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GEOLOGICAL SURVEY

# Engineering geology studies in the National Petroleum Reserve, Alaska

By

Reuben Kachadoorian

and

Frederick E. Crory[1]

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[1] U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, N. H.

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# Engineering geology studies in the National Petroleum Reserve, Alaska

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## Abstract

Engineering geology studies were conducted in direct support of the exploration program in the National Petroleum Reserve, Alaska. The studies included laboratory and field tests and observations to address design and construction problems of airfields, roads, drill pads and foundations, and to evaluate their actual performance. Permafrost containing large amounts of near surface ground ice as wedges, masses, and intergranular ice, required that all construction activity not disturb the thermal regime of the ground surface, which could lead to thaw of permafrost and ground subsidence. Summer activity, therefore was not allowable, yet the winter climate was so harsh that winter work was slow and inefficient. To allow summer operations at well sites planned for all year activity, it was necessary to adapt existing techniques for arctic construction and to devise new ones.

The design and construction of facilities at the deep exploration wells at Inigok, Tunalik, and Lisburne posed the greatest challenge. These sites, requiring a year or more to drill, could only be attempted if continuous access to drilling and logistic supplies could be assured throughout the year, including the possibility of bringing in another drill rig, in the event of a blowout. Thus all-seasons airstrips were required at these wells. Sufficient quantities of local gravel were not readily available at the Inigok and Tunalik sites to construct the airstrips with the required 6 feet or more of gravel to prevent the underlying permafrost from thawing. Therefore, insulation was used to maintain the sub-base of local sands in a continuously frozen state, which in turn was overlain by 18 inches of gravel or sandy gravel. Tests at the U.S. Army Waterways Experimental Station defined the minimum thickness of gravel required above the insulation to provide the desired bearing capacity for the C-130 type aircraft without crushing the insulation.

Field testing also included the evaluation of another design option, using military landing mat underlain by insulation. Temperature recording devices were installed beneath the landing mat test sections, insulated runways, roads, drill pads, and reserve pits, to monitor the actual conditions and confirm the design assumptions. Investigations of thaw-settlement, erosion, and revegetation of all areas affected by construction were also conducted in anticipation of abandoning the sites, or, upgrading the facilities in the event the design life was extended.

## Introduction

### Purpose and scope

The Geological Survey has been charged with the responsibility of evaluating the petroleum potential of the National Petroleum Reserve in Alaska (NPRA). This work had already been initiated by the U.S. Navy, from whom NPRA was transferred to the Department of the Interior. To help fulfill its responsibility, the Geological Survey started an engineering geology program in February 1977, to provide the geotechnical support necessary for the exploration program. As part of the program, the Geological Survey requested the U.S. Army Waterways Experiment Station (WES) at Vicksburg, Mississippi, and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) at Hanover, N.H., to conduct studies to obtain the physical parameters required to evaluate and solve some of the geotechnical and engineering problems associated with the program.

All of the NPRA is underlain by permafrost, and thus virtually all of the engineering and geotechnical problems encountered during the construction of the well sites and subsequent drilling were associated with permafrost. The widespread occurrence of permafrost containing large amounts of near surface ground ice in the form of wedges, masses, and intergranular ice, required that construction activity not disturb the thermal regime of the ground surface which, in turn, could lead to thaw of permafrost. Once the permafrost was thawed, ground subsidence, sediment flow, and impassable conditions would result. Construction problems were compounded by the constraint that all construction in the NPRA be done during the winter months to meet the environmental requirements. Therefore, the engineering geology program consistently addressed the impact of the environment on the facilities, and the effect of the facilities on the environment.

## Location

The National Petroleum Reserve, Alaska, lies in the North Slope of Alaska north of the latitude 68$^{o}$ N. (fig. 1). The northern boundary extends from the mouth of the Colville River on the northeast edge of the reserve along the Arctic Coast west to Icy Cape, at about long. 161$^{o}$52'32"W. on the west edge of the reserve. The boundary then extends south to the crest of the DeLong Mountains, then eastward following the crest of the DeLong and Endicott Mountains of the Brooks Range to about long 155$^{o}$22'30"W. The boundary then goes north and intercepts the Colville River in the vicinity of Killik Bend. It then follows the Colville River east to Umiat and then north to the Arctic Ocean.

## Geography

The northern half of the NPRA lies in the low, poorly drained, lake-dotted Arctic Coastal Plain physiographic province (Wahrhaftig, 1965). The Arctic Coastal Plain rises imperceptibly from the Arctic Ocean to an altitude less than 500 feet. The southern half of the reserve lies in the rolling plateaus and low linear mountains of the Arctic Foothills and in the rugged glaciated mountains of the DeLong Mountains and Central and Eastern Brooks Range physiographic provinces. With the exceptions of Seabee, Lisburne, and Awuna (fig. 1), all of the wells drilled in the reserve between 1975 and 1981 are in the Arctic Coastal Plain physiographic province.

## Geologic setting

The National Petroleum Reserve, Alaska, is underlain by unconsolidated sediments of Quaternary age, which are in turn underlain by bedrock ranging from Devonian to Cretaceous in age. The unconsolidated sediments consist of marine silt, sand, and beach deposits, upland silt, eolian sand, alluvium, and glacial debris (fig. 2 and Williams and others, 1977). The marine beach deposits, consisting chiefly of fine-grained gravel, occur north of Barrow, on barrier islands, and along the coast as isolated patches west of Barrow to the edge of the reserve. The marine silt occurs along the coast from Barrow to about the eastern edge of the reserve. Marine sand occurs chiefly in the western part of the reserve with isolated patches in the eastern part. The most widespread unconsolidated sediments are aeolian silt and sand that occur mainly in the flat-lying lake-dotted central and eastern part of the reserve. Much of the aeolian silt and fine-grained sand have been reworked by stream and lake action. A band of upland silt extends from the eastern to the western boundary of the reserve and marks the geologic boundary between the unconsolidated sediments in the north and the bedrock area in the south. Alluvium occurs in all the streams and rivers and consists of fine-grained sand and silt in the low-lying area of the reserve and as gravel in the larger rivers, such as the Colville, that drain the mountainous terrain of the reserve. The glacial debris occurs only in the southern part of the reserve and consists chiefly of till and minor amounts of outwash.

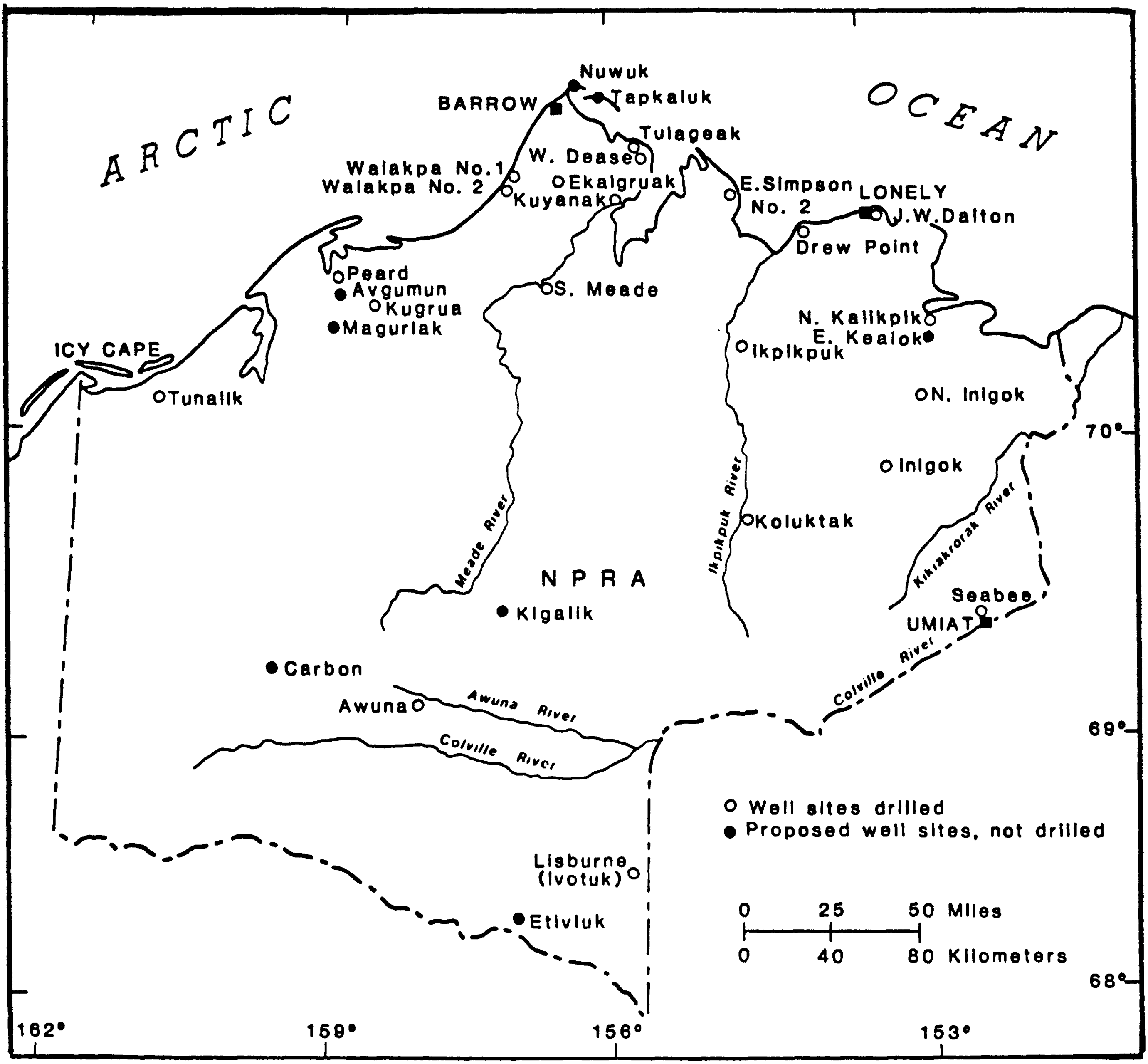


**Figure 1.** **Locations of proposed and drilled well sites, National Petroleum Reserve, Alaska (NPRA).**

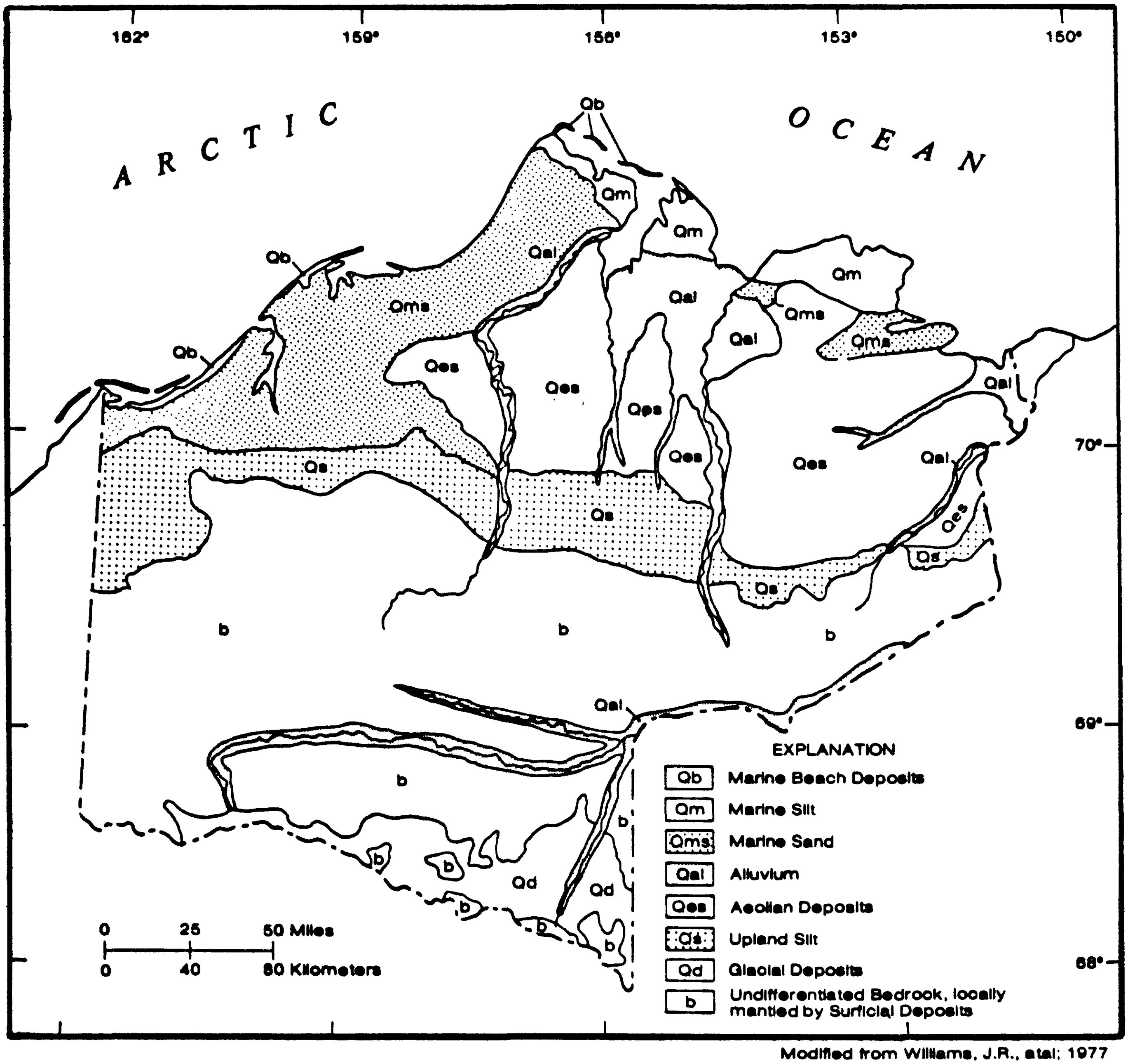


**Figure 2.—Surficial geology of the NPRA.**

The bedrock underlying the unconsolidated sediments in the northern part of the reserve consists chiefly of sedimentary rocks. Igneous and metamorphic rocks occur in the southern part of the reserve, but locally are mantled by colluvium and glacial debris.

## Investigations

The engineering geology program in the NPRA consisted of engineering studies by the Cold Region Research and Engineering Laboratory (CRREL) and the Waterways Experiment Station (WES) under contract to ONPRA, and geologic studies by the Geological Survey. The engineering and geologic studies consisted of cooperative and interrelated investigations between CRREL, WES, and the Survey and were designed to help solve or minimize the effects of permafrost related geotechnical problems. CRREL's studies included both field and laboratory investigations. Laboratory studies included thermal analysis of insulation, gradation of available soils in relation to compaction and bearing capacity, and thaw settlement. The field studies concentrated on the installation of thermocouples and monitoring of ground temperatures at the facilities and special test sections.

The Waterways Experiment Station conducted several large-scale tests at Vicksburg, Miss., to evaluate different concepts for runway construction. These included five separate test sections trafficked by a test cart simulating the wheel loading of the C-130 Hercules aircraft.

The authors conducted geological and engineering field investigations of 29 proposed well sites during the field seasons of 1977 to 1980, inclusive (fig. 1 and table 1). The investigations included a determination of the geological setting, a search for sources of construction material, and determination and evaluation of possible geotechnical and construction problems. All of the sites selected were drilled during the winter months with the exception of Tunalik, Inigok, and Lisburne which were drilled the year around. The Awuna well required two winters of drilling because the operations ceased during the summer months. The field studies concentrated on evaluating the geotechnical problems at the deep all-year well sites at Inigok, Tunalik, and Lisburne (the airstrip at the Lisburne well site is called Ivotuk). Such studies were necessary because these facilities required the construction of all-seasons airstrips and associated facilities to support the long and continuous drilling effort.

The major purpose of this paper is to discuss the all-seasons well sites of Tunalik, Inigok, and Lisburne (Ivotuk). We have also included a discussion of the winter-only drilling site at Seabee because special engineering studies were made at that site.

The Engineering Geology Investigations Program of NPRA, which included all work done under contract by CRREL and WES, was funded by the Office of the National Petroleum Reserve, Alaska (ONPRA), of the U.S. Geological Survey. Fieldwork was greatly facilitated by the cooperation and support, of John Ireton and Tom Brooks of Husky Oil NPRA Operations, and the Husky Oil personnel at Camp Lonely. Arthur Gidney, David Atwood, Mark Connolly, and Richard Berg of CRREL provided office and field support. Ronald Hutchinson, Alfred Joseph, and Cecil Burns of WES furnished advice and counsel on many of the engineering problems.

## Winter well sites

### General statement

Investigations of the winter well sites included geologic and engineering evaluations of the proposed sites, drilling pads, and ice airstrips, and searches for sources

Table 1.—Location, geologic setting, and construction-material sources of proposed and drilled well sites, NPRA.

| Well site | Location | Geologic Setting | Construction Material | Remarks |
|---|---|---|---|---|
| Awuna | Lat: 69°09'11.58"N<br>Long: 158°01'21.37"W | Site on 5° slope underlain by colluvium with ice-rich permafrost within 1 ft of surface. Locally, ice 30 ft thick. Shale underlies colluvium. | From terrace deposits along Awuna River 1 mi north of site or from reserve pit. | Ice-rich permafrost and slope presented maintenance problems because well drilled during 2 winters. No summer drilling. |
| Drew Point | Lat: 70°52'47.14"N<br>Long: 153°53'59.93"W | Site on low-lying area underlain by marine silt containing permafrost, locally ice-rich; permafrost within 2 ft of surface | From reserve pit containing silt. | No major geotechnical-related problems encountered; drilled during winter. |
| E. Simpson No. 2 | Lat: 70°58'42.51"N<br>Long: 154°40'25.74"W | Site on flat-lying area underlain by marine silt containing permafrost, locally ice-rich; permafrost within 2 ft of surface; site in center of one of many polygons that are common in area. | From shoreline of Smith Bay about 2 mi east of site or from reserve pit containing silt. | No major geotechnical-related problems encountered; drilled during winter. |
| Ikpikpuk | Lat: 70°27'19.68"N<br>Long: 154°19'52.78"W | Site on reworked dune sand in low-lying swampy area underlain by eolian silt and sand containing permafrost; permafrost within 1 1/2 ft of surface. | From ancient lake shoreline containing silt and sand or from reserve pit containing silt. | No major geotechnical-related problems encountered; drilling during winter. |
| Inigok | Lat: 70°00'17.48"N<br>Long: 153°05'56.92"W | Site on dune sand modified by lake action; eolian sand is fine-grained containing permafrost within 1 ft of surface. SEE TEXT | SEE TEXT | SEE TEXT |
| J. W. Dalton | Lat: 70°55'13.79"N<br>Long: 153°08'15.10"W | Site on flat-lying area underlain by marine silt with some sand. Depth of permafrost unknown but probably within 3 ft of surface. | From ancient-bay mouth bars 3 1/2 mi SE of site. Deposits are sandy gravel of marine origin. | Borrow sites are about 3 to 3 1/2 ft above sea level. Inward side of bay mouth bars are lagoon areas containing liquefiable silt and sand; drilled during winter. |
| Koluktak | Lat: 69°45'08.62"N<br>Long: 154°36'40.12"W | Site on terrace containing sand that has been modified by eolian sand and silt. Site underlain chiefly by fine- to medium-grained sand containing permafrost within 1 1/2 ft of surface. | Ample supply of material can be obtained locally. Material fine- to medium-grained sand with some gravel about 1 1/2 mi NNW of site. | No major geotechnical-related problems encountered; drilled during winter. |
| Kugrua | Lat: 70°35'13.28"N<br>Long: 158°39'43.26"W | Site on flat, poorly drained area underlain by lake sediments overlying marine silt. Permafrost within 1 1/2 ft of surface in ice-wedge polygons. | Best source from terrace containing marine and nonmarine medium-grained sand with some gravel about 1 1/2 mi NNW of site. | No major geotechnical related problems encountered; drilled during winter. |
| Kuyanak | Lat: 70°55'53.48"N<br>Long: 156°03'53.08"W | Site in abandoned lake, generally swampy, and underlain by lake sediments that, in turn, are underlain by marine silt and sand. Permafrost is within 1 1/2 ft of surface and, locally, is ice-rich. | From reserve pit containing marine swampy lake sediments. | No major geotechnical related problems encountered; drilled during winter. |

| Well site | Location | Geologic Setting | Construction Material | Remarks |
|---|---|---|---|---|
| **Lisburne** | Lat: 58°29'05.44"N<br>Long: 155°41'35.51"W | Site on dry moderately steep slope underlain by colluvium and glacial debris. Depth to permafrost unknown but may be within 5 ft. SEE TEXT | SEE TEXT | SEE TEXT |
| **N. Inigok** | Lat: 70°15'17.32"N<br>Long: 152°45'57.53"W | Site on dune sand, about 100 ft wide and 1/2 mi long, that was once shoreline of ancient lake. Eolian sand is fine-grained with generally ice-poor permafrost. Permafrost within 3 ft of surface. | From local area or reserve pit consisting of fine-grained sand. | Upper 5 ft of permafrost is dry permafrost. No major geotechnical-related problems encountered; drilled during winter. |
| **N. Kalikpik** | Lat: 70°30'33.023"N<br>Long: 152°22'04.169"W | Site on low-lying swampy area in old drained lake underlain by silt. Permafrost is within 1 ft of surface. | From borrow sites about 4 1/2 mi southeast of well site containing silty sands. | No major geotechnical problems encountered; drilled during winter. |
| **Peard** | Lat: 70°42'56.21"N<br>Long: 159°00'02.52"W | Site on low-lying swampy area underlain by swamp debris that in turn is underlain by marine silt. Permafrost is within 1 ft of surface and locally ice-rich. | From Kugrua Bay about 4 1/2 mi NNE of site and from reserve pit. Kugrua Bay site contains fine gravel; peat; researve pit contains swamp debris. | Kugrua Bay borrow site contains peat debris. No major geotechnical related problems encountered; drilled during winter. |
| **Seabee** | Lat: 69°22'48.12"N<br>Long: 152°10'31.29"W | Site on high relatively dry old Colville River terrace containing gravel; permafrost within 3 ft of surface. SEE TEXT | SEE TEXT | SEE TEXT |
| **S. Meade** | Lat: 70°36'53.92"N<br>Long: 155°53'23.60"W | Site is an old terrace of Meade River and is underlain by fine-grained sand containing permafrost; permafrost within 2 ft of surface. | From terrace deposits at site containing fine-grained sand. | No major geotechnical related problems encountered; drilled during winter. |
| **Tulageak** | Lat: 71°11'26.62"N<br>Long: 155°44'00.82"W | Site in flat-lying area with less than 2 ft of relief underlain by marine silt containing ice-rich permafrost; permafrost within 1 ft of surface. | From reserve pit containing ice-rich silt. | No major geotechnical related problems encountered; drilled during winter. |
| **Tunalik** | Lat: 70°12'21.45"N<br>Long: 161°04'09.15"W | Site on relatively high area underlain by marine silts with some sand; permafrost within 1 ft of surface. SEE TEXT | SEE TEXT | SEE TEXT |
| **W. Dease** | Lat: 71°09'32.65"N<br>Long: 155°37'45.19"W | Site on old drained lake in low-lying swampy area; underlain by frozen silt that, in turn is underlain by marine silt; permafrost within 9 in. of surface and locally ice-rich. | From reserve pit containing silt. | No major geotechnical related problems encountered; drilled during winter. |
| **Walakpa No. 1** | Lat: 71°05'57.63"N<br>Long: 156°53'03.79"W | Site on flat-lying terrain underlain by marine site containing permafrost, locally ice-rich; permafrost within 10 in. of surface. | From reserve pit containing silt. | No major geotechnical-related problems encountered: drilled during winter. |

| Well site | Location | Geologic Setting | Construction Material | Remarks |
|---|---|---|---|---|
| **Walakpa No. 2** | Lat: $71^{o}15'27.32''$N<br>Long: $152^{o}45'57.53''$W | Site in low-lying swampy area containing polygons and underlain by frozen marine silt, locally sandy; permafrost within 10 in. of surface and locally ice-rich. | From reserve pit containing silt. | No major geotechnical-related problems encountered; drilled during winter. |
| **Avgumun** | N 1/2 sec 12, T15N R29W, Umiat Meridian | Site on flat-lying area with polygons. Site underlain by locally ice-rich marine silt. Permafrost within 1 ft of surface. | From reserve pit containing silt. | Well not drilled |
| **Carbon** | NW1/4, NE1/4, sec 31, T2N, R34W, Umiat Meridian | Site on relatively high dry slope underlain by colluvium of unknown thickness overlying sandstone. | From borrow site about 1/4 mi SE of site containing colluvium and friable sandstone. | Well not drilled. |
| **E. Kealok** | NW1/4 sec 19 T12N, R2W., Umiat Meridian | Site on $1^{o}$ to $2^{o}$ sloping surface, generally dry and underlain by marine fine-grained sand and silt. Permafrost within 1 1/2 ft of surface. | From reserve pit containing fine-grained sand and silt. | Well not drilled. |
| **Ekalgruak** | Sec 34, T19N, R11W Umiat Meridan | Site is low-lying swampy area underlain by frozen marine silt; permafrost within 1 ft of surface and locally ice-rich | From reserve pit containing silt | Well not drilled |
| **Etivluk** | NW 1/4 SE 1/4, Sec. 20, T12S, R21W Umiat Meridian | Site on relatively high dry area underlain by windblown silt and sand that in turn is underlain by colluvium of unknown thickness. Depth to permafrost unknown but estimated to be about 3 ft below the surface. | From four borrow sites 1/2 mi north and east of well site in cherty or quartzitic sandstone and from site about 4 3/4 mi southeast of well site containing terrace gravels. | Well not drilled. |
| **Kigalik** | SE 1/4, Sec 6, T1N, R22W, Umiat Meridian | Site on relatively high dry area underlain by colluvium of unknown thickness overlying sandstone; depth to permafrost unknown but probably within 3 ft of surface. | From borrow site about 1/3 mi NW of site containing arkosic sandstone, locally friable. | Well not drilled. |
| **Maguriak** | NE1/4, Sec 15, T12N, R8W, Umiat Meridian | Site on swampy area of drained lake. Underlain by lake sediments that in turn are underlain by marine silt; permafrost, locally ice-rich, within 1 1/2 ft of surface. | From borrow site, about 1 1/2 mi NNE well site, containing medium- to coarse-grained sand. | Well not drilled. |
| **Nuwuk** | Sec 32, T24N, R17W Umiat Meridian | Site on beach gravel about 10 ft above sea level; permafrost at unknown depth but estimated to be 10 ft below surface. | From reserve pit containing gravel. | Well not drilled; locally gravel beach has ice scars caused by overriding of winter ice from Arctic Ocean. |
| **Tapkaluk** | On largest of Tapkaluk Islands between Elson Lagoon and Beaufort Sea, about 13 1/2 miles east of Barrow. | Site on gravel island about 3 ft above sea level; depth of permafrost unknown. | From reserve pit containing pea-sized gravel. | Well not drilled |

of construction materials. The location, geologic setting, sources of construction, and pertinent remarks regarding each site are described in table 1. Special studies were made at the winter Seabee site and are discussed in more detail in the following section. The wells at the winter sites, with the exception of Awuna, were drilled in a single winter and thus were not subjected to the effects of thaw during the summer months. The Awuna well required two winters to drill and was shut down during the intermediate summer. The Awuna drill pad and reserve pit had some subsidence because the frozen material in the pad and reserve pit thawed during the summer. This subsidence required some maintenance before starting up for the second winter of drilling.

### Seabee well site

The Seabee well was located about one mile northwest of the existing State-owned airport at Umiat. The well site was at lat 69°22'48.12" N. and long 152°10'31.29" W., Umiat Meridian. During the summer of 1978 the airfield was closed to all large aircraft, because a C-130 blew a tire on landing. Large surface cobbles and boulders were considered the cause of the blow out. The Umiat airfield, accordingly, was overlain with a new gravel surfacing in the spring of 1979, permitting drill-rig movements and year round access for supplies and crew changes. To avoid congestion at the existing parking apron near the south-central portion of the airfield, a new parking apron with a short taxiway was constructed just north of the west end of the runway. From this new parking apron an uninsulated gravel road was constructed to the well site. Gravel borrow pits, on both sides of this road, provided the gravel for the parking apron, road, drill pad, and runway resurfacing.

Previously constructed gravel roads on a thin pad at Umiat, especially to the north of the airfield, had suffered serious damage from permafrost degradation (Ferrians and others, 1969). The uninsulated access road to the Seabee well was designed on the basis of a gravel-fill section from 4 to 6 ft thick. The drill pad was also constructed as a thick gravel-fill section like the road; only the areas beneath and adjacent to the drill rig and camp were underlain with insulation.

A view of the Seabee drill pad is shown in figure 3. All construction took place between January and April 1979. Personnel were based at a temporary construction camp located just east of the new parking apron.

Only minor maintenance was required on the new access road to the Seabee well. To evaluate the effectiveness of this thicker gravel roadway, thermocouples were placed at two locations, several hundred yards apart. One assembly was installed in a new section of the road, while the other assembly was in a section where the new road was built over an old road. Although little road damage was anticipated in the first year or two, these initial temperature observations will be important in assessing the long term changes. Both assemblies were left in place for future monitoring. The greatest problem experienced was on the Seabee access road where several culverts were washed out during the sudden spring breakup of 1980.

Selected pilings around the Seabee well were instrumented with thermocouples to define the radial heat flow. Attempts to monitor the temperatures on the outside of the conductor pipe failed when the thermocouple temperature assembly was ruined during the initial cement grouting operations. The thermocouples on the rig piling however, provided the desired information throughout the drilling period. Two additional temperature assemblies were used to determine the effectiveness of the reserve pit slope insulation, in the area where the drill cuttings were deposited and beneath the bottom of

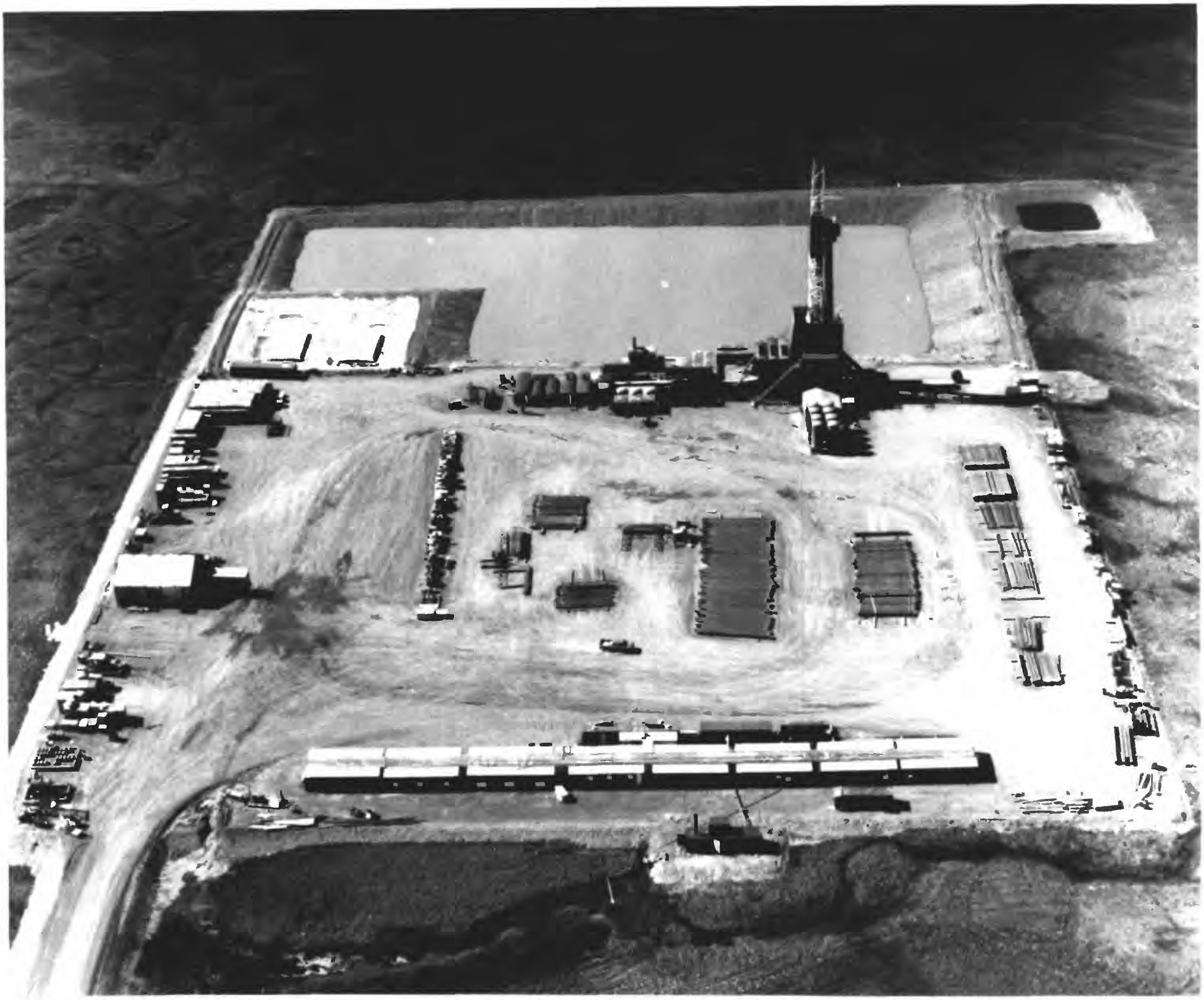

Figure 3. Seabee well site with drill camp in foreground and reserve pit in background. Note polygonal ground features. Photo taken in July 1979, looking west.

the reserve pit. Another assembly in the north dike, in an active erosion area, will be used to measure the long term thermal changes at this location.

Two attempts were made to install temperature assemblies beneath the uninsulated Umiat runway for direct comparison with the insulated runways installed at Inigok, Tunalik, and Lisburne (Ivotuk). Both attempts failed, however, when large cobbles and caving holes stopped the drilling efforts below 6 or 8 ft.

## All-season well sites

### General statement

The Tunalik, Inigok, and Lisburne wells had target depths greater than 17,000 feet and required more than 360 days of continuous drilling to complete. In support of these all-season wells, geologic and engineering studies were made to evaluate the geotechnical problems of the proposed well sites, airstrips, parking aprons, and roads, and to determine sources of construction materials. These all-season wells required all-year airstrips to ensure a means of getting continuous supplies to the well sites, including the bringing in of another drill rig in the event of a blowout. This required an airstrip 150 feet wide and 5,200 feet long to handle the C-130 aircraft necessary to support the drilling programs.

A thorough search was made during the summer of 1977 to find a source of gravel necessary to construct the all-year airstrips, parking aprons, roads, and construction pads for the Tunalik and Inigok wells. However, an ample, readily available local source of gravel was not found and therefore a serious design problem for the Tunalik and Inigok wells arose. The lack of readily available gravel to construct an all-gravel airstrip, at least 5 feet thick, led us to consider other design concepts such as the use of a landing mat or insulation. Such insulation had been recently used for several roads, portions of the work pad for he Trans-Alaskan Pipeline and the Kotzebue airport (Penner, 1976; Esch and Rhode, 1977; and Wellman, and others, 1977).

### Tests of design concepts

Local frozen material, overlain by insulation, and covered by a limited thickness of gravel had not been used to construct an airstrip where heavy aircraft were to land. Consequently, the Waterways Experiment Station at Vicksburg, Miss., was requested to undertake large-scale tests to obtain the physical parameters necessary to design and construct such airstrips. The results of these tests were published by WES (Burns, 1979).

WES constructed five separate test sections and traffic-tested them with a load cart, simulating a C-130 aircraft, to evaluate the following designs:

(1) Prefabricated aluminum landing mat over Styrofoam[2] insulation overlying a high-strength subgrade representing frozen material,

(2) Gravel base course overlying Styrofoam insulation, overlying a high-strength subgrade representing frozen material,

(3) Gravel base overlying a loosely placed saturated sand fill,

[2]The use of trade names in this report does not constitute endorsement of the product by the U.S. Geological Survey, the U.S. Army Cold Regions Research and Engineering Laboratory or the U.S. Army Engineer Waterways Experiment Station.

(4) Sand-grid confinement in loosely placed saturated sand fill, and

(5) Sand-grid confinement in highly compacted sand fill.

Small-scale runway test sections were constructed for each of the designs and were evaluated on their performance under simulated C-130 aircraft traffic conditions. Select materials for the construction of the sections simulated as closely as possible the materials that would be available for the construction of the airstrips at the Inigok and Tunalik well sites. CRREL conducted laboratory analyses of the sand from selected borrow sites in the vicinity of the airstrips, gravel from a borrow pit about 6 miles from the Tunalik site, and gravel from the confluence of the Colville and Kikiakrorak Rivers about 36 miles from the Inigok site. WES used the data to simulate as closely as possible the type of sand and gravel that would be actually used in the construction of the Tunalik and Inigok airstrips.

Landing mat and gravel over insulation.--The objective of this test section was to evaluate the performance of a runway using Styrofoam insulation over frozen material, with a prefabricated landing mat or gravel surfacing over the insulation. The test section was 80 ft long by 25 ft wide and consisted of two test items, each 40 ft long and 25 ft wide. The subgrade of both test items consisted of a lean clay, well compacted to produce a relatively high-strength soil representing frozen material. The subgrades of each item were overlain by 2 layers of 1 1/2-in-thick HI-60 (60 psi compressive strength) Styrofoam insulation material. One of the test items was surfaced by an XM 19 aluminum landing mat and the other by 20 in. of gravelly sand.

The test items were then subjected to 1,250 passes, representing about 850 C-130 operations, with a 35-kip (35,000 lbs) single-wheel C-130 load. No damage to the insulation was evident at the conclusion of the testing. Since there had been no damage to the insulation under the 20 in. of gravel, it was decided to remove the top 10 in. to determine if the lesser thickness of gravel would still protect the insulation. About 240 passes of the 35-kip single-wheel load were then made on the gravel-covered test section. An examination of the insulation at the conclusion of this test indicated that the Styrofoam boards had been compressed.

As a result of these tests, it was concluded that (1) an XM 19 aluminum mat placed over HI-60 Styrofoam insulation would provide a satisfactory runway for C-130 aircraft, provided the insulation kept the sub-base frozen, (2) a 20-in. thick, good quality, gravel base course over HI-60 Styrofoam insulation would protect the insulation from compressing under the C-130 aircraft loading, but it might require some surface maintenance during repeated aircraft operations, especially during the spring thaw, and (3) a 10-in.-thick gravel base course over the insulation was insufficient to protect the HI-60 Styrofoam. If the insulation were crushed or cracked it was assumed that the insulating value would degrade and that the sub-base would thaw and subside, rendering the airfield inoperable.

Gravel over saturated sand.—The objective of this investigation was to determine if a fill initially consisting of frozen sand and overlain by 20 in. of gravel would sustain C-130 aircraft traffic after the sand thawed and was in a saturated condition.

The section in which gravel overlying saturated sand was tested was 140 ft long by 25 ft wide and consisted of 3 test items, each 40 ft long, with a 10-ft transition between them. Item 1 consisted of 20 in. of gravel overlying 6 in. of saturated sand; item 2 consisted of 20 in. of gravel overying 36 in. of saturated sand; item 3 was the same as item 2 except that filter-cloth fabric[3] was used to line the walls of the excavation and was placed horizontally at 1-ft intervals in the sand fill. The filter fabric was used to reinforce the sand and improve the drainage of the sand, thereby increasing its load-carrying capacity.

All the items in this test section were subjected to 35-kip, single-wheel C-130 loads and a 70-kip, single-tandem, gear assembly representing one main landing gear of the C-130 aircraft. The results from this test indicated that 20 in. of gravel placed over a frozen sand similar to that at Inigok, without insulation, would be marginal at best for C-130 aircraft operations after the sand thawed, depending on how well the sand drained. If the sand were saturated, an unstable condition would probably exist. If the sands at Inigok could be completely drained and consolidated as thawing progressed, stability could be maintained by surface compaction and maintenance. However, this might render the runway unserviceable during the first spring breakup following construction.

Sand-grid confinement.--The lack of readily available gravel for airfields, roads, and drill pads in the NPRA prompted an investigation of ways to confine the wide spread sands in a flexible grid, so that perhaps only limited gravel would be required. This concept was studied at WES by placing a paper-grid material in the upper portions of sand fills[4].

This test section was constructed in a trench, 25 ft wide by 160 ft long, and consisted of five test items, each 30 ft long and 25 ft wide. The sand in items 1 through 4 was 48 in. deep, overlain with 6 in. of washed gravel. In item 1 a single layer of 6-by-6-by-6-in. grids was placed in the top 6 in. of the sand underlying the gravel. In item 2, two layers of the same grids were constructed in the top 12 in. of sand fill. In item 3, three layers of the grids were placed in the top 18 in. of the sand fill underlying the gravel. These items were designed to determine the depth of sand confinement needed to support the C-130 aircraft loading. Item 4 consisted of two layers of sand-filled grids overlying a variable-strength subgrade. This item was designed to determine the performance of the sand-grid system when differential thawing and settlement occurred. Item 5 consisted of two layers of the sand-filled grids, placed on insulation lying on a firm foundation simulating a frozen material.

In addition to the test section described above, WES also made studies to determine the feasibility of placing frozen sand in the grid confinement system.

The test section was evaluated by using a load cart equipped with a 70-kip single-tandem gear load simulating one main gear of a C-130 aircraft. Results of the test indicated that (1) a single 6-by-6-by-6-in. paper grid would not confine saturated loose sand adequately to sustain traffic of C-130 aircraft or vehicular traffic, (2) two or three layers of grids (6-by-6-by-6-inch grids at 12 to 18 in. depths) filled with highly compacted sand will adequately confine the sand and prevent shear and displacement of the sand

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[3]The filter fabric was a span bonded, needle-punched, polyester, nonwoven material called "Bidim", with a unit weight of 12 oz per sq yd manufactured by Monsanto Textiles Co.

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[4] The paper-grid was manufactured by the Hexcell Corporation and employed linerboard treated with a phenolic resin.

below the grid layers under C-130 aircraft traffic, (3) the paper grid overlying a variable-strength foundation conformed to the settlement in the foundation, but was still effective in confining the sand, (4) the concept of using grids filled with saturated frozen sand was not considered feasible because of the difficulties in placing the frozen sand in the grids, the low density and high water content of the sand after thawing, and the probability of very slow drainage after the sand thawed, and (5) after drainage and drying to about optimum water content, the sand can be compacted in the grids to high densities with standard techniques without damaging the grid.

Gravel thickness required to protect the insulation.--WES's earlier tests indicated that 20 in. of gravel over HI-60 Styrofoam would protect the board insulation from compression under the C-130 aircraft loading, but, a 10-in. thickness of gravel overlying the insulation was inadequate to protect the insulation. Once the decision to use gravel over insulation for the runway construction at the Inigok and Tunalik well sites was made, it became imperative to determine the lower limit of gravel thickness required to protect the insulation. The high costs of mining and hauling the gravel, especially at Inigok during limited winter construction period, made a clear definition of the minimum thickness of gravel required extremely important.

Accordingly, a new test section 75 ft long and 25 ft wide consisting of three test items, each 25 ft long and 25 ft ft wide, was constructed. The thicknesses of gravel, overlying a lean, compact, clay soil representing a frozen soil, were 15, 17.5 and 20 in.

Fourteen patterns of C-130 traffic, in 480 passes, were applied to the test section resulting in 280 coverages of a loaded tire in the center 45 in. of the traffic lane or an equivalent of 1,134 C-130 aircraft operations. Based on these tests it was determined that a minimum thickness of good quality well-compacted gravel of 15 in. would protect the HI-60 Styrofoam insulation material from detrimental crushing under C-130 aircraft.

## Inigok well site

The exploration well at Inigok was to be deeper than 19,000 ft. Such a well would require about 380 days to drill. For such a prolonged drilling period an all-seasons airstrip was required. In the summer of 1977, immediately following the siting of the well at lat 70°00'17.48" N. and long 153°05'56.92" W. Umiat Meridian (fig. 1), the search for a suitable location for the all-seasons airstrip was initiated. The most promising location was a long ridge, about 0.5 mile east of the well, approximately paralleling the direction of the prevailing winds (northeast). This location required the shortest connecting road and avoided crossing any streams between the well site and airfield.

The Inigok site is surrounded by numerous lakes which are common in the Arctic Coastal Plain province. The well and airstrip were just south and north of two large ones (fig. 4). The site is underlain by fine reworked eolian sand and silty sand which are permanently frozen, except in the active layer which annually thaws and refreezes to a depth of 1 to 3 ft. Polygonal ice wedges are found on the ridges' gentle slopes, and low-lying terrain throughout the area, although in some areas there is little or no surface indication of such features. The ground surface is mantled with low grass tussocks and dwarf willows except on the hill tops, where the exposed sand supports isolated grass tussocks, mosses, lichens, and wild flowers. The organic layer or "A" horizon at the Inigok airfield seldom exceeds 1 ft thick along the ridge, and no peat or other organic material is found at depth.

Although many low-level helicopter flights were made to locate gravel along nearby streams, the closest sources were found to be on the Kikiakrorak River, 35 miles

Figure 4. Inigok well site, road and airstrip. Darker area on runway centerline is due to sprinkling. The large lake on the right is used as an airstrip in the winter. View looking westward in July 1978.

to the southeast of the Inigok site, and at the confluence of the Kikiakrorak and Colville Rivers, some 36 miles to the east of Inigok. The latter source was easier to develop, because of the lack of frozen overburden and the easier route over which the gravel would have to be transported.

The lack of nearby gravel forced the consideration of several design options for the Inigok airstrip road and drill pad. The options included the use of soil-cement, military landing mats, or insulation with a relatively thin layer of gravel. Laboratory studies at USA CRREL, using the Inigok sand, indicated that acceptable soil-cement pavements would require 10 to 15 percent cement and would have to be constructed at above freezing temperatures (Crory and others, 1978; Crory, 1979). Problems associated with the availability of landing mats from military supply depots and the intensive hand labor required to place and remove the mats, made the landing mat option seem less attractive. If the mats could have been used successively at 3 or more airfields in NPRA they would have been more attractive financially.

A full-depth gravel runway (4 to 6 ft thick) would have required an amount of gravel that was unobtainable and would have imposed great geotechnical problems as well, because the local sand would have thawed and subsided in both the cut and fill sections. Laboratory studies of the Inigok sand, both at in situ densities and in the frozen remolded state (simulating frozen fill conditions), indicated that substantial settlements could be expected when the sand thawed (Crory and others, 1978; Crory, 1973). Deep and abrupt depressions would have also occurred at the edges of the polygonal ice wedges, particularly in the cut sections. The cost of hauling the gravel from remote locations and the limited time available to haul it led to the decision that an insulated runway at Inigok was the best option.

The construction of the Inigok airfield and its taxiway and parking apron made maximum use of the locally available sand and a minimum amount of gravel. The design, using insulation on top of the frozen sand, assumed that the insulation would be sufficient to keep the sand frozen, provided the insulation was in place before the advent of warm weather. The thickness of the insulation was based on calculations using both the modified Bergren equations, and Lachenbruch's periodic heat transfer equations (Aitken and Berg, 1968; Berg, 1976; Brewer, 1958; Lachenbruch, 1959). The possible range of seasonal thawing and freezing indices were estimated, using records from Barrow and Lonely, to the north, and Umiat to the south. Conservative estimates of the density and thermal properties of the gravel, the insulation, and the underlying frozen sand, indicated that 3 in. of insulation would be required to prevent any thawing of the sandy sub-base. The insulation selected, that had both the desired thermal properties and the compressive strength, was the extruded polystyrene foam board Styrofoam HI-60. This material was to be placed in two 1-1/2 in. layers, with overlapping joints between each layer, and covered with a plastic membrane. The insulation would then be covered with gravel to complete the temporary runway. A typical cross section of the airstrip is shown in figure 5.

Construction of the Inigok airstrip and drill pad began in Feburary, 1978. The major portion of the construction and camp equipment had been brought overland on snow trails, and additional supplies and personnel were flown to an ice airstrip on the large lake just north of the well site. This temporary airstrip on the lake was also used for the airlift of the drill rig and camp. The ice runway was utilized until May 22, when spring melting rendered it inoperable.

Construction began at the knoll at the south end of the runway. First all organic material was stripped off and later placed on the shoulders of the runway and along the

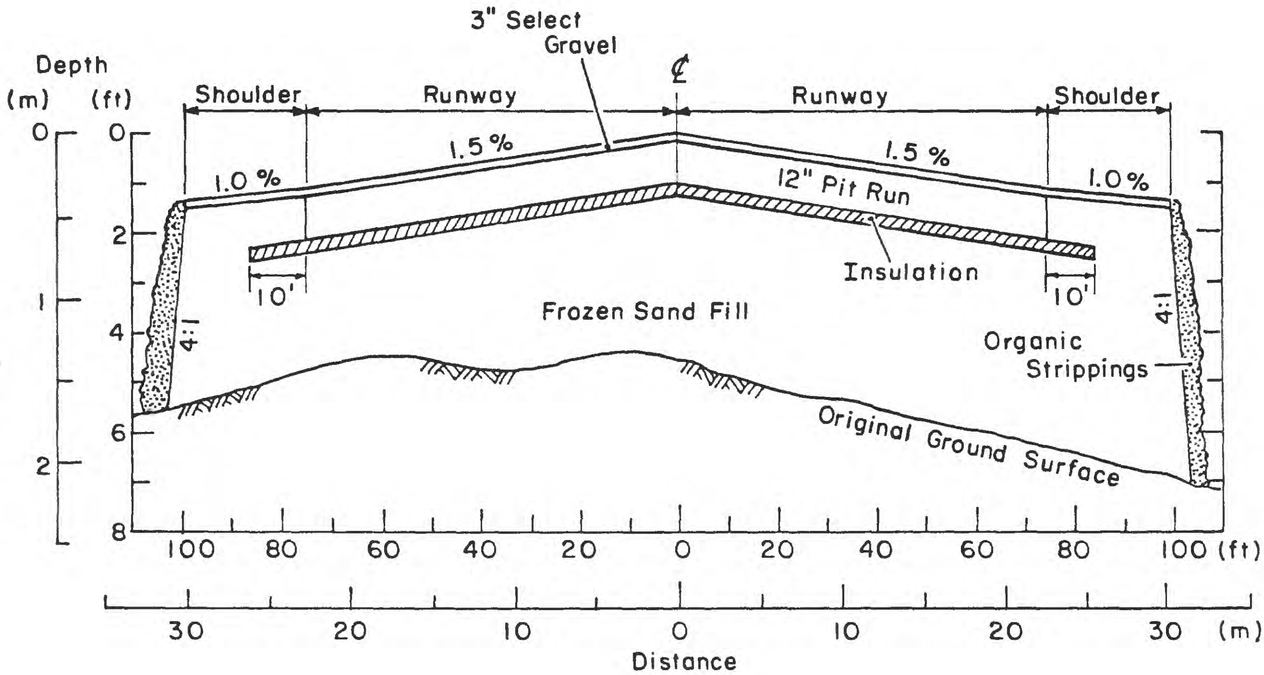


**Figure 5.—Typical section through the insulated airfield at Inigok. Depth of fill, thickness of gravel over insulation, and lateral width of shoulder insulation are different from those at Tunalik and Ivotuk.**

north edge of the parking apron. The drier and cleaner sand from the top of the knoll was then easily ripped and stockpiled for later use. Construction by late February had settled into conventional cut and fill operations. The frozen sand in the borrow area was mined by repeated passes of large ripper-equipped tractors. After ripping, the frozen sand was crushed by repeated passes of heavily loaded segregated wheels and sheepsfoot rollers. When the sand had been broken down so that it contained only small frozen lumps in a matrix of loose sand, it was removed and pushed into stockpiles. While the rippers proceeded to loosen the next layer, the stockpiled material was loaded and trucked to the fill sections.

The snow cover was removed just before placing the fill, but no stripping of the original vegetative cover was permitted. The fill was constructed in lifts, each lift being compacted by rollers. The special sand previously scalped from the surface of the knoll was placed last and the sub-base brought up to grade by careful grading and rolling, producing a hard, smooth surface upon which the insulation was placed.

Two-by-eight-foot insulation boards were placed with their long dimensions parallel to the runway centerline, care being taken to keep the joints tight and the rows straight. Placement of both layers commenced at the south end of the runway and proceeded northward. No wooden stakes or other types of tie downs were used to secure the insulation. Immediately following placement of the two layers of insulation, a plastic membrane was laid on top of the insulation. The membrane[5], a cross-laminated, 4-mill plastic having a tensile strength of 8,000 psi, was used to keep water from seeping down into the joints between the insulation. The membrane, supplied in 20-ft-wide rolls, was shingle lapped 2 ft and sealed. Gravel was placed, by end dumping, immediately after the placement of the membrane.

The gravel was carefully placed in a single lift of a foot or more, advancing the end-dumped gravel with a bulldozer. Rolling the gravel off the raised dozer blade was essential, because any substantial horizontal push could have displaced the insulation. The thick initial foot or more lift of gravel also served to protect the insulation from being crushed under the direct loading of the gravel trucks or other heavy equipment. Compaction of the gravel by sheepsfoot rollers was forbidden. Only smooth-wheel rollers were used in compacting the gravel above the insulation. The second and final lift (generally 9 to 12 in.) was a screened gravel, with a maximum diameter of 1.5 inch. The screened gravel was, unfortunately, poorly graded, lacking fines. To remedy this deficiency, sand from the borrow pit was added after the screened gravel had been placed. This procedure was only partially successful, however, because the stockpiled sand was still frozen and difficult to spread uniformly. The sand was first blended into the surface gravel by using a disc harrow, but this proved to be ineffective, so the blending was primarily accomplished by windrowing and spreading with road graders. Finally, the runway surface was compacted by using both rubber-tired rollers and vibratory smooth-wheel rollers. Plans and specifications called for a minimum of 85 percent (modified AASHO) of maximum density of the finished gravel surface when first placed, and then recompaction to 95 percent as thawing of the gravel progressed.

The runway, taxiway, parking apron, road, and drill pad at Inigok used a total of only 88,000 cubic yards of gravel, obtained from the confluence of the Kikiakrorak and Colville Rivers. The gravel was hauled in 10 $yd^3$ dump trucks with pup trailers at normal

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[5] TU-TUF 4, a product of Sto-Cote Products, Inc., Richmond, Va.

highway speeds over a 36-mile snow/ice road. The road was routed across a series of lakes, in order to reduce the amount of roadway to be constructed. The route avoided the high banks along some lake shores, which would have created steep grades and necessitated the building of snow ramps. The roadway across the tundra was constructed by first compacting the existing snow cover and then building up the thickness and strength of the roadway by multiple applications of snow and water. In some sectors, ice aggregate was used to build up the roadway; the ice was obtained, by ripping, in the shallow lakes which freeze to the bottom each winter. Such work does not pose a threat to the dozer; whereas it might break through the ice in deep lakes. The steepest grade on the snow/ice road was from the bluff into the Kikiakrorak River bed, near the gravel borrow pit. This section of the road, after being ramped to an acceptable grade with snow, which in places was over 20 ft high, was covered with gravel for better traction. The gravel was removed at the conclusion of the work, leaving the slope virtually undisturbed.

Construction of the Inigok facilities was nearly finished when the spring breakup occurred during the last week in May, 1978. Forced to abandon the airstrip on the lake, all light aircraft (Twin Otter) operations were shifted to the new runway. After several days in which the runway froze at night, but was soft and wet during the day, the runway suddenly began to dry out and respond to compaction efforts. The first C-130 aircraft landed on June 6, 1978, and the airstrip continued in service for more than a year without interruption. A view of the completed airfield is shown in figure 6.

Grading and rerolling was continued on a daily basis during the first half of the 1978 summer. Considerable watering was required for compaction and to limit the loss of fines caused by the operations of large aircraft. Only one section of the runway had to be dug up and replaced. Apparently a truck-load of sand and organic material, originally destined for the runway shoulder, had been inadvertently dumped and spread as part of the pit-run gravel. Upon thawing, this small area turned wet and soft and had to be removed. Only minor maintenance was required to regrade and recompact the gravel on the parking apron and at the ends of the runway where large aircraft made "locked wheel" turns. Throughout the year of active operations the Inigok runway was acclaimed by pilots as being one of the smoothest and best runways in Alaska.

In June 1979, after completing the well to a depth of 20,102 ft, the drill rig and camp were airlifted in C-130's to Umiat for the Seabee well. Several inspections of the Inigok airstrip made during the summers of 1980, 1981 and 1982 revealed no change in the excellent conditions of the runway, taxiway, and parking apron; no rutting, differential displacements, or erosion were evident. Vertical-movement observations taken at 200-ft intervals along the centerline of the runway immediately following construction and several times during the summers of 1978, 1979, and 1980, confirmed the stability of the runway.

During construction, ground temperature sensors (thermocouples) were installed in 20-ft-deep drill holes at stations 14+00 (cut section) and 34+00 (fill section) beneath the centerline of the runway. Similar assemblies were placed beneath the shoulder of the runway and in the undisturbed tundra, south and east of station 14+00. Four test sections were also incorporated into the southeast corner of the parking apron, to determine the effect of different thicknesses of insulation. These and other special thermocouples, installed later above and below the insulation, were observed twice weekly during the summer of 1978, and monthly during the following winter and spring, to monitor the effectiveness of the insulation. The extreme maximum and minimum temperatures beneath the runway, for the period of active use, are shown in figure 7a. The maximum recorded temperature immediately beneath the insulation was -2°C. The penetration of

Figure 6. The all-season airstrip at Inigok, showing insulated runway, taxiway, parking apron, and road to drill site. Darker area along road was the result of a tundra fire in 1977. View looking northeast taken in July 1978.

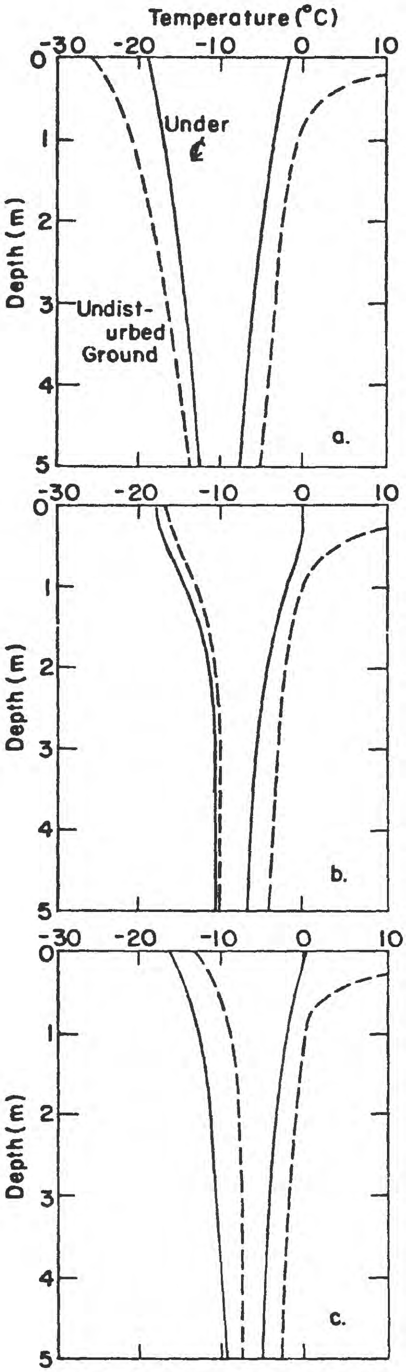


**Figure 7.—Maximum and minimum ground temperatures and depths beneath centerline of insulated runways and adjacent undisturbed tundra at (a) Inigok, (b) Tunalik, and (c) Ivotuk during period of active use in 1978 and 1979. Solid line represents temperatures below insulation; dashed line in tundra.**

cold temperatures through the insulation during the winter was increased by snow removal while the runway was in active use. Temperature observations have been continued to define the long-term thermal regime of this insulated runway, particularly the effect of the snow cover on the abandoned runway.

Another problem to be solved in drilling deep wells through permafrost is to find the best foundation design for the drill rig. Mud temperatures in such deep wells increase with time, and the heat is dissipated radially during the year or more of drilling. Although extremely high temperatures on the wall of the 42-in. surface conductor pipe could be reduced by insulating the upper section of the pipe and controlling the mud temperatures, the influence of this long-term heating on the nearby frozen piling is still a major concern.

The foundation design for the rig placed the timber foundation piles no closer than 12 ft from the center of the well, the area around the well being spanned by steel girders. The rest of the foundation consisted of timber piles, laid out in 5 rows, about 6.5 ft apart with piles 3.0 to 6.0 ft apart in each row. The location of the piles and the timber-pile caps were specifically designed for the actual drill rig to be used. A total of 207 timber piles were used at Inigok for the rig and for the auxillary buildings, mud tanks, pipe racks, etc. All piles were set tip down, to a depth of 25 ft, with the exception of the 10 piles closest to the well and the "rat hole" which were 45 ft long. The piles were installed in dry augered holes, with the annulus backfilled with sand and water. Because of the cold ground temperatures at this site, the piles were frozen into place within a few hours. The ground surface beneath the drill rig was also protected with 6 in. of insulation and sealed with the plastic membrane. The 144-ft X 580-ft area around the drill rig was also insulated with 2 in. of insulation and covered with gravel. The central portion of the drill pad, about 100 ft x 250 ft, was also insulated as was the entire area under the drill camp. The remainder of the 537-ft x 580 ft drill pad was a 4- to 5-ft embankment of sand, with a thin gravel surfacing.

Eight piles beneath the drill rig were equipped with temperature-mesuring assemblies to monitor the three-dimensional heating around the well. The temperature observations, taken at the same frequency as the runway observations, were compiled and plotted monthly. These data were periodically compiled in status reports, indicating the changes in temperature to date and short-range forecasts of temperatures expected in the forthcoming months. Vertical-movement surveys taken periodically of the Inigok drill rig confirmed the stability of the foundation.

The access road between the drill pad and the parking apron was one of the last facilities to be constructed at Inigok; a temporary ice road was used during the initial construction period. The 24-ft-wide roadway, with 4-ft shoulders was constructed by first placing a nominal 1-ft thickness of frozen sand on the unstripped tundra surface. After compaction, a single layer of 2 in. thick insulation (HI-35) was laid down and covered with the plastic membrane. Although the specified thickness of gravel over the insulation called for 9 in. of pit run and 3 in. of select gravel, the actual thickness was less than specified and contained a high percentage of sand. By early summer the road showed signs of distress, and repairs were required. While making the repairs it was noted that the single layer of insulation in many areas had been deformed, the edges of the insulation being much lower than the center of the boards. Thus a gap formed between the boards, and thawing of the sand between the boards was initiated. The insulation was also crushed and compressed, to the extent that in some sections the insulation was only 1/2 in. thick, whereas it originally had been 2 in. thick. The plastic membrane was also punctured in many places, allowing water to infiltrate between the insulation boards, causing soft spots. Failure of sections of the road was also blamed on the heavy vehicle loads (of pipe, cement, and other equipment), as well as the frequent passage of the heavily loaded Foremost vehicle used to supply water to the equipment maintenance camp north of the parking apron, and to sprinkle the runway, taxiway and parking apron.

The road was repaired, in sections, by replacing the original insulation with 3 in., and sometimes 4.5 in., of the HI-60 insulation left over from the runway construction. The insulation was then covered with a foot or more of sand and gravel from stockpiles left for just such contingencies. By late summer the road was firm, well drained, and easily maintained by periodic grading and rolling. The road was still in excellent shape when inspected on visits during the summer and fall of 1981, although minor settlement was evident in those areas having the least insulation.

To evaluate the possible use of military landing mats for roads, airfields, and drill pads in the NPRA, three types of military matting were installed at Inigok in late May 1978. Two test sections were installed on a level area of the borrow pit, just southeast of the parking apron. This area represented a cut section in the frozen sand. Two smaller test sections were installed directly on undisturbed tundra, to the west of the parking apron.

The installation on the bare sand consisted of four continuous sections of AM-2 matting on loan from the U.S. Marine Corps. The first two sections had 3 and 1 1/2 in. of insulation under the matting, while the last two sections were placed directly on the frozen sand. The mat section having 1 1/2 in. of insulation and one of those placed on the frozen sand were painted white, while the matting in the other two sections were olive drab. Thermocouples were installed above and below the matting, and at close intervals to a depth of 10 ft, to monitor the effectiveness of the white paint and the insulation.

The second series of tests on the bare sand used the square XM19 matting. Since this mat had been previously painted white, it was simply given a new coat of white paint. The first two sections of this matting were underlain with 3 and 1 1/2 in. of insulation and similarly equipped with temperature sensors. The last two sections were placed directly on the sand.

Both types of matting, when not underlain with insulation, caused thawing of the underlying frozen ground. Thawing in the sand ranged from 33 in. to 53 in., and large (4 ft) caverns developed beneath the mats where ice wedges existed. The insulated sections had only an inch or two of thawing and no melting of the massive ice wedges, confirming the original assumptions that the military matting could have been used for this and other airfields. These two test sections were removed in early September, 1978.

The matting installed on the undisturbed tundra consisted of both XM18 and the Am-2 matting, both being 1 1/2 in. thick, 2 ft wide, and 12 ft long. One section was installed on insulation, half the section being on 3-in. and the other half on 1 1/2-in. insulation board. The entire test section was painted white. This test section experienced no subgrade thawing in a year's time and when removed in May 1979 there was a layer of ice up to 4 in. thick directly beneath the insulation. The other test section was placed directly on the tussocks, without insulation, and left olive-drab. This test section had only about 14 in. of thawing in the subgrade, when removed in the fall of 1978. The insulating effect of the organic material and the dead air space beneath the matting were apparently instrumental in limiting the depth of thawing to that which normally occurs in the undisturbed tundra at that location. Details of the testing of the landing mats at Inigok has been described by Crory (1981).

Experimental grass plots were laid out in the borrow pit area at Inigok to determine the best types of grasses and optimum rates of application of fertilizer to restore a site following the completion of drilling. Initially, 20 plots were laid out in late May 1978, some plots receiving no fertilizer, others with 1, 1 1/2, and 2 times the normal rate (600 lbs/acre). Several varieties of grasses were sown, using 1, 1 1/2, and 2 times the normal quantity of seed (50 lbs/acre). On three of the plots a surface tackifier was applied to limit wind erosion and retain the surface moisture in the sand. Ten additional test plots were seeded and fertilized in mid-July to determine the effect of the time of seeding. Additional test plots were laid out in the stripped organic material, along the edge of the road, and around the landing-mat test sections. Good stands of grass were obtained at normal rates of application of seed and fertilizer at all sites planted in the spring. Poor results were attained in the mid-summer plantings and in all the plots on organic-material. An accurate assessment of the growth of each species of grass was impossible, because of the severe browsing by a small herd of caribou which, despite the nearby activity, visited the grass plots almost daily during August and September, 1978. Initial seeding of the borrow areas by Husky and its contractors, began with dormant seeding in the fall of 1978. Further seeding was done during the spring of 1979; both seedings were successful. All exposed sand areas had good stands of grass during the summer of 1980 and 1981.

## Tunalik well site

The Tunalik well, like Inigok, was a deep exploratory test hole and required a temporary all-year airfield to support the year or more of continuous drilling required to complete the well. The Tunalik well is located at lat 70°12'21.45" N. and long 161°04'09.15" W. Umiat Meridian, just east of Icy Cape (fig. 1). Although there were several suitable locations for a runway at Tunalik because of the relatively flat terrain surrounding the well, the final location was based on runway grades. A location was selected which avoided deep fills and required no cut sections. Easy access to the borrow sites and the availability of a lake for a winter airstrip were also important. The magnetic bearing at the runway centerline was N75°53'E, parallel to prevailing winds.

Although there are several small lakes 2 to 3 miles east and west of the Tunalik site, the area is drained by the Ongorakvik River which flows northwest for about 10 miles and empties into the Kasegaluk lagoon and the Chukchi Sea. The area appears to be quite flat, but in fact has gentle grades. The site is underlain with varying thicknesses of organic material (peat) and organic marine silt and sand, covered with a uniform stand of grass and sedge tussocks. Beneath the organic layer, which in places was found to be only 1 to 2 ft thick, the soils grade to a silty sand or sand. In some places, such as runway station 32+40 and at the drill site reserve pit, more than 10 ft of ice was found immediately below the 1 1/2 ft organic layer. At depths of 15 feet or more, the sand was virtually free of silt-size particles in some of the drill holes. Although bedrock was exposed in some of the valleys to the north, bedrock at the runway and well sites was below the bottom of the test holes drilled to depths of 50 to 80 ft.

Extensive deposits of sand were located along the left bank of the Ongorakvik River at the confluence with the Nokotlek River about 6 miles north of the well. Development of such a borrow site so close to the river, however, was not considered desirable. An ancient Pleistocene beach deposit on a bluff about 4 1/2 miles west of the drill site, provided a closer and better source of construction material. This material ranged from sandy gravel at the surface to gravelly sand at depth. Borrow was obtained from two pits that were well drained and easily developed. The snow road to the borrow pits was extended another mile and a half to a large lake, capable of accommodating the C-130 aircraft when frozen. A smaller lake, a mile northwest of the runway, was used only for the Twin Otters and smaller aircraft during construction.

The design options at Tunalik, like Inigok, were limited by the amount of gravel available. Constrained by winter construction, the only viable option was to prepare a subgrade using the local sand, maintaining the sand in a frozen state with insulation, and using the limited gravel for the wearing course. The runway having a downhill grade of about 0.3 percent from west to east required fill depths ranging from only 2 to 3 1/2 ft. No cuts were required, as at Inigok. The thickness of insulation required to maintain the sand in a frozen state was calculated to be only 2 in., because of the cooler and foggier weather at such a coastal location (Crory and others, 1978). The high density (HI-60) insulation was used on the runway, taxiway and parking apron, while the lower density (HI-35) insulation was used on the road and drill pad, as at Inigok.

The building of a snow/ice road to the borrow pits commenced in January, 1978. This haul road made good use of the local snow cover but utilized ice as the major construction material. The ice was readily available from the shallow ponds on both sides of the road and required much less water than compacted snow to build up a 1 1/2 to 2 1/2 ft roadway. The road surface was periodically scarified with a road grader, producing a rough surface, so that the rubber-tired dump trucks could travel at close to normal highway speeds.

Borrow pits were developed by first removing all snow and then stock piling the drier surface gravel. This gravel was later used as the surface wearing course for the runway and road. The borrow pits were worked in the same manner as the Inigok borrow site. As the two borrow pits were relatively small, the borrow material was quickly loaded into the 10-$yd^3$ trucks with pup trailers, for the short haul to the runway, road, and drill pad. An ice road just north of the runway, and west of the half-mile road connecting the runway to the well, kept traffic flowing smoothly.

Placement of the gravelly sand fill began on the higher west end of the runway and proceeded eastward. The snow cover was removed just before placing the gravelly sand. No stripping of the surface vegetation was permitted. As soon as the sub-base had been brought to final grade (fig. 8), the insulation placement began, also working from west to east. The insulation was placed as a single layer, 2 in. thick, with the long dimension parallel to the runway centerline. Care was taken to ensure that all joints between the 2x8 ft boards were tight and the rows were kept straight. The boards were staggered in each row and covered with the same kind of plastic membrane as was used at Inigok. No pins or other fasteners were used to secure the insulation to the frozen subgrade.

The pit-run gravelly sand was placed atop the insulation by end dumping and spreading of the gravel with a bulldozer, care being taken not to displace the insulation. The initial lift was a foot or more in thickness and compacted to 85 percent of maximum density, using the segregated and smooth-wheel rollers. The 6-in. wearing course of the stockpiled, select pit-run sandy gravel was similarly placed and compacted. No sheepsfoot rollers were permitted to operate above the insulation. The completed runway is shown in figure 9.

The roadway between the parking apron and the well site at Tunalik was to be constructed in the same manner as the insulated workpad at Inigok, where a single layer of 2-in. insulation boards were placed directly on the carefully prepared tundra surface. To maintain a smooth grade for the insulation, a thin leveling coarse of sand was used. In some sections, however, the 12-in. nominal depth of sand used at Inigok was not placed at Tunalik. No membrane was used above the insulation on the Tunalik road. The 24-ft-wide roadway was completed by using a 1-ft layer of pit-run gravelly sand and then a 6-in. layer of the select sandy gravel for the wearing surface, both layers being compacted to 85 percent of maximum density. The entire road was constructed as a fill section.

Figure 8. Placing final lift on sub-base before placing the insulation at Tunalik runway. Photo taken in March 1978.

Figure 9. All-season airstrip at Tunalik, showing ponding by taxiway and parking apron. Dark line shows location of winter snow/ice road to borrow sites. Note polygonal ground patterns. Clean up of construction camp is underway on lower portion of parking area. View looking west taken in 1979.

As at Inigok, the drill pad was constructed at the same time as the runway. The 150 x 580-ft area surrounding the drill rig was underlain with 2 in. of insulation as was the area beneath the drill camp and a 100 x 275 ft rectangle between the drill rig and the camp. HI-35 insulation was used and was placed in the same manner as in the roadway. Six inches of insulation was used under the drill rig. The membrane above the insulation was tightly sealed around all the timber foundation piles. Although the original intent was to use the sand or silty sand from the excavation of the reserve pit for the initial sub-base fill at the Tunalik drill pad, this plan was changed when massive ice was encountered in the excavation of the pit. The spoil from the reserve pit, which included organic material and silt, was stockpiled and later spread as top soil for reseeding. Material from the borrow sites was used for the initial sub-base and surface at the drill-pad site.

Because of the shorter haul distance and the use of only fill sections, the Tunalik facilities were completed before Inigok. The first C-130 landed at Tunalik on May 1, 1978, and made several more trips that day. The pilot reported that the still-frozen runway surface was in excellent shape. The drill rig was delayed at Kugrua, because the spring breakup occurred before the rig could be moved to Tunalik by land or by air. Thus the start of drilling at Tunalik was delayed until the winter of 1978. Accordingly, construction and maintenance activities at Tunalik were drastically reduced throughout the summer of 1978.

During the first week in June 1978, active thawing of all gravel surfaces began with little or no overnight refreezing. Compaction of the gravel surfaces, particularly the runway and parking apron, were hampered by both excessive moisture and the mechanical failure of the rubber-tired roller. The gravel was dried primarily by windrowing with a grader, although the foggy weather hampered the operation. Because of the soft condition, the airfield facilities were closed to all but light aircraft during June. During the spring breakup, a culvert beneath the road washed out. This washout, together with the soft condition, rendered the road unusable. Because there was no activity at the drill pad, the small maintenance crew was able to concentrate on the runway, taxiway, and parking apron.

With improving weather in late June and July of 1978, the maintenance crew was able to regrade and compact the runway, road, and other facilities to their prescribed 95 percent compaction. Except for the drill pad, all facilities at Tunalik performed well from mid-summer of 1978 until the well was completed in late January 1980. No problems were reported during the spring breakup of 1979. During the summers of 1978 and 1979, the drill pad was consistently a problem. Although additional gravel had been placed there in the late summer of 1978, the pad was still soft and wet throughout the major portion of the summer of 1979. The lack of sufficient slope for drainage and the poor quality of the material above the insulation were considered the major factors responsible for the poor performance in those areas underlain by insulation, and the lack of insulation was the major factor in other areas.

In mid-March 1978, before placing the insulation, two thermocouple assemblies were installed to a depth of 20 ft along the centerline of the Tunalik runway. The thermocouples were installed at stations 16+10 and 32+40, the stationing beginning on the east end of the 5,000-ft runway. A similar thermocouple assembly was installed about 50 ft south of the runway shoulder at station 32+40 to monitor the normal thermal regime of the undisturbed tundra. The maximum and minimum temperatures beneath the tundra and insulated runway are shown in figure 7b. The temperatures directly beneath the insulation reached $0^{\circ}$ C in the mid-summer of 1978 and were very close to $0^{\circ}$ C during 1979 and 1980. Two test pits along the centerline of the runway, dug in mid-August

1978, confirmed that the sub-base was indeed still frozen. Another test pit, to examine the condition of the insulation, was dug in early September 1980 beneath the taxiway. The sub-base was again found to be frozen, with ice in the joints between the boards. Level surveys and careful inspection of the runway did not reveal any low spots or depressions which would indicate localized thawing beneath the insulation. The grass, planted in early June 1978, in the overrun section on the east end of the Tunalik runway continued to show good growth through the summer of 1980.

During the abrupt breakup in the spring of 1980, a 4- to 6-ft-wide section of the taxiway was washed out. A pond had been formed at the junction of the parking apron, taxiway, and runway since the original construction (fig. 9). The breach through the 20 in. or more of gravel and gravelly sand above the insulation was caused by a ditch containing a fiberglass pipe used to pump water into and out of the small pond. The washout across the taxiway had not been repaired, as of our last visit in July 1982.

Eight foundation pilings at Tunalik were equipped with ground-temperature sensors to evaluate the thermal regime immediately surrounding the well, as at Inigok. Installation of the foundation piles at Tunalik is shown in figure 10. Two additional thermocouple assemblies were installed on June 21, 1979 near the southeast corner of the drill rig, where a cavity formed by thawing of ground ice in permafrost was noted. The temperature observations indicated that thawing was occurring only near the ground surface and the pilings were not in jeopardy. After the rig was removed in the early spring of 1980, these cavities had enlarged to form several depressions 4 to 5 ft deep. The fill beneath the rig had originally been graded level with the top of the pile caps.

### Lisburne (Ivotuk) well site

Because the insulated runways at Inigok and Tunalik worked well during the summer of 1978, a similar runway was constructed in early 1979 at Ivotuk to service the deep exploration at Lisburne. The Lisburne well was only a few miles west of the north-south boundary of the NPRA in the northwest corner of the rolling Ivotuk Hills north of the Brooks Range (fig. 1). The Lisburne well site is connected by a 2-mile gravel road running west across Otuk Creek to the Ivotuk runway. The 150-ft wide by 5,000-ft-long gravel surfaced runway is oriented north-south (magnetically) at about lat 68°29' N. and long 155°45' W.

The well site is in an east-west valley between two ridges at lat 68°29'05.44" N. and long 155°41'35.51" W., Umiat Meridian. The ridges have extensive exposures of bedrock, but the valley is underlain by organic material, silt, and gravel chiefly of glacial origin. Because the well site was located on a steep grade, the drill pad was constructed at three different elevations: the upper level for the camp and rolling stock, the middle level for the drill rig, service buildings, and pipe storage, and the third level for the reserve pit. The fill for the camp and drill pads was obtained from the excavation of the reserve pit.

The runway was oriented parallel to the major drainage, its profile on a 1 to 1.5 percent grade sloping to the north. The original site was covered with low tussock grasses and sedges growing on a brown to black organic surface layer. The soil at shallow depths ranged from organic silt to silty colluvium, overlying weathered bedrock which ranged from 5 ft to more than 15 ft deep. The bedrock beneath the airfield consisted of sandstone and shale, with occasional layers of limestone. Frost-rived boulders were exposed along the ridge just west of the runway. Gravel was found along virtually every stream in this area, although only limited quantities were available for the construction of the all-seasons airstrip, road, and drill pad within 1 mile of the Otuk Creek crossing (fig. 11).

Figure 10. Installing piling for drill rig at Tunalik. Drill in the background is drilling the conductor hole for well. View looking east taken in March 1978.

Figure 11. The Otuk Creek bridge on access road between Ivotuk airfield and Lisburne well. Disturbed areas are former borrow pits. View looking north taken in July 1979.

Two main considerations influenced the design and construction sequences for the facilities at the Lisburne well: (1) To meet drilling schedules and avoid any trafficking over bare tundra; all work had to be done in the winter, and (2) the only frozen lake large enough to accommodate the C-130 size aircraft was Lake Betty, about 20 miles to the west. Thus the plan was to quickly construct a thin frozen-gravel mobilization airstrip, which could later be used as the sub-base for the all-seasons airfield. This sub-base, of pit-run gravel from Otuk Creek, was levelled and iced to provide a smooth, rock-free surface. Runway construction was then halted, providing a limited time window during which the drill rig, drill camp, and other supplies, including the insulation for the airfield, could be brought in by C-130 and other aircraft. The mobilization strip was then closed to all but short takeoff and landing (STOL) aircraft while the insulation and gravel overlay was placed to complete the all-seasons airstrip. The major design problem for this airfield was the layer of ice on the surface of the mobilization strip, some 1 to 3 in. thick, and the thickness of insulation required to prevent this ice and the underlying gravel from thawing during the summer. As a result of the experience gained at Inigok and Tunalik, 2 1/2 in. of insulation was recommended for Ivotuk. The insulation was placed in two 1 1/4-in. layers and was covered with a plastic membrane, like that used at Inigok and Tunalik.

After constructing a winter trail from Lake Betty, a temporary construction camp was set up just north of the proposed road to the west of Otuk Creek. The screening and crushing plant was set up on the east side of Otuk Creek just south of the newly constructed road leading to the well site. The gravel borrow pits along Otuk Creek (fig. 11) both up- and downstream of the bridge were developed by first stripping off the snow and organic cover, which was later used to restore the pits. The size and depth of each borrow pit were carefully controlled to avoid any possibility of changing the channel of the creek.

While there were some anxious moments about completing the mobilization strip in time for the planned shutdown period, it was completed without difficulty. During this initial construction period, and while the airlift was still underway, the screened and crushed gravel for the airfield was being processed and stockpiled. The insulation for the runway, in plastic-covered bundles, was temporarily stored along both shoulders of the runway, making it readily available for placement after the mobilization strip was closed to the larger aircraft. Once closed, the Twin Otters and other small aircraft continued to use sections of the airfield during placement of the insulation and the overlying gravel. The completed all-seasons airstrip is shown in figure 12. Although no problems had been experienced with wind during the placement of insulation at Inigok and Tunalik, the strong winds at Ivotuk, particularly during the third week in April 1979, made it necessary to stop work for several days.

Although the shorter access roads at Inigok and Tunalik were built with insulation, the longer road between the Ivotuk airstrip and the Lisburne well was constructed with gravel without insulation. This construction made it possible to place the over-size gravel from the screening and crushing operation in the lower sections of the roadway embankment. The roadway embankment at the centerline normally ranged from 4 to 6 ft thick, although several sections on abrupt grades were even thicker. To minimize both the construction cost and the amount of gravel use, the design road width was only 12 ft with 4 ft shoulders. This width tended to increase with time as the traveled way was regraded. The narrow road was used without serious traffic delays by building turnouts at 1,000 to 1,500 ft intervals.

Otuk Creek was bridged with a double-span, laminated timber bridge supported by timber piling (fig. 11). The abutments of the bridge were protected by rock-filled gabions up- and downstream of the bridge. The single-pile bent in mid-stream was

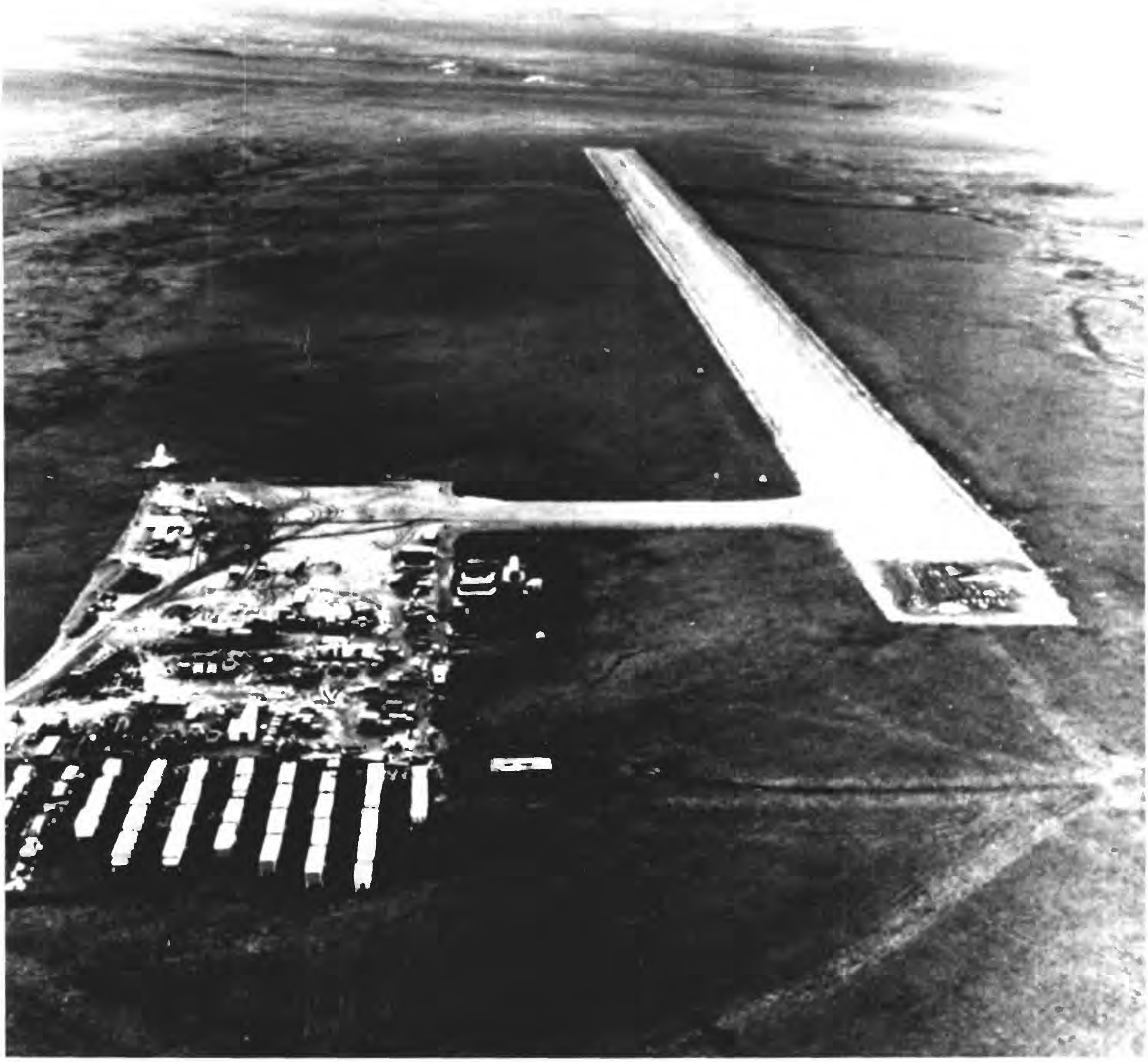

Figure 12. Insulated all-season airstrip at Ivotuk with parking apron and equipment storage area at left. Note wet over-run section at end of runway. View looking south taken in July 1979.

protected by a steel raker extending from the pile cap into the stream bed at a 45° angle on the upstream side. This protection against ice during the spring breakup was later found to be unnecessary.

The construction of the Lisburne drill pad was a difficult undertaking as compared to other pads in the NPRA which were built on relatively flat ground. Because of the limited working area and steep slopes, excavation was by blasting rather than ripping. The blasted material from the reserve pit was used to form the two side-hill benches for the drill pad and camp. Insulation was used beneath and adjacent to the drill rig, under the camp, and on the high slope of the reserve pit adjacent to the drill. All slopes and pad surfaces were blanketed with pit-run gravel, as were the reserve-pit dikes. These dikes had to be quite steep to avoid the small creek which drains the valley.

During construction, the runway, road, bridge, and drill pads were instrumented with temperature sensors. Initial elevations were taken, the level observations being referenced to frost-free benchmarks near the taxiway, the southwest end of the bridge, and the south end of the drill pad. Thermocouples were installed beneath the centerline of the airstrip at stations 29+00 and 52+00; station 12+50 is the north end of the airstrip and station 64+00 is the south end. Station 29+00 was selected as being representative of the thinner cross sections; station 52+00 had the greatest depth of sub-base, because this location had originally been a low swale. Temperature assemblies were also installed in the undisturbed tundra at station 29+00 and 64+00 to the west of the runway. Station 64+00 was selected rather than station 52+00 for this tundra assembly because the original plan was to incorporate several test sections in the 200-ft overrun on the south end. Unfortunately, the incorporation of these test sections, using several thicknesses of two different types of insulation, could not be coordinated with the airfield construction schedule, so they were switched to the drill pad. Two additional thermocouple assemblies were installed, however, in the uninsulated north overrun, to determine the thermal regime of a thin gravel overlying undisturbed tundra. An additional, deep thermocouple assembly (to a depth of 100 ft) was installed near the tundra assembly at station 29+00 in mid-June 1979 to determine the permafrost temperatures at depth. The envelope of maximum and minimum temperatures beneath the insulated runway and the undisturbed tundra at Ivotuk is shown in figure 7c. Although the temperatures just beneath the insulation approached the melting point, no apparent thawing or subsidence of the runway was noted during the summers of 1979 and 1980. The only operational problems at Ivotuk were those encountered during the initial thaw in May 1979 when soft spots and rutting under the C-130 traffic occurred in isolated areas. The remedy was to excavate the affected areas and refill them with select compacted gravel. The wet spots were directly related to what appeared to be about a truck load of silty sand and organic material which had been placed directly on the insulation. The wet, soft conditions lasted about 10 days, during which time dozens of such soft areas were replaced by select gravel. After the repairs were completed and the gravel overlying the insulation had become thawed and recompacted, according to specifications, the runway was easily maintained by periodic blading and rolling. No recurrences of the soft spots were noted during the spring of 1980.

Ground-temperature assemblies were also installed at three locations to a depth of 15 ft beneath the centerline of the road. The temperature observations, taken weekly during the thawing period and monthly in the winter, measure the thermal regime beneath the uninsulated road. Six temperature assemblies installed on the abutments and center pier of the Otuk Creek bridge, were designed to define the temperatures beneath the stream bed and to confirm the design temperatures for the frozen-in piles The data indicated that no thawing occurred around the frozen piles. There was, however, about an inch of heave of the upstream side of the bridge pier cap because of the heaving of the ice raker.

At the Lisburne well site the temperatures at depth along the conductor pipe as well as on selected foundation piles beneath the rig were monitored throughout the active drilling period. Because of the high dikes surrounding the reserve pit at this site, in contrast to Inigok and Tunalik, special temperature assemblies were installed beneath the bottom of the reserve pit, within the core of the highest dike, and on the insulated slope beside the drill rig. Eight test sections were also incorporated in the drill pad, to compare the effect of two thicknesses of two different types of insulation board. All dikes and pads performed well and in accordance with design assumptions. The only wet and soft spot on the drill pad was at the uninsulated south end--an area which received drainage from the adjacent ramp road to the upper camp pad.

Small revegetation plots were established in the spring of 1979 in a borrow pit south of the Otuk Creek bridge and just northeast of the bridge. Initial growth was encouraging, but to determine whether these grasses will become firmly established or replaced by native species requires long-term observations.

**Summary and conclusions**

The information gathered during the design, construction, and performance of these facilities in the NPRA could only be described in general terms in this paper. However, the three insulated airstrips constructed in the NPRA have demonstrated that such facilities can be built in the winter, using both cut and fill sections. The insulated airstrips provided a viable design alternative at locations having limited quantities of gravel. Maintaining a frozen sub-base by the use of 2 to 3 in. of insulation overlain by at least 15 in. of clean compacted gravel provides the desired bearing capacity for the heavy C-130 type aircraft and avoids the undesirable settlements associated with the thawing of frozen fill or permafrost.

The failure of sections of the insulated road at Inigok confirmed the requirement for 12 in. or more of gravel above the insulation and the necessity for the high-compressive-strength insulation when subjected to heavy loads. The incorporation of undesirable material in the gravel above the insulation, which caused the isolated soft wet spots in some sections of the runways and parking aprons during the initial spring breakup, can be minimized or eliminated by closer inspection of materials during construction. Rolling and rerolling of the gravel above the insulation is apparently essential during the initial thawing period. The grades on large areas, such as parking aprons and drill pads, should be sufficient to accommodate the initial melt water and subsequent precipitation during the first and subsequent spring breakups. The almost flat grades on the large drill pads for the deep wells does not appear to be justified as much of the pad is used for storage. The failure of culverts on the Tunalik and Seabee roads during the spring breakup suggests that more attention should be given to the design, construction and maintenance of these drainage structures.

The strict control of all off-road construction activities associated with the NPRA exploration program, using well-prepared snow/ice roads and trails and prohibiting traffic over bare tundra, minimized or avoided the environmental disruptions experienced a generation ago in the reserve. The airfields, roads, and well sites constructed since 1977 reflect the current state of the art of northern engineering. Since that time the interrelationships between the environment and the facilities have been considered to the advantage of both. The facilities constructed in support of the deep explorations performed remarkedly well, considering they were built in the winter, with frozen material, and were intended for use over such a short length of time.

The new concepts for winter construction of large all-year airstrips at Inigok, Tunalik, and Lisburne (Ivotuk) are also applicable to permanent airfields, roads, and construction pads. By using insulation, only 15 in. of compacted gravel is required as compared to the 6 ft required to prevent thawing of permafrost beneath uninsulated airstrips in the Arctic.

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