Air-Ducted Hangar Foundations at Thule, Greenland

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ABSTRACT
The late 1940's and early 1950's was a pivotal era for permafrost engineering as studies of the fundamentals paved the way for new concepts in design and advances in technology. The United States air base at Thule, Greenland was originally constructed in 1951 and incorporated some of those advances, most notably the air-ducted foundation. More than 50 years have now passed offering an opportunity to critique this design and compare to the current engineering methodology. Also the unforeseen problem with ground water infiltration is discussed.

RÉSUMÉ
Les études fondamentales réalisées en ingénierie nordique à la fin des années 1940 et au début des années 1950 ont pavé la voie pour le développement de nouveaux concepts et de nouvelles technologies adaptés aux régions froides. Par exemple, lors de la construction en 1951 de la base aérienne américaine à Thulé au Groenland, certaines de ces technologies, dont notamment les fondations ventilées en hiver pour maintenir froid le pergélisol sous les infrastructures, ont été intégrées dès le départ dans la conception et la construction des bâtiments militaires. Plus de 50 ans après la construction de cette base militaire, l'analyse de la performance des fondations ventilées et sa comparaison aux méthodes actuelles en ingénierie nordique permettent de tirer des leçons utiles au domaine. Les problèmes associés aux fondations ventilées et à la dégradation du pergélisol sous les infrastructures sont aussi présentés et discutés.

1 INTRODUCTION

Thule Air Base is located in Northwest Greenland (N 76° 32', W 68° 45') on an ice free margin between the Greenland Ice Cap and the waters of North Star Bay (Figure 1). This region consists of permanently frozen glacio-fluvial soils with an estimated thickness of approximately 350 m (Davies et al 1963). These soils contain massive ice in the form of ice wedges, segregated ice and relict ice (Corte 1962), and polygonal ground is visible throughout the area.

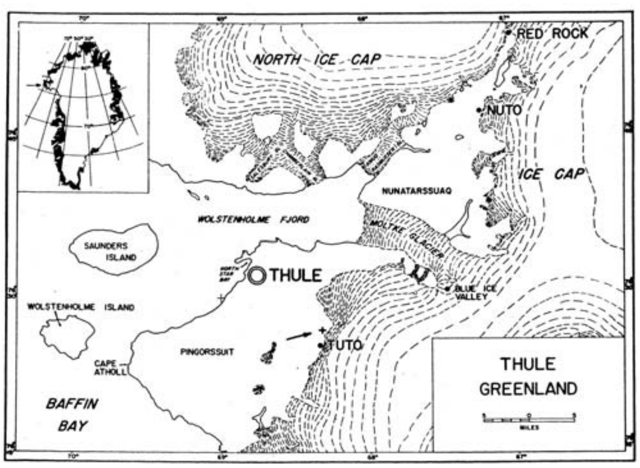

Figure 1. Location and area map Thule, Greenland.

The air base was constructed in 1951, and the foundation design for the structures incorporated the latest in permafrost engineering technology to insure that degradation of the massive ice and ice-rich soil did not occur. However, design inadequacies of the air-ducted systems have resulted in thaw settlement problems. This paper discusses the design, problems encountered, and advantages of this type of foundation.

1.1 Permafrost

The permafrost soils of the Thule area are glacio-fluvial in origin, and are composed of glacial till, sand to cobble and boulder sized material, with occasional zones of finer grain silts and clays. They overlie an inclined sequence of shale and dolostones intermittently intruded by diorite rock. The thickness of the soil increases with proximity to the ice cap, and at the location of the airfield the thickness is 5 m to 10 m with some bedrock outcropping.

Massive ice, in the form of ice wedges up to a meter wide and meters deep, are predominate in the area. The ice wedges extend laterally up to 5 m and form polygonal ground with high centers. The terrain in the immediate area of the base was highly disturbed during construction; however an isolated undisturbed location exists next to the airfield containing significant ice wedge surface expression, giving an indication of the amount of massive that exists elsewhere. Additionally, oblique aerial photography from prior to construction shows the entire airfield area to have consisted of polygonal ground.

The top of the wedges are located at the bottom of the active layer which is from 30 cm to 100 cm in depth depending on soil type and vegetation. In locations were shallow bedrock exists, the wedges terminate at the soil bedrock interface. The active layer can be 2 m in depth under non-vegetated fill material. Also, a few isolated remnants of glacial ice buried and preserved have been found in the area (Corte 1962).

Vegetated areas consists of lichens, moss, and cotton grass, and the climate of the area is high-arctic marine with an annual freezing degree day index of 4450 °C, and an annual thawing degree day index of 423 °C.

1.2 Air Ducted Foundations

Horizontal structures such as the airfield, roadways, and raw water dam utilized a specified thickness of non-frost susceptible (NFS) material for protection against thaw degradation. Vertical structures with slab-on-grade floor systems utilized ambient air-ducted foundations, while the remaining structures were raised on post and pad.

The air-ducted foundations are all similar in concept, but differ in design and materials depending on the building footprint. All the systems were designed to best utilize the winter air temperatures to maintain the foundation soils in the frozen state. The concept involves the utilization of either an inverted metal pan with a monolithic concrete pour over the top of the pans, or a horizontal pipe installed below the floor system. Both type of systems then connect to surface vents via piping manifolds. The prevailing wind direction, which blows from the east to the west from the Greenland Ice Cap, was utilized by orienting the structures with the air duct inlets on the east side of the structure, and the outlets on the west side.

2 HANGARS 9 AND 10

Of the ten hangars located at Thule, nine are similar in design but vary slightly in size. Hangars 9 and 10 are two of the larger hangars and were the last to be constructed in 1953. These structures have experienced significant thaw degradation under the slab-on-grade floor system, despite utilizing the air ducted foundation concept, and much information is available regarding the history.

2.1 Design

The structure and foundation of Hangars 9 and 10 consists of buttressed, near-parallel chord trusses, supported on concrete pile caps. Each cap rests on a minimum of twelve 28 cm diameter timber piles that were placed in blasted trenches up to 6 m in depth. Ultimately the piles extend to approximately 10 m below the pile cap onto the permafrost (Figure 2a and 2b). The pile system is also utilized on the south wall of the hangar to support the large aircraft door. The north wall is not load bearing and therefore utilizes a poured concrete grade beam. Approximately 6 m of fill was placed on top of the native soil under the hangar. The floor consists of 10 cm of Portland cement concrete (PCC), overlain with 10 cm of foam glass insulation, overlain with 37 cm of PCC. The buttressed end of the trusses is enclosed in an unheated envelope on each end of the hangar, and this envelope is connected over the top of the hangar (Figure 2a). The long dimension is 91 m and the shorter dimension is 52 m with approximately 4500 m^2 of heated space.

The air duct piping in these hangars are constructed of 28 cm diameter corrugated pipe separated from adjacent ducts by 60 cm, yielding approximately 64 rows and at a depth of 1.5 m below the floor surface. The ductwork runs from east to west emerging from the ground inside the unheated buttress areas on the east and west ends of the hangars into manifolds that group the ductwork into 9 stacks (Tobiasson 1970). The ductwork then runs vertically and penetrates through the buttress area walls to the outside (Figure 2b). Chimney draft is incorporated into the design and the air duct outlets (west) are approximately 7 m taller than the inlets on the upwind wall (east), and this is to induce a convective draft effect. All plenums are equipped with dampers located within easy reach, to shut the ductwork in the summer season preventing flow of warmer than freezing air.

2.2 Thaw Degradation

The floor of Hangar 10 was completed in February of 1953, the superstructure was completed that summer, and heating began August 8, 1953. During the construction sixteen boreholes and test pits were drilled through the finished floor of Hangar 10 for the installation of 428 temperature sensors. The boreholes were located

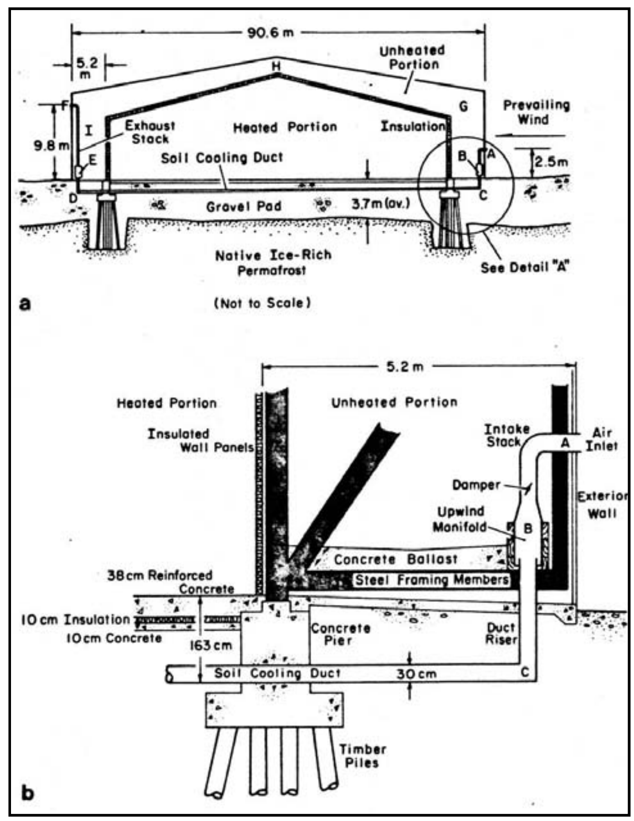

Figure 2. a) Hangar Cross-section b) Detail of pile system and air duct system. (Tobiasson 1973)

down the center of the hangar in both the north-south, and east-west directions (for exact locations see Tobiasson 1970) to a minimum depth of 7 m, with one sensor string installed to a depth of 12 m. The sensors were placed in the soil and in and around portions of the cooling ductwork.

In the early months of 1954 the temperatures in the downwind section of the ductwork were found to be 22°C warmer than temperatures in the upwind section, but still below freezing. This prompted an inspection and the ductwork was found to be clear. Because of the temperature differential, a theoretical analysis was conducted by Takahashi (1956) on the cooling system and problems were found that increased friction loss and decreased air flow velocity (Tobiasson 1970). No modifications were made due to this study.

In 1956 it was observed that the 0°C isotherm was deepening below the portion of the non-productive ductwork section and that ice, snow and silt blockages were beginning in the productive portions of the ductwork. This prompted steam cleaning in the winter of 1956-1957 and again in the summer of 1957. A drainage study was conducted during the summer of 1957 (Metcalf and Eddy 1957) and two water wells and two observation wells were installed in each hangar to ascertain water flow and direction. It was theorized that subsurface flow from Lake Eddy, located 200m to the south of the hangar and across the ramp and taxiway, was the source of the water.

Excavations in the unheated portions of the hangars in 1957 revealed that the ductwork was almost completely inundated with layered ice that the previous winter steam cleaning failed to mitigate. The groundwater system was again studied in 1958 (Metcalf and Eddy 1958) and during that summer the level of Lake Eddy was lowered by 2.5 m and this level was maintained by pumping from the lake and hangar water wells. The lake was lowered again in 1960 by 1.2 m with lake and hangar well pumping, and when the pumping was discontinued in July, over 8,700,000 litres of water were pumped from the lake. Interestingly, from that time until freeze-up no further pumping was needed to maintain the water level. Despite all this effort, winter steam cleaning of the ducts was still required.

The floor settlement in Hangar 10 was first noticed in the vicinity of the northwest water well between 1962 and 1963. The northwest well was the most actively used well for pumping. In 1964 a test pit was excavated to twelve feet below the center of a depression in Hangar 10, and the depression at that time was 33 cm. The reports indicate that steam cleaning continued from 1963 to at least 1969. In 1969 the depression in Hangar 9 was 30 cm deep and Hangar 10 it was 69 cm (Tobiasson 1970). The floor settlement in Hangar 9 was first noticed in 1966.

In 1983/1984 a floor repair project was carried out in Hangar 9 and 10 where all the thawed NFS fill material was removed and replaced with fresh NFS material, and the floor was recast with underlying insulation and AM-2 aluminum aircraft mats placed on the surface (GC 2009). In 1989 concrete was added to the depression in Hangar 9. In 1993 an investigation was conducted to determine alternatives for hangar renovation (Hansen, 1994).

In 1996 Hangars 7 and 8 were reconstructed due to severe thaw degradation by elevating the floor onto a post-and-pad foundation allowing for free flow of ambient air under the floor. Up to this time Hangar 8 had up to 150 cm of settlement in the floor with a maximum rate of 30 cm per year (COWI 1988).

In 1998 a load-carrying evaluation was performed in Hangar 9 and two test pits were excavated and water flow tests were conducted (Brown, 1998). In Test Pit #1 the static level of the water was 73 cm below the floor surface. Water was flowing from all directions and entering at 89 cm below floor surface at a rate of 2 litres per second. In Test Pit #2 the static water level was at 78 cm below floor surface. Water was entering the pit primarily from the southwest corner at 89 cm below floor surface at 4.5 litres per second. The depression in Hangar 10 at that date was 102 cm. Some areas were excavated and new fill placed, and steel plates laid at the surface (GC 2009). Maximum settlement in either hangar is unknown. In 2000 the heat was discontinued in Hangar 10 and the use changed to cold storage, and thaw settlement has stopped since that time.

2.3 Observations

During September 2009 the floor in Hangar 9 was noted to be gravel fill with aircraft mat (AM-2) overlay on 70% of the floor. A 27 cm depression approximately 6 m by 9 m is centered in the western half of the structure. The building is in constant use and is heated in the winter. In Hangar 10, a large depression exists that at one time had been levelled with coarse grain fill material, but now measures 60 cm in depth at the deepest location. The depression runs nearly from the interior partition wall to the north, to within 6 m of the large hangar door on the south wall. It begins 9 m from the eastern wall and continues across approximately half the distance of the western half of the structure. The depression is deepest in the eastern half and becomes shallow moving westerly. There appears to be a dramatic beginning to the depression on the south, and northern edges. In both hangars the interior partition walls that create storage and office space to the north are severely distorted and leaning in the direction of the floor settlement.

For both hangars, interior and exterior examination of the load bearing walls on all sides discovered no visible distress. All corners, eve lines, and ridge lines appeared to be plumb and level within reason for structures of this age and construction type. All man doors were operable and there are no problems with the large south facing aircraft doors. Test pits and subsurface drilling was performed in the hangar floors. The excavations were performed by the base contractor with a track mounted excavator. Significant layers of concrete and steel reinforcing bar were encountered during the excavations. The drilling was conducted utilizing a track mounted direct push soil sampling drill.

The excavation in Hangar 9 was conducted entirely in coarse grain fill material in a slight depression of 27 cm in the western half of the hangar. The original floor surface at that location is 97 cm below current floor elevation. The water was entering at 91 cm below the current floor elevation with an estimated inflow rate of 6.5 litres per second while pumping. Static level of the water was 61 cm below current surface. During backfilling of the excavation a 15 cm inside diameter casing was installed to the surface to allow for drilling of the sub floor soils. The drilling was performed to a depth of 4.5 m below the surface in coarse grain fill material and no permafrost was encountered. This is consistent with the heated use of this structure with inoperable soil cooling system.

The excavation in Hangar 10 was conducted entirely in coarse grain fill material in a 71 cm depressed area in the eastern half of the hangar. At the location of excavation the original floor is 66 cm below the current floor elevation. The groundwater table is 99 cm below the current floor elevation with an undetermined flow rate estimated at 1.0 to 1.5 litres per second, and the permafrost table was located at approximately 1.5 m below the current surface. During backfilling of the excavation a 15 cm inside diameter casing was installed to the surface to allow for drilling of the sub floor soils. The drilling was performed to a depth of 2.4 m below the surface and solid ice with metal debris was encountered from 1.7 m to 2.4 m in coarse grain fill material and this is consistent with the unheated use of this structure.

3 PROBLEMS

Rigorous methodologies for permafrost engineering were in infancy when Thule AB was constructed, and more advanced designs such as air ducted foundations were in the early stages of study at the Arctic Construction and Frost Effects Laboratory, Permafrost Research Field Station in Fairbanks, Alaska in 1950 (ACFEL 1955). Full understanding of the possible consequences was not realized for the design at Thule.

3.1 Air Ducted Foundation Deficiencies

Prior to the foundation reconstruction of Hangars 7 and 8, approximately forty five air ducted foundation structures existed at Thule. Ten of these are hangars, with seven experiencing thaw settlement, and the settlement is extreme at greater than one meter. This is directly attributable to deficient thaw prevention design.

All of the hangars have long air duct lengths between 70 m and 90 m, oriented parallel with the long dimension of the structure. In the seven hangars that experienced thaw degradation, the locus of the depressions was centered in the western portion of the hangar floors and this coincides with results of the air flow analysis conducted in 1956, which found that the freezing effectiveness was only available for the upwind 75% of the ducts. Specifically, the roughness of the corrugated pipe used for ductwork, excessive airflow mixture at the manifolds, and insufficient chimney draft, were all contributing factors to the insufficient cooling capacity.

Additionally the plans specified the use of ‘open joints with loose joint cover’ on the corrugated pipe ducting, and man-operated louvers to prevent warm airflow through the ducts in the summer season. The loose joints allowed infiltration of groundwater which occluded the pipes and decreased airflow, and the louvers were subject to human error in operation and accidental opening or closing.

Of the remaining thirty five structures, only two have thaw settlement. The settlement in these two structures is considered extreme at equal or greater than one meter, but has been directly attributed to thermal erosion from domestic water and steam leakage, not deficient permafrost preservation design. These structures have the ductwork oriented parallel to the shorter dimension yielding considerably shorter duct no greater than 50 m in length.

3.2 Massive Ice Occurrence

The permafrost and massive ice morphology of the Thule region is dominated by late Pleistocene ice retreat. During the Illinoian, and possibly before that time, a thick extension of the Greenland Ice Sheet covered the Thule area extending into North Star Bay and beyond Saunders Island. The Sangamon Interglacial (ca 120 ka) began the slow retreat of the ice sheet, and it is estimated that thick ice existed in the Thule area as recently as 33 ka (Davies et al 1963). By the beginning of the Holocene (ca 12 ka) the ice sheet was not located in the valley currently occupied by Thule AB (Funder 1990). No further advances or retreats are known to have occurred after this time.

A relatively thin blanket of glacial material exists over the bedrock, and due to the glacial history it is assumed this deposition occurred during the last retreat. The ice wedges that exist at the surface today are therefore geo-cryologically young in age, with an estimated start of emplacement at the end of the Wisconsinan or beginning of the Holocene. It is assumed that the mode of permafrost development is epigenetic, and this in turn has controlled the ultimate vertical extent of the ice wedges to no more than 2 to 3 meters. The glacial advances or retreats from before the Illinoian are not understood, and it is plausible early Pleistocene emplacement of ice wedges could have occurred and now lie at deeper depths in older sediments, however no evidence has been found to suggest this.

During the excavation of the pile trenches for Hangar 10, a detailed mapping was conducted of the underlying soil and ice conditions, and an isometric diagram of the conditions found, is shown in Figure 3. Bedrock was encountered in the western portion of the trench excavation. The bottom of massive ice, which is assumed to be ice wedge ice due to the linear nature, was located approximately 3 m above the bedrock. The full ice wedge extents are unknown

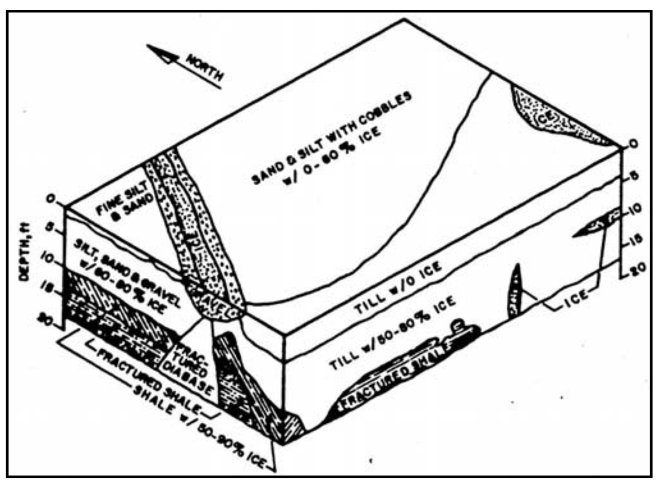

Figure 3. Isometric diagram of the soil conditions beneath Hangar 10. Note the massive ice in the northwest corner and bedrock at 3 m depth. Figure units in feet. (Tobiasson 1970).

Additionally, the information from the boreholes drilled for temperature sensor installation, indicate the native surface is 6 to 8 meters below finished floor elevation, it is assumed that the top of the excavation shown in Figure 3 is the native surface encountered during this drilling, with organics removed and the site leveled.

Based on the glacial history and the knowledge of permafrost of the area, massive ice morphology, and the results of the drilling and trenching for construction, it can be suggested that some amount of over-excavation of massive ice would have been an option to prevent future thaw degradation. The availability of fill material at Thule was abundant from both borrow river material and blasted quarry bedrock, where both sources were used extensively for construction of the base.

3.3 Groundwater

The drainage studies conducted in the late 1950's established that the primary flow of surface water and ground water occurs from southeast into the airfield area. This flow is primarily from the higher elevation of the up-stream valley combined with flows from South Mountain directly to the south. For the subsurface water problems with Hangar 9 and 10, surface water infiltration from snow removal and other sources were ruled out.

Considerable groundwater seepage is noted along the runway shoulders starting at approximately Lake Eddy and moving westerly. No seeps are noted around Hangar 9 and 10. It has been noted by the author that while the runway seeps are at the most active during the early to mid summer, no significant water is impounded against the runway and taxiway embankments, and the surface drainage pathways around the embankments and hangars, exhibit very minor flows, unless immediately after a precipitation event. The previous drainage studies suggested that springs must exist under the runway embankment to account for the total water flow observed in observation wells and at the surface. This is highly improbable due to the continuous extent of the permafrost of the area, which should prevent vertical and lateral intra-permafrost water migration, with subsequent resurfacing as artesian flow under the airfield embankments.

3.3.1 Runway and Taxiways

Photographs and topographic maps from prior to construction of the airfield indicate that Lake Eddy existed, but was smaller prior to construction. Hangars 9 and 10 were placed on a significant fill thickness at the down sloping edge of a topographic high (Figure 4). The topographic high became a cut portion for the runway and bounds Lake Eddy to the south. Taxiway Alpha became a topographic boundary to the north, and Taxiway Bravo became a topographic boundary to the west. The main outflow for the lake is a culvert structure under Taxiway Bravo to the west, and secondary outflow to the northeast under Taxiway Alpha. A relatively low elevation difference exists in a direct line between Lake Eddy and Hangars 9 and 10. The surface elevation of Lake Eddy during August of 2009 was 2.3 m lower than the water table elevation below Hangar 9 and 10.

The previous drainage studies suggest that the runway and taxiway embankments act as conduits for the flow of water from the southeast, moving it north and westerly through the airfield, with some collection occurring in Lake Eddy and the remaining flow continuing under the runway embankment resulting in the noted seepages (Figure 4). These studies also suggest the water flow within the embankments is focused under the centerline, and this infers that a thaw bulb type basin exists under the embankment with the deepest thaw under the centerline. The concept of water flow under the embankments is not disputed, but finite element thermal modeling of the taxiway and runway embankments suggests that the deepest thaw would occur at the toe of the embankment shoulder due to a significant crown in the embankments, not under the centerline, where the permafrost table has been raised and nearly mirrors the topography of the embankment. The raised permafrost table is exacerbated by the 40 years of white painting of the runway and taxiways which decreases the depth of annual thaw by nearly 1.0 meter in comparison to natural black asphalt pavement. This subsurface permafrost topology would cause water transmission to occur under the shoulders, not the centerline, and this is validated by the seepage locations. Probable water flow pathways are shown in Figure 4.

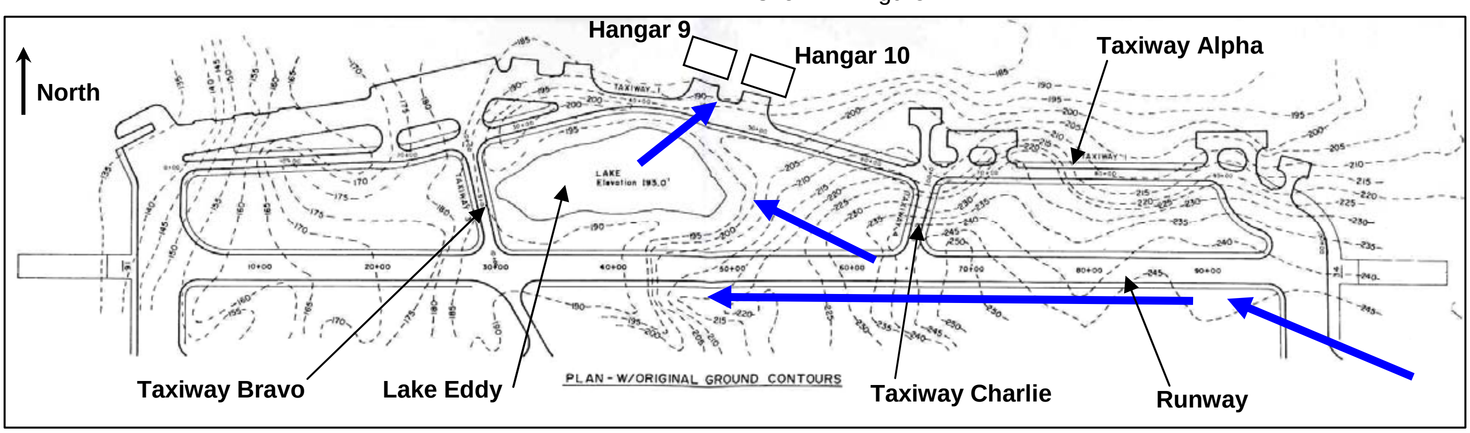

Figure 4. Area map. Bold arrows indicate water flow paths. Preconstruction contours in feet.

3.3.2 Hangars

Galvanic and capacitive coupled electrical resistivity surveys were conducted between Lake Eddy and the Hangars in August 2009. In addition, 400 and 200 MHz ground penetrating radar (GPR) surveys were also performed. The resistivity surveys indicate that a narrow, highly conductive region exists directly in the pathway of the lake and the hangars, within surrounding highly resistive material, possibly indicating a location of preferential subsurface water flow on top of the permafrost. In addition, the GPR surveys were successful in imaging the interface of the bottom of the active layer and top of permafrost. These surveys were conducted parallel to the front of the hangars indicate this interface is lower in depth by over one meter at the area in front of Hangar 9. This is possibly an additional indicator of subsurface flow where thermal erosion from water has lowered the permafrost table in this area. The results of the geophysical surveys suggest a preferential ground water flow path exists between Lake Eddy and Hangars 9 and 10.

The overall surface water elevations, flow rates, and flow paths are a function of the depth of seasonal frost through the year. In the early spring when the active layer is fully frozen, ponded water is bounded by a frozen active layer. Later in the spring when the active layer begins to thaw, the bounding elevation is now dropping into the subsurface, and will allow water to drain out of the ponded area via subsurface flow within the active layer. Applying this analogy to the area between Lake Eddy and Hangars 9 and 10, this subsurface flow may be steady to the hangars due to melt water input into Lake Eddy, and continue until the time the lake surface elevation is equal to the top of the frozen ground under the hangars, after spring melt has began to abate.

During the 1960 dewatering, the lake pumping was stopped in July, with no further rise in the level of the lake for the rest of the season. This helps to confirm that the inflow to Lake Eddy is primarily by melt water, and when the melt water ceases to flow by mid-summer, no further contribution of lake water should be occurring to the hangars via the conduit possibly identified by the geophysical surveys. It is unknown if flow decreases under the hangars at the end of the season, but it was found during the August 2009 hangar pit excavations that water continued to flow under the hangars even though the spring melt was complete. This suggests that another source exists to the hangar area, but specific sources and contributions may never be known.

3.3.3 Drainage Design

Examination of pre-construction photography does not indicate there were significant flow paths or ponding at the hangar area prior to construction. However, It can be assumed that surface and subsurface water existed to some limited extent prior to construction. Therefore the vertical and horizontal airfield structures, with significant fill material and the subsequent raising of the permafrost table under these structures, most probably created new water flow paths and areas for ponding. There is no evidence from plans, reports, or the structures themselves that altering of the surface and subsurface water was understood prior to construction and accounted for during design. In fact, the use of corrugated piping for the air ducted foundations with loose fitting bands for joining, clearly demonstrates that groundwater was not anticipated under the hangars in the deep fill material.

This illustrates the complex problems that can arise with altered surface water and ground water paths over frozen terrain due to the construction of vertical and horizontal facilities such as an airfield. The altered surface and ground water pathways have seriously effected Hangars 9 and 10 and contributed in good part to the thaw degradation and eventual disuse. Because the exact source remains illusive to this day after numerous studies of the problem, it is highly doubtful that any preliminary study would have predicted this end result.

4 DISCUSSION

State-of-the-art permafrost engineering technology was incorporated in the construction of Thule AB. This allowed for the advanced concept of placing very large heated slab-on-grade structures on ice-rich permafrost. Unfortunately serious problems existed with the design illustrating the lack of engineering knowledge and the unknown parameters that could cause serious problems, as previously discussed.

4.1 Air Ducted Foundation Failure

It is not known what design methodology was used to determine the air flow through the air-ducted foundations. Convective heat transfer utilizing forced ambient air and chimney draft effects is complex and does not allow for a straight forward closed form solution, therefore it is plausible the cooling failure can be traced to miscalculation. If the flow rate and velocity were designed correctly however, the air duct system would still have suffered failure due to the use of improper duct material and pipe joining allowing for groundwater migration leading to occlusion with ice and soil. Additionally, the extreme number of air ducted foundations, all with manually operated damper valves to regulate seasonal air flow, has shown that human error must be calculated into a design such as this. Failure to open or close can have detrimental effects leading to increased maintenance and/or deepening of the thaw layer.

4.2 Water Flow Problems

Altering of the surface water and groundwater flow due to airfield construction must not have been fully appreciated or understood. As mentioned previously, subsurface water now migrates to the sub-floor of the hangars, most of which were constructed on deep structural fill, causing unintended problems leading to near total failure. The primary reason for these altered flow regimes is assumed to be due to two components. The first is the placement of the airfield and roadway embankments directly in the pathway of surface water and subsurface water courses.

The most obvious drainage features that were crossed by the construction did obtain culverts to allow for passage of water. However, the subsurface water flow in the active layer and on the top of the permafrost, which is highly complicated and partially invisible, could not have been completely taken into account.

Secondly, due to the rigorous climate of the Thule area, any embankment greater in height than 2 m will cause the permafrost to aggrade upward into the embankment, creating an obstacle lasting through the summer season. Not only does the embankment become emplaced across the flow path, it effectively becomes a dam structure causing the water to migrate along the frozen core instead of under or through the structure. The result is that water will accumulate and migrate at preferential locations with greater flow than when the water was dispersed about the terrain. Water then follows the built environment with the result of flow paths occurring in undesirable locations.

4.3 Successful Foundation Design

As shown in Figure 2, nearly the full load of the hangar structure is bearing on timber piles that were placed in deep trenches at the margin of the heated floor footprint. As noted previously, the hangars which have experienced extreme thaw settlement in the floor system exhibit no problems that would suggest differential thaw settlement is occurring under or around the piles or pile caps. This observation suggests that thaw front under the floor had not progressed to a location where the piles could be affected. A finite element simulation was completed utilizing the full scale dimensions of a hangar and load bearing system, estimations of the soil thermal properties, and simulating a heated interior for 25 years.

The results indicate that the thaw front will extend to a depth of 15 m below the center of the hangar floor, and the thaw front obtains a depth and lateral position that is approximately 3 to 4 m from impinging on the load bearing ends of the timber piles (Figure 5), and the thaw front does envelope the pile cap.

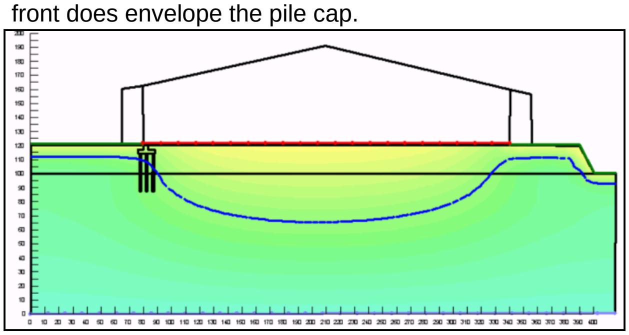

Figure 5. Thaw depth extent estimation utilizing Temp/W commercial software. 0°C isotherm after 25 years of heated hangar operation. Figure axes in feet

It is not known to what lateral extent the cooling system was intended to maintain frozen soil under the structure, and it is also unknown the design function of the pile, either end-bearing or adfreeze. But the modeling suggests that the conservative deep seated pile design located at the margin of the floor footprint, has prevented these structures from settlement failure. This observation offers no breakthrough for contemporary permafrost engineering practice. However it does suggest that state-of-the-art design for that time period provided sufficient factors-of-safety to prevent total failure due to thaw settlement.

4.4 Geocryology

The fundamentals of thaw settlement were clearly understood during the design of Thule Air Base. This observation is based on the 100% utilization of either elevated heated structures with post and pad foundations, or substrate cooled slab-on-grade heated structures. However, there is no indication that isolation of thaw-stable or thaw-unstable soils was performed across the airbase as a whole. Subsequently it appears the design methodology assumed the entire area as thaw-unstable. Contemporary permafrost engineering may practice this procedure on the scale of a single structure, or on the scale of a tightly spaced group of structures, but the current knowledge of geocryology, coupled with relatively low subsurface exploration costs, clearly outweighs the undesirable expenditure of over-engineering. And this is especially true on the scale of an entire airbase.

Based on the current observations of the geocryology of the Thule area, an understanding of the physical extent and frequency of massive ice and thaw-unstable soils would have greatly benefited most construction endeavours at the airbase, especially the large aircraft hangars and linear projects such as airfields and roadways. The design for these types of structures may have benefited from isolated removal of near surface massive ice, or larger scale over-excavation and replacement with structural fill.

5 CONCLUSIONS

The early 1950's was a time of advancement for permafrost engineering, and novel ideas were being developed to address issues of thaw prevention and thaw settlement. Although serious deficiencies were realized with some of the early designs at the airbase, these problems were not necessarily the result of a lack of understanding of the fundamentals of permafrost engineering, but more the result of specific miss-calculation of air flow dynamics and permafrost ground water hydrology. Contemporary modeling would allow for a successful outcome with regard to the airflow problem encountered in the air ducted foundations, but the hydrology issue still would present considerable challenges in successfully identifying the altered surface water and groundwater pathways, and their effect on the built environment. Additionally, a more complete understanding of the geocryological subsurface environment most probably would have decreased initial capital costs, and have prevented serious thaw degradation. Advancements have been made in permafrost engineering in the last 50 years, but as the performance of the structures at Thule Air Base suggests, some unsolved physical issues still remain.

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