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Review

Sustainable Strategies to Current Conditions and Climate Change at U.S. Military Bases and Other Nations in the Arctic Region: A 20-Year Comparative Review

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Abstract: Amidst the backdrop of growing great power competition, heightened United States presence via military bases has manifested in the Arctic. However, the then design and implementation have hampered the resilience of these bases in a region warming at nearly four times the rate of the rest of the globe. Two-thirds of the United States' 79 military bases in the Arctic remain underprepared against permafrost thaw and rising sea levels despite rampant calls for sustainable strategies. Damages emanating from climate-related failures will continue to cost the U.S. billions of dollars and render crucial infrastructure unusable. The objective of this study is to present a comprehensive literature review of the extent of Arctic warming and its significance for U.S. bases, the negative implications of military infrastructure deterioration, and methods to adapt both existing and forthcoming bases to a rapidly warming atmosphere. Eighty published papers that directly or indirectly referenced U.S. military bases or climate-oriented engineering in the aforementioned contexts were identified and analyzed over a 20-year period from 2004 to 2024. The literature review concludes that warming concerns were often not taken into much account by civil engineers during initial base construction, an oversight that now jeopardizes runways, docks, and highways. Other nations that have a sizeable footprint in the Arctic Circle, such as Canada and Russia, have demonstrated progress by utilizing pile-driven substructures, thawing permafrost before construction, and ventilated crawlspaces. Alternative solutions, such as cooling permafrost via thermosiphons or refrigeration systems, employing spatially oriented foundations composed of specific materials, and preventative measures such as floodwalls and revetments, have also shown considerable promise in simulations and practice. A table illustrating a holistic literature summary of sustainable strategies to current conditions and climate change at U.S. Military Bases in the Arctic region is also developed. Modeling successful engineering concepts and incorporating existing innovations into military infrastructure should be at the forefront of the United States' sustainable policy.

Keywords: U.S. military base deterioration; arctic; sustainable infrastructure; climate change resilience; global warming; permafrost; sea level rise

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1. Introduction and Background

1.1. Arctic Warming

According to remotely sensed data of the Arctic from the satellite era (post–1979) and parameters of the Arctic Circle as the southern boundary, the region is seen to be warming nearly four times the rate of the rest of the planet in recent decades [1,2]. CMPI6 models project warming of the Arctic by 2100 to be higher than previously thought—including 6 months with 5 °C warming—due to fluctuations in precipitation overlooked in the CMPI5 [3–5]. There are several explanations for this phenomenon, called Arctic Amplification (AA) [6,7].

Ice-albedo feedback is among the most popular explanations [8,9], which occurs when warming decreases the sea ice cover, compounding future warming impacts due to less reflectivity. Indeed, an analysis of five SRES A1B models for the 21st century corroborated that the relationship between albedo and polar temperatures was linear [10]. Furthermore, the accumulation of black carbon on the Arctic Sea ice alters albedo and accelerates melting [11]. Another explanation is the uncharacteristically warmer temperatures of the water flowing into the Arctic Basin, which will continue to warm the region [12]. Global temperature patterns, including incursions of heat, warm the cooler atmosphere of the Arctic disproportionately faster. Warming caused by these factors, along with warmer winds, increased heat waves [13], and drift causing ice to exit the area, has caused Arctic Sea ice to decrease every year since the 1970s [14,15], and the abundance of thick ice is 60% lower than the 1980s levels [16]. Cultural erosion rates will escalate in the near future, increasing by a factor of 1.8 to 2.9 by the end of the century [17]. This is because of erosion sensitivity to Arctic surface air temperatures (SAT), which have been increasing at a higher rate than global SAT compared to the historical period [18]. Global mean sea level (GMSL) rise is an immediate consequence of rising temperatures [19]. increasing from a rate of change of 1.1 mm/yr in 1900–1930 to 4.4 mm/yr in 2010–2015, specifically impacting low-lying coastal areas [20]. This heightens flooding and erosion, threatening infrastructure in said regions.

Permafrost thaw is another prevalent concern. Climate models that show an increase in temperatures also forecast rapid increases in permafrost thaw [21], increasing the depth of the active layer and shrinking near-surface ice by as much as 12% since 1850, and 20% in most impacted areas [22]. Temperature monitoring of five sites in the West Russian Arctic found an increase in surface permafrost temperature across the board: increasing from −8.0 °C to −6.0 °C in northern sites and from −3.8 °C to −1.9 °C at southern sites to −4.8 °C and 0 °C, respectively [23]. These developments are a point of concern for U.S. military installations.

1.2. Current Base Conditions

After assessing the threat posed by warming to U.S. military bases, the Department of Defense (DoD) issued *Climate Change Adaptation and Resilience (2016)*, which delegated responsibilities to the major organizations within the DoD, created a climate change task force, and developed a long-term roadmap [24]. In 2019, the DoD expressed climate change as a national security issue regarding military base conditions, specifically referring to thawing permafrost and recurring flooding from sea level rise as areas of concern [25]. However, a follow-up report conducted in 2022 still found that two-thirds of the United States's 79 military bases in the region were vulnerable to climate change [26]. At the six installations analyzed, U.S. military leaders, despite DoD directives, did not develop plans to increase resilience against climate change, posing a threat to infrastructure. Specifically, Army and Air Force leaders were either unfamiliar with sustainability procedures, refused to follow civil engineering climate risk recommendations, or did not use available climate projection tools. Similarly, interviews of Coast Guard officers and military engineers revealed one or more of the following: engineers did not have the means to focus on sea level rise and felt it should be addressed by higher-ups, the Coast Guard does not anticipate climate change any more than existing federal, state, or local guidelines, or that warming impacts are not a priority until they have already damaged infrastructure [27].

1.3. Objective, Scope, and Methodology

The objective of this study is to present a comparative literature review of the extent of Arctic warming and its significance for U.S. bases, the negative implications of military infrastructure deterioration, and methods to adapt both existing and forthcoming bases to a rapidly warming atmosphere. To accomplish this, 80 published papers that directly or indirectly referenced U.S. military bases or climate-oriented engineering in the aforementioned contexts were identified and analyzed over a 20-year period from 2004 to 2024. Published papers were sourced from databases such as Google Scholar, ResearchGate, and ScienceDirect. For the first half of the paper, the scope is predominantly limited to U.S.

military installations in the Arctic, broadening in some instances to include examples of bases in similar coastal environments. The study also provides engineering solutions put forth by countries like Russia and Canada and experimentation from environments similar to the Arctic to suggest solvencies that the United States can model. A table illustrating a literature summary of sustainable strategies to current conditions and climate change at U.S. Military Bases in the Arctic region is also developed.

2. Evaluating Warming Impact on Bases

2.1. Thawing Permafrost

Permafrost thaw has an adverse impact on infrastructure. Variances in ice aggregate, thickness, and temperature, render engineering volatile in these areas [28,29]. Essentially, the frozen soil initially built upon is secure and resistant to force, but when the ice content in this soil melts, its capabilities disappear. Thaw also incites thermokarst and thaw slumping which vary the freeze–thaw cycles of the soil [30], releasing forces of up to 300 kPa that deteriorate infrastructure [28]. A lack of risk frameworks and the inability to conduct quantitative risk analyses to predict permafrost thaw has forced engineers to rely on qualitative data collection, decreasing base performance [31]. Specifically, entire bases have been constructed on now-thawing permafrost, threatening military infrastructure [32]. Roughly 70 percent of the infrastructure within the Arctic is built on top of permafrost, 33 percent of which is vulnerable to the impacts of warming [33]. Permafrost in the Arctic varies in form: sporadic or continuous [34]. Sporadic permafrost lies beneath the surface and serves as a sealant to hold soil components together. When melted, uneven, misshapen land replaces previously leveled areas. Continuous permafrost constitutes the understructure on which the majority of military installations in Alaska are built [35]. Indeed, 15% of U.S. training operations infrastructure and five Department of Defense facilities within Alaska depend on a permafrost foundation. The accelerated melting of continuous permafrost subsides land, thereby threatening the various infrastructures, including runways and testing facilities (Figure 1), that rely on subzero temperatures to withstand the harsh Arctic environment.

The consequences of thawing permafrost have already manifested. Several instances such as a Russian storage tank bursting open, propelling 150,000 barrels of oil toward the Arctic Ocean, and damages to transportation infrastructure, manufacturing facilities, and pipelines have totaled hundreds of billions of dollars [33]. Specific to the United States, the Thule Air Force Base has experienced severe flooding on runways due to thawing permafrost. At the Eielson Air Force Base in Alaska, a report emphasized the complications for the F-35A fighter jet from the thawing beneath the infrastructure [26]. Hangars and other facilities overlay a combination of actively thawing permafrost, impacting the capacity to support these loads [36]. Before the 1960s, climate criteria were hardly considered during the design and construction of these bases [32]. Even after this became a part of the planning process, bases were still constructed without long-term sustainability in mind, making infrastructure susceptible to the unpredictable thaw of the Arctic today. Damages from the deformation of surfaces, cracks and cavities at foundations, and water pooling around roadsides are the most common concerns in Alaskan and Canadian infrastructure [28]. Over the next couple of years, these damages will cost the United States upwards of 2 billion dollars [32], skyrocketing to $7.3–14.5B by 2080 [37]. Furthermore, engineers initially responsible for constructing the Alaska–Canada Highway (ASCAN) disregarded the implications of their activities on the organic material that protected the permafrost [38]. Construction decimated miles of temperate forest and tundra, now hastening the pace of permafrost melting beneath a critical highway network used to service military installations.

2.2. Rising Sea Levels

Warming of the Arctic region contributes to rising sea levels induced by rapid ice melt. This has numerous repercussions, including the deterioration of coastal infrastructure, various maritime facilities, training areas, and supply chains [35]. Although a 1990 U.S. Naval

War College paper outlined the implications of rising sea levels on coastal infrastructure, a lack of substantiated claims at the time failed to evoke an adequate response from civil engineers and planners. Currently, 128 U.S. military bases, primarily in the Arctic region, are at risk of succumbing to rising sea levels [33]. Specifically, the DoD outlines that two-thirds of the bases in the Arctic are in danger of perennial flooding (Figure 2) [26]. Military installations can be made effectively futile even without explicit physical damage done [40]. Rising sea levels threaten the support infrastructure crucial to military facilities. Bases cannot operate without internet availability, transportation connections, power supply, and essential materials.

Figure 1. Cracked runways at Thule AFB, Greenland, from permafrost thaw and refreezing adapted from [39].

Figure 2. Storm damage to hangars at Eareckson Air Station, Alaska adapted from [39].

Rising sea levels amplify the threats to base sustainability and have various aftereffects. Firstly, flooded runways and docking sites inhibit ships, submarines, and aircraft from deployment and docking. Servicing this military equipment can also be impossible during times of high tide. Second, government monetary distribution will be shifted from the research and development (R&D) sectors into preventative measures, floodwalls, and land recovery. Thirdly, water-logged infrastructure impedes access to certain parts of bases. Finally, training exercises and various simulations, which require a constant, controlled environment to be performed in, would need to be reevaluated to account for environmental change [35]. The ramifications of climate change-induced sea level rise have already played out domestically in the mainland United States. For example, the Norfolk Naval Station in Virginia has seen a 1.5-foot sea level rise over the past 100 years. The installation is projected to see an additional, equivalent increase over just the next 30–50 years, an increase that would push the base past the brink [35]. Higher tides forced the shutdown of several low-lying docks, hampering the base at only 33 percent capacity. A gradual sea level increase of 14 inches since 1930 is also observable at Joint Base Langley-Eustis (JBLE-Langley AFB) in Virginia, which has increased the frequency and intensity of flooding [25].

Furthermore, reports analyzing the Navy Base Cornado corroborate heightened sea levels, impairing access and servicing. The Hampton Roads in Virginia have already begun succumbing to intensified flooding, restricting access to the 29 military bases in the area [41]. In the Arctic, these conditions are further worsened. For instance, Fort Greely in Alaska experienced flooding covering nearly five acres and reaching 20 feet in depth at some places due to a rise in the water level of a neighboring stream [26]. This recurrent flooding has been the culprit for roadway erosion throughout the base.

3. Sustainable Solutions and Discussion

3.1. Modeling Other Countries

Canada. Canadian military bases in the Arctic region have also taken the brunt of the damage facilitated by climate change. From 2010 to 2018, the Canadian Armed Forces (CAF) has been forced to handle 23 instances of environmental disaster. The nature of these disasters is indicative of global warming heightening the frequency of catastrophes, as the CAF responded to one such instance in 2010, compared to a staggering six in 2018 [42]. The CAF has published several ordinances regarding sustainable base construction practices, including the 2003 Sustainable Development Strategy (SDS) which introduced a CAF initiative to incorporate green building concepts into a specific percentage of new plans. This was the preliminary course of action to integrate green engineering within military activities preceding a more targeted 2006 rendition of the SDS. The Strategic Commitment outlined in the resolution seeks green principles to be a part of all new projects [43]. These developments fit nicely with Canada's broader Arctic strategy to ensure that infrastructure is environmentally friendly [42]. The rest of this section will focus predominantly on how Canada altered their civil engineering capacities for frigid environments.

The first is grasping the basic principles of permafrost itself. Ross Mackay's various 1970s publications regarding the importance of ground ice for engineers practicing in the far north started this conversation in Canada [44]. It enabled engineers to begin relying on extensive land and terrain surveying techniques (including stereo air photos) to predict ground ice implications. Whilst anticipating near-surface ice, which corrodes land that infrastructure occupies and creates sinkholes, there was heightened government-industry monitoring for appropriate avenues for infrastructure, such as highways and pipelines [45]. Even for inescapable cases, engineers began implementing methods to prevent landslides and water pooling at the shoulders of highway networks, sustained by increased maintenance [44]. Using these understandings, engineers learned from the Dempster Highway failure caused by near-surface ice and began construction of a roadway to Tuktoyaktuk, NT. By acknowledging the following factors, this highway is projected to be a success: an awareness that ground ice below the network is so extensive that it should be considered continuous, a minimum thickness for the highway fill dependent on terrain factors, thorough construction plans for a volatile tundra environment, and building in the summer months to decrease ice abundance. Many of these principles can be incorporated into the U.S. military strategy for constructing highways to and from bases and runways within the encampments.

Permafrost adaptation techniques were pioneered in other initial Northern Canada infrastructure developments. After the #391 provincial road section in Northern Manitoba experienced thaw-induced deformation, engineers replaced existing black asphalt, which absorbed high amounts of solar radiation, with 4 m of gravel, which kept it functional [46]. Increased temperatures beneath the Hudson Bay Railway led to permafrost thaw and subsequent sinkholes along the tracks; two effective solutions emerged. First, heat pipes that removed excess heat from frigid soil during the summer, were 90% and 60% effective at the two sites analyzed, and successfully refroze the ground. Secondly, surface insulation reduced heat transfer from infrastructure to the underlying soil in winter months and prevented thermal absorption in summer months. The following are various foundations engineered specifically for permafrost in Canada [47]. Methods discussed throughout this paper, such as crawl spaces, ducts, insulation, and thermosiphons, should be used in tandem with these foundations to maximize resilience. Spread footing, primarily used for smaller applications, utilizes a concrete pad underlaid in an excavated region of the soil. Fill material like gravel, which is less susceptible to thaw, is placed beneath and around the foundation. The wood-blocking method is applicable where permafrost damage has already occurred, and replaces current foundations with regionally sourced wood blocks, successfully stunting the lateral movement of buildings. Finally, Jack pads are metal supports placed beneath infrastructure and atop non-frost susceptible (NFS) soil and can be employed without excavating permafrost. These methods should be incorporated into new Arctic U.S. military installations or existing ones that have already sustained damage.

Russia. The Russian engineering strategy against permafrost takes two distinct pathways: permafrost maintenance (the passive method) or thawing of permafrost layers before construction (the active method) [48]. First, this section will focus on the passive method. In Vorkuta, a Russian town built slightly above the Arctic Circle, the most prevalent foundation is a crawlspace which was implemented in a hundred one and two-story buildings [49]. Nine years after construction, the permafrost layer rose, reversing thaw. Secondly, piling foundations, developed by Mikhail Kim in the late 1950s, involved long steel cylinders filled with either soil or concrete [50] inserted into the ground, and were a breakthrough in permafrost engineering capacities [48]. This cost-effective technique reduced heat conduction from the infrastructure above to preserve underlying ground ice and allowed development on both continuous and shallow permafrost-containing regions. The spatial orientation of the piles is also important. In an analysis of the Novaya Chara Station in Russia utilizing SCAD software, it was found that three factors—metal piles with an annular cross-section, hinging to attach the piles to the ground, and placing the smaller piles in closer proximity—reduced the seismic load on a structure by 25–30% and fared better against permafrost [51]. Another contemporary strategy under the passive method utilizes the GET system, a horizontal heat stabilizer, and the VET system, a vertical heat stabilizer used in tandem with piles running the length of the piles underground [52]. In an efficiency study of the GET system on the foundation of a reservoir, the horizontal heat stabilizer formed a plate of frigid soil to serve as a dependable understructure. In the case of a compressor station near Vorkuta, GET systems decreased the base temperature by 4 °C. In select areas, the use of GET systems might make the use of piles redundant, saving capital.

Next, is the active method. This involves adapting to any haphazard surfaces during construction, thawing the soil, and reinforcing the permafrost for a stable foundation [49]. In a place like Vorkuta, 18–31 m of permafrost needed to be thawed before building which is determined by calculations. Cement grout is inserted into the ground to counteract the thawing of hard, frozen soil, that would have served as the foundation for infrastructure [52]. This measure will prevent subsidence and strengthen the remaining soil after thawing begins. The foundations are located in a thawed layer and are stabilized by a ventilation cycle—alternating between a negative air temperature cold period for 5–15 years and a positive air temperature warm period for 2–5 years—which preserves the existing permafrost table [49]. The only real applications for the active method are in coarse-grained soils that are near settled during thawing [53]. or in discontinuous permafrost, as excavation must reveal fully thawed soil, and the residual heat of overlying buildings must keep it that way [54]. In permafrost-abundant soils (continuous zones), the thawed soil would likely not provide adequate support to infrastructure.

3.2. Global Solutions

Permafrost Cooling and Solar Refrigeration. Cooling permafrost should be at the forefront of considered solutions for the U.S. military. Available datasets from the permafrost-dominated Qinghai—Tibet and Qinghai–Kangding highways show that passive measures, such as increasing the height of infrastructure, only decelerate permafrost thawing but fail to fully prevent it [55]. The first method to counteract the implications of thawing permafrost is to stabilize its temperature. One existing concept is to make incoming sun rays cool down the soil, rather than heating it and contributing to permafrost thaw [56]. This theory opts for photovoltaics, or other similar technologies, which convert solar radiation directly into electricity whilst simultaneously safeguarding the underlying soil. Implemented in warm summer months, this solar energy would then be used to cool the soil using either vapor compression refrigeration systems (VCRS) or absorption refrigeration systems (ARS) (Figure 3), each having their respective benefits [57]. VCRS has low electricity consumption, economical refrigeration capabilities, and reaches temperatures much cooler than that of permafrost. ARS has a refrigeration temperature under 0 °C, an uncomplicated structure, and fares well against seismic activity. In an analysis of VCRS throughout 15-day-night cycles and ARS throughout 3 days, refrigeration temperatures reached −23.55 °C and −1.83 °C, respectively, during the warm seasons, which is more than low enough to maintain existing permafrost tables. Projections estimate that an implementation of this model at the Baikal-Amur railroad would decrease thawing from 4.0 m to 1.51 m in 5 years [56]. In a field test of VCRS, the most optimal configuration was determined by varying cooling power, cooling time, the distance between the compression systems, and the buried depth of the evaporation section of the VCRS, which is where heat is absorbed and transformed into low-pressure vapor [58]. Thus, a design using 200 W of cooling power, 12 h of cooling time, a 6 m separation distance between systems, and a 5 m depth of the evaporation section decreased permafrost temperature and moved the permafrost table up 1.5 m after 30 years.

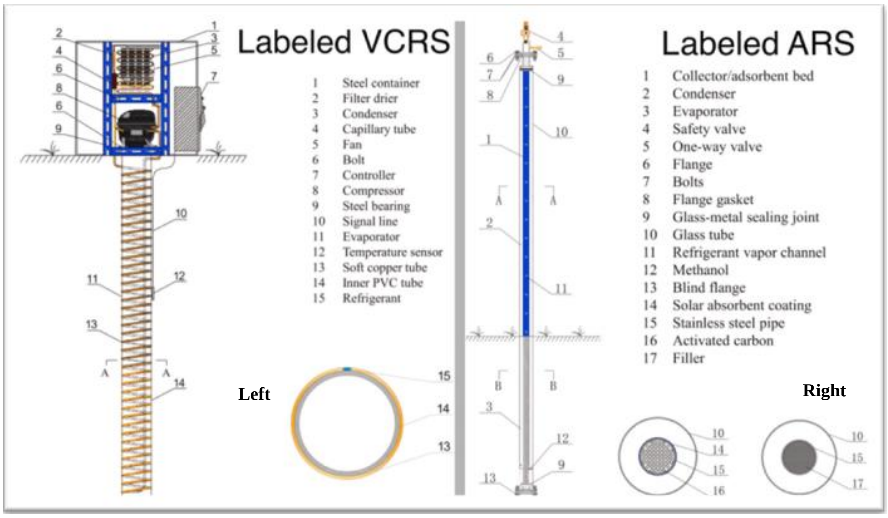

Figure 3. Vapor compression refrigeration system (**left**) and absorption compression system (**right**) adapted from [57].

Thermosiphons, thermal management devices that enable passive heat exchange (Figure 5), have been successful in permafrost terrains around the globe [55,59]. They use the naturally occurring circulation of fluids like water to relay heat from frozen soils to the atmosphere, cooling large regions of soil and moving areas of permafrost upwards [47]. These devices have a range measuring 1.8–2.0 m in radius and work best when inserted into the ground or sides of slopes at a 25–30° angle. After conducting a CPT test, one that determines soil properties in the first 100 m of soil, it was found that the presence of thermosyphons cooled the soil from −0.5 °C to −0.8 °C [60].The pile-bearing capacity, a strategy discussed above, was also found to increase by 42% to 77 tons. In a peat subarctic environment, most commonly used to test refrigeration applications due to peat's resistance to freezing, two thermosiphon systems were tested: the simple thermosiphon (STS) and the advanced thermosiphon (ATS) [61].

Although the minimum temperatures beside the ATS (−13.3 °C to −14.2 °C) were lower than beside STS (below 0 °C), STS in tandem with snow reduction cones, devices that significantly increase cooling effects, is a cost effective, reliable, and versatile solution compared to ATS. Thermopiles, a combination of thermosiphons and piles (Figure 4) [47], maintain permafrost tables in cases with larger loads and greater threat of foundation movement [62]. During winter, when the atmosphere is colder than the ground, fluid from inlaid cooling devices circulates between an evaporator and condenser, enabling naturally occurring heat transfer [63]. However, when the disparity between ground and atmospheric temperatures falls below a threshold during the summer, the convection process does not occur. In a simulation, thermal coils, placed at varying distances within the piles, were supplied with a slightly negative refrigerant-supplied coolant [64]. This orientation, with carbon dioxide as the safest coolant, reduced the temperature of surrounding soil much more than standard piles and lowered the extent of thaw by 50% [63].

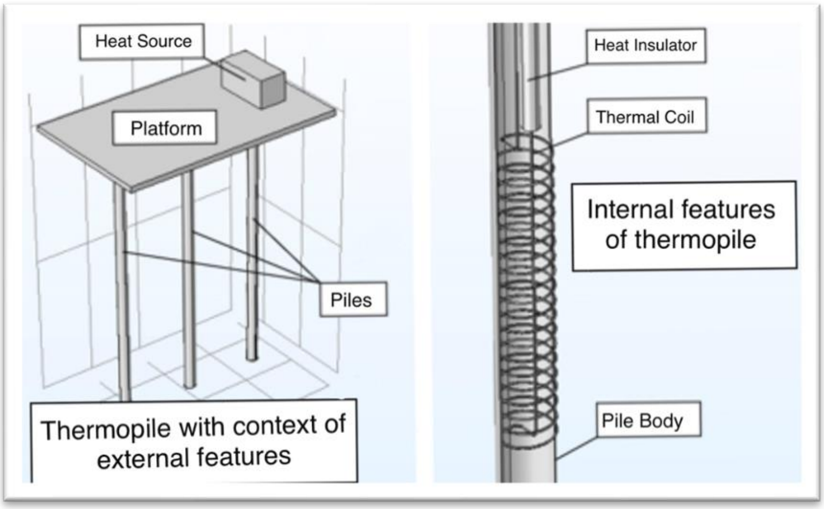

Figure 4. A labeled thermopile design adapted from [64].

Although requiring ventilation ducts to stabilize soil temperatures in warmer permafrost conditions [65], crushed rocks use natural convection to counter thaw [55]. In the winter, when the external air is colder than the temperature of the permafrost, convection within the rocks allows the permafrost to lose heat to the surrounding atmosphere. In the summer months, the rocks serve as insulators and decrease heat transferred to the permafrost, countering thaw. The three types of crushed rock-based embankments—U-type crushed rock embankment (UCRE), the crushed rock-based embankment opened (CREO), and the crushed rock-based embankment closed (CREC)—were analyzed in Beiluhe [66]. After two years, the lowest soil temperatures beneath the UCRE and CREO were similar at −9.5 °C, outperforming CREC at −4.0 °C—revealing the superior implementations. Layered rushed rocks as runways have been successful in small airports across permafrost regions, including the Alaska Arctic Coastal Plain Airport, Brookes Mountain Area Airport, and the Mohe Gulian and Yichun Airports in China [67]. Further tests concluded that a crushed rock layer with an optimal particle size of 6–8 m and a layer depth of 0.5 m followed by an insulation layer measuring 0.15–0.20 m thick was the best configuration: it sustains permafrost tables and the load of aircraft, preventing changes in settlement and preserving aircraft safety. This presents a unique solution to the situations of U.S. military runway installations enduring the deterioration listed above.

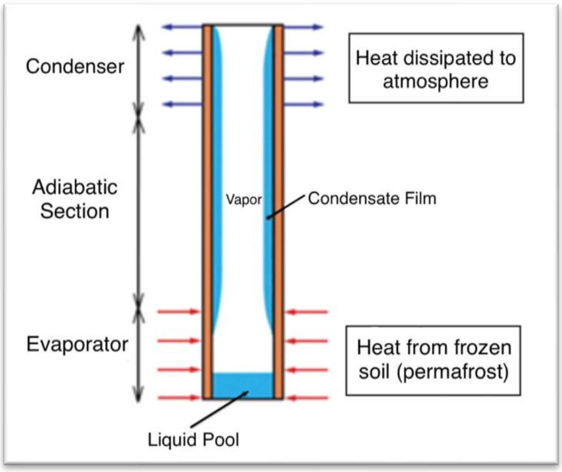

Figure 5. A labeled thermosiphon design adapted from [68].

Foundations. Another important consideration for the U.S. military when designing future military infrastructure is the impact of foundation design on the permafrost itself. The two major engineering questions behind the substructure are as follows: how will it maintain the frozen conditions of the soil to not cause critical deformations or how will it sustain on already thawed terrain [50]? In tandem with the more popular piling solutions discussed earlier in the paper, there exists Multipoint Foundations (Figure 6) that have not been as utilized in the Arctic region. These are spatially designed understructures, constructed from substances such as reinforced concrete, metal, or timber, that are ventilated to be less prone to deterioration caused by permafrost thaw. A ventilation space of around 1.5 m is advised for ease during maintenance [69]. Explicitly, the Abovsky spatial foundation has a concrete structure composed of a lower belt, inserted on the outer soil, and an upper belt, connected to the former via a metal beam [50]. There are several ways to spatially orient the structure—plate-rod, a structural plate, a cross-beam system, folds, shells, and adjustable height—which are utilized depending on soil composition and overall building design.

Figure 6. Multipoint Foundation made of a steel shell adapted from [50].

This is an encouraging alternative for numerous reasons: not much excavation is necessary, which can be challenging with frigid soils, its spatial structure is more resistant to permafrost-induced deformation, meaning it can be erected on even volatile soils, and the components being manufactured in non-Arctic facilities means maintenance access is easy as well. They also dispense infrastructure loads over a wider area and do not need reinforcements from NFS soil [47]. Furthermore, this is practically incentivizing for the U.S. military as construction can be conducted year-round, rather than just in the summer months. The impact of Abovsky spatial foundations on underlying soil was analyzed using the COMSOL Multiphysics software, which revealed that after 4 years, even during the hottest month, temperatures beneath the medial part of the foundation were negative [69].

Another engineering strategy for foundations is to introduce ventilation ducts [55], which cool permafrost with the forced convection of residual heat from overhead buildings, dissipating it to the surroundings [65,70]. Concrete ducts analyzed in Beiluhe had an internal temperature only 1.6–1.8 °C higher than the air, effectively cooling permafrost [55]. However, the addition of shutters on the open end of the ducts demonstrated a soil temperature of 0.45 °C lower than non-shutter ducts at the same depth of 3.5 m. To protect ducts from stress-induced deterioration, the concrete used should be precast with admixtures—fly ash, ground-granulated blast furnace slag, or silica fume—which improve resilience against Arctic processes and outfitted with insulation on the exposed end, slowing moisture penetration and physical wear [70].

Materials used in the construction of the foundation have several implications for the maintenance of existing permafrost conditions. For example, wood is often a suggested choice (Figure 7) not only because it is lightweight and easy to transport, but also because it is environmentally friendly compared to alternative options [50]. Wood also possesses a minuscule coefficient of thermal conductivity, which means that less heat is transferred from the above infrastructure to the underlying permafrost it is built upon, decreasing thaw. The use of other materials, such as reinforced concrete or metals, is discouraged as they heighten heat conduction worsening permafrost conditions, are harder to transport due to being heavier, and cannot be constructed year-round as there is a lack of availability on how seasons will impact them. Materials for road pavement foundations have also been studied. Modular pavements, made of composites or rubber granules, are encouraged for being easy to transport and install, sustaining heavy loads, and their flexible nature means they are resilient against the thaw of underlying soil [71]. Alternatively, constructing a foundation of locally sourced materials and concrete covering treated with a binding adhesive would be economical and structurally sound.

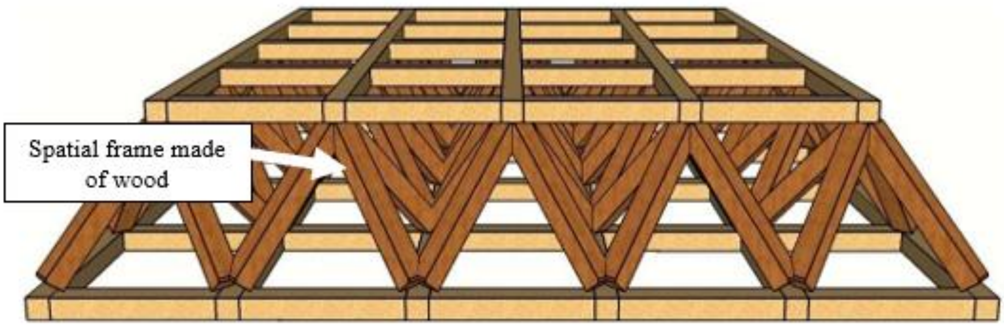

Figure 7. Structural plate foundation made of wood adapted from [50].

Preventative Measures. This section will analyze several solutions the U.S. military can incorporate to prevent the existing concerns posed by rising sea levels and melting permafrost from getting even worse. The following suggestions have been analyzed regarding cost effectiveness, environmental impact, and resilience over time. The first are revetments (Figure 8), composed of individual stone and concrete shapes and placed along shorelines to draw a line between the coast and bodies of water [72]. Unlike seawalls, these modular units mean that revetments can move and settle to accommodate rising sea levels while having a limited impact on the environment as they do not restrict water flow. A meta-analysis of erosion control methods in the Arctic concluded that revetments have the fewest reported failures and are utilized at sites with erosion rates ranging from 0.3 to 2.4 m/yr as they are cost effective and easy to maintain [73]. Among every erosion control method, revetments are applied the most (41%), primarily in coastal villages. In the Beaufort Sea in the Arctic, another study of revetment performance against storms ranging from the 2 to 500-year frequencies found that they were the most cost-effective solution [74]. For these reasons, they should be considered around U.S. military installations concerning sea level rise. A secondary, but less encouraged, example of an accommodation strategy against sea level rise in the Arctic region is levees— dikes built up using earth to delineate the coast from the sea [72]. A case study of the use of this strategy in the coastal city of Rotterdam reveals that they provide excellent protection against sea level rise and can even be multi-purposed to accommodate storage areas. However, the upfront cost of installing levee systems is quite high, and annual maintenance fees total 2% of initial project costs. Levees can also last nearly indefinitely, provided that the aforementioned servicing regularly takes place. Other strategies along the coastline, such as bulkheads, grounds, and breakwaters are often dissuaded as they either cannot withstand storm surges or are prone to sea level rise—both conditions that are common in a rapidly warming Arctic [73] (Figure 9).

Figure 8. Rock revetments along the Alaskan Arctic coast adapted from [75].

Next are methods that fall under the accommodation strategy, which improves the resilience of existing infrastructure. Foremost is building new or raising the height of existing floodwalls—temporary or permanent concrete structures built 1–20 ft high to protect infrastructure from rising sea levels or storm surges [72]. Relative to the solutions listed above, they are cost effective and require periodic maintenance only to patch up cracks in any drywall. This can be specifically applicable to the military as floodwalls can be integrated into clusters of buildings and the security of the base. At 7 of the 15 Arctic military bases visited by GAO researchers, officials cited raising the existing floodwalls as a viable solution to the heightened frequency of storms [76]. At one particular location, bolstering floodwalls would protect vessel and submarine systems from being damaged by salt water, inducing delays of 3 or 4 months. An alternative option is dry floodproofing, making the exterior of a building watertight to prevent salt water from seeping inside [77,78], which can be implemented in both existing and new infrastructure [72]. Existing military bases should be modified by bolstering exterior walls and filling any cracks in the foundation, whereas new infrastructure should make use of waterproof walls and watertight doors and windows. Concrete, brick, aluminum, and fiberglass alternatives to drywall should be among the first materials considered by the U.S. military as they are the most water-resistant [77]. The cost and maintenance of dry floodproofing remain low, and when used in tandem with floodwalls, will remain resilient against thawing permafrost and rising water levels. Although current DoD climate policies allow bases to individually determine their courses of action against warming, accommodation strategies, when implemented, have been successful [79] For example, the American JBLE Langley Air Force base took the initiative to use flood projection models to identify risk areas and install door dams, cutting sand bag use by 70%. Such measures should be expanded to all bases in the Arctic as well.

Figure 9. Floodwall along the coastline adapted from [80].

Table 1 illustrates a literature summary of sustainable strategies to current conditions and climate change at U.S. Military Bases in the Arctic region.

Table 1. Literature summary of sustainable strategies to current conditions and climate change at U.S. Military Bases in the Arctic region.

Literature	Study Focus	Scope	Findings
[1]	Arctic warming	Arctic Circle	Region warming 4× faster than rest of the world
[3]	Arctic warming	Arctic Circle	CMPI6 models predict greater warming by 2100 than previously expected
[8]	Arctic warming	Arctic Circle	Ice-albedo feedback accelerates warming
[16]	Arctic warming	Arctic Circle	Arctic Sea ice decreased 60% since the 1980s
[17]	Arctic warming	Arctic Circle	Erosion rate increases from 1.8 to 2.9 by the end of the century
[20]	Arctic warming	Arctic Circle	Rate of sea level rise increased from 1.1 mm/yr in 1900–1930 to 4.4 mm/yr in 2010–2015
[22]	Arctic warming	Arctic Circle	Permafrost declined 20% in most impacted areas
[23]	Arctic warming	Arctic Circle	Ground ice temperature increased significantly across five sites

Table 1. *Cont.*

Literature	Study Focus	Scope	Findings
[25]	Current base conditions	U.S. bases in Arctic	Bases are susceptible to recurring flooding and permafrost thaw
[26]	Current base conditions	U.S. bases in Arctic	Two-thirds of 79 bases are vulnerable to warming
[27]	Current base conditions	U.S. bases in Arctic	Engineers and the Coast Guard did not prioritize climate resilience
[28]	Permafrost impact	U.S. bases in Arctic	Thaw releases 300 kPa of force that collapses infrastructure
[29]	Permafrost impact	U.S. bases in Arctic	Thawed soil loses its structural stability
[32]	Permafrost impact	U.S. bases in Arctic	Damages will total $2B over the coming years
[33]	Permafrost impact	U.S. bases in Arctic	Nearly 33% of U.S. bases are susceptible to thaw impacts
[35]	Sea level rise impacts	U.S. bases in Arctic	Rising sea levels flood runways, impede training and servicing, and decrease R&D
[36]	Permafrost impact	U.S. bases in Arctic	Hangars at the Eielson AFB are built on thawing permafrost, causing failure
[38]	Permafrost impact	U.S. bases in Arctic	Alaska–Canada highway impacted underlying organic material, causing permafrost thaw
[40]	Sea level rise impacts	U.S. bases in Arctic	Threatens critical infrastructure like power
[41]	Sea level rise impacts	Coastal U.S. bases	Hampton roads flooded and restricted access to several U.S. bases
[42]	Modeling countries	Canadian Arctic infrastructure	CAF incorporates green principles in a percentage of new plans
[44]	Modeling countries	Canadian Arctic infrastructure	Near-surface ice influences building characteristics
[45]	Modeling countries	Canadian Arctic infrastructure	There is increased government–industry monitoring of permafrost
[46]	Modeling countries	Canadian Arctic infrastructure	Black asphalt, which altered albedo and led to thaw, was replaced with 4 m of gravel on roads, and heat pipes and insulation also combatted thaw
[47]	Modeling countries	Canadian Arctic infrastructure	Spread footing, wood-blocking method, and jack pads decreased lateral movement of impacted buildings
[48]	Modeling countries	Russian Arctic infrastructure	Piling foundations maintain existing permafrost
[49]	Modeling countries	Russian Arctic infrastructure	Ventilation cycles stabilize a thawed foundation
[50]	Solutions	Arctic Circle	Wooden Abovsky spatial foundation preserves permafrost
[51]	Modeling countries	Russian Arctic infrastructure	Specific orientation of piles increases load-capacity and reduce thaw
[52]	Modeling countries	Russian Arctic infrastructure	GET system freezes soil to create understructure
[54]	Modeling countries	Russian Arctic infrastructure	Active method only viable in discontinuous permafrost
[55]	Solutions	Permafrost conditions	Crushed rocks use natural convection to transfer heat out of soil
[56]	Solutions	Permafrost conditions	Photovoltaics provide energy for VCRS and ARS
[57]	Solutions	Permafrost conditions	VCRS and ARS produced soil temperatures of −23.55 °C and −1.83 °C, respectively, during the testing periods
[58]	Solutions	Permafrost conditions	Optimal orientation for VCRS is 200 W of cooling power, 12 h of cooling time, a 6 m separation distance, and a 5 m depth
[60]	Solutions	Yamal Polar Agricultural College	CPT test found thermosiphons cool soil
[61]	Solutions	Permafrost conditions	STS in tandem with snow reduction cones is cost effective, reliable, and versatile compared to ATS
[62]	Solutions	Permafrost conditions	Thermopiles are used for stabilizing heavier loads
[63]	Solutions	Permafrost conditions	Specific orientations of thermopiles reduced thaw extent by 50%

Table 1. *Cont.*

Literature	Study Focus	Scope	Findings
[66]	Solutions	Permafrost conditions	UCRE and CREO are the best orientations for crushed rocks, producing low temperatures of −9.5 °C
[67]	Solutions	Permafrost conditions	Crushed rocks can be used in runways, as they sustain aircraft load and maintain permafrost
[69]	Solutions	Permafrost conditions	Ventilation beneath Multipoint Foundations maintain negative soil temperatures even in summer months
[70]	Solutions	Permafrost conditions	Ventilation ducts cool soil via natural convection
[71]	Solutions	Permafrost conditions	Modular pavements of rubber granules or composites are easy to install and are resilient to underlying thaw
[72]	Solutions	Coastal environments	Revetments, levees, dry floodproofing, and floodwalls protect again sea level rise
[73]	Solutions	Arctic Circle	Revetments are most commonly used for being cost effective
[74]	Solutions	Permafrost Conditions	Revetments have the least failures in simulations of 2 to 500-year frequency storms
[76]	Solutions	U.S. bases in Arctic	7 of 15 U.S. Arctic base officers identified floodwalls as a solution to rising sea levels
[79]	Solutions	Permafrost conditions	When implemented, accommodation strategies have been successful

4. Conclusions and Recommendations

This study thoroughly analyzed the resilience of United States military bases in the context of accelerated warming in the Arctic region, the negative implications of infrastructure deterioration, and the viability of various solutions that could be incorporated into existing and upcoming installations (as shown in Table 1). The conclusions and recommendations are as follows:

1. Two-thirds of U.S. military facilities in the Arctic remain susceptible to permafrost thaw and rising sea levels, attributable to the absence of consistent regulations from the DoD and the lack of initial sustainable engineering when the bases were constructed. Sunken runways and docks degraded foundational infrastructure, and an inability to service or repair machinery will total $2B over the next few years. Rapidly changing conditions make it imperative that the U.S. military take resilience into consideration as they bolster their footprint in the region.
2. The U.S. may consider looking at the Canadian strategies—heat pipes, surface insulation, and specialized foundations for varying abundances of permafrost—and Russian strategies—passive and active methods—that have successfully maintained permafrost tables.
3. Implementing permafrost cooling methods, such as vapor-compression or absorption refrigeration systems, thermosiphons and thermopiles, and crushed rocks, should be heavily considered as they are the only ways to prevent permafrost thaw entirely. These solutions cool permafrost by transferring heat to the atmosphere and can be installed near existing installations to uphold stability.
4. Foundational considerations, notably the Abovsky spatial foundation, ventilation ducts, and materials used for both building and road infrastructure understructures, can eliminate climate-related structural concerns. These methods used in tandem with one another will stabilize rapidly deteriorating permafrost tables beneath bases.
5. DoD expansion of tested preventative measures to all installations in the Arctic, such as revetments, levees, floodwalls, and dry floodproofing, will provide an effective solution against rising sea levels. Rather than the aforementioned solutions which primarily recommend that forthcoming bases plan around resilience, these can be

implemented at existing installations. Revetments have shown considerable promise against sea level rise and can be added to banks. Similarly, doors and windows can be retrofitted to prevent water seeping.

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Nomenclature

AA	Arctic Amplification
ARS	absorption refrigeration systems
ASCAN	Alaska–Canada Highway
ATS	advanced thermosiphon system
CAF	Canadian Armed Forces
CMPI5	Coupled Model Intercomparison Project Phase 5
CMPI6	Coupled Model Intercomparison Project Phase 6
CPT	cone penetration test
CREC	crushed rock-based embankment closed
CREO	crushed rock-based embankment opened
DoD	Department of Defense
GET system	horizontal naturally-acting tubular system
GMSL	Global mean sea level
JBLE-Langley AFB	Joint Base Langley-Eustis Air Force Base
NFS	non-frost susceptible
SAT	Surface air temperatures
SDS	Sustainable Development Strategy
SRES A1B	Special Report on Emissions Scenarios A1B
STS	simple thermosiphon system
UCRE	U-type crushed rock embankment
VCRS	vapor compression refrigeration systems
VET system	vertical naturally-acting tubular system

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