temperature difference between the evaporator and condenser sections. To ensure good heat transfer at higher temperature differences, a second performance criterion of 18 watts/ft for a 6°F temperature difference was also included in the design. The heat pipes are made of mild carbon steel, and ammonia is the working fluid. The inner diameter is 1.5 in. and the outer diameter is 2.0 in. The wall thickness was determined by requirements for handling during manufacturing, transportation, and installation and external corrosion resistance rather than pressure vessel requirements. The lengths range from 28 ft to 75 ft. The ammonia charge varies with length. It includes the amount of ammonia in the liquid film and the gas phase when the heat pipe is operating at design conditions plus a residual liquid pool which serves as a safety margin. Typically, when the heat pipe is inactive, the liquid pool at the bottom of the heat pipe is 1 to 2 ft deep.

A uniform circumferential distribution of the liquid film along the evaporator section of the heat pipe is necessary for good heat transfer. If the liquid is concentrated in one or two rivulets as it flows down the heat pipe and only part of the evaporator surface is wetted, the overall internal thermal resistance of the heat pipe can be significantly increased. To prevent this, the evaporator wall is artifically roughened to ensure an even fluid distribution.

Up to this point, only the internal heat transfer mechanisms of the heat pipe have been discussed. However, the heat transfer between the heat pipe and the environment, the soil and the atmosphere, controls the overall effectiveness of the heat pipe.

To improve heat transfer between the heat pipe and the atmosphere, an extruded aluminum radiator is press-fit onto the upper portion of the heat pipe. The press-fit provides a low contact resistance between the heat pipe and radiator. The radiator has 20 vertical fins with an outer diameter of 10.9 in. The fin surface area is 12.6 ft^2/ft of radiator length. For heat pipe lengths of 37 ft or less, the radiator length is 4 ft. For longer heat pipes, a 6-ft radiator is used. Where the radiator is attached, the heat pipe outer diameter is increased to 3 in. This provides the necessary stiffness for the pressing operation and mechanical protection after the heat pipes are installed.

The term "radiator" is somewhat of a misnomer. The major heat transfer mechanism is <u>convection</u> and not <u>radiation</u>. Since proper sizing of the radiator is important, a conservative approach was taken. The heat transfer coefficient used to model the radiator in thermal calculations was based on laboratory tests conducted under still air conditions. This was done even though other tests showed that wind speeds of just a few miles an hour can more than double the still air value.

The emissivity of the radiator is important. When the temperature difference between the air and radiator is low, the heat loss by radiation can be approximately equal to the heat loss by convection, if the emissivity is high. Further, an infrared imagery system was developed to monitor the performance of the heat pipes and radiators during the winter. For good infrared visibility, the emissivity of the radiator must be about the same as the emissivity of the background snow cover. The snowcover emissivity can be 0.9 or higher. Unfortunately, the emissivity of aluminum with a normal mill finish can be as low as 0.1. Therefore, the radiators were anodized to provide a high emissivity. Painting the radiators was also considered but could not provide adequate long-term performance.

Since the radiators are aluminum and the heat pipes are steel there is a potential for corrosion if an electrolyte enters a gap between the radiator and the heat pipe. Using a press-fit to install the radiator essentially eliminated this possibility. The gaps that exist are small, on the order of 0.001 in., and filled with oil applied to the heat pipe to facilitate the press-fit. To prevent water from entering, the boundary between the heat pipe and the radiator was caulked at the top of the radiator.

Hoar frost and snow can coat a radiator for short periods of time and reduce thermal efficiency. Because the radiator is warmer than the air, the coating is cleared relatively quickly due to sublimation. High winds and wet snow can increase the coating thickness and the time required to clear the radiator.

The design life assumed in the development of the heat pipe was 30 years. One of the major problems in obtaining this length of service is the generation of non-condensing gas inside the heat pipe. In general, non-condensing gas might be formed as a by-product of internal corrosion. Once formed, non-condensing gas would collect at the top of the heat pipe when the heat pipe is operating. This would block working fluid from reaching the upper part of the radiator and reduce heat loss to the atmosphere. To allow for some formation of non-condensing gas, a gas trap was provided above the radiator. This was done simply by pressing the radiator on the heat pipe so that the heat pipe extended 6 in. above the top of the radiator.

Heat Pipes in VSM

Essentially all the heat pipes used along the pipeline were installed in pairs in 18-in.-diameter steel pipe piles. The piles are referred to as vertical support members (VSM), and most VSM support the elevated pipeline. Non-load bearing VSM were also used and are referred to as free-standing VSM. VSM containing heat pipes are referred to as thermal VSM while VSM without heat pipes are called non-thermal VSM. Other VSM nomenclature was based on the assumptions used to calculate the load capacity of a VSM.

Placing heat pipes inside the VSM had many advantages. No additional drilling was required to install the heat pipes, and the VSM provided support for the aboveground portion of the heat pipes. One disadvantage was that, when the aboveground portion of the VSM was lengthened for structural reasons, the heat pipe length also had to be increased. Examples are raising the elevated line because of the terrain or to provide road or animal crossings. Other thermal and mechanical advantages are discussed below.

The major thermal resistance limiting the amount of heat removal from the ground during the winter is the thermal resistance between the heat pipes and the soil. The VSM geometry provided a convenient means of reducing this thermal resistance. Spacer bars were attached to the heat pipes to position them as close as possible to the metal VSM wall. The remainder of the belowground portion of the VSM was filled with a saturated sand slurry. The slurry provided good thermal coupling to the VSM wall, and the VSM wall served as a belowground fin to increase heat transfer with the soil.

A saturated sand slurry was used to fill the inside of the VSM because of its high thermal conductivity. The maximum particle size was set at 1 in. to prevent interference with positioning of the heat pipes. The fines content was limited to provide for a dense well-graded slurry and to prevent ice lens formation. Since the slurry was saturated, pressure could develop in the VSM when the slurry froze, even without ice lens formation. The confinement provided by the soil surrounding the VSM helped to resist this pressure and prevent any damage to the belowground portion of the VSM.

The initial thermal VSM design called for the aboveground portion of the VSM to be filled with unsaturated sand slurry. This would have provided additional surface area for heat loss to the atmosphere. The slurry had to be unsaturated to allow room for expansion when the water in the slurry froze. Unfortunately, a satisfactory method of placing unsaturated slurry in a VSM was never developed. Therefore, the aboveground portion was left empty. To prevent water accumulating inside the VSM, the top of the VSM was capped, and a small weep hole was drilled in the VSM wall just above the ground surface.

To fully thermally protect a VSM, the heat pipes had to extend to within 3 ft of the bottom of the VSM. Therefore the heat pipes were manufactured in length increments of 3 ft. There was one 5-ft increment. It occurred between 37-ft and 42-ft heat pipes. The additional 2 ft was needed because this is where the radiator length increased from 4 ft to 6 ft. In some cases, minor variations in VSM design resulted in 4-ft radiators on one side of a VSM bent and 6-ft radiators on the other side.

In addition to the maximum 3-ft standoff from the bottom of the VSM, the heat pipes were positioned vertically in the VSM so that the bottom of the radiators were 6 in. above the top of the VSM. This allowed air circulation around the radiators and helped to prevent snow accumulating on top of the VSM from blocking the bottom portion of the radiator fins. Further, the section of heat pipe with a 3-in. outer diameter was 6 ft long for heat pipes with a 4-ft radiator and 8 ft long for heat pipes with a 6-ft radiator. With the 6-in. gas trap at the top of the radiator and the 6-in. gap between the bottom of the radiator and the top of the VSM, the thick-walled section extended 1 ft below the top of the VSM. The thick-walled section of the heat pipe and the VSM wall thus provided continuous mechanical protection for the aboveground portion of the heat pipes. Until the internal slurry was added, the heat pipes were temporarily supported in the VSM by wire hangers which fit under the base of the thick-walled section of the heat pipes and over the lip of the VSM.

During the winter when the heat pipes are operating, the radial temperature gradient near the VSM can be very high, as much as several degrees per inch. Early in design there was some concern that such high gradients could cause tension cracks due to contraction of the soil, which could reduce the vertical load capacity of the VSM. Partially as a solution to this problem, the outer surface of the VSM was artificially roughened to provide a better mechanical connection between the VSM and soil. The goal was to provide circular ridges at 1-ft intervals that were about 0.75 in. thick. This was done either by welding rebar rings on the VSM or deforming the VSM using a corrugator lowered down the inside of the VSM. The latter method was quicker but required a reduction in the bending resistance of the steel pipe when determining lateral load capacity. The surface roughening was only applied below the design active layer to prevent any increase in jacking forces. Laboratory and field experiments later showed no evidence of reduced vertical load capacity caused by thermal cracking. However, all thermal VSM were corrugated because the same tests also showed that the surface roughening substantially improved the load carrying capability compared to smooth-walled adfreeze VSM.

Thermal VSM Supporting the Elevated Pipeline

Heat pipes were installed in approximately 80% of all VSM. The benefits of the specific geometry used were described above. The more important improvements in the structural performance of the pipeline are discussed below.

Heat pipes were used to maintain initially frozen soil frozen, to cool frozen soil significantly below the freezing temperature, to freeze initially thawed soil, and to provide for radial freezeback of the active layer. The specific reasons applicable to a given VSM depended on the soil conditions and geographic location. In general, heat pipes are more effective in finer-grained soils and for colder air temperatures. Heat pipes were always used in pairs even though in many cases standard design procedures indicated that only one heat pipe was actually required. This provided redundancy in case of a failure and also a significant safety margin.

Essentially all VSM were installed through a gravel work pad. The work pad provides a stable base for construction of the pipeline and will also allow ground access for surveillance and maintenance during pipeline operation. North of the Brooks Range, the environment is relatively cold, and the work pad was designed to prevent permafrost degradation. South of the Brooks Range, the environment is relatively warm, and in general, it was not possible to prevent long-term degradation. For design purposes, it was assumed that everywhere south of the Brooks Range the thaw depth below the bottom of the gravel pad would, after 30 years, range from 20 to 30 ft depending on soil conditions.

With widespread stable permafrost north of the Brooks Range, a conventional adfreeze pile design could be used, and heat pipes were only occasionally needed. Heat pipes were used in isolated areas of thawed ground, warm permafrost, and massive ice. The first two situations will be dealt with when the design south of the Brooks Range is discussed.

Normally, no strength was taken for massive ice when determining VSM load capacity. This was becuase of its poor long-term creep characteristics which are temperature dependent. For every foot of massive ice encountered while drilling a VSM hole, the embedment of the VSM was increased 1 ft. In some cases, this required unreasonably long VSM. If heat pipes were installed to ensure cold ground temperatures, then a low strength could be used for the ice. This was only done north of the Brooks Ranges.

South of the Brooks Range, an adfreeze pile design was not possible. When calculating the resistance to downward load, all the soil above the 30-year thaw depth was neglected. Further, an additional downward load had to be added to the structural load to account for downdrag on the VSM as the permafrost thawed and consolidated. The soil that did remain frozen could be relatively warm and the long-term strength could be very low. All soils were assumed to be frost susceptible, even clean sands and gravels, and the upward load due to jacking of the VSM as the active layer froze was assumed to be high. Therefore, even where soil conditions were good for downward load, the upward load could control the design and require a long embedment. Lateral load capacity, slope stability, and liquefaction were other problems aggravated by permafrost degradation caused by the work pad. As a result, adfreeze VSM had to be quite long with embedments often exceeding 100 ft. VSM this long were unacceptably expensive and beyond the capability of current construction equipment.

Using heat pipes alleviated these problems and resulted in typical VSM embedments ranging from 20 to 30 ft below the bottom of the gravel pad. In some cases, the embedment was still greater than 50 ft.

Most importantly, heat pipes prevented long-term permafrost degradation in the vicinity of the VSM. Properly designed, the additional cooling provided by the heat pipes during the winter can offset the additional summer heating caused by the surface disturbance of the gravel work pad. Away from the VSM, the permafrost will still degrade beneath the gravel pad, but near the VSM the active layer will stabilize after a few winters of heat pipe operation. The new active layer may be slightly deeper than the original one occurring beneath an undisturbed ground surface, but it will be stable. As a result, downdrag is eliminated, lateral load capacity is increased, and problems associated with slope stability and liquefaction are reduced.

With the elimination of downdrag, the upward load due to jacking often controlled the design. Heat pipes also solved this problem. Near a VSM with heat pipes, most of the active layer freezes radially outward rather than vertically downward. A foot or so below the ground surface, heat loss from the soil to the heat pipes is more efficient than heat loss from the soil to the atmosphere. Jacking forces develop due to ice lens formation and are parallel to the direction of movement of the freeze front. Therefore, the jacking forces near thermal VSM are horizontal and, due to symmetry, off-setting rather than upward and additive. Further, when any upward force might develop, the soil below the active layer is colder than assumed for long-term design because the heat pipes are currently operating. This increases the resistance to upward load above the long-term design value. Based on radial freeze-back and colder winter soil temperatures, it was assumed that heat pipes reduce jacking below the downward structural load, and thus eliminate jacking as a design problem.

Heat pipes were also used in initially thawed soil. In southern Alaska, the elevated pipeline often crossed small areas of thawed ground because of the sporadic occurrence of permafrost. During the summer, groundwater flow can significantly reduce or eliminate the freeze bulb generated by the heat pipes during the previous winter. Substantial groundwater flow can occur in areas with coarse-grained soil and high ground slope. Such areas were avoided or crossed assuming no permanent freeze bulb was formed. With or without groundwater flow it was assumed that heat pipes reduced jacking below the downward structural load.

Up to this point, the only restriction on the use of heat pipes has been the occurrence of groundwater flow. For an extremely wide range of soil conditions, heat pipes can maintain existing permafrost and generate permafrost in thawed ground. That is, heat pipes can maintain the soil just below its freezing temperature. Significant additional benefit is obtained for incremental cooling below the soil freezing temperature. However, this improved performance is obtained over a more limited range of soil conditions.

The strength of frozen soil is strongly dependent on temperature, especially near the freezing point. The variation increases as the ice content increases, and the colder the temperature is the stronger the soil. Depending on the specific soil type, decreasing the soil temperature from 0.1°F below the freezing point to 0.5°F below the freezing point can increase the soil strength by 20% to 100%.

Heat pipes installed in initially frozen soil were assumed to increase frozen soil strength only if the soil was a silty sand or silty gravel or finer-grained soil. For heat pipes installed in initially thawed soil, an increase in strength was assumed to occur only if the soil was silt or clay. In layered soil profiles, an increased strength was used for initially frozen clean sand and gravel if it was beneath a relatively thick layer of initially frozen silt or clay.

The soil temperature used to evaluate soil strength did not vary with soil type. To be conservative a relatively warm temperature was used. This temperature was equivalent to the maximum length-weighted average temperature calculated to occur below the active layer for a thermal VSM installed in initially frozen silty sand or silty gravel. The temperature used to evaluate frozen soil strengths was also conservative because it was assumed to be constant in time. Actually, the temperature variation during the year is large, and the yearly average value is much less than the maximum value.

The maximum soil temperature occurs at the end of summer just before the heat pipes begin operating for the winter. Once the heat pipes start to operate, the soil temperature near the VSM quickly drops to well below freezing. During the winter, the soil temperature remains warmer than the air temperature but follows the variations in the air temperature. A sharp reduction in air temperature during a cold spell causes a sharp reduction in soil temperature. The minimum soil temperature is at least 30°F to 40°F below the freezing temperature. When the heat pipes shut off at the beginning of summer, the soil initially warms very quickly because the soil near the VSM is much cooler than the soil a few feet away. The rate of warming slows as the freezing point is approached. Some of the ice in the soil melts below the freezing point, increasing the effective heat capcity of the soil. This phenomenon is referred to as unfrozen moisture. During the last months of summer the soil temperature asymptotically approaches its maximum value.

Unfrozen moisture below the soil freezing temperature is the major variable affecting heat pipe performance which is determined by soil type. Because of interactions between water molecules and soil particles, all of the moisture in soil does not freeze or thaw at a single temperature; phase change of some of the soil moisture occurs over a temperature range below the freezing point. (The freezing point is the temperature at which on cooling the soil moisture first begins to freeze and on warming the last ice thaws.) For a given dry density, increasing the fines content increases the soil particle specific surface area and therefore the unfrozen moisture content at a given temperature. Increasing the unfrozen moisture content decreases the maximum temperature occurring near a thermal VSM. As the soil warms toward the freezing temperature, latent heat as well as sensible heat must be supplied to raise the temperature further.

Unfrozen moisture content is also related to soil strength. Fine-grained frozen soil usually has a relatively low dry density, high ice content, and large reduction in strength near the freezing point. The large reduction in strength is at least partly due to high unfrozen moisture content. Coarse-grained frozen soil usually has a relatively high dry density, low ice content, and small reduction in strength near the freezing point. The strength reduction is smaller because of lower unfrozen moisture. Exceptions to this comparison are massive ice and very low density soil. Both have essentially no unfrozen moisture and no strength when thawed.

The relationship between unfrozen moisture, soil temperature, soil strength, and heat pipe performance is fortuitous. The thermal performance of heat pipes is best in soil types whose strengths are most sensitive to increases in temperature. Therefore, thermal VSM were extremely useful for supporting the pipeline in poor soils.

In a few cases, it was necessary to increase the load capacity of a VSM after the VSM and heat pipes had been installed. One way this was done was by placing insulation on the ground surface around the VSM to reduce the active layer and to increase the frozen embedment. The insulation was polystyrene board stock overlapped to form a layer 6 in. thick and extending 15 ft away from the VSM. The insulation was covered with gravel to keep it in place and to provide mechanical protection. The insulation could reduce the active layer by several feet but could not significantly reduce the temperatures along the frozen embedment. A few feet below the active layer, heat transfer near the VSM is primarily radial rather than vertical. Surface insulation has very little effect on the radial heat flow.

Insulation was also used around a VSM if there was significant massive ice in the active layer. By reducing the thickness of the active layer, the insulation reduced the potential for thaw settlement lowering the top of the permafrost relative to the VSM. No increase was assumed for the load bearing embedment of the VSM.

Construction Problems Associated with Heat Pipes

Using heat pipes did complicate construction. One of the major problems was getting the right length heat pipes in each VSM. This required a significant bookkeeping effort and continuing coordination with the heat pipe manufacturer to ensure that the correct length distribution of heat pipes was available. The heat pipe length distribution based on the original mile-by-mile design was changed significantly during construction. This was caused by two factors. Design optimizations were made during construction that were not considered during the initial design. Also, the soil conditions for each VSM hole were logged as the hole was drilled. If there was any doubt about the adequacy of the original design, the VSM embedment was increased.

Near the end of construction, several methods were used to conserve heat pipe lengths in short supply. These methods were applied to a very limited number of VSM. In some cases, VSM were installed deeper than required to carry the required vertical and lateral loads. For some of these VSM, the heat pipes were installed with reference to the load bearing length of embedment rather than the bottom of the VSM. For some VSM where heat pipes were required only to prevent jacking, the heat pipes were installed only so they extended well below the active layer and without reference to the load bearing length or bottom of the VSM. For some VSM requiring relatively long heat pipes, the required heat pipe length was obtained by mechanically overlapping two shorter heat pipes. The upper end of one heat pipe was attached to the lower end and a second heat pipe using u-bolts. The overlapped length was made much greater than the extended length to provide for adequate heat transfer between the two heat pipes.

In thawed soil, caving during drilling of VSM holes was a problem. Using casing slowed construction and sometimes unusually long casing lengths were required which could not be easily pulled after the VSM was installed. An alternate VSM installation procedure was developed which consisted of driving an open-ended VSM. The soil was removed from the inside of the VSM as it was driven. A grout plug had to be placed inside some of these VSM to prevent highly unstable soil from flowing into the VSM after it was installed. This grout plug sometimes interfered with installing the correct length heat pipes. Special care was required when installing the VSM and grout plug to ensure that the required load bearing length could be thermally protected by the heat pipes.

Although the heat pipe installation procedure was conceptually simple, it was a procedure for which the contractors had no experience and initially progress was slow. The procedure consisted of several steps: verify which VSM receive heat pipes, determine correct heat pipe lengths; check ammonia level in heat pipes, press radiators, string heat pipes along right-of-way, remove any debris from inside VSM, hang heat pipes in VSM, install internal slurry, drill weep hole, and cap VSM. The very long heat pipe lengths presented additional problems for transportation and installation. There were temperature restrictions on the internal sand slurry when it was placed inside the VSM. It had to be kept as cool as possible to prevent thawing a significant amount of soil outside the VSM.

Heat pipe installation affected construction timing. Heat pipes were generally not installed until after the mainline pipe was in place. Trying to lift the pipe over the radiators could easily result in damage to the heat pipes. The internal slurry had to be installed either well before hydrotesting or after hydrotesting so that the external slurry would be frozen and the VSM could support the required load. If the permafrost was very warm, the slurry may not have been completely frozen; but for the short-term hydrotest loads this was acceptable. Further, the heat pipes had to be installed so that there was one winter of operation before pipeline startup. If the VSM were in initially thawed ground and if credit was taken for frozen soil strength, there had to be two winters of heat pipe operation before startup.

By itself, any one of the problems described above seems relatively minor. However, taken as a whole and placed in the context of a project as large as the pipeline, the use of heat pipes required a major effort. Nevertheless, using heat pipes was cost effective. The reduction in VSM embedment heat pipes made possible offset their cost. Regardless of cost, in some cases heat pipes provided the only feasible design alternative.

Other Uses for Thermal VSM

Thermal VSM were used in situations other than support of the elevated pipeline. They were used to provide thermal protection for bridge piers, buried pipe and buildings. In most cases, the VSM were free-standing and not load bearing. The thermal VSM design was used in these situations because of the mechanical and thermal advantages previously discussed. It also provided for uniform design and construction.

Several bridge piers at five different locations were protected using free-standing thermal VSM. The typical bridge pier design consisted of several load-bearing piles installed at a batter and terminated at a belowground concrete pile cap. A vertical concrete column extended aboveground from the pile cap and supported the bridge itself. The geometry of the pier prevented heat pipes from being placed directly in the load-bearing piles. Free standing VSM were spaced around the bridge pier to thermally protect all the load-bearing piles. Usually four VSM were used. The soil strength and temperature criteria used in developing the design were the same as for thermal VSM supporting the elevated pipeline.

Free-standing thermal VSM were used to limit thaw below buried mainline pipe. The pipe was insulated using annular insulation applied directly to the pipe and/or slab insulation applied to the trench bottom and walls. The pipe is a continuously operating heat source, but the heat pipes only provide cooling during the winter. Therefore, south of the Brooks Range, heat pipes and insulation can only reduce the thaw below the pipe; they cannot eliminate it. North of the Brooks

Range, the environment is cold enough so that insulation alone can essentially eliminate thaw below the pipe.

This type of design was used for soil conditions where the pipe normally would have been elevated, but had to be buried for other reasons. Since thaw could only be reduced and not eliminated, the sites had to be carefully selected to ensure that excessive thaw would not occur. The principal example of this type of construction is the buried animal crossing. Other examples are a highway crossing and a section of buried pipe where remedial work was required.

In long sections of elevated pipeline the pipe was dipped below ground for a distance of about 60 ft to provide an animal crossing. This type of crossing was necessary because there was concern that some animals would not cross beneath the elevated pipe. The pipe was insulated with 4.5-in. thick polystyrene slats cut to conform to the pipe. The ditch walls and bottom were covered with polystyrene board stock overlapped to provide a total thickness of 12 in. At either end of the crossing, four free-standing thermal VSM were placed in a rectangular pattern centered on where the pipe entered the ground. The heat pipe and insulation design and soil conditons were chosen to limit thaw settlement at the ends of the crossing. There is no thermal benefit from the heat pipes at the center of the crossing so the settlement is greater there. With the pipe partially supported by the soil at either end, the pipe can span this area of relatively high settlement. Further, due to the flexibility provided by the elevated pipe, the settlement for the entire buried crossing could be greater than that allowed in a long buried section. Fourteen buried animal crossings were built in this manner.

At a few buried animal crossings, the free-standing thermal VSM were replaced with an alternative design. This was caused solely by the availability of certain construction equipment. Each VSM was replaced by two separate heat pipes, each in its own 6-in.-diameter metal casing. All design details were similar to those for the VSM. This alternate design might have somewhat better thermal performance because the spacing between heat pipes could be increased slightly over that allowed by the standard VSM design. Increased spacing will reduce the thermal interference between nearby heat pipes and allow more heat to be removed from the soil during the winter.

At all major highway crossings, the pipeline was buried to prevent damage from traffic. At two such crossings permafrost posed a potential thaw settlement problem. The frozen soil was relatively dense at one crossing so thaw settlement was relatively low and heat pipes and insulation could be used. At the other crossing, the soil was ice rich and mechanical refrigeration was required.

For the crossing with heat pipes the insulation configuration was the same as that for the buried animal crossings. Groups of four free-standing thermal VSM, two VSM on either side of the pipe, were spaced at 40-ft intervals on both sides of the highway. Approximately 450 ft of buried pipe were protected in this manner, and 52 free-standing thermal VSM were used. The thaw bulb previously generated by the highway itself prevented any thaw settlement problems directly beneath the road.

During a review of the as-built pipeline before startup, it was discovered that two short sections of buried pipe did not strictly comply with design criteria. The two sections were each about 100 ft long and were a few thousand feet apart. There was a potential for both thaw settlement and soil liquefaction. A relaxation of the design criteria on a site specific basis may gave been possible. However, due to the approach of startup, performing remedial work to bring the buried sections within the design criteria was determined to be more expedient.

To prevent thaw settlement, the pipe was carefully excavated and placed within an insulation box. The sides of the box were 21 in. thick and were fabricated in 8-ft lengths using polystyrene board stock. A row of free-standing thermal VSM was placed on either side of the insulation box. To prevent soil liquefaction upslope from the pipe, a 6-in.-thick layer of overlapped polystyrene board stock was placed on the ground surface, and an array of free-standing thermal VSM was installed through the insulation. A total of 22 VSM were installed near each section of pipe.

At some locations where heat pipes were installed next to buried pipe, the permafrost table was well below the bottom of the pipe. Here the heat pipes may freeze some initially thawed soil beneath the pipe; however, heaving of the pipe will not be a problem. As previously discussed, the growth of the freeze-bulb around a VSM is radial rather than vertical. Further, the size of the freeze-bulb is relatively small, and there is significant overburden pressure.

Equipment buildings at remotely controlled gate valves were supported on thermal VSM. The buildings rested on crossbeams supported by the VSM. The buildings therefore did not interface with heat pipe installation, and the standard VSM design could be used. Buried propane tanks at these sites were also supported using thermal VSM. An equipment building at one microwave station was placed directly on top of several VSM. To provide thermal protection, heat pipes were placed in the external slurry of the VSM around the periphery of the building.

There were two applications of heat pipes at pump statons. At one station, several free-standing thermal VSM were installed near a refrigerated corridor for the buried mainline pipe. The heat pipes were to assist the refrigeration system in preventing thaw below the corridor. The refrigeration system alone was not adequate because a large soil test pit dug at the beginning of station construction resulted in a thawed area with some groundwater flow. The heat pipes helped freeze the test pit area. Heat pipes in 6-in. casing were also used to provide stable foundations for accelerometers at some pump stations. The accelerometers were remote from any pump station buildings and were part of the earthquake monitoring system.

Heat Pipe Design Development

The heat pipe and thermal VSM designs were developed using extensive laboratory tests, computer simulations, and field tests. Laboratory tests were conducted to evaluate commercially available heat pipes and different radiator configurations. Two field tests were also conducted for the same purpose. The results of these tests and numerous computer simulations established the viability of the thermal VSM concept. Computer simulations were also used to refine the design and to develop the performance criteria to be met by the heat pipe manufacturer. Several manufacturers participated in a qualification program based on these criteria. Each manufacturer had to perform rigorous laboratory tests to prove his heat pipes satisfied the criteria. Additional laboratory tests and analyses were also performed to finalize the radiator design. After a manufacturer was chosen, several prototype heat pipes and radiators were produced, and a third field test was conducted using a section of the actual pipeline. This provided a full-scale test of the heat pipes and design procedure.

The computer program used is a general purpose program which simulates two-dimensional heat transfer by conduction with change of phase. Mass movement due to settlement and heave and heat transfer by convection are not modeled. The program uses a finite element approximation in space and a finite difference approximation in time. The storage and run time requirements are modest; this allowed a wide range of situations to be considered when developing the design. Thousands of simulations were conducted.

The soil properties modeled include a step change in heat capacity, thermal conductivity, and latent heat content at the freezing temperature and temperature-dependent latent heat content due to unfrozen moisture below the freezing temperature. A different set of soil properties can be specified for each element in the finite element grid. The freezing temperature can be specified for the entire grid. Values for the soil properties were obtained using published correlations based on experimental data.

A variety of temperature and heat flux boundary conditions is built into the program. One of the most useful is a surface heat balance. The surface heat balance uses standardly measured meteorological data and easily estimated surface properties to model heat transfer between the ground surface and the atmosphere. The heat transfer mechanisms modeled include convection, radiation, evaporation, conduction through a snow layer, and snow melting.

The computer program was validated against closed form analytical solutions, laboratory tests, and field tests. It was found that the major factor limiting the usefulness of the program was the accuracy of the input data.

The heat pipe operation was not modeled in detail by the computer simulations. Rather, a gross approach was used. The heat pipes inside a VSM were modeled by coupling the soil temperatures at the VSM wall to the air temperature through a heat transfer coefficient. The heat transfer coefficient was constant for the entire belowground length of the heat pipes. The heat transfer coefficient was zero when the air temperature was greater than the soil temperature at the bottom of the heat pipes and nonzero when the air temperature was less than the soil temperature. The nonzero value was based on the results of laboratory and field tests and computer simulations of a cross-section of a thermal VSM including the heat pipes and internal slurry.

The early laboratory tests used a freezer box and water bath. A heat pipe was suspended in the water bath, and the attached radiator was enclosed in a freezer box on top of the water bath. The temperatures of the freezer box and water bath were controlled, and the heat loss from the water bath could be calculated. Using the apparatus, the general heat transfer characteristics of the heat pipe and radiator could be determined as a function of temperature.

The first two field tests were conducted at sites in central Alaska originally used for pile installation and load tests. After the pile tests were completed, heat pipes were installed. Thermocouple strings were used to measure soil temperatures. The first field test lasted one year and the second test lasted two years. Both field tests showed that heat pipes could provide adequate soil cooling and indicated improvements which could be made to increase the amount of cooling.

For the heat pipe manufacturer qualification program, certain physical and thermal characteristics were specified for the heat pipes. The heat pipes had to have a geometry compatible with the VSM design, had to transfer a minimum of 12 watts/ft of belowground embedment at a 3°F temperature difference between the condenser and evaporator sections, and had to have a design life of 30 years. The manufacturers had to select materials, fabricate prototypes, conduct thermal performance tests and accelerated life corrosion tests, and develop a production scheme for making the required number of heat pipes in a timely ma..er. The conduct of the qualification program was similar for each manufacturer, but only the program for the manufacturer eventually selected will be described below.

Different methods of roughening the evaporator surface were evaluated. The method selected provides a uniform liquid distribution with minimum liquid hold-up even with the heat pipe tilted at a slight angle.

Different methods of attaching the radiator to the heat pipe and minor variations in the radiator configuration were studied. A press-fit was found to be an easy installation procedure which provided a low contact resistance between the heat pipe and the radiator. The number of radiator fins versus the width of each fin was optimized, and the type of radiator surface coating to provide a high emissivity was determined.

Small 4-ft-long heat pipes were used to investigate chemical reactions between different working fluids, metal pipes, and possible contaminants. Scaling laws for the accelerated-life tests were derived, and noncondensible gas generation was identified as the most likely cause for a heat pipe failure. Material specifications, fabrication procedures, and other design details were also developed.

Twenty 40-ft-long heat pipes were used in the thermal-performance and accelerated-life tests. Both tests showed better than required performance. Only a 2±F, rather than a 3±F, temperature difference was needed to transfer 12 watts/ft. The generation of noncondensing gas was minimal and much less than the rate needed for a 30-year design life. Destructive tests indicated no changes in any of the heat pipe components. Destructive tests on a heat pipe in service for three years at one of the field test sites gave the same results.

The radiator length for a given length heat pipe was determined from laboratory tests using a prototype radiator. The radiator was maintained at a constant temperature by supplying a known heat flux. Tests were conducted at room temperature and in a refrigerated trailer for both still air conditions and low wind speeds. Using the measured data, a correlation was developed for predicting heat loss from a radiator. The heat transfer capability of a given length radiator was then matched with the corresponding heat transfer capability of an equivalent length of heat pipe. For simplicity only two different radiator lengths were used, 4 ft and 6 ft.

If the radiator design criteria are strictly applied, the radiators for the longest length heat pipes should have been 8 ft instead of 6 ft long. Due to the conservativeness of the overall design, it was decided that the complications arising from the use of three different size radiators were not worth the improvement in performance.

The prototype heat pipe and radiator field test was conducted outside Fairbanks. A 150-ft section of the actual pipeline was built for the test. The section included an anchor, a gate valve, and two intermediate bents for a total of 12 VSM. All VSM received heat pipes. To measure soil temperatures, thermistor strings were installed near four VSM and beneath the gravel pad and undisturbed tundra. A total of 230 thermistors were used, and each thermistor was individually calibrated at three different temperatures. Meteorological data such as air temperature, solar radiation, wind speed, snow depth, and snow density were also measured. Data collection started in October 1974 when the first heat pipes were installed.

To summarize the most important field test results. consider the length-weighted average temperature below the active layer for the VSM with the warmest soil temperatures. After one year of heat pipe operation, at the end of summer 1975, the temperature near the VSM was 1°F cooler than the corresponding temperature below the undisturbed tundra and 1.5°F cooler than the corresponding temperature below the gravel pad. By the end of summer 1977, after three years of operation, there was an additional 0.8°F cooling compared to the undisturbed tundra. No comparison can be made with the gravel pad because that thermistor string was no longer operational. These end-of-summer temperatures were the warmest temperatures occurring during the year. The minimum temperature during the winter was a slow as -15°F.

This performance was better than that expected based on standard design computer simulations. Computer simulations trying to match the measured temperatures indicated that the heat pipes were more efficient at removing heat from the soil than assumed in the design calculations. The match calculations also indicated there was less unfrozen moisture than expected. Because of its importance on heat pipe performance, this finding resulted in laboratory tests to measure unfrozen moisture.

Before the prototype heat pipe field tests, estimates of unfrozen moisture were obtained from published correlations based on experimental data for remolded soils amples. Specific surface area was one of the major correlation variables, and conservatively low values of specific surface area were used for a given soil type. The field test indicated this may not give conservative estimates of unfrozen moisture. One possible explanation may be the error resulting from testing remolded samples rather than undisturbed samples.

A calorimeter test method was used to determine unfrozen moisture content as a function of temperature for several undisturbed Alaskan soil samples. The soils considered ranged from sand to silt. A soil sample was first cooled well below 32°F so that essentially all the mositure was frozen. The sample was then placed in an insulation module which was in turn placed in a temperature controlled bath mainted at 40°F. As the sample warmed, the temperature of the sample and the temperature difference across the insulation were measured at regular time intervals using thermistors.

The insulation module was designed so that the soil sample warmed very slowly. In a typical experiment, the sample temperature increased from -10°F to 33°F over a period of 8 days. A slow heat transfer rate was essential. Reduction of the data depended on the assumptions that the sample temperature was uniform and that heat flow into the soil sample was steady state. The second assumption meant that the rate of heat transfer was proportional to the temperature difference across the insulation. The constant of proportionality, the overall heat transfer coefficient, was determined by calibration with a copper slug before and after the soil tests.

With the overall heat transfer coefficient and the measured temperatures, it was possible to calculate the total heat content of a soil sample as a function of temperature. Well below 32°F, this relationship was linear with the slope of the line being the heat capacity of the frozen soil. Near 32°F, the relationship became nonlinear as some of the soil moisture melted. The deviation from a straight line was used to calculate the amount of unfrozen moisture.

Only a limited number of tests were conducted so the results could not be considered conclusive. However, a conservative analysis of the test data resulted in significantly lower unfrozen moisture than predicted by the published correlations. This was especially true near 32°F, which is the most important area for heat pipe performance.

Using the new lower values of unfrozen moisture, standard design computer simulations for the coarser-grained soils resulted in end-of-summer temperatures slightly above the design temperature used to evaluate frozen soil strengths. Nevertheless, the VSM design was still determined to be adequately conservative.

There were several conservatisms built into the design computer simulations of thermal VSM. Thermal reinforcement between the two VSM in a bent was ignored. The reinforcement was found to be significant at the prototype field test site. The heat transfer coefficient used to model the heat pipes was lower than the actual value based on the field test data. A simple heat transfer coefficient could not account for heat transfer from a warmer, lower soil strata to colder, higher soil strata after the air temperature rises above the soil temperature. The surface thermal disturbance caused by stripping of the organic layer and placement of a gravel pad was assumed to extend infinitely far away from the VSM. Soil surface parameters such as solar absorptivity and evaporation were assigned conservative values to bias the calculations toward more warming. The initial soil temperatures were assumed to be very close to 32°F. The heat pipe embedment considered was the shortest possible. Finally, the warmest occurring temperature during the year was the design value.

In addition to the conservatism in the thermal calcualtions, there was significant conservatism in the soil strengths used and the structural design of the elevated pipeline. As a result, the overall conservatism in the design of the entire elevated system was very high.

Alternatives to Heat Pipes

In addition to heat pipes, two other natural convection devices were considered. In these devices, there was no phase change of the working fluid. Therefore, although the amount of cooling was adequate for some situations, it was relatively low compared to heat pipes.

The air convection pile used air as the working fluid. It consisted of a small-diameter pipe suspended inside the structural pile. Cold air flowed down the outer annulus and was warmed by the soil. The warm air then flowed up the inner pipe. Circulation could also occur in the opposite direction. No radiator was needed but a manifold was placed at the top of the pile to help separate the inlet and outlet air streams. One disadvantage of the device was that, during the summer, wind induced circulation could cause heating of the soil. A field expedient design was developed for speeding the freeze-back of the external slurry of a VSM. The design was never used.

The thermo-tube used an ethylene-glycol and water solution as the working fluid. This was a closed device with internal baffles to facilitate the internal natural convection. A radiator was required.

Heat Pipe Monitoring

While developing the heat pipe design, emphasis was placed on reliable long-term operation. During construction, quality control checks were performed at the factory and in the field to ensure that the heat pipes met design criteria. The reliability of the heat pipes was demonstrated to be very good, but due to the large number of heat pipes used along the pipeline, it was inevitable that a very small percentage would be faulty. Therefore, the heat pipes were designed so that a smaller replacement heat pipe would fit inside, and a monitoring system to detect deficient heat pipes was developed.

A decrease in the heat transfer efficiency of a heat pipe can have several possible causes: generation of noncondensing gas, leakage of the working fluid, or poor thermal coupling between the heat pipe and the radiator. Whatever the cause, the result is a decrease in radiator temperature during the winter compared to radiators on properly functioning heat pipes. Therefore, the heat pipe radiator temperature was used as the failure detection parameter.

An infrared system mounted in a helicopter was found to be the best method of monitoring radiator temperatures. Data are recorded on black and white video tape and are displayed and analyzed on a standard TV screen. Different temperatures appear as different shades of gray. This system has several advantages. The data can be evaluated in the helicopter as it is being collected so the system can be adjusted to give the best possible data. The data are also immediately available for analysis once data collection is completed.

To accentuate deficient heat pipes and minimize measurement errors, data are collected during periods of relatively low air temperatures when the heat pipes are operating near their peak. Data collection has to be conducted during twilight or darkness because the sun shining on the radiators causes anomalously warm temperatures. The radiators were anodized to provide a high emissivity and good infrared visibility.

Qualitative infrared systems similar to the one used on the pipeline have been available commercially for several years. This system was made quantitative by incorporating two black body references into the optical system of the infrared scanner. The temperatures of these black bodies are controlled by the instrument operator and serve as upper and lower reference temperatures. Over the temperature range between the references, temperature is linearly proportional to the output voltage from the infrared scanner. Temperatures between the two black bodies can be determined by linear interpolation.

Reference radiators were installed along the pipeline to assist in data analysis. These radiators are not attached to a heat pipe but are mounted on a pipe stub at the same elevation as the other radiators. The temperature of a reference radiator is equal to the temperature of a radiator on a totally failed heat pipe at the local ambient conditions. In between reference radiators, the upper portion of the VSM is used as a secondary reference.

During analysis, the data are scanned visually to detect radiators that appear cooler than nearby radiators. When a cool radiator is found, the temperature difference between that radiator and the reference radiator is compared to the temperature difference between the other radiators in the bent and the reference radiator. If this comparison satisfies certain criteria, then the heat pipe is replaced. This method assumes that all heat pipes in a bent have the same embedment. In a few cases this is not true and additional analysis is required.

To replace a deficient heat pipe, the heat pipe is simply cut off below the bottom of the radiator and a smaller replacement heat pipe is slipped inside the standard heat pipe. The replacement heat pipes have an internal diameter of 1 in. compared to 1.5 in. for the standard heat pipe. Because of the smaller size, the replacement heat pipe is slightly less efficient. The annulus between the two heat pipes is filled with an ethylene-glycol and water mixture and the two heat pipes are then welded together.

Two infrared monitorings of the heat pipes have been conducted, one during the winter of 1976-77 and one during the winter of 1977-78. Only about 0.1% of the heat pipes have been replaced. The number of deficient heat pipes identified in the second winter was only about 10% of the number identified during the first winter. Most of the deficient heat pipes from the first winter had little or no ammonia. Thus the heat pipes appear to be working well, with most of the failures resulting from construction damage or manufacturing defects. The failure rate in the future is expected to be very low.

Soil Temperature Monitoring

Over 150 thermistor strings have been installed to monitor soil temperatures along the pipeline. Most of the strings are near VSM supporting the elevated pipeline, but some strings are near buried pipe, bridge piers, and other thermally sensitive pipeline structures. On each string there are 6 to 12 thermistors. Each thermistor was individually calibrated in an ice bath to ensure accurate readings near 32°F. Data collection strated in 1976. Before startup and immediately thereafter, the data were used to verify that the heat pipes had provided adequate cooling during the previous winter. This despite the fact that the winter air temperatures were unusually warm. Data collection is continuing at a frequency of several times a year.

Inspection Hole Observations

During construction, large-diameter holes were drilled next to selected VSM. These VSM were installed in initially thawed soil and had one year of heat pipe operation. These holes allowed direct visual verification of the freeze bulb generated around the VSM. It was found that the freeze-bulb radius was 3.5 to 4.5 ft from the VSM centerline. This was consistent with design computer simulations. No large ice bodies were found, but very thin ice coatings were observed over portions of some of the VSM.

The phenomenon of "skin melting" was also observed. Skin melting is the local depression of the active layer immediately around a VSM caused by heat conduction down the VSM wall. A few feet away from the VSM, the top of the permafrost table was horizontal. About 2 ft away, the top of the permafrost began to slope downward. At the VSM wall, the thaw was 1 to 2 ft deeper than it was a few feet away. These observations were also consistent with computer simulations.

Future Applications of Heat Pipes

There are several possibilities for future applications of heat pipes:

1. Heat pipes could be used at dams to provide a frozen foundation. If it is an earth-fill dam, heat pipes could also maintain the impermeable clay core frozen. Electrical transmission cables leading from the dam might be supported on towers with heat pipe protected foundations.

2. Heat pipes could be used for building foundations. Either pile or slab-on-grade foundations could be used. For a pile foundation, the heat pipe radiators could be exposed to the air beneath the building. For a slab-on-grade foundation, the heat pipes could be installed around the periphery of the building and slanted beneath the foundation. In this case, the evaporators may be large rectangular cavities rather than small circular pipes.

3. Thickened ice sheets could be formed using heat pipes. To form a large ice mass, an array of heat pipes could be installed in one location and then moved after a freeze bulb had formed. Heat pipes could also be used to anchor an offshore structure to the sea floor.

4. Heat pipes could be installed near a chilled pipeline in initially thawed ground to prevent heave. The heat pipes would result in vertical freeze fronts moving radially away from the heat pipes rather than a horizontal freeze front moving downward from the pipeline.

For these application, several areas of the heat pipe design require additional work. These areas include the effect of groundwater flow, better correlations for unfrozen moisture, the effect of installing heat pipes at an angle to the vertical, and faster methods of installing heat pipes.

Conclusions

The design, functioning, and monitoring of heat pipes along the Trans Alaska Pipeline have been reviewed. It is clear from the information presented that the application of heat pipes on the pipeline project represented an advancement in the state-of-the-art of cold regions construction. It is likely that heat pipes will be used in future projects.

Additional information on heat pipes and VSM is contained in the references listed in the bibliography.

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