The Trans-Alaska Pipeline System workpad — an evaluation of present conditions

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The workpad, from which the Trans-Alaska Pipeline System was built, was constructed of either granular fill or a combination of granular fill and insulation. A granular fill (structural) workpad was used south of the Brooks Range and for buried segments of the oil line north of the Brooks Range. The insulated, granular fill workpad was utilized adjacent to elevated segments of the oil line north of the Brooks Range.

Since there was no need to construct a workpad capable of supporting heavy traffic for the life of the project (30 years) the workpad was designed to support heavy construction traffic during the construction period (three years) and light operational-type traffic thereafter. Thermal disturbance on permafrost soils was therefore expected where only a structural workpad was utilized. The insulated workpad, however, was used north of the Brooks Range in cold permafrost areas to minimize gravel requirements and to prevent an increase in active layer depths and permafrost temperature adjacent to the above-ground support system.

It has been four years since the completion of construction. The anticipated effects of the thermal disturbance caused by structural workpad construction on permafrost soils and of the operation of the warm oil pipeline are becoming more apparent. Additionally, enough time has passed to evaluate the effectiveness of the insulated workpad as a mitigative measure to minimize thermal disturbance in cold permafrost areas. The field program carried out during the summer of 1980 documented the performance of both insulated and non-insulated workpad adjacent to both above-ground and below-ground segments of the Trans-Alaska Pipeline System.

The evaluation was initiated at the request of the Trans-Alaska Pipeline System owners to determine if the workpad could be rehabilitated to support heavy construction loads associated with the construction of a second, large-diameter pipeline.

L'appui utilisé lors de la construction du pipeline Trans-Alaska fut construit soit à l'aide d'un remblai de gravier soit en combinant un remblai de gravier et un isolant. Un appui en gravier fut utilisé au sud de la chaîne Brooks et pour les tronçons enfouis de l'oléoduc au nord de cette chaîne. L'appui isolé fut utilisé à côté des tronçons surélevés de l'oléoduc au nord de la chaîne Brooks. Puisqu'il n'était pas nécessaire de construire un appui capable de supporter une circulation lourde pour la vie utile du projet (30 ans), l'appui fut conçu pour supporter une circulation de construction lourde pendant la période de construction (3 ans) et une circulation légère d'exploitation par la suite. Les perturbations de type thermique dans les pergélisols furent par conséquent prévues seulement où l'appui de gravier fut utilisé. L'appui isolé, toutefois, fut utilisé au nord de la chaîne Brooks dans des zones de pergélisol pour réduire au maximum les besoins en gravier et empêcher une augmentation de l'épaisseur du mollisol et de la température du pergélisol adjacent au système de support des tronçons surélevés.

Il y a quatre ans déjà que les travaux sont terminés. Les effets prévus des perturbations thermiques causées par la construction de l'appui en gravier sur les pergélisols et de l'exploitation d'un oléoduc transportant un liquide chaud, commencent à se manifester. En outre, il s'est écoulé assez de temps pour permettre une évaluation de l'efficacité de l'appui isolé comme mesure préventive pour réduire au maximum les perturbations thermiques dans les zones de pergélisol. Le programme d'études sur le terrain réalisé au cours de l'été 1980 a fait état du rendement des deux types d'appui (isolés ou non) adjacents aux tronçons surélevés et enfouis du pipeline Trans-Alaska.

L'évaluation fut entreprise à la demande des propriétaires du pipeline Trans-Alaska, pour voir si l'appui pouvait être remis en état de supporter les lourdes charges reliées aux travaux de construction d'un deuxième pipeline de diamètre important.

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[Ed. note: Data have not been converted to SI units.]

Introduction

The Trans-Alaska Pipeline System (TAPS) crosses the State of Alaska from the northern oil fields at Prudhoe Bay to the southern, ice-free port of Valdez. The route crosses continuous and discontinuous permafrost and represents the first major Arctic pipeline project.

The design conditions along the TAPS alignment were highly variable and required criteria and design solutions to accommodate this variability. The principal design considerations included soil type, existence of permafrost, topography, embankment construction materials, hydrology, season of construction, mode of pipeline construction, anticipated construction procedure, degree of terrain disruption, efficiency in the use of resources, and compliance with right-of-way stipulations.

The TAPS workpad was designed to support heavy equipment during the two- to three-year construction phase of the pipeline and, with periodic maintenance, light surveillance traffic during project operations[1]. The intent was, therefore, to provide only the thickness of gravel and in some cases polystyrene insulated workpad, which allowed short-term passage of heavy equipment.

The insulated workpad was designed to limit the thaw into permafrost, whereas surface distress caused by thawing of frozen soils was anticipated beneath the non-insulated or structural workpad along the alignment. Yearly maintenance programs by the operator of TAPS (Alyeska Pipeline Service Company) have been developed to maintain the workpad in a state that is generally trafficable by light surveillance vehicles.

The proposed Alaska Natural Gas Transportation System (ANGTS) will follow the same general route as TAPS from Prudhoe Bay to Delta Junction (approximately 540 miles). At Delta Junction the ANGTS gas line turns east and follows the Alaska Highway into Canada. Original plans called for construction of ANGTS using the existing TAPS workpad with the new pipeline placed on the opposite side to the TAPS pipeline. The TAPS owners undertook a workpad assessment program in the spring of 1980 as these plans gained support from federal agencies. The purpose of the program was to determine the condition of the TAPS workpad and to provide a basis for formulation of criteria for rehabilitation of the workpad and construction of a second pipeline in close proximity to TAPS. The U.S. Congress granted right-of-way for the ANGTS project in mid-1980 precluding the location of a second pipeline proximate to TAPS except in areas where compatibility of the two lines can be shown.

This paper describes the early phase of the workpad assessment program. The types of surface distress observed are discussed and the causes of distress are postulated. For the purposes of this report the following definitions are used:

[1]Alyeska Pipeline Service Company. 1973. Geotechnical aspects of the Trans-Alaska Pipeline. September. Appendix A-3.

Insulated workpad: A thermally designed workpad in which a synthetic insulation layer is provided in the embankment to limit subgrade thaw.

Structural workpad: A workpad embankment for regions of either permafrost or thawed soil conditions with design thickness based on the strength of thawed subgrade soils immediately below the embankment.

Field Observations

The TAPS workpad between Prudhoe Bay and Delta Junction was inspected during three trips of three to four days each in the summer of 1980. Helicopters were used to allow low-level observations and frequent stops for on-the-ground inspections. The first two trips were scheduled to observe the workpad during and directly after the spring break-up in different areas along the pipeline alignment and were centred on the first of May and June. The third trip was scheduled to observe the workpad in drier midsummer state. The northernmost fifty miles of workpad were obscured by snow cover at the times of the first two trips. All other areas were inspected two or more times during the field efforts. Areas of surface distress identified during the earlier trips were reexamined during subsequent trips for indications of a deteriorating condition. Detailed photographic records were compiled to document each trip and to create a basis of comparison for future observations.

During the winter and summer of 1979-1980 a field drilling and trenching program was completed on the insulated workpad section north of the Brooks Range.

Insulated Workpad

Portions of the workpad from which the Trans-Alaska Pipeline was built were designed to limit thaw into permafrost with the placement of a layer of synthetic foam insulation (polystyrene) within a soil embankment. This insulated workpad was used adjacent to elevated segments of the oil line north of the Brooks Range.

Design Summary

The insulated workpad was designed to maintain frozen soil immediately below the insulation during construction. The requirement for the insulated workpad to carry heavy wheel loads was limited to the period of heavy construction activity (three years). Therefore, some long-term thaw under the insulation was allowed in the design. Thaw below these insulated sections equal to 1.5 times the depth of the original active layer was considered acceptable for the long-term design case. This depth was chosen because massive ground ice is normally encountered substantially below the active layer. With this amount of thaw the workpad would therefore still be capable of supporting light surveillance and maintenance equipment.

Insulated workpad construction included snow removal and tundra levelling, placement of an insulation layer, and the installation of a traffic course with a minimum thickness of 24 inches. The thickness of the insulation layer ranged from 1.5 inches at Prudhoe Bay to 4.5 inches at Galbraith Lake. The thickness used was dependent not only on the geographic location but also on the gradation of the workpad material. The design thickness included allowances for mechanical damage to the insulation and for an increase in conductivity above that specified by the manufacturer.[2]

Minimum total embankment thermal resistances have been established (Table 1). Minimum values of thermal resistances are listed for both short- and long-term performance of thermal workpads. Short-term thermal performance requirements are for the initial three years of construction use and are designed to limit thaw to the bottom of the workpad. The long-term requirements are for light operations traffic with thaw limited to 1.5 times the preconstruction, naturally occurring, active layer.

TABLE 1. Thermal design values

Thermal design district	Minimum required thermal resistance of embankment insulation R^a $\left(\frac{ft^2 \cdot hr \cdot °F}{BTU}\right)$	
	Short-term performance	Long-term performance
Brooks Range (Continental Divide to Pump Station No. 4, and Pump Station No. 4 to Pump Station No. 3)	13.4	5.0
Foothills (Pump Station No. 3 to Pump Station No. 2)	11.7	4.5
Coastal Plain (Pump Station No. 2 to Pump Station No. 1 at Prudhoe Bay)	8.4	3.4

$^a R = \frac{x}{k} = \frac{\text{insulation thickness (inches)}}{\text{insulation thermal conductivity (BTU·in./hr·ft}^2\text{·°F)}}$

[2]Additional information concerning the design and construction of synthethically insulated ground pads is given by Wellman, J.H., Clarke, E.S., and Condo, A.C. in "Design and construction of synthetically insulated gravel pads in the Alaskan Arctic: Presented at 2nd Int. Symp. Cold Regions Eng., Univ., Alaska, August 12-14, 1977.

Required R values for the insulation were determined based on computer simulations of the workpad thermal regime. They varied from 3.4 to 13.4 hr·ft^2·°F/Btu depending on location and the short- or long-term design case. The specification utilizing an R value allowed the contractor to select from available commercial products and vary thickness to obtain the required short-term R value. The insulation selected was polystyrene with a maximum k value of 0.24 Btu·in./hr·ft^2·°F at 40°F, a minimum compressive strength of 40 psi at ten per cent deflection, and a low moisture absorption.

A 24-inch minimum thickness of gravel was required for Types A, B, and C traffic courses (Table 2).

TABLE 2. Traffic course gradations

Sieve size	Gradation type		
	A	B	C
	%	%	%
12-inch	100	100	100
4-inch	100	80 - 100	80 - 100
No. 4	7 - 32	10 - 70	4 - 70
No. 40	7 - 32	6 - 42	0 - 42
No. 200	0 - 12	0 - 15	0 - 20

Note: Gradations given as percentage passing by weight.

The embankment materials were classified thus to allow for some localized compression of the insulation. The insulation thickness required for Type A was computed from Table 1 using an insulation conductivity of 0.25 Btu·in./hr·ft^2·°F. For Type B the insulation thickness was increased by 15 per cent and for Type C 40 per cent. Increased insulation thickness was required for Types B and C to compensate for damage to insulation by large particle size. Compressive strength specifications for the insulation were based on the ASTM D-1621-64 test procedures. Shear strength was required to be 21 psi as determined by ASTM C-273.

The insulated workpad is strictly an overlay structure. The snow removal and tundra-levelling operations were accomplished during the winter months and tundra disturbance was limited to scalping the upper portion of the organic materials. Guidelines of 50 per cent exposed organic materials were used during construction to determine scalping limits. The polystyrene board stock was placed directly on the scalped and levelled tundra. Where two or more layers of insulation boards were used, the joints between boards were staggered from layer to layer. All phases of embankment construction were conducted in the minimum practical space to minimize snow clearing. The traffic course was placed by end dumping and spread with a rolling surcharge technique to prevent damage and slippage of the insulation.

Foremost in establishing structural criteria for the insulated workpad was consideration of compressive and shear stresses developed within the insulation. The traffic course thickness was determined by the structural requirements necessary to sufficiently attenuate traffic-induced stresses at the depth of the insulation. The analysis was based on the load imposed by the rear wheels of a loaded Euclid R-35 end dump construction vehicle at rest on the insulated workpad; a 1.3 factor of safety accounted for impact loadings and minor deviations from the design thickness.

Insulated Workpad Evaluation Program

The field program to evaluate the condition of the insulated workpad was completed in two parts during the winter of 1979-1980 and the summer of 1980 (Clarke *et al.* 1981).

During the winter of 1979-1980, test borings were completed on areas of anticipated workpad distress. Sixteen borings were put down at eight locations. At each location one boring was near a vertical support member (VSM) and the other was between two VSM bents. Standard sampling methods were used to obtain insulation and soils data. Thermistor tubes were installed to permit the installation of thermistor strings. The insulation and generalized subsurface conditions encountered during this portion of the investigation are listed (Table 3).

In July, 1980, a team of engineers was assembled to investigate the condition and performance of the insulated workpad by observing surface conditions; excavating shallow trenches with a backhoe; sampling and laboratory testing of traffic course material; observing in-place condition of insulation; sampling and laboratory testing of insulation; sampling of subgrade material where thawed; probing for thaw depths across the workpad; installing thermistor strings in borings; and observing surface and subsurface water conditions below and adjacent to the workpad.

At nine sites north of the Brooks Range, a backhoe trench was excavated to the top of the insulation, where present. The average thickness of the workpad over the insulation was measured, and groundwater conditions were noted. Hand excavation was used to expose the surface of the insulation and enabled the field crew to cut sections for testing. Once the insulation sample was removed, the thermal state of the subgrade was noted. Where thawed subgrade was encountered, a sample was obtained for examination and classification under laboratory conditions. The insulation samples were replaced with pieces of new insulation. Conditions encountered during the field program are summarized (Table 4).

Indicators of workpad performance were noted in detail as part of the field program. Categories of indicators included topography, drainage, workpad characteristics, insulation characteristics, subgrade soil and thermal conditions, and evidence of post-construction remedial activity.

Insulation characteristics in particular were considered to be a key in assessing workpad performance.

TABLE 3. Insulated workpad: summary of boring results

Milepost* location	Insulation thickness	Workpad material	*In situ* soil
156.8	No insulation	Sandy gravel with trace of silt 3.5 ft deep. Numerous cobbles and boulders.	Silty sand to 18.5 ft changing to gravelly sand to 35 ft.
141.6	3"	Gravelly sand with cobbles 3.5 ft deep.	Organic material and silt to 6 ft, sand and silt with 5% visible ice to 20 ft.
118.8	3½"	Sandy gravel with silt 1.5 to 3 ft deep.	Snow and ice 1.5 ft deep. Organic material and silt with 15 to 20% visible ice to 10 ft.
101.9	Varies 0-3"	Sandy gravel with silt 1.5 to 3 ft deep.	Organic material and silt with 15 to 40% visible ice to 30 ft.
91.7	3"	Sandy gravel 1.5 ft deep.	Gravel with boulders and gravel, refusal at 3 ft.
88.2	3"	Sandy gravel 2.5 ft deep.	Organic material over massive ice to 25 ft.
11.2	1.5"	Sandy gravel 2 ft thick.	Sandy silt with 15 to 60% visible ice to 13 ft.
11.1	1.5"	Sandy gravel 1 foot thick.	Organic material and silt up to 100% visible ice to 15 ft.

*Milepost 0 is at Prudhoe Bay.

TABLE 4. Insulated workpad conditions

Milepost location	General site conditions	Traffic course thickness	Insulation thickness	Insulation condition/ gaps	Estimated insulation dent Diameter	Estimated insulation dent Depth	Estimated percentage of surface effected	Subgrade conditions	Remarks
MP 156.8	Good workpad surface, some ponding.	1.0'-2.8'	No insulation.	No insulation.				Thaw to >5 ft.	Subgrade material gravel with no visible ice.
MP 156.7	Good surface.	2.6'	3 1/2" (2" and 1 1/2")	Good No gaps >2"	1 1/2"	3/4"	50%	Frozen below insulation.	Ice under the insulation.
MP 157.1	Water flowing through workpad material.	2.0'	No insulation.	No insulation.				Thawed below workpad material.	Water table 18" below workpad surface.
MP 141.6	Good workpad surface.	2.2'	3 1/2" (2" and 1 1/2")	Good, minimal gaps.	1 1/2"	1/4"	40%	Frozen but minor thaw likely each season.	Slight amount of water above insulation due to ponding.
MP 118.8	Good workpad surface.	1.7'	3" (1 1/2" plus 2")	Good, gaps <1"	1"	1/2"	40%	Frozen compacted snow.	Subgrade under insulation has no indication of any melt in preceding years.
MP 101.9	Workpad subsidence due to low-water crossing and thaw.	1.5'-2.0'	3" (1 1/2" plus 1 1/2") where evident.	Gaps >2 ft	2"	1/4"	90%	Thaw >1 foot under insulation.	Groundwater above insulation at part of test site.
MP 88.2	Settlement due to low-water crossing expected.	3.0'	3" (1 1/2" plus 1 1/2")	Some gaps to 2".	4"	1/2"	70%	Marginally frozen 31.9°F thaw 1-2".	Thaw due to low-water crossing deterioration.
MP 11.2	Good	1.5'-2.5' varies.	1 1/2" single layer.	Some gaps to 4" - thaw at joints.	2"	1/4"	50%	Varies thawed to frozen.	Thaw under insulation at toe of slope and under gaps.
MP 11.1	Settlement due to low-water crossing.	1.5'-2.5'	1 1/2" single layer.	Gaps to 2 ft.	2"	1/4"	50%	Varies thawed to frozen.	Moving water through workpad material; low-water crossing.

The number of layers and care of their placement appear to have a more significant effect than the physical properties of the insulation material, such as thermal conductivity, moisture absorption, and deformation (compression, cracking, denting). Significant thaw below the workpad was only observed where the insulation was missing or where there were gaps in the insulation. Other indicators of insulation performance included depth of thaw beneath the bottom layer, evidence of previous melting and refreezing, and presence of snow.

Fourteen samples of insulation were sent to a commercial testing laboratory for a series of tests. These tests include determination of thermal conductivity, moisture content, density, and moisture absorption. The eleven samples tested had thermal conductivities at 40°F of 0.21 Btu·in./hr·ft^2·°F or lower. These conductivities were within the parameters assumed in the original design calculations. Moisture content of the eleven insulation samples tested ranged from 0.83 to 0.03 per cent by volume.

The condition of the soil or snow under the insulation was used as an indicator of the performance of the insulation. In some cases, large ice crystals were encountered under the insulation. This recrystallization could have occurred as a result of warmer, but still subfreezing, temperatures and recrystallization, and suggests that the insulation has prevented melting under the insulation. This type of feature was observed at milepost (MP) 141.6 and MP 118.8. In the event that melting had occurred, a layer of ice would be expected under the insulation. A layer of ice was encountered at MP 156.7.

In some cases, compressed frozen organic material and snow were encountered under the insulation. This would indicate that minimal temperatures were maintained under the insulation. These conditions were encountered in portions of the test trenches at MP 88.2 and 11.2.

In areas where there was no insulation or gaps in the insulation, thawed conditions were encountered. This condition was encountered in the test trenches at MP 156.8, MP 157.1, MP 101.9, MP 88.2, MP 11.2, and MP 11.1. The size of the gap greatly influenced the amount of thaw.

The areas which had 1.5 ft, or more, of workpad material over the insulation did not exhibit excessive compression of the insulation. Pre-construction planning assumed that up to 40 per cent of the effective thickness of the insulation would be lost through compressive failure of the insulation due to wheel loads transmitted by the very rocky workpad material. During the test trench program this degree of deformation was not apparent.

Of particular interest was the observation that the insulation under the traffic lane showed no more evidence of compressive failure than the insulation between VSM bents. This adds credibility to the assumption that damage to the workpad and insulation occurs mostly during the construction of the workpad and not during pipeline construction.

Thermistor strings were installed at each field site investigated and readings have been obtained on a periodic basis since June, 1980. The data available so far is limited and has not yet been analyzed in detail. Nevertheless, in July, the temperatures a few feet below the insulation ranged from the mid- to low-20's, which is below the VSM design temperature of 30°F.

Notably, the majority of test site locations were selected by the authors as potential problem areas. Emphasis was placed on studying areas of expected poor performance. During the period of intense construction activity the insulated workpad successfully supported all of the heavy construction wheel loads except in the following areas: First, where low water crossings (LWCs) were not excavated to sufficient depths and maintenance grading exposed the insulation to wheel loads; and secondly, where the workpad became saturated with ponded water and was breached to allow drainage across the workpad. Some of the drainage areas where the workpad was breached and the insulation removed have experienced settlement due to melting of the underlying ice-rich soils. A temporary repair was made by filling the settled area with gravel.

Conclusions

The use of a polystyrene-insulated workpad resulted in significant cost savings for owners of TAPS through a reduced requirement for gravel embankment materials and reduction in the embedment length of VSM. The reduction in use of borrow sources also reduced terrain disturbance and environmental damage associated with this development. With the exception of areas of localized distress, typical of those discussed in this report, the eighty miles of insulated workpad performed within the design intent. Due to the expected and verified thaw at some locations, significant damage to the workpad could be expected at these locations if utilized for another major construction effort.

The evaluation program documented that the major cause of settlement of the workpad surface and subgrade thaw was due to construction problems where insulation either was not placed or was placed with gaps between the adjacent panels. The effect of placement problems was most pronounced in the northernmost sections of the insulated workpad where only a single layer of insulation was needed to obtain the required thickness. the second cause of workpad settlement and subgrade thaw was post-construction activity (such as LWC construction) which removed or damaged the insulation layer. This generally resulted in localized areas of distress.

In areas where insulation was not placed or where post-construction activity damaged or removed the layer of insulation, there is a potential for active layer growth in excess of design. Preliminary results of the thermistor data indicate subsurface soil temperatures are still below design values, but thaw depths beyond the design values could result in increased heave forces acting on the VSM. Temperature measurements from the thermistors will allow continued monitoring to assure long-term VSM integrity.

The insulation samples tested met the original design intent for thermal conductivity. Compression or damage from wheel loads transmitted through the traffic course was less than expected.

In several areas less than the required amount (two feet) of structural traffic course material was encountered. Failures and significant compression of the insulation, however, due to excessive subgrade pressures resulting from heavy construction wheel loads were not encountered. Evidence indicates that the original design criteria for minimum traffic course thickness which was based on the overlapping effects of the rear wheels of a loaded R-35 end dump may have been conservative. Future projects should consider the use of either reduced insulation thickness or reduced thickness of traffic course.

Structural Workpad

The structural workpad was designed to support equipment and to allow its mobility on various types of terrain, while minimizing disturbance of the terrain. To accomplish this objective, an embankment of select soils was used where in-place soils were unsuitable for equipment operation. The embankment reduced high bearing pressures associated with construction wheel loads and compensated for thaw strain in the underlying soils during the period of intensive use during construction activities. Loss of capacity to support heavy wheel loads on the workpad due to thawing permafrost was not expected to be a problem after construction, since operations traffic would consist of light maintenance and inspection equipment.

Design Summary

Design requirements for the TAPS pipeline construction structural workpad differed from those of roadway embankments, in that workpad requirements call for a limited-life embankment capable of bearing repetitive traffic during summer pipeline construction. Acceptable standards of performance for the workpad surface are relatively low, with an allowance for continual maintenance. Design life was based on a three-year construction schedule. A workpad surface condition which permitted vehicle speeds of ten miles per hour, except where limited by steep grades and rutting less than twelve inches deep, was considered to be the minimum performance level (*see* Footnote 1). Where this minimum speed could not be achieved, corrective maintenance was required.

For design purposes, it was assumed that the workpad must be capable of a trafficability loading requirement equivalent to 20,000 passes of an on-highway truck with a 4.5-kip wheel load during summer trafficking throughout the period of pipeline construction.

The equivalent wheel loads (Table 5) represent equivalent performance for general different vehicle loading conditions. One pass of a loaded R-35 Euclid is approximately equal to 2.4 passes of an empty R-35 or 26 passes of an on-highway truck. An approximate embankment design will allow either 700 passes of a loaded R-35, 1818 passes of an empty R-35, or a combination such as 385 passes of a loaded R-35 plus 10,000 passes of a 4.5-kip wheel load from an on-highway truck.

Load repetitions, which are imposed during winter periods when both the embankment and foundation material are frozen, did not apply to equivalent load computations.

Equipment loads on the work surface were expected for both summer and winter construction activities. Such equipment included earth-hauling equipment, earthmoving equipment, pipe-stringing trucks, drill rigs, sideboom tractors, cranes, pipe benders, and other such equipment. The heaviest traffic on the workpad, however, occurred during the actual pad construction.

The thickness design was based on the expected loading conditions during the summer season. In areas where this base design traffic loading condition was to be exceeded, additional requirements for embankment thickness were anticipated. Similarly, where loading conditions in the field were determined to be less than the base design, less embankment thickness was required.

The procedures used for determination of the construction workpad embankment thickness for the pipeline construction in non-permafrost and warm permafrost areas, where permafrost thaw could not be prevented practically, were collectively referred to as the "components procedure". The components procedure was modified from highway design procedures and reflected the limited trafficability requirements of the pipeline construction workpad.

The workpad thickness was determined by the following relationship:

$$D = d_b + d_t + d_s$$

where: d_b = basic thickness component to support anticipated wheel loadings for a particular subgrade type;

d_t = thickness resulting from relatively low strengths of thawing permafrost soils; and

d_s = thickness for summer workpad construction in permafrost areas.

These three components reflected special design considerations for construction in permafrost terrain. The d_b component provided for adequate structural embankment thickness to overlay various soil types, regardless of their thermal state. The d_t component was the additional embankment thickness to account for the weak, deformable nature of thawing ice-rich permafrost. Soil strength and thaw settlement were both related to ice content. Thaw settlement which had been calculated for a thaw depth of five feet below the bottom of the embankment was used as an index of thawing-permafrost strength. The d_s component was the additional embankment thickness required for summer workpad construction. During the summer period, thawed, subgrade, active layer

TABLE 5. Equivalent wheel load for several vehicle loading conditions

Vehicle	Wheel load (kips)	Repetitions required to equal 20,000 repetitions of a 4.5-kip load	Equivalent wheel load factor	Ratio of repetitions
R-35 Euclid loaded	21.4	700	26	1
R-35 Euclid empty	14.7	1,818	11	2.4
On highway truck	4.5	20,000	1	26

soils were considered to have low strength and to not fully compact, thus additional overlay of the structural embankment was required.

To verify the components method, field tests were performed at two locations along the pipeline alignment. These tests provided verification of the components summation procedure by displaying performance characteristics which agreed with values determined from the components procedure. In addition, these field tests provided input data for the development of an analytical structural model. The analytical model was a finite-element simulation of stress–strain conditions in a multi-layered embankment. Data from the field workpad tests were used to calibrate the model for actual field performance. The analytical model was used to determine embankment thickness values for 496 sections along the alignment for comparison with components method values. The values determined by both methods were equivalent within the accuracy of field test results, analytical procedures, and soil data along the alignment. The components method had been used early in the design for practical reasons and the results of this design approach were considered to be generally reasonable.

Structural Workpad Evaluation

The field program for evaluation of the TAPS structural workpad was partially complete when the U.S. Congress aproved a 200-foot separation distance between the ANGTS gasline and existing facilities such as the TAPS oil line. That portion of the field program which included drilling and trenching was suspended. The evaluation of the reasons for distress of the structural workpad are therefore restricted to surface field observation and boring/trench log data collected during the design and construction of TAPS.

Several of the observed distress features discussed and illustrated are often found at the same inspection site. In other words, it was not uncommon to find two or more types of distress at one location. This can be explained by the fact that several types of surface distress features are characteristic of the same or a similar cause.

Thermokarst settlement resulting in the formation of sink-holes ranging in size from as small as one foot diameter and one foot deep to as large as 20 feet in diameter and six feet deep were observed on, and adjacent to, the workpad. One of the larger sinkholes adjacent to the buried pipeline approximately 20 miles south of Prudhoe Bay (Figure 1). These thermokarst depressions (Figure 2) in some cases encompassed the entire workpad area. Numerous areas of both uniform and differential workpad settlement (Figure 3) caused by thawing of underlying soils were observed adjacent to both the above- and below-ground pipeline segments.

When the ditch backfill material adjacent to the workpad has settled below the adjacent native soils, longitudinal cracks develop at the edges of the former trench (Figure 4). The settlement is typically due to poor compaction of the ditch backfill or thawing of a backfill material which was placed in a frozen state (Figure 5). Although this type of distress does not materially affect the trafficability of the workpad, it can aggravate drainage and erosion problems proximate to the pad. When ice-rich overburden soils thaw and settle adjacent to a ditch backfilled with granular material, a mounding condition over the buried pipe is observed with longitudinal cracks at both the edge of the former trench and the limits of the thaw bulb. Longitudinal tension cracks may also be present over pipe centreline due to loss of backfill side support (Figure 6). Typically the pipe is founded in an

FIGURE 1. Massive sinkhole adjacent to the buried pipeline. This is a polygonal ground area where the workpad and pipeline intersect ice wedge.

FIGURE 2. Thermokarst depression encompassing the travel lane of the workpad.

FIGURE 3. Differential settlement of the workpad in an elevated pipeline segment.

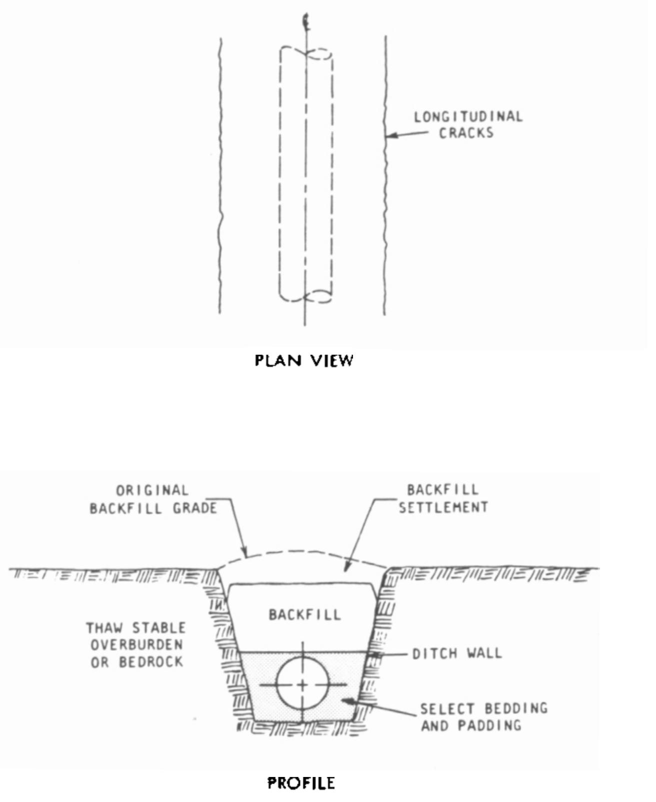

FIGURE 4. Settlement of ditch backfill material

FIGURE 5. Cracking adjacent to a buried pipeline with a depressed area over pipe centreline.

underlying stratum of thaw-stable soil or bedrock and the observed differential settlement is due to the thaw bulb advancing through the ice-rich overburden (Figure 7). Continued growth of the thaw bulb in these ice-rich overburden areas results in almost complete loss of trafficability of the workpad.

Lateral movement of the workpad was observed on cross-sloping ground. This was evidenced by longitudinal cracking and mounding on the uphill side of the vertical support members (Figure 8). This distress occurred where frozen fine-grained soils with high moisture content were thawing below the workpad embankment.

When ice-rich and fine-grained soils beneath the workpad thermally degrade due to disturbance associated with construction, surface distress occurs in a number of forms. Surface distress is commonly observed in above-ground segments (Figure 9). Longitudinal cracks develop near the outside edge of the workpad and adjacent to the VSM due to differential settlement associated with the shape of the thaw bulb. The longitudinal cracks can also indicate lateral workpad movement or edge of pad failures on a weak, thawing bearing layer. Sinkholes and massive depressions occur where the bulb advances through a zone of massive ice or a strata of ice-rich material. Where the soils underlying the workpad are fine-grained, the granular workpad material can become contaminated with fines and lose its capability to support even light operational-type traffic.

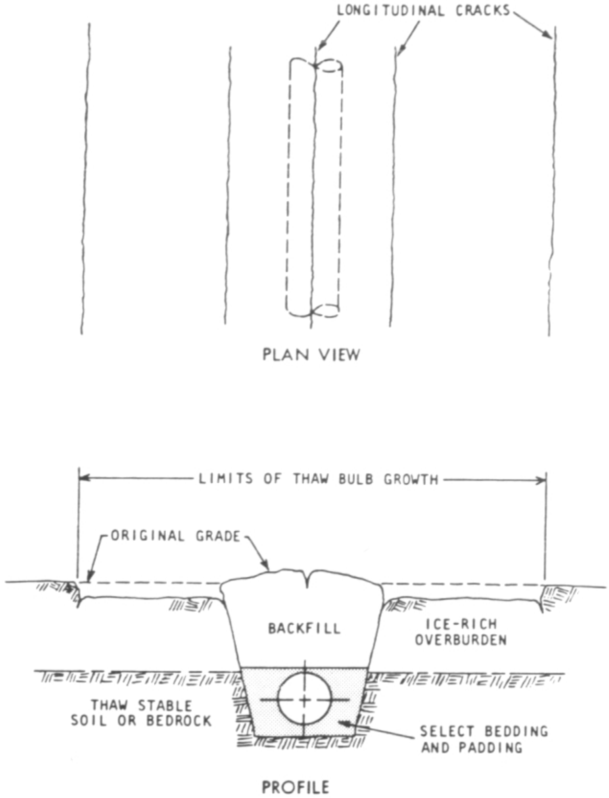

FIGURE 6. Thaw settlement of ice-rich overburden.

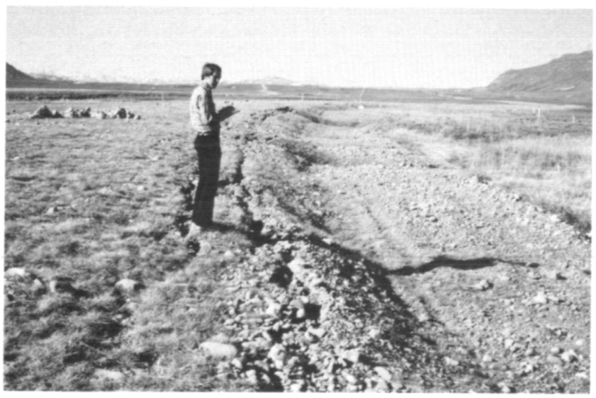

FIGURE 7. Cracking adjacent to a buried pipeline with mounding over pipe centreline.

FIGURE 8. Lateral workpad movement on a cross slope with resulting mounding on the uphill side of the vertical support member and a gap on the downhill side.

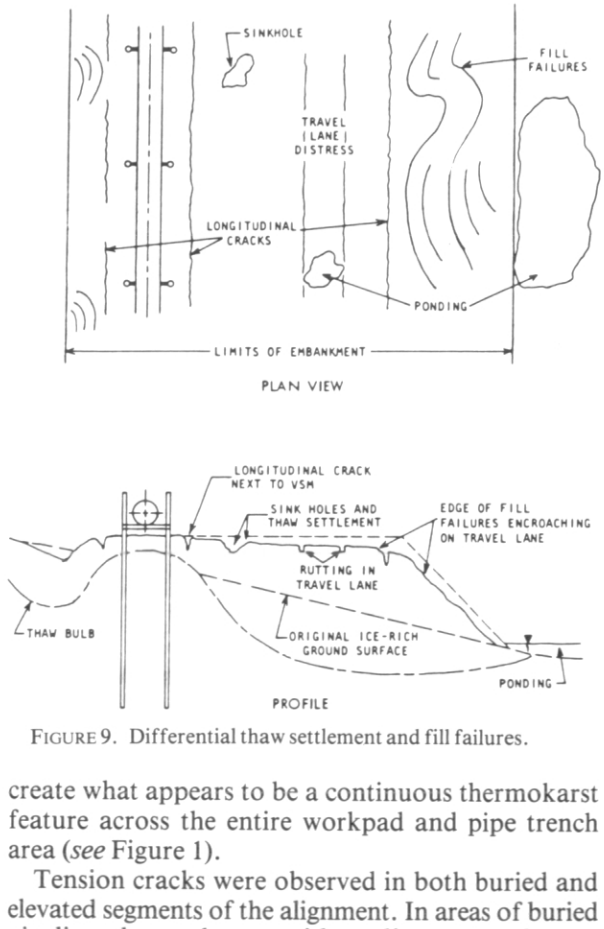

FIGURE 9. Differential thaw settlement and fill failures.

When the pipe is buried in an area of polygonal ground, settlement due to melting of massive ice within the thaw bulb occurs. Due to the irregular shapes and sizes of the ice masses, ground surface deformation is varied, but typically includes massive sinkholes, differential settlement, and ponding in the resulting depressions (Figure 10). The melting of ice wedges that intersect the trench area can cause a slumping of the ditch backfill into a sinkhole and create what appears to be a continuous thermokarst feature across the entire workpad and pipe trench area (*see* Figure 1).

Tension cracks were observed in both buried and elevated segments of the alignment. In areas of buried pipeline, the cracks were either adjacent to a depression over the pipeline or adjacent to mounding over the pipeline. In elevated segments, the cracking was observed at various locations on the workpad but

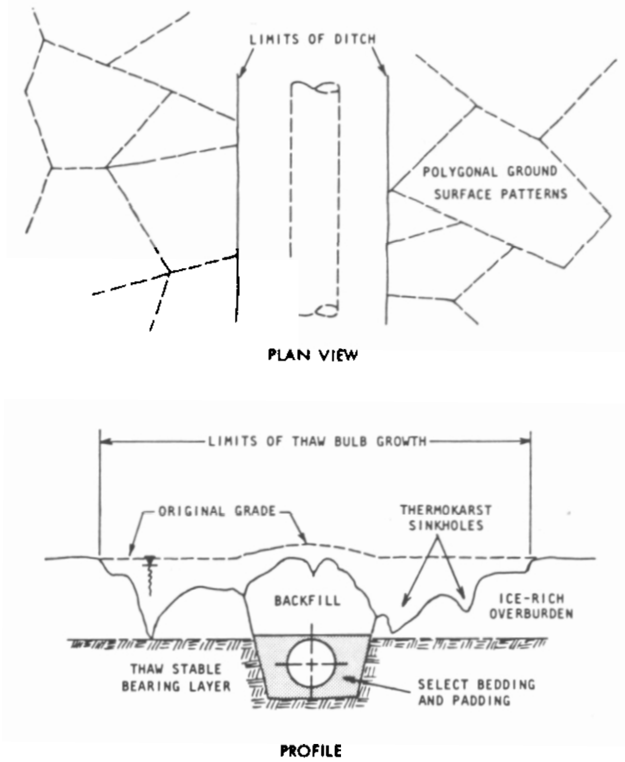

FIGURE 10. Melting of massive ice wedges in overburden.

FIGURE 12. Edge of workpad mudflow failures. Saturated fine-grained workpad material.

FIGURE 13. Ponding on, and adjacent to, the workpad in an elevated pipeline segment.

FIGURE 11. Longitudinal tension cracks on the workpad in an elevated segment of the pipeline.

FIGURE 14. Soft, saturated, and badly rutted workpad.

predominantly in the longitudinal direction (Figure 11).

Edge of workpad failures in the form of ravelling fill slopes, minor rotational slumping of fill slopes, and mudflows on saturated pad material were inpected. These minor failures were encroaching on the travel lane of the workpad at several locations. Figure 12 illustrates an edge of workpad mudflow.

Ponding on and adjacent to the workpad was observed at many locations (Figure 13). Saturation of the workpad, especially in areas of ponding and workpad subsidence, have reduced trafficability even for light, wheel load vehicles (Figure 14).

Conclusions

The design of the structural workpad on TAPS was adequate to allow the application of heavy construction wheel loads during up to three years of pipeline construction. Deterioration of the structural workpad in permafrost areas was as expected and has resulted in weakening of the subgrade. In many areas of soft subgrade materials and/or the thawing of soils with high moisture content the design life of the workpad has been reached. Fines have been pumped into the overlay material which has resulted in a loss of trafficability. Present maintenance allows for passage of light, wheel load surveillance and pipeline maintenance vehicles but overall these areas cannot withstand additional summer trafficking by heavy wheel loads without the addition of new overlay or removal and replacement of existing workpad material.

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Reference

CLARKE, E.S., KRZEWINSKI, T.G., AND METZ, M.C. 1981. Trans-Alaska Pipeline System Synthetically insulated Workpad—An Evaluation of Present Conditions. Energy-Sources Technol. Conf. and Exhibition; Houston, Texas; January 18-21, 1981, 9 p.