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ABSTRACT

The development of vitally important Arctic petroleum resources presents new and interesting challenges. Although the answers to some questions will undoubtedly undoubtedly go unresolved until considerable operating experience has accrued, we can improve our present insight through an awareness of the work performed by others under similar conditions. This presentation focuses on Soviet pipelining experience in arctic and subarctic regions of Siberia.

Discovery of North America's largest oilfield, Prudhoe Bay, came at a time when oil production from traditional sources within the United States was dwindling. At the same time, our proven natural gas reserves had also begun to decline.

The United States was not only being forced into increasing dependence upon foreign supplies but its *eventual* ability to meet overall future energy demands was questionable.

The motivation for prompt development of these vast new reserves of oil and gas is evident. However, the uncertainties emanating from a lack of experience in both petroleum production and pipelining in permafrost areas have proven to be more of a problem than had been contemplated by many early observers.

Ironically, this extremely forbidding area of our nation also has a very fragile ecology. The slightest damage to the skin of this rugged land may be capable of causing irreparable damage.

Moreover, this comes at a time when civilization has, as a matter of selfpreservation, been forced into an awareness of the critical environmental problems which confront us. Many Americans in the lower 48, as well as Alaskans, are determined to preserve our last major wilderness.

It is obvious that we must tap the enormous energy resources which exist in our Arctic and subarctic regions. However, we must be able to establish that the ultimate gains will outweigh the ultimate losses.

This basic economic reality is certainly not a new concept, but within the realm of today's values and priorities emphasis is placed on the proposition that we must be reasonably assured that no serious, permanent ecological damage will be incurred.

The most persuasive arguments in this area will be provided by examples derived from experience gained from actual operating facilities or from full-scale on-site test facilities.

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EXPERIENCE LACK

By virtue of the nature of our geography, our operating experience in pipelining under these conditions is nil. On the other hand, the Russians, with half of their territory underlain with varying forms of permafrost, began construction of gas pipelines in Arctic areas in 1964. To date, the Soviets have completed Arctic pipelines in sizes through 48 in., are constructing a 56-in. pipeline, and are planning others in sizes through 99-in. Although the design criteria for these gas-transmission pipelines are quite different from those of our proposed hot-oil pipelines, we feel that our endeavors in both the oil and gas Arctic-pipelining fields can profit from an awareness of their work.

In this regard, Williams Brothers Engineering Co. has collected and translated a number of articles on the subject which have been published in Russian periodicals and trade journals.

Although a number of papers on similar subjects have been translated and frequently published by others, to the best of our knowledge the material in this collection represents its first translation and distribution outside the Soviet Union.

PREVAILING CONDITIONS

The geographical scope of the articles encompasses the regions of the Soviet Union which lie to the north of the 60th parallel, as well as areas of permafrost extension. Despite the diverse climatic, geologic and hydrologic conditions of this immense territory, several common natural characteristics bear relevance to the technological aspects of Arctic pipelining.

Among these are:

1. An enduring winter season of 8-10 months with polar nights and air temperature dropping to as low as -65°F.

2. A short but relatively hot summer with air temperature as high as 85°F.

3. Wind velocities to 85 mph and substantially higher in certain maritime regions; and

4. Extensive swamps and floodlands consisting of moisture-saturated silty soils which have a propensity to heave and that, when thawing, have little load-bearing capacity.

Furthermore, railroads and highways are nearly non-existent, the river-navigation period is very short, and many areas are totally uninhabited.

A combination of low temperatures and high winds necessitates particularly strict observance of safety regulations. For instance, experience in Northwestern Siberia has shown that with air temperatures of +5°F., and a wind velocity of 20 mph, continuous open-air work can only be permitted for a maximum of 50 min. Then, a 10-min rest period must follow for warming.

When wind velocities reach 50 mph, all open-air work stops completely, regardless of the temperature. Work during completely calm -50°F. weather is also prohibited.

Winter clothing normally used in northern climates is unsuitable beyond the Arctic Circle where fur or other special clothing is required.

Construction conditions in regions of permafrost are exceptionally sensitive and unique. They are manifested in different ways depending upon the magnitude of the permafrost layer, its temperature conditions, and the characteristics and moisture content of the soil.

The geocryologic character is determined by the heat and mass transfer between the atmosphere and the frozen stratum, as well as by the prevailing soil composition.

In the construction of buildings, felling of clearings, building of roads, construction of pipelines, and any other activities associated with a change of the surface the heat-transfer conditions are disturbed. The new surface heat balance leads to a change of the heat condition of subsurface-rock formations and the depth of the seasonal freezing and thawing.

This generates such cryogenic processes as: frost cracks; soil bulging and sagging; overglazed ice; sloughing of soil by means of mud flow, called suffusion; and creeping of the thawed-soil layer along the inclined upper surface of the permafrost, known as solifluction.

Such occurrences alter the ground surface and can cause considerable stresses in underground pipelines. A combination of these stresses and those caused by temperature changes and internal pipeline pressure could result in pipeline failure.

SURVEYING, PLANNING

One of the main problems of planning an Arctic pipeline is providing special techniques which will prevent surface disturbance and thereby, assure the stability of the pipeline.

In permafrost regions, selection of the pipeline route, determination of the appropriate installation method, and formulation of an adequate logistical support system must be considered not only in relation to existing conditions, but also in relation to those conditions originating as a result of the interaction of the pipeline with the natural environment.

Consequently, the problem arises of forecasting the new geocryologic conditions brought about by the nonambient characteristics of the pipeline. To accomplish this, comprehensive investigations must first be made along the pipeline route to determine the natural conditions.

A determination must then be made as to the direction and intensity of the generated cryogenic processes. In doing so, each of the local variations must be considered in order to obtain an exact definition of the new heat balance which can then be applied to specify the new conditions.

Exploration to determine these factors is very complex. In addition to the usual operations associated with pipeline-route selection it is necessary to study the thickness of the active-soil layer that is above the permafrost and which can be expected to freeze and thaw during normal season cycles.

Of equal importance are: (a) the depth and thickness of underground ice formations; (b) heaving properties of the soil; (c) places of potential formation of swelling mounds and soil collapse known as thermokarst; (d) temperature conditions of frozen soils; (e) the predicted dynamics of the temperature field caused by the pipeline, and (f) anticipated changes in the heat-moisture content of the soils.

Conventional methods of exploration, such as drilling and poking, for locating vein-structured underground-ice formations have not proven to be reliable. This makes special electrosounding geophysical studies necessary.

The complexity of the situation makes it rather difficult to fully establish the parameters needed to determine the possibility and intensity of most of these phenomena. This is particularly true during the course of a one-time survey along a considerably lengthy pipeline route.

Should parameters be based upon the results of one-time surveys, they must be conservatively formulated from the most unfavorable combinations of conditions. In all likelihood, they will not provide adequate criteria for the optimum design.

NEEDS VARY WITH TYPES

The extent and direction of exploration is strongly dependent upon the type of pipelaying adopted for the project. This is a factor which generally cannot be decided prior to initial exploratory work.

Aboveground pipeline installation requires a more detailed topographic examination, while the extent of the geotechnical work may be sharply reduced. At river crossings it is necessary to carefully study soil conditions on the shore, where supports for the crossing are located, while detailed exploration of the river bed is unnecessary.

On the other hand, underground installation requires a less detailed topographic exploration, but more detailed geotechnical and cryological investigations. Also, a full set of topographic, geotechnical, and hydrological investigations of the river bed and its water conditions will be required.

If the pipeline is to be laid directly on top of the ground, or semi-buried, the problem of surface-water drainage must be resolved.

It can be seen that the geocryologic studies that permit the development of reliable and complete information for forecasting are an integral part of the engineering surveys in permafrost areas. Only after careful consideration of the information derived from these studies can be optimum route and installation system be proposed..

GEOCRYOLOGICAL GROUPS

The diverse landscape complexes occurring in the northern part of Western Siberia can be assembled into six representative groups:

1. The most prevalent conditions are those of the first group. This consists of level, slightly hilly, or forested tundra, with an 8-10-in.-thick moss cover. It is dissected by vertical ice wedge polygons and is often swampy and covered with tussocks.

The soil is generally an uncohesive sandy loam or a highly icy loam, and thin veins of ice are often found. One of the main peculiarities of this group is the thixotropic nature of the soil, which is expressed by deterioration under the influence of dynamic loads.

The temperature of the soil at the depth where seasonal variations cease to have any effect ranges from 15°F. to just below freezing. The depth of summer thawing is 2-5 ft, although individual spot thawing of 5-7 ft is found. The moisture content of the active layer varies from 15-25% in sandy varieties to 35-50% in loams.

2. The second group is characterized by peat massifs 1,000-1,200 ft across, 7-15-ft-thick, and often dissected by polygons. The peat temperature is 25°-28°F. and its moisture content seldom exceeds 50% by volume. The depth of summer thawing is not more than 20-30 in.

3. The third group includes well-drained sections of plateaus and water-sheds. These are made up of loams with icy sandy patches, and the permafrost is interfluent. The temperature of the soil is 28°-30°F. and the depth of the summer thawing is 5-8 ft.

4. The elements of the fourth group possess the best characteristics for pipelining, that is, surfaces of dry, well-drained strata, composed of sandy loams and loams that are interspersed with gravel. The permafrost is not interfluent and the temperature of the frozen soil is 31°-32°F.

As a rule, the surface is forested and the depth to the uppermost layer of permafrost is a minimum of 25-30 ft. This group can include sections where noncrumbling rocky ground is directly exposed to the surface or covered by a thin layer of loose, low-moisture-content deposits.

5. To the fifth group belong the flood plains of large rivers. Normally, the depth to frozen rock deposits exceeds 25-35 ft and the soil is composed of a highly moist alluvial material that, in the majority of cases, is superimposed by highly moist loams.

6. The sixth group combines the least desirable elements such as peat hillocks, swelling mounds, thermokarst formations, and sections of slopes that are unsafe from the viewpoint of the generation of solifluction or earth creeping.

UNDERGROUND CONSTRUCTION

The Soviets have found that underground gas pipeline installation, despite being the most widely used method under normal conditions, is generally not feasible in the regions under discussion. The main reason is the difficulty of eliminating the heat effect of the pipeline in highly moist frozen ground.

Underground installation in dry, well-drained environment of the fourth group is feasible. However, the effect of burying a pipeline in ground with conditions described in the other groups would be the subsequent generation of a thick thawing aureole along the entire length of buried section.

Such a condition would be accompanied by the pipeline's sagging or floating in the melted soil pulp. This thermokarst phenomena develops from the collapse of the surface due to a melting of fossil ice with a corresponding diminution of volume resulting from the transformation of ice into water.

A primary threat to the pipeline is the condition of highly disparate soil and ice-content conditions closely adjacent to each other that result in widely different active thaw levels and frost forces.

This can cause irregular sagging and thrusting thereby producing high stresses that will destroy the pipe. Replacing the ground underneath the pipeline with heat insulation does not by itself appear to be a remedy as the insulation would become saturated with water, obviating its effectiveness.

Ground heaving caused by frost creates similar problems and is observed in areas of highly contrasting rock formations and soil humidities. Bulging mounds, emerging in areas with a continued inflow of interfrost waters during soil freezing, are especially dangerous.

Continuously widening ravines with subsequent destruction of the gradually exposed pipeline can be produced either by: (a) thermokarst phenomena or, (b) by soil suffusion that starts in trenches and ruts produced on the right-of-way during construction.

It is difficult to calculate the stresses on an underground pipeline located in a suffusion landslide area. It can be destroyed along the borders of the slide.

SURFACE CONSTRUCTION

Pipeline installation directly on top of the ground is occasionally practiced under normal conditions, but does not appear to be exceptionally practical in permafrost areas unless the pipe is highly insulated. Some of the same adverse heat effects discussed for buried installations also apply here.

Furthermore, the use of an earthen cover for large-diameter on-the-ground pipelines would notably change the surface geometry. This would interfere with natural drainage as well as alter the heat-transfer conditions of the surrounding area.

Much of the success of a surface line covered by an earth berm depends upon the type of soil. Earthen cover in permafrost zones in areas of high ice content is closely tied to seasonal variations. If the cover is placed in the summertime, the thawed active layer is buried below it.

For large-diameter pipelines, requiring thick cover, this means that a defrosted trough-shaped layer may be maintained beneath the center of the cover. In the case of filtrating soils this layer acts as a drain, its depth and moisture content increasing during the summer period.

Observation of earthern cover in permafrost zones has shown that this often results in the ground's acquiring the consistency of running sands. Propagation of the defrosted layer causes sags along the axis of the cover and any uneven sagging causes deformation of the cover and stress on the pipeline.

Furthermore, a partial draining and drying of adjacent fields leads to a considerable increase in the thickness of the active layer; a factor that in itself can be a source of intensification of the thermokarst processes.

Conversely, when the cover is placed in the wintertime a layer of frozen ground is buried below it. During the ensuing summer periods, part of the cover and the active layer beneath it thaws. A layer of frozen ground is maintained axially underneath the center of the cover.

Consequently, the degree of sag in the center of the cover is less than that on the sloped embankments. This leads to creeping embankments and diminishment of the cover. The frozen layer can also act as an ice dam, thus prohibiting draining and altering the moisture content of the surrounding ground.

It should be noted here, however, that a loop-line section laid upon a low-ice-content earthern pad insulated with 4-in. of polyurethane and waterproof outer plastic wrapping, and covered with a low-ice-content berm has shown hopeful signs of stability during six months of hot-oil pumping at the test facility near Inuvik, NWT, Canada.

ABOVE GROUND CONSTRUCTION

If the pipeline is installed on low supports, or on leveled fill, the direct effect of the pipe on the base ground is not appreciable. Nevertheless, this type of construction is not without problems. In addition to the drainage blocking of such surface lines, immense snow drifts can accumulate on the leeward side of large-diameter pipelines.

Snow, being a good heat insulator, prevents deep freezing and, therefore, non-uniform zones of frozen ground are developed. This nonuniformity in the active layer results in a greater degree of sagging on the leeward side of the pipeline than on the windward side and creates the problem of maintaining alignment of the supports.

The Russians have observed that disturbance of the cryologic conditions of permafrost can be avoided by laying the pipeline well above ground. A gas pipeline laid above the maximum level of snow cover has virtually no heat effect on the ground and insures maximum stability of the installation.

It is generally unnecessary to work the frozen ground or insulate it from the heat effects of the pipeline with this type of design. However, increased pipeline heat losses to the atmosphere during the winter, the problem of precipitation of condensate, etc., have to be considered.

The efficiency of an uninsulated aboveground gas pipeline increases as its operating temperature approaches that of the cold Arctic ambient temperature. One investigator calculated that, compared with a buried pipeline, a specific 56-in.-

diameter aboveground gas pipeline in Western Siberia would have an overall efficiency increase of 5%, considering an average annual temperature of +20°F.

It must be emphasized that what is appropriate for gas-transmission lines may or may not be appropriate for liquids pipelines. The results would be quite contrary for an oil pipeline. Lower temperatures would greatly increase the fluid viscosity which in turn would necessitate inordinately high pumping power requiremens, if the liquid could be pumped at all.

DESIGN ELEMENTS

An example of the complexity of aboveground construction can be seen in a Soviet research institute's scheme for aboveground support design. The structural design was calculated considering: (a) the weight of the pipe; (b) the weight of the gas in the pipeline; (c) the weight of icing; and (d) wind pressure.

Additional dynamic forces resulting from the motion and periodic stopping of cleaning scrapers are reported to have been neglected. Likewise, no consideration was given to the additional loading of water generated from the melting of snow that was introduced into the pipeline during construction and was accumulated ahead of initial cleaning scrapers.

The report does not state whether this design was applied to any actual projects and, if so, the consequences therefrom. Nevertheless, this does point up the fact that each situation is unique and that certain problems exist with each mode of installation.

Pipeline supports can be in the form of piles, frames, or ground prisms. Experience has shown the pile supports provide maximum stability.

ADVANTAGES OF PILES

Many problems associated with Arctic pipelining can be eliminated by installing the pipeline on nonheat conductive piles that have been placed into the permafrost. Such supports would be unaffected by the seasonal vertical dislocations of heaving and sagging created by freezing and thawing of the active layer.

However, the cost of this type of construction is high compared with that of frame-type supports or ground prisms. Analysis of a specific case might show various combinations of pile, frame, and prism supports to be the most feasible solution.

There are several pipelaying techniques which are used to compensate for stresses caused by temperature and pressure variations in aboveground pipelines.

The most prevalent methods employ either: (a) a constant zigzag, that is referred to as a snake-type pattern, or (b) a straight line with periodic slightly curved compensating sections that are usually located on the same side of the pipeline axis.

The straight-line methd uses a combination of fixed, longitudinally mobile, and free-moving supports. It is generally preferred to the snake type of construction that has a complex system of fixed and oscillatory-hinged supports.

The straight-line method requires approximately 2% less pipe than the snake method. This, combined with 60% fewer pipe bends, results in greater pipeline hydraulic efficiency. The straight-line system is also subjected to less wind load and only requires approximately one-third as many costly fixed supports.

In any event, an uninsulated aboveground gasline would be subject to severe stresses from temperature changes that could exceed desired limits in certain sizes. Also such a line would have excessively high operating temperatures in summer and, conversely, low in winter.

In spite of the complexity of the various supports, aboveground installation results in the minimization of the heat effect of the pipeline on the frozen ground and the consequent maximization of pipeline stability. For this reason, the Russians feel that, in nearly all instances, this is the best method for installation of gas-transmission lines in Western Siberia.

The test loop facilities in northern Canada may, however, alter this conclusion for permafrost construction.

When these tests are complete, it is possible that a buried refrigerated line may prove best for gas; with a combination of insulated line laid in a berm, or on high supports, for a hot-oil line depending on the ice content of the soils.

LOGISTICAL CHALLENGE

The Russian pipelines are being laid in vast uninhabited territories and present complex logistical challenges. Housing, and ground communication, and transportation are virtually nonexistent.

The transportation problem consists of, on one hand, the need for development of equipment capable of traversing the terrain with large pay loads. On the other hand, it is necessary to prevent surface destruction that would result in heat transfer variations.

The solution to the former problem is in the selection of equipment iwth exceptional mobility and traction. The latter problem can only be solved by careful analysis of the geocryologic variations that will be produced by alteration of the surface heat transfer.

The primary factor contributing to geocryologic stability, and thus to the load-bearing capacity, is the 8-10-in.-thick moss blanket that insulates the ground from external heat. With the passage of a vehicle the moss blanket may collapse or be destroyed, leaving the surface uninsulated.

As more heat flows into the ground, there is an increase in the depth and intensity of seasonal melting under the tracks. As a result of the melting process in ice-impregnated ground, a gully develops along the pipeline route.

This becomes a natural drain for the surrounding environmental surfaces and, in turn, creates a thicker active layer which promotes even more melting. The melting depth below the tracks can amount to 10 ft in one season, while the gully in this area may deepen by as much as 3 ft.

The presence of vein ice may lead to ground collapse that can spread, causing disintegration of adjacent terrain. Furthermore, these soils often have thixotropic properties and have a tendency to lose their load-bearing capacity even under the effect of relatively minor dynamic loads.

These processes are sources of numerous transportation delays, as well as being significant ecological problems.

TRANSPORTATION PROBLEMS

The winter period, when the vegetation blanket is protected by snow, is more opportune for transportation. However, even during this period the traffic must be limited to special winter roads. Blackening and compaction of snow and underlying vegetation can cause a change in the surface-heat balance.

Although certain equipment and material items must invariably be moved overland, the Russians have realized definite economies through the use of helicopters whenever possible. Helicopters have been used to transport pipe joints of up to 120 ft. in length from welding bases to the right-of-way.

The use of such transport, even under the adverse conditions of the polar nights, has permitted a considerable reduction in construction time.

Undoubtedly, many unique pipelining techniques will emerge as a result of man's conquest of the Arctic. Some of these will probably serve to improve upon our pipelining know-how in more conventional environments.

CONCLUSION

Successful pipelining across the varying conditions of permafrost demands selection of the proper construction equipment plus the flexibility to apply a distinctly unique construction philosophy to each of the prevailing conditions. Furthermore, completely different sets of criteria for equipment, material, and construction methods are applicable to gas and to liquids Arctic pipelines.

Despite local variances, there appears to be strong agreement on basic project precepts. Arctic pipelining requires extensive and carefully contrived planning and timing.

It is essential to select a pipeline route that is feasible from construction logistical support, operational, and ecological viewpoints Surface disturbances and permanent geocryological imbalances must be minimized and restoration of disturbed areas to their natural states must be effected as quickly as possible.

This type of pipelining is understandably expensive, although, in order for Arctic energy reserves to be competitive with other sources of supply, it is essential to have low unit-transportation costs. To attain this, sufficient throughput volumes are necessary to permit long-distance pipelines to be of large diameter, thereby, taking advantage of the economies of scale.

Our observations of Soviet Arctic pipelining experience are intended to offer insight into areas that the Russians consider to be critical, based upon their firsthand experiences in Arctic pipelining from conception through operation.

It should be apparent that it would be irrational to consider such observations to be a "how to do it" of pipelining in permafrost areas. Rather, the one concept that pervades the realm of Arctic pipelining is the uniqueness of the problems and their requisite solutions.

This uniqueness compounds the magnitude of the Arctic challenge, although, however formidable this challenge may seem to be, it must and will be met, by methods confirmed in full-scale test facilities under actual operating conditions.

The oil and gas industry in North America remains responsive to environmental considerations and public opinion and will meet its responsibilities both to provide the energy required and to preserve our natural heritage.

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He received a BSME degree from Rensselaer Polytechnic Institute.

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