REPORT TO CONGRESS

Permafrost Thaw on Infrastructure, Facilities, and Operations of the Department of Defense

Office of the Under Secretary of Defense for Acquisition and Sustainment

May 2023

House Report 116-617, page 1584, accompanying H.R. 6395, the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (Public Law 116-283)

The estimated cost for this report or study for the Department of Defense is approximately $265,000 for the Fiscal Years 2022 - 2023. This includes $500 in expenses and $264,550 in DoD labor.
Generated on 2023Apr18 RefID: 5-330AF77

House Report 116-617, page 1584, to accompany the William M. (Mac) Thornberry National Defense Authorization Act (NDAA) for Fiscal Year 2021 (Public Law 116-283) requested the Secretary of Defense to provide a report to the congressional defense committees on "the impact of changes in permafrost on the infrastructure, facilities, and operations of the Department of Defense." The report is to include:

1) An identification of the infrastructure, facilities, and operations of the Department of Defense that could be impacted by permafrost thaw;

2) For each element of infrastructure and each facility and asset identified, an assessment of the threat posed by permafrost thaw and an estimate of potential damage in the event of likely permafrost thaw; and

3) A description of the threats and impacts posed by permafrost thaw to military and other national security operations.

EXECUTIVE SUMMARY

Impact of Permafrost Thaw on Infrastructure and Facilities:

The Department of Defense (DoD) reviewed all military installations within the Arctic[1] and Subarctic[1] regions where infrastructure and facilities may be constructed on permafrost. The DoD found the following eight (8) installations listed in Table 1 below are within the study area and evaluated associated potential risks posed by changes in permafrost to buildings, structures, and facilities. For the installations at a higher risk, we've identified the installation's mission and the primary mission asset(s) that could be put in jeopardy from structural failure(s) within the built environment due to permafrost thaw.

Table 1. DoD installations located in known permafrost areas

Installation	Location	Type of permafrost	Structures on permafrost	Assessed Risk Due to Permafrost Changes
Clear SFS	Anderson, AK	Discontinuous[1]	None	No Risk
Ft. Wainwright	Fairbanks, AK	Discontinuous	Numerous	Minor to Moderate
Eielson AFB	North Pole, AK	Discontinuous	Numerous	Moderate to Considerable
Ft. Greely	Delta Jct, AK	Discontinuous	Few	Minor
Joint Base Elm-Rich	Anchorage, AK	Sporadic[1]	None	No Risk
Eareckson AFS	Shemya, AK	None	None	No Risk
Alaska Radar System and North Warning System	Across AK and Canada	Continuous[1] & Discontinuous	Most	Considerable
Pituffik Space Base	NW Greenland	Continuous	All	Moderate to Considerable

[1] See Key Term Descriptions in Appendix 2.

See the Discussions and Findings section that follows for Table 1. risk definitions.

Potential permafrost thaw poses no risk for facilities and assets located at three of the eight installations (Joint Base Elmendorf-Richardson, Clear Space Force Station (SFS), and Eareckson Air Force Station (AFS)). Permafrost thaw poses minor risk to facilities at Fort Greely. The remaining four (Pituffik Space Base (SB), Eielson Air Force Base (AFB), Fort Wainwright, and the Alaska Radar System and North Warning System (61 total sites with 57 on permafrost) are susceptible to moderate to considerable risk that thaw would cause differential settlement, thus impairing structural integrity or allow ground water infiltration into ground voids leading to freeze/thaw heave. The impacts to the DoD Arctic mission and assets stationed at the at-risk installations, Pituffik Space Base (SB), Eielson AFB, and Fort Wainwright, or located at the at-risk radar sites of the Alaska Radar System and North Warning System could be significant.

Impact of Permafrost Thaw on Operations:

Fort Greely:

- A small facility, operated by the Army Test Center, located at the Donnelly Training Area was rendered unusable approximately 10 years ago due to structural degradation resulting from permafrost thaw.

Alaska Radar System (ARS) and North Warning System (NWS) Sites: (Both systems together consist of 25 minimally attended long range radars (21 of which are on permafrost) and 36 unattended short range radar stations (all of which are on permafrost), 6 forward supply points, and 3 central maintenance facilities. (See Appendix 3 for a list of ARS and NWS radar sites)**:**

- Oliktok: Receding shoreline threatens key buildings and site access.
- Point Barrow: The road to the site is severely eroded; receding shoreline enables sea surges which flood facilities.
- Barter Island: Receding shoreline threatens key structures and necessitated closing the Air Force runway due to continual flooding.
- Guyed towers supporting the Long Range Radar Sites have recently been reported to need periodic re-tensioning.

Pituffik Space Base (formally known as Thule Air Base)**:**

- There have been instances in the past where structures (primarily aircraft hangars) suffered from thaw settlement due to mechanical system failures or infiltration of water into underlying soils. This impacted aircraft hangar operations until the floor slab repairs could be made. Airfield pavements may be at significant risk due to warming of the underlying soils. There is an increasing probability chronic permafrost degradation may develop, particularly if water and runoff conditions continue to increase.

Impact of Permafrost Thaw on Primary Mission Assets:

The impact that permafrost thaw would be expected to have on military assets comes largely because of the structural degradation on the facilities that the assets rely on. For example, differential settlement of aircraft runways, taxi ways and hangar floors would impact aircraft flight and maintenance operational assets. Differential settlement in foundations that support radar assets could impact the operational capability of the radar. Below we look at the primary missions of the four installations that are in the moderate to considerable risk categories to project an overview of the vastness of assets that could be impacted at each due to permafrost thaw.

Ft. Wainwright: (Minor to Moderate risk) – Mission assets primarily consist of those required to train, equip, and house approximately 7,700 Soldiers in support of the 1st Stryker Brigade Combat Team, 25th Infantry Division, 1st Battalion, 52nd Aviation Regiment, 1st Attack Reconnaissance Battalion, 25th Aviation Regiment and the Medical Department Activity.

Eielson AFB: (Moderate to Considerable risk) – Mission assets are those required to train, equip, and provide aircraft maintenance to support the 354th Fighter Wing's F-16 and F-35 aircraft, the 168th Air Refueling Wing of the Air National Guard's KC-135 air refueling tankers, Det 460 Air Force Technical Applications Center, 66th Training Squadron Arctic Survival School, as well as other tenant units on Eielson AFB.

Alaska Radar System and North Warning System: (Considerable risk) –The ARS and NWS provides early warning of possible incursions into U.S. and Canadian airspace and covers nearly 3,000 miles across North America from the Aleutian Islands in southwestern Alaska to Baffin Island in northeastern Canada. A part of what puts the system in the considerable risk category is the number of assets which are supported on permafrost with different soil types. (See Appendix 3 for a list of NWS sites.)

Pituffik SB: (Moderate to Considerable risk) – The primary mission assets at the base are the Ballistic Missile Early Warning System's solid-state phased-array radar, the Remote Satellite Tracking Station, and Satellite Telemetry Tracking and Commanding Antennas. The aircraft runway and hangars are also priority facilities as transient aircraft assets provide the only means of access and resupply for Pituffik SB for most of the year.

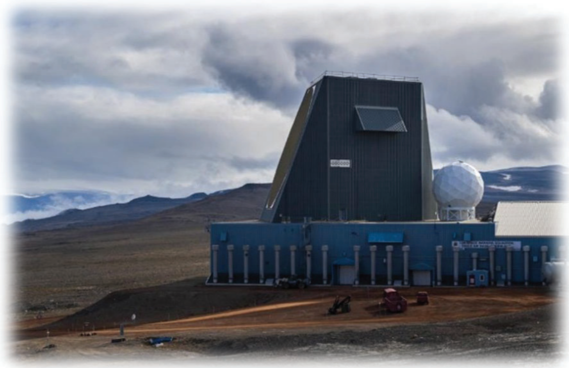

Figure 1. – Pituffik SB Ballistic Missile Early Warning System
Note the vertical air ducts along the side of the structure. Cold air is forced through the system to maintain permafrost in a frozen state under the structure.

BACKGROUND

Title 15, United States Code (U.S.C.), § 4111 defines the Arctic as all U.S. and foreign territory North of the Arctic Circle and all U.S. territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas; and the Aleutian Islands chain. This is the area of study for this report.

Arctic temperatures can drop as low as -51°C (-60°F) in Alaska and Canada and -62°C (-80°F) in Yukutia, Russia. Winters are long, eight to nine months in duration, with limited to no direct sunlight from November to February. During the winter months, lakes, rivers, and seas remain frozen, and winter storms often bring hurricane force winds. The persistent cold produces a unique landscape and conditions that result in perennially frozen ground, also known as permafrost.

When subjected to above freezing temperatures, thawing of the ground ice causes unstable soil conditions, such as slumping and loss of bearing capacity for foundations and pavements, with sometimes dramatic differential settlement that structures often cannot accommodate. Horizontal structures, such as roadways, railroad tracks, and airfields, can become impassible or unsafe due to slope instability and changes in the surface. Vertical structures (buildings, towers, etc.) can suffer foundation stress and failures which can lead to structural failures and conditions where windows and doors bind, and utility connections can become separated. The severity of the structural problems can range from nuisance and cosmetic to dangerous and unsafe for use.

As noted in Table 1, permafrost distribution can be categorized as continuous, discontinuous, or sporadic. Although the range of geographical area that is underlain by permafrost varies across reported studies, these areas are frequently defined as continuous (greater than 90 percent), discontinuous (50 to 90 percent), and sporadic (10 to 50 percent). A structure or building located in a permafrost-prone area does not necessarily mean that the structure exists on permafrost. Conversely, the existence of permafrost under a given facility does not directly correlate to a potential problem, should the underlying permafrost thaw. Determining the potential impacts of permafrost thaw to a facility would require an in-depth review of underlying soil conditions for each facility.

Figure 2 below offers a North Pole perspective of the Arctic sphere of influence and areas of permafrost.

Figure 2. - Areas of Permafrost in the Arctic Region from North Pole Perspective

Prior to World War II (WWII) the DoD had limited large-scale operational experience in the high latitude regions of the world. Necessitated by the Japanese occupation of American soil in the Aleutian Islands and the threat of further invasion, the U.S. began a major build-up of several military installations in Alaska in the early 1940's. The construction of the

Alaska/Canada Highway facilitated growth of U.S. presence in the Arctic. Throughout the Cold War, the U.S. expanded military reconnaissance and surveillance operations to guard against an "over-the-pole" attack resulting in the construction of additional installations scattered across Alaska, Canada, and Greenland.

SITUATION – POTENTIAL THREAT TO INFRASTRUCTURE

The climate of the Arctic is formidable. DoD infrastructure must provide reliable and robust shelter capable of high thermal efficiency, wind and snow drift resistance, humidity control for modern electronic instrumentation, limited thermal expansion and contraction, and resistance to freezing/thawing cycles. Regardless of purpose and performance requirements, all facilities rely on the structural stability of underlying soils to bear loads without settlement post construction.

Prolonged rising air temperatures are creating change in the Arctic domain, which increases economic opportunities as well as geo-political concerns. Current projections of an opening of the Arctic, which would increase demands on the DoD to safeguard U.S. interests there. In preparation, DoD has created Arctic strategies with subsequent implementation plans. DoD infrastructure, some of which was constructed over 50 years ago with a vastly different engineering perspective, may face unanticipated future foundation issues, should the underlying permafrost soils thaw and settle. Appendix 1 contains a summary of potential threats due to climate change.

DoD Unified Facilities Criteria (UFC) 3-130-01, *General Provisions - Arctic and Subarctic Construction*, defines permafrost as perennially frozen ground. It may be defined more specifically as a thermal condition in soil or rock in which temperatures below 0°C (32°F) persist over at least two consecutive winters and the intervening summer. Permafrost consists of soil, rock, and most importantly, ground ice. In some cases, depending on geomorphology, large volumes of ground ice exist. In the frozen state, permafrost generally provides rigid base material suitable for the foundation of Arctic infrastructure.

It is important to note that not all permafrost is the same and will not behave the same should it thaw. Soils that contain voids that are filled with ice are the most suspectable to losing bearing capacity should the permafrost thaw. Some types of permafrost soil, while frozen, lack the ice filled voids and a thaw will not significantly alter its load bearing capacity. Permafrost, by definition, can also include solid rock with no ice associated that will have no strength or volume changes if thawed. In these instances, engineers do not anticipate impacts to these facilities. Appendix 2 to this report provides a description of permafrost types and engineering techniques used to interact with them.

The analysis in this report is based upon the knowledge and experience of DoD engineers skilled in permafrost design and construction and familiar with the installations and facilities listed in this report. Additionally, DoD is a contributing and active member of the Interagency Artic Research Policy Committee's Permafrost Community of Practice along with five other federal agencies, the University of Alaska Fairbanks, The National Science Foundation, and the Woodwell Climate Research Center. Science and data obtained through that collaboration is reflected in this report. In future efforts, DoD engineers can consolidate facility soil information into comprehensive installation subsurface models and conduct in-depth research on the effects of permafrost thaw on facilities. DoD would then involve military leaders in evaluating potential impact to mission and operations, which could elevate the classification level of such a report.

DISCUSSION AND FINDINGS

DoD reviewed all installations and facilities located in the Arctic and Subarctic study area and determined the following fit the NDAA request as potentially being affected by permafrost thaw:

1. Clear Space Force Station (CSFS), 100km (60mi) southwest of Fairbanks, Alaska
2. Fort Wainwright (FTW) near Fairbanks, Alaska
3. Eielson Air Force Base (EAFB) adjacent to FTW in North Pole, Alaska
4. Fort Greely (FGA), 160km (100mi) southeast of Fairbanks, Alaska
5. Joint Base Elmendorf-Richardson (JBER) near Anchorage, Alaska
6. Eareckson Air Force Station (EAFS), located on Shemya Island, Aleutian Island chain
7. Alaska Radar System and (ARS) North Warning System (NWS) of surveillance and tracking radars stretching across the western and northern coast of Alaska through Canada to the Atlantic Ocean.
8. Pituffik Space Base in northwestern Greenland and the northernmost DoD installation

Note: No Navy or Marine Corps installations are located on permafrost soils.

The following analysis details knowledge, experience, and available information about the soil conditions at each location. Using the best judgement of DoD engineers, this report quantifies associated risk to facilities and their military operations using the following risk definitions:

- **No Risk** – Frozen ground does not exist, or if frozen, the soil and ground ice conditions are not subject to strength or volume degradation if thawed. These soils are termed 'thaw stable', under-saturated and normally consolidated.

- **Minor Risk** – Frozen ground does exist; however, the ground ice condition is very low. In this condition the ground ice is only within the pore spaces of the matrix (ice-poor), so soil particles have grain-to-grain contact even in the frozen condition. Thawing does not change the volume and experiences only minor reductions in strength when the pore ice turns to pore water. In this condition the soils would be termed 'thaw-stable[1]', saturated and normally consolidated.

- **Moderate Risk** – Frozen ground does exist, and the ground ice condition is either at or just above saturation (ice-moderate) causing soil particles to be separated from one another by some limited amount, or the soil type is known to host segregated ice (ice lenses), which are horizontal bands of ice in the soil column emplaced during the freezing process. In this condition thawing causes volume displacement as soil particles come back into contact, causing volume and strength degradation, with surface elevation decrease and localized depressions. In this condition the soils are termed 'thaw-unstable[1]', saturated and under-consolidated.

- **Considerable Risk** – Frozen ground does exist, and the ground ice condition is ice-rich causing significant displacement of soil particles from one another, in addition to hosting segregated ice and massive ice (ice wedges). Ground ice content is generally greater than 50 percent by volume, and thawing causes large scale depression and gullying (thermokarst[1]). The soil conditions to host segregated and massive ice generally are of the finer grained variety, which when thawed with considerable liberated water, these fine-grained soils have very low bearing strength. In this condition the soils are termed 'very thaw-unstable', over-saturated and super-unconsolidated.

As noted above, the following installations were evaluated for potential to be affected by permafrost thaw:

1. **Clear Space Force Station (CSFS)**, 100km (60mi) southwest of Fairbanks. This installation is constructed on what was once pre-historically frozen ground that is now considered to be mostly in the thawed state. No permafrost problems were reported with the cantonment or operation of the Ballistic Missile Early Warning System or its current successor the Upgraded Early Warning Radar. No permafrost has been encountered during the construction of the new Long-Range Discriminating Radar. Assessed risk: **NO RISK.**

2. **Fort Wainwright (FTW)** near Fairbanks, Alaska. The main cantonment area is constructed upon a thick layer of gravel extending much deeper than the depth limit of permafrost (approximately 45m to 60m (150ft. to 200ft)). The removal of vegetation over large portions

[1] See Key Term Descriptions in Appendix 2.

of the cantonment during initial construction in the 1940's and 1950's caused the permafrost to thaw to depths of 12m to 15m (40ft to 50ft), which is greater than traditionally investigated for project design. The gravels appear to be thaw-stable and pose little risk to existing facilities in the event of further thaw.

Approximately 30 percent of the greater cantonment area not currently cleared of vegetation, portions of which are identified as potential building sites for future use, very likely contains near surface permafrost. Vegetation insulates and protects the permafrost from thawing. It is believed these soils are thaw-stable gravels and will pose little problem. No construction is planned for the upland areas which have proved to be problematic at Eielson Air Force Base. Future construction will require proper subsurface investigation and risk mitigation during design as required.

Most of the cantonment infrastructure was constructed on ice-poor to ice-moderate warm permafrost. Recent construction in the last 10 years has provided sporadic evidence of near surface permafrost. Records indicate buildings 1001, 4070, and Old Bassett Army Hospital were some of the larger structures built on frozen thaw-stable gravels, with no problems reported. It is also known Ladd Field suffered thaw depressions in the runway soon after construction, however this section was excavated with the icy material replaced and no problems have existed since that time[2]. Assessed risk: **MINOR TO MODERATE RISK.**

3. **Eielson Air Force Base (EAFB)** is adjacent to FTW in North Pole, Alaska. The permafrost and terrain conditions at EAFB proper are very similar to those previously described for FTW. Approximately 97 percent of the facilities are constructed at the main cantonment area on the same river gravels as FTW. Vegetation removed in the cantonment area during construction long ago caused the permafrost to thaw to a significant depth and generally does not pose further risk.

   A few structures are located on ice-rich, thaw-unstable frozen ground away from the main cantonment on a nearby hillside and do have minor problems. Additionally, Air Force bombing ranges well distant of EAFB are located on shallow ice-rich permafrost with reports of some degradation issues. The following are examples of reported issues due to permafrost thaw or new military construction projects that took steps to address permafrost encountered during design soil investigation:

   - New hangars for aircraft beddown were identified during design to be located over shallow permafrost soils in a recently cleared area. Construction efforts pre-thawed the

[1] See Key Term Descriptions in Appendix 2.
[2] Narrative Report of Alaska Construction 1941 – 1944. Col. James D. Bush, Jr.

soils down to 7m – 8m (23ft – 26ft), then dynamically compacted the thawed gravel to consolidate for seismic stiffness and mitigate permafrost thaw risk.

- Construction activities for one of six new earth covered magazines (ECM) for munitions storage in the uplands adjacent to the cantonment area found the proposed building (B-6362) to be located over very ice-rich fine-grained soils. This required a design change during construction to excavate as much of the excessive ice as possible and replace it with compacted structural fill. Thermosyphons[1] were installed to maintain the subgrade in the frozen state.

- The Conventional Munitions Maintenance facility, B-6385, located very near to the ECMs on Quarry Hill was replaced due to inadequate design for permafrost conditions resulting in destructive thaw settlement. The new facility constructed is much better equipped for the sensitive permafrost conditions with deep driven piles to counter additional permafrost thaw.

- Blair Lakes Bomb Range is a remote airfield and fuel depot used for Air Force bombing training and is located 20 miles southwest of EAFB in the Tanana Flats of Fort Wainwright Military Reservation. The region consists of very ice-rich near surface permafrost underlain by ice-poor gravels. Permafrost degradation has been reported at this small facility, but degradation has not compromised bombing training to-date.

While conditions are very similar to FTW on the main cantonment area, approximately 30 percent of the greater cantonment area is not currently cleared of vegetation and very likely contains near surface permafrost. Construction in these thaw-stable gravels will pose little problem with proper investigation and construction mitigation. Future development on Quarry Hill or similar upland locations will require careful investigation to ascertain the ground ice condition. Training range facilities may require restorative maintenance to insure operable facilities. Accelerating climate warming may cause moderate threat at the main cantonment and considerable acute threat to infrastructure located in the uplands. Assessed risk: **MODERATE TO CONSIDERABLE RISK.**

4. **Fort Greely (FGA)**, 160km (100mi) southeast of Fairbanks. FGA is at the foothills of the northern slopes of the Alaska Range. The terrain which almost surrounds FGA consists of glacial deposits including permafrost and buried ice remnants from receding glacial activity. The cantonment area, however, is largely constructed on thawed gravels of Jarvis Creek which bisects this para-glacial terrain. This flood plain has and is currently inundated with excessive runoff, removing any emplaced ice which may exist.

Although FGA is surrounded by permafrost, the main installation facilities are located on thawed gravels believed to be thaw stable. FGA infrastructure includes the Missile Defense Agency (MDA) Ground-based Midcourse Defense system (GMD) with no known permafrost issues. No reports exist of problems due to permafrost during the long-time operation of this installation. Training areas outside of the cantonment area include one small facility operated by the Army Test Center (ATC) located at the Donnelly Training Area (DTA), which experienced detrimental thaw degradation rendering it unusable approximately 10 years ago.

No further large-scale expansion is anticipated for FGA. If the MDA were to expand, ample thawed ground is available. Minor disruption to outlying training structures, many of which are semi-permanent in construction may occur in the future. Continued climate warming is anticipated to cause only a minor chronic threat to infrastructure in the near or longer term. Assessed risk: **MINOR RISK.**

5. **Joint Base Elmendorf-Richardson (JBER)** is located near Anchorage, Alaska. JBER is in south central Alaska where permafrost is very sporadic and generally not encountered. No problems have been reported due to permafrost and it is not believed any structures are constructed on or could be impacted by permafrost. Assessed risk: **NO RISK.**

6. **Eareckson Air Force Station (EAFS)**, located on Shemya Island. This location is in the Alaska Aleutian Island chain 2400km (1500mi) southwest of Anchorage and 320km (200mi) east of Russia. There is no permafrost in the Aleutian Island chain and no problems have been reported. Assessed risk: **NO RISK.**

7. **The Alaska Radar System and North Warning System** consists of 25 Long Range Radars (10 in Canada and 15 in Alaska), 36 Short Range Radars (all in Canada), 6 Forward Supply Points, and 3 Central Maintenance Facilities, stretching across the west and northern coast of Alaska, interior Alaska, through Canada, and on to the Atlantic Ocean. The ARS is operated by the Pacific Air Force Regional Support Center located at Joint Base Elmendorf-Richardson. See Appendix 3 for a list of the NWS radars.

   Twenty-one of the 25 Long Range Radars and all 36 Short Range Radars are located on continuous or discontinuous permafrost. Generally, the sites consist of a small grouping of buildings, guyed towers, roadway, and often an airfield. The NWS predecessor, the Defense Early Warning (DEW) Line, consisted of considerably more infrastructure for a greater number of personnel. The structures were designed to maintain the underlying ice-rich permafrost in a frozen state.

The permafrost terrain is varied due to distal nature of the sites, ranging from discontinuous and warm at the Interior Alaska sites, to continuous and cold at the northern and western sites along the coasts. Coastal erosion and permafrost degradation presents risk to North Slope Long-Range Radar Sites, endangering infrastructure, and access. Several sites are currently experiencing erosion and extensive damage with risk to mission expected in the future. Erosion rate studies indicate some Long-Range Radar sites are losing 6 – 24m/yr (20 – 80ft/yr) of coastline depending on the installation. Assessed risk: **CONSIDERABLE RISK.**

- Oliktok: This is the most at-risk Long Range Radar Site. Receding shoreline threatens key buildings and site access. To reduce vulnerability and ensure operational readiness requires facility projects include the relocation of access roads, electrical service, sewer outfall, and a warehouse.

- Point Barrow: The road to the site is severely eroded; receding shoreline enables sea surges which flood facilities. The U.S. Army Corps of Engineers (USACE) was recently awarded $364M in Civil Works funding for a sea wall to protect the road to the radar site and town.

- Barter Island: Receding shoreline threatens key structures and necessitated the closing the Air Force runway due to continual flooding. Guyed towers supporting the Long-Range Radar have recently been reported to need periodic re-tensioning.

8. **Pituffik Space Base (PSB)** in northwestern Greenland is located 695 miles above the Arctic Circle, see Figure 3. This is the northernmost U.S. military installation, and every structure is located on ice-rich cold permafrost. The terrain conditions consist of very cold permafrost, significant glacial deposits, and large-scale para-glacial features consisting of ice-poor bedrock overlain by ice-rich glacial deposits. Significant ground ice exists in the near surface glacial deposits across the cantonment. The prolonged winter cold is very favorable to passively maintaining the permafrost in a frozen state by elevating structures above grade and providing free air flow between the soil surface and the underside of the structure (surface foundation), or by providing passive airflow or blown air via mechanical systems through a ducted floor system.

   All facilities are constructed on permafrost terrain and have various types of conventional and innovative permafrost foundations. For example, structures with heavy floor loads utilize a floor ducting system which pipes ambient cold winter air under the floors to minimize excessive heat transfer to the supporting soils. These systems meet their intended purpose, provided they are maintained and operated correctly. There have been instances in the past where structures (primarily aircraft hangars) suffered from thaw settlement due to mechanical system failures or infiltration of water into underlying soils.

Should the permafrost soils underlying the facilities thaw due to climate change, winters becoming shorter/less cold, or ambient air temperatures rising to the point to render the current foundation systems inadequate, the facilities will be at considerable risk. Some elevated structures may need periodic releveling to remain operational. Structures with heavy floor loads utilizing ducted floor systems are not conducive for releveling and may require costly structural repairs or replacement. Additionally, airfield pavements may be at significant risk due to warming of the underlying soils. There is an increasing probability chronic permafrost degradation may develop, particularly if water and runoff conditions continue to increase. Assessed risk: **MODERATE TO CONSIDERABLE RISK**.

Figure 3. – Pituffik Space Base (formally known as Thule AB)

CONCLUSION

DoD has maintained a presence in the Arctic region since World War II. With that presence comes over eight decades of engineering, construction, and facilities management experience in formidable and extreme climatic conditions. Permafrost thaw will affect structures and installations differently, depending upon the presence of ice in the underlying soils, increased water infiltration, and coastal erosion. Table 1 (reprinted below) summarizes the findings of this report. Four of the eight installations are likely to not experience significant negative effects of permafrost thaw due to the presence of thaw-stable soils. However, the risk to Fort Wainwright is determined to be minor to moderate, Eielson AFB and Pituffik SB are moderate to considerable, and the Alaska Radar System and North Warning System is in the considerable risk category.

Table 1. DoD installations located in known permafrost areas

Installation	Location	Type of permafrost	Structures on permafrost	Assessed Risk Due to Permafrost Changes
Clear SFS	Anderson, AK	Discontinuous	None	No Risk
Ft. Wainwright	Fairbanks, AK	Discontinuous	Numerous	Minor to Moderate
Eielson AFB	North Pole, AK	Discontinuous	Numerous	Moderate to Considerable
Ft. Greely	Delta Jct, AK	Discontinuous	Few	Minor
Joint Base Elm-Rich	Anchorage, AK	Sporadic	None	No Risk
Eareckson AFS	Shemya, AK	None	None	No Risk
Alaska Radar System and North Warning System	North and Interior AK	Continuous & Discontinuous	Most	Considerable
Pituffik Space Base	NW Greenland	Continuous	All	Moderate to Considerable

Quantifying the potential impacts of permafrost thaw to an asset's foundation requires in-depth review of underlying soil conditions for each facility and facility monitory for differential settlement impairing structural integrity. Such a review will require substantial resources in terms of manpower, time, and funding. Table 1 can focus future research and planning efforts, should funding become available to test and monitor for condition changes.

APPENDIX 1

Potential Threats Due to Climate Change

Coastal erosion – As air temperatures warm, annual sea ice is being generated later in the autumn season. This, coupled with the weaker warmed permafrost soils, leaves shorelines highly susceptible to erosion from autumn aggressive storms. This was highlighted during the discussion on the NWS where coastline constructed radar facilities are being highly impacted. Some western Alaska villages are greatly under threat from receding coastlines and USACE is working with state and tribal leaders to find solutions to move these villages to safer locations.

Increased precipitation – Warmer air temperatures allow higher moisture carrying capacity, therefore greater amounts of precipitation are expected across the circum-polar north. Water is one of the greater enemies to permafrost, and flowing water teamed with warmer permafrost temperatures will create greater ease and higher occurrence of thermo-erosion[1] gullying and thermokarst (i.e., irregular terrain because of ice-rich permafrost thaw). Once started water will flow in pathways not experienced previously. This is already occurring in Interior Alaska. Engineering at installations will be taxed with installing more frequent and larger drainage appurtenances and directing flow away from infrastructure.

Slope instability – Ice strength is very temperature dependent where near freezing ice, although not yet changing state from solid to liquid, is considerably weaker bonding soil particles than at colder temperatures. As air temperature warms, the frozen mantle of soil, currently existing in a stable manner on slopes and hillsides, will become unstable and begin to detach or slump toward valley bottoms. Retrogressive thaw-slumps are occurring across the Northwest Territory of Canada, and active layer[1] detachments are occurring across Alaska and the Yukon. Installations adjacent to or in upland areas may be subjected to these slope instabilities where buildings, roadways, pipelines, tanks, and towers can be affected. These will occur rather randomly and will show minimal warning prior to movement.

Techno-genesis – Ground ice is often very heterogeneous across the terrain with contents differing by an order of magnitude or more within tens of meters. Current construction procedures exploit this fact by positioning structures on the least problematic areas. This methodology was not an option when our current northern installations were constructed, and layouts are in a gridded fashion with facilities often close to one another. As temperatures continue to warm, the consequence of this proximity will be exacerbated by

[1] See Key Term Descriptions in Appendix 2.

the excess runoff, snow piling versus snow removal, and mishaps with above ground utilities. All these factors work together to begin thermokarst processes within the installation. This is termed techno-genesis and is similar to the 'heat island' effect for large cities in the summer.

APPENDIX 2

Description of Permafrost Terms, Characteristics, and Change Indicators

Key Terms

Active layer – The layer of soil or rock at the surface which freezes and thaws on a regular annual basis. Also known as the seasonally freezing layer. In the ideal thermal model of a permafrost terrain, in the winter the active layer freezes down to the top of the permafrost (permafrost table). In areas experiencing rising air temperatures, the permafrost table is receding downward, and increasingly warm winters prevent the active layer from meeting the permafrost table.

Arctic – The northern polar region of the earth which includes almost the whole area of the Arctic Ocean and adjacent areas of Eurasian and North American continents. This implies the area at and above the Arctic circle at 66'33" latitude, often including geographic areas spanning below the Arctic circle.

Continuous permafrost – Permafrost terrain where perennially frozen ground is generally everywhere regardless of other natural features. The temperature of this type of permafrost terrain is less than -5°C (23°F) and is termed 'cold permafrost'. These terrains are more robust to changes in the thermal condition.

Discontinuous permafrost – Permafrost terrain where perennially frozen ground is not located everywhere, but is dependent on other features of the environment, e.g., vegetation (insulation), snow, groundwater, and surface water. The temperature of this type of permafrost terrain is greater than -5°C (23°F) and is termed 'warm permafrost'. These terrains are sensitive to changes in the thermal condition.

Sporadic permafrost –Discontinuous permafrost can be sporadic or isolated. Sporadic means 10 percent to 50 percent of the surface has permafrost under it. It is called isolated if less than 10 percent of the surface has permafrost under it. (The last 10% is considered isolated permafrost. Certain permafrost, casted from a shadow of a mountain or covered in thick vegetation, stay all year.)

Subarctic – Belonging or relating to the cold regions of the northern hemisphere adjacent to the Arctic Circle, and locations where mean annual average air temperatures are near 0°C, such as Northern Scandinavia, Alaska generally south of the Brooks Range of mountains, and Southern Siberia.

Thaw-stable – An engineering classification indicating the amount of ground ice is minimal and upon thawing little to no destabilization will occur.

Thaw-unstable – An engineering classification indicating the amount of ground ice is considerable and upon thawing detrimental destabilization will occur.

Thermo-erosion- Water flowing over frozen ground thaws the intergranular ice cementing the soils together. The soil grains are then flushed away by the flowing water. This leads to gullying in terrain that otherwise had remained intact.

Thermokarst – Thawing volumes of ice in permafrost results in uneven and undulating, hummocky terrain. Water often pools at the location of greatest depressions causing further degradation.

Thermosyphon - A passive ground freezing device which utilizes the low boiling point of carbon dioxide gas under pressure to extract heat from the ground. No pumps or electricity is required.

Key Characteristics

Key characteristics of a permafrost area are thickness and degree of continuity. Figure 1 depicts permafrost continuity in the northern hemisphere based on data from the International Permafrost Association. Permafrost is extensive across the glacial margins of Greenland, and across northern Canada to include all the North Warning System installations. Over 60 percent of Russia is composed of permafrost terrain, particularly large portions of Siberia and the Far East. Nearly 25 percent of the northern hemisphere land surface, and 85 percent of Alaska, is composed of permafrost. At extreme northern latitudes such as Utqiagvik (Barrow), Alaska and Thule AB, Greenland, the permafrost is very cold (-11°C or 12°F), very thick (greater than 300m or 1000ft), and extends laterally without discontinuities. Moving southward, the thickness and continuity of the permafrost decreases with the increasing mean annual air temperature. Interior Alaska permafrost is very warm at -2.0°C to -0.8°C (29°F to 31°F), seldom greater in thickness than 60m (200ft), and predictably absent at certain locations such as on the south side of slopes. Further south in Anchorage, the permafrost is located only in scattered isolated pockets.

Climate Change Indicators:

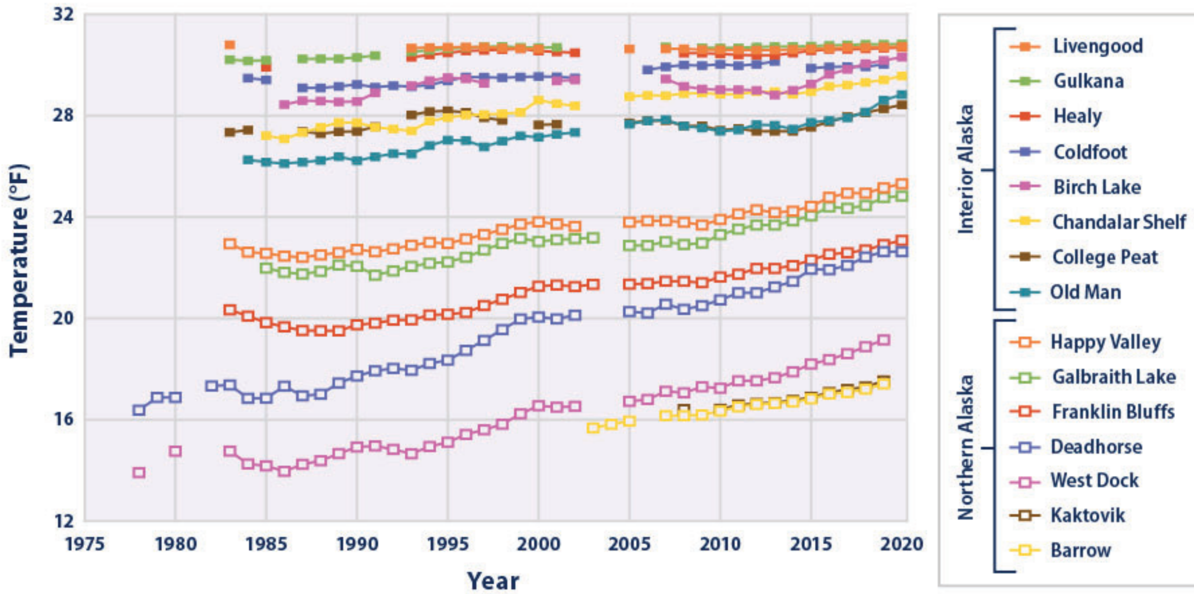

Figure 4. – Permafrost Borehole Sites

Figure 4 shows permafrost temperature at borehole sites in interior Alaska, measured at the end of summer (approximately September of each year). Measurements at these sites were taken at depths between 49 and 85 feet. (Data source: University of Alaska Fairbanks, 2021)

For more than 40 years, a group of scientists from the University of Alaska Fairbanks has been studying permafrost across Alaska. They measure temperature every year in 15 boreholes drilled at least 50 feet deep and analyze the data for long-term trends. This data set provides valuable information about how rapid climate changes observed in Alaska are influencing permafrost. Because permafrost temperatures can also be influenced by land use change such as urban development, agriculture, and other human activities, this indicator focuses on a select set of boreholes that are relatively remote and undisturbed for better assessment of changes associated with climate. The figure above shows temperature measurements for each borehole site in the interior and northern Alaska regions.

Key points:

- Between 1978 and 2020, permafrost temperatures increased at 14 of the 15 borehole sites. Warming was statistically significant at 13 of the 14 boreholes that had increases.
- In general, permafrost has warmed more quickly in northern Alaska than interior Alaska. The increasing rate of change in the north is consistent with changes in air temperatures, which have increased more quickly in northern Alaska than in other parts of the. State.
- The Deadhorse site in northern Alaska had the highest rate of temperature change, at +1.5°F per decade. The Livengood site in interior Alaska was the only site to get cooler over the period of record, though only slightly. Overall, permafrost temperatures have increased at an average rate of 0.6°F per decade.

- Changes in permafrost temperature shown in this indicator are consistent with changes observed in Russia, Canada, and other parts of the Arctic.

APPENDIX 3

Alaska Radar System (ARS) and North Warning System (NWS)

Site Name	U.S / Canada	Surveillance Radar Type	System
King Salmon	Alaska	FPS-117 long range	ARS
Cold Bay	Alaska	FPS-117 long range	ARS
Cape Romanzof	Alaska	FPS-117 long range	ARS
Cape Newenham	Alaska	FPS-117 long range	ARS
Fort Yukon	Alaska	FPS-117 long range	ARS
Cape Lisburne	Alaska	FPS-117 long range	ARS
Kotzebue	Alaska	FPS-117 long range	ARS
Sparrevohn	Alaska	FPS-117 long range	ARS
Tatalina	Alaska	FPS-117 long range	ARS
Tin City	Alaska	FPS-117 long range	ARS
Indian Mountain	Alaska	FPS-117 long range	ARS
Murphy Dome	Alaska	FPS-117 long range	ARS
Point Barrow	Alaska	FPS-117 long range	NWS
Oliktok	Alaska	FPS-117 long range	NWS
Barter Island	Alaska	FPS-117 long range	NWS
Komakuk Beach	Yukon Territory	FPS-124 short range	NWS
Stokes Point	Yukon Territory	FPS-124 short range	NWS
Shingle Point	Yukon Territory	FPS-117 long range	NWS
Storm Hills	Northwest Territory	FPS-124 short range	NWS
Tuktoyaktuk	Northwest Territory	FPS-124 short range	NWS
Liverpool Bay	Northwest Territory	FPS-124 short range	NWS
Nicholson Peninsula	Northwest Territory	FPS-124 short range	NWS
Horton River	Northwest Territory	FPS-124 short range	NWS
Cape Parry	Northwest Territory	FPS-117 long range	NWS
Keats Point	Northwest Territory	FPS-124 short range	NWS
Croker River	Nunavut Territory	FPS-124 short range	NWS
Harding River	Nunavut Territory	FPS-124 short range	NWS
Bernard Harbour	Nunavut Territory	FPS-124 short range	NWS
Edinburgh Island	Nunavut Territory	FPS-124 short range	NWS
Cape Peel West	Nunavut Territory	FPS-124 short range	NWS
Cambridge Bay	Nunavut Territory	FPS-117 long range	NWS
Sturt Point	Nunavut Territory	FPS-124 short range	NWS
Jenny Lind Island	Nunavut Territory	FPS-124 short range	NWS
Hat Island	Nunavut Territory	FPS-124 short range	NWS
Gladman Point	Nunavut Territory	FPS-124 short range	NWS
Gjoa Haven	Nunavut Territory	FPS-124 short range	NWS

Shepherd Bay	Nunavut Territory	FPS-117 long range	NWS
Simpson Lake	Nunavut Territory	FPS-124 short range	NWS
Pelly Bay	Nunavut Territory	FPS-124 short range	NWS
Cape McLoughlin	Nunavut Territory	FPS-124 short range	NWS
Lailor River	Nunavut Territory	FPS-124 short range	NWS
Hall Beach	Nunavut Territory	FPS-117 long range	NWS
Rowley Island	Nunavut Territory	FPS-124 short range	NWS
Bray Island	Nunavut Territory	FPS-124 short range	NWS
Longstaff Bluff	Nunavut Territory	FPS-124 short range	NWS
Nudluardjk Lake	Nunavut Territory	FPS-124 short range	NWS
Dewar Lakes	Nunavut Territory	FPS-117 long range	NWS
Kangok Fjord	Nunavut Territory	FPS-124 short range	NWS
Cape Hooper	Nunavut Territory	FPS-124 short range	NWS
Broughton Island	Nunavut Territory	FPS-124 short range	NWS
Cape Dyer	Nunavut Territory	FPS-117 long range	NWS
Cape Mercy	Nunavut Territory	FPS-124 short range	NWS
Brevoort Island	Nunavut Territory	FPS-117 long range	NWS
Loks Land	Nunavut Territory	FPS-124 short range	NWS
Resolution Island	Nunavut Territory	FPS-124 short range	NWS
Cape Kakiviak	Newfoundland Province	FPS-124 short range	NWS
Saglek	Newfoundland Province	FPS-117 long range	NWS
Cape Kiglapait	Newfoundland Province	FPS-124 short range	NWS
Big Bay	Newfoundland Province	FPS-124 short range	NWS
Tukialik	Newfoundland Province	FPS-124 short range	NWS
Cartwright	Newfoundland Province	FPS-117 long range	NWS