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Concept for Artificial Freezing of Sea Ice at Winter Quarters Bay, Antarctica

Anna M. Wagner and George L. Blaisdell

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Concept for Artificial Freezing of Sea Ice at Winter Quarters Bay, Antarctica

Anna M. Wagner and George L. Blaisdell

*U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290*

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Abstract

McMurdo Station serves as a major research and logistics hub for the United States Antarctic Program (USAP). Adjacent to the Station is Winter Quarters Bay (WQB), where vessels dock to unload cargo and fuel. The ice pier at McMurdo is essential for this annual vessel resupply but represents a failure potential, occasionally breaking up during or immediately after vessel operations.

This study aimed to determine the feasibility of using thermopiles, a passive cooling technology, to artificially freeze seawater to “grow” the existing WQB bottomfast-ice edge so that ships can dock directly against it. Finite element simulations using modeling-parameter assumptions indicate that each row of thermopiles can grow a frozen wall to a depth of 9 m in about a month if installed on 1 July with an initial sea-ice thickness of 1 m and a thermopile spacing of 1.5 m. For our simulation scenarios, we approximate that it would take 255 to 820 days to complete a 40 m by 140 m wedge of bottomfast ice. The estimated cost ranges from about \$600,000 to \$1,600,000. These results serve as a preliminary feasibility study of successfully using thermopiles for generating a direct docking bottomfast-ice wharf at McMurdo.

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Preface

This study was conducted for the National Science Foundation (NSF), Office of Polar Programs (OPP), Antarctic Infrastructure and Logistics (AIL), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-19-08, “Toward Lower Risk McMurdo Resupply.” The logistical guidance and technical supervision was provided by Ms. Margaret Knuth, Operations Manager, NSF-OPP-AIL, U.S. Antarctic Program.

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COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

2-D	Two-Dimensional
2R	Two Row
3-D	Three-Dimensional
4R	Four Row
AFI	Arctic Foundations Inc.
AIL	Antarctic Infrastructure and Logistics
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EL	Evaporator Length
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	Engineer Research and Development Center
FEM	Finite Element Method
NSF	National Science Foundation
OPP	Office of Polar Programs
SD	Snow Depth
SOP	Standard Operating Procedure
TP	Thermopile
USAP	United States Antarctic Program
WQB	Winter Quarters Bay

1 Introduction

1.1 Background

McMurdo Station (77°51' S, 166°40' E) is located at the southern tip of Hut Point Peninsula on Ross Island (Figure 1). The United States Navy established the Station during the International Geophysical Year (1955–1956), and it remains the largest Antarctic research facility and logistics hub on the continent of Antarctica. The Station and its activities are managed solely by the National Science Foundation (NSF) through contracts and interagency agreements, involving the many government and commercial support groups that make up the U. S. Antarctic Program (USAP). The Station is accessed by intercontinental aircraft at one of several snow airfields on the McMurdo Ice Shelf and by ship at Winter Quarters Bay (WQB) immediately adjacent to the Station. WQB is approximately 250 m* wide at its mouth and 250 m long with a maximum depth of about 33 m, allowing vessels a somewhat protected ship-docking location for unloading cargo and petroleum products (Crockett and White 1997).

Up until 1965, ship-delivered cargo for the USAP was offloaded directly onto sea ice where a robust ice edge could be found adjacent to reasonably ice-free open water. At times, cargo and fuel offload took place as much as 10 km from McMurdo and was then traversed by vehicles into the Station. Thin ice in the 1964–1965 austral summer season precluded ice-edge ship operations, which were then moved to bottomfast ice along the shoreline of WQB (Figure 2). This resulted in a safer and more efficient resupply and became adopted as the new scenario for ship operations at McMurdo.

Occasionally natural forces, but more often icebreakers, facilitated removal of annual sea ice in WQB to allow ship docking against the bottomfast ice. This exposed the ice edge to increased wave action, ship's impact and liquid discharge, and warmer air temperatures and solar gain. This caused the bottomfast-ice edge to erode landward, lessening available draft for docking ships. Attempts to arrest this erosion and to replace the

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *U.S. Government Publishing Office Style Manual*, 31st ed. (Washington, DC: U.S. Government Publishing Office, 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

bottomfast-ice vertical face with a steel and timber façade were wholly unsuccessful (Kirkpatrick 1973).

Figure 1. McMurdo Station, Antarctica, located on the southern tip of Hut Point Peninsula on Ross Island (U.S. Geological Survey 1960).

Figure 2. Resupply ships docking against the bottomfast-ice edge, Winter Quarters Bay, January 1966 (Hoffman et al. 1979).

In the winter of 1972, crews constructed a floating “fender” in the form of a “sea-ice-berg” by repeatedly flooding the annual sea-ice surface in a snow-

bermed rectangular area immediately adjacent to the bottomfast-ice edge. This solution allowed ship operations for the 1972–1973 austral summer. Refinements in this approach eventually led to the creation of today’s ice pier: an artificially thickened rectangle of ice, floating free of the bottomfast-ice edge, secured to Ross Island via bollards and cables and accessible via a modular bridge span.

Ice-pier construction procedures were first published by the Naval Civil Engineering Laboratory in 1976 (Barthelemy 1976). They have since been updated and modified numerous times (e.g., Vaudrey 1994); USAP personnel now follow a mature standard operating procedure (SOP) that prescribes all aspects of construction, operation, maintenance, and repair.

An ice pier at McMurdo is without question a vital piece of infrastructure necessary to ensure annual resupply from the container ship and backhauling of goods leaving Antarctica. While the ice pier has proved capable of supporting this once-a-year event, there have been a number of times when the operation was compromised by near or complete failure (major cracking or fragmentation) (e.g., Barthelemy 1992).

Construction of a new ice pier is a major winter workforce effort and requires significant planning. And, despite a mature SOP, there is no certain “formula” for building the pier to ensure its adequate performance and duration (Figure 3). Additionally, use of the ice pier requires deployment of a Bailey bridge, which has its own structural risks and creates a major operating bottleneck for ship access (width and weight limits). In the truest sense, the ice pier (and connected Bailey bridge) represents a single-point-failure potential, and it has demonstrated such by occasionally breaking up during and often immediately after resupply operations.

Figure 3. History of McMurdo Station ice piers (R&M Consultants and Glosten 2017; M. Knuth, pers. comm., 2019).

1.2 Objective

The objective for this work was to determine the feasibility of using thermopiles to artificially freeze seawater. The broader goal was to assess the viability of using thermopile technology to grow the bottomfast-ice edge of the McMurdo wharf southeastward to a point where resupply ships can dock directly against bottomfast ice, thus avoiding the need for an ice pier and connecting bridge.

1.3 Concept

Between the mid-1960s to 1972, McMurdo ship resupply took place directly at the bottomfast-ice edge on the northwest coast of WQB (Figure 2). With the ships of the day having a shallower draft than those used today and the bottomfast-ice edge extending closer to the center of WQB and thus in a deeper water, this docking posed no problem even for simultaneous docked operations of several ships. The concept proposed in this study would see a portion of the bottomfast ice in WQB regrown into deeper water to allow resumption of direct ship docking without the need for an ice pier and connector bridge.

We envision that growth of the existing bottomfast-ice edge into deeper water would take place along approximately 200 m of current shoreline, tapering to about 100 m of docking face, parallel to and 40 m distant from the current shoreline (Figure 4a). The shape is intended to, in the west, deflect incoming waves and swells from McMurdo Sound and, in the east, remain somewhat removed from warm meltwater draining into the head of WQB.

Construction of new bottomfast ice would take place in rows or vertical slabs progressively added seaward from the existing bottomfast-ice face. Thermopiles would be installed through annual sea ice in the winter as soon as the ice can safely support the equipment needed to deploy a thermopile array. We propose that during construction one or more rows of thermopiles would initially be installed parallel to the existing bottomfast-ice face and offset seaward (and separated from each other) by a distance determined by the calculated cylindrical freezing-front rate (freezing-to-closure) and target time for slab completion (Figure 4a and b). Such an array is common in thermopile applications (Figure 5).

Upon the freezing cylinder from each thermopile being linked, the thermopile rows would be removed and reinstalled seaward to begin construction

of a second (and subsequent) slabs of bottomfast ice (Figure 4a). Removal of the thermopiles will utilize external heating of the metal thermopile body. The time required to complete each slab will likely be greater with each progressive slab since the volume of ice to be generated will increase owing to the seabed being deeper.

This process of seaward migration of the bottomfast-ice edge will continue until it has reached into WQB to a depth to seabed of about 15 m (50 ft) (Figure 4a and c). The number of slabs (and the overall construction time) will be predictable based on calculations determined from model output. Using existing bathymetry maps, we estimate that about 76,500 m³ of ice will be grown (Figure 4d).

Figure 4. Concept of construction for an extended bottomfast-ice edge at Winter Quarters Bay.

(a) A plan view of the position of the extended bottomfast ice.

(b) A cross section of the first slab of the added bottomfast ice.

Figure 4 (cont.). Concept of construction for an extended bottomfast-ice edge at Winter Quarters Bay.

(c) A completed extension of the bottomfast-ice edge.

(d) A three-dimensional sketch of an added wedge of bottomfast ice.

Figure 5. Thermopile array adjacent to a roadway in Alaska.

We propose using tie-in materials to ensure secure connections between the existing bottomfast ice and the newly grown ice. Likewise, tie-in connectors may be prudent with the seabed at the base of the new bottomfast ice. Alternatively, perhaps dense ballast could be placed on the seabed to be enveloped by the new bottomfast ice and thus help resist buoyancy uplift and separation from the seabed.

1.4 Approach

We conducted a series of finite element simulations using SoilVision (SoilVision System Ltd.), a commercial finite element method (FEM) solver package, to estimate at what rate thermopiles will grow artificial sea ice in WQB. To investigate the efficiency of artificially creating sea ice, we simulated a series of vertical slabs using thermopiles, varying the snow depth, thermopile spacing, evaporator length, date of installation, and total performance of the thermopiles. From these simulations, we yielded estimates of time to generate a frozen wall by merging of the frozen columns of adjacent thermopiles (freezing-to-closure). We also estimated the time it would take to build a bottomfast-ice extension 40 m seaward from the existing ice wharf; and for the three-dimensional (3-D) scenarios, we also estimated the thermopile cost of such scenarios.

2 Technical Approach and Methods

2.1 Thermopiles

Thermopile (a type of thermosyphon) technology is mature and has been used extensively and successfully in arctic, subarctic, and temperate locations to create or maintain frozen ground below buildings, pipelines, and earth structures since the 1960s (Richardson 1979). By 2008, over 900 installations in Alaska alone utilized thermopiles for maintaining frozen ground (Wagner and Yarmak 2012). Thermopiles can facilitate the convection cycle passively, actively, or a combination thereof. In a passive mode, thermopiles function when the air temperature is colder than the ground temperature by using gravity to move thermal mass (usually ammonia or carbon dioxide) cooled from ambient air downward into the ground (Figure 6). Active thermopiles are linked to a heat pump and use electrical power to cool refrigerant. Hybrid thermopiles function passively when air temperatures are sufficiently cold, but they also use power and refrigerant when environmental conditions dictate.

Figure 6. Passive thermopile (Wagner 2013).

The overall thermopile performance is directly linked to the air temperature, wind velocity, and fin size (see Figure 6). The heat removal and cooling rates are also highly dependent on the surrounding material. Arctic Foundations Inc. (AFI) is the only commercial company in the United States that currently manufactures thermopiles. Figure 7 shows the total performance of AFI units and how these units vary with wind speed, as higher winds yield a higher-performing unit. For the simulations in this report, we used an average measured wind speed of 4.2 m/s (estimated from the McMurdo meteorological station). The size of condensers are readily modified and available to meet the need of each installation. In this modeling effort we applied the performance of off-the-shelf 6.5 and 15.8 m² fin-size units from AFI that have approximated performances of 117 and 285.1 W/K, respectively (black solid dots in Figure 7), where the temperature is the difference of temperature between the evaporator and condenser. These thermopiles have a 0.089 m diameter.

Figure 7. Total installed thermopile performance (*vertical axis*) for different fin areas ranging from 0.9 m² to 44.6 m² and for a varying wind speed (E. Long, AFI, pers. comm., 2006). The *black solid dot* represents the total performance used for the AFI thermopiles in this study.

At McMurdo Station, there are existing single-phase thermopiles (also referred to as freeze cells and hereafter referred to as the McMurdo piles) that have been used to cool the sea ice. The McMurdo piles are 12.2 and 15.4 m long with a diameter of 0.089 m. No fins are attached to these piles, and glycol is used as the coolant, suggesting that they would not be as efficient as the AFI thermopiles (smaller cooling area and a lower heat transfer rate of the coolant). These units have a high internal friction to overcome before heat transfer will take place, resulting in a lower cooling

capacity. There are currently no measurements of the performance of the McMurdo piles. With a 0.089 m diameter pipe, a 12.2 m long freeze cell yields 3.2 m of the pile above the sea-ice surface when 9 m is buried in the sea ice and seawater. This results in an area of 0.89 m² above the sea ice. The area is 13.7% of the AFI 6.5 m² unit. Therefore, we used in the two-dimensional (2-D) simulations of this study an approximated performance for the McMurdo piles of a tenth of the AFI units.

2.2 Physical parameters

2.2.1 Meteorological parameters

The annual temperature profile in McMurdo makes thermopile application remarkably attractive. Figure 8 shows the temperature record from the meteorology office at McMurdo from 2001 to 2010 and the balloon inflation facility at McMurdo from 2010 to 2019. The temperature record from these stations follows the same trend. In our 3-D simulations, we applied both average and maximum air temperatures; Figure 9 illustrates the difference between the two.

Figure 8. Air temperature at McMurdo from January 2001 through September 2019: (a) McMurdo meteorology office air temperatures from 2001 to 2010 (blue), and McMurdo balloon inflation facility air temperatures from 2010 to 2019 (red). In (b) the meteorology office maximum 5-day average air temperatures (green) have been added to the 2010 air temperatures.

1990). Most sea-ice models use the Maykut and Untersteiner (1971) model for thermal conductivity:

$$k = 2.03 + 0.117S/\theta \text{ [W/mK]},$$

where S is sea-ice bulk salinity (ppt) and θ is the temperature in degrees Celsius. For simplification, our study used a constant estimate of 2.03 W/mK for the thermal conductivity (Fichefet and Maqueda 1997) and a sea-ice density of 917 kg/m³ (Pringle et al. 2007).

2.2.3 Seawater properties

In the summer, the seawater flow is a counterclockwise gyro south to southeast offshore of the Station (Barry 1994). Between 1991 and 1993, net transport in the austral summer was between 1 to 2 cm/s. Water-current measurements by Raytheon (1983) showed that the current in WQB is practically stagnant. In a water- and wastewater-quality monitoring study at McMurdo Station, Crockett (1997) found unvarying water temperatures of -1.9°C both vertically and among measured sites. Tides range from 0.1 to 1 m through a 13-day cycle. In 2002, Pringle et al. (2007) measured similar water temperatures (-1.85°C) in McMurdo Sound. Ocean temperatures of approximately -1.9°C represent the local freezing point for typical salinities. Our study used a seawater density of 1026 kg/m³ and a thermal conductivity of 0.56 W/mK.

2.3 Model setup

For our modeling effort, we used SVHeat, which is a part of the SVOOffice 5GE suite produced by SoilVision Systems Inc. of Saskatoon, Saskatchewan, Canada. The simulations used a daily time step, and the total length of the simulations varied depending on the output needed. For example, the calibration simulations were performed for a total of 15 years (5475 time steps), and some 3-D simulations were performed for only 30 days (30 time steps). A total depth of 20 m was applied to the 2-D simulations (Figure 11). To allow for more efficient simulation times to maximize CPU usage (process times), the model width was varied depending on the thermopile spacing. For the simulations with a thermopile spacing of 1.5 m, the total model width was 16.5 m; and for simulation with a doubled thermopile spacing (3 m), the total model width was 22 m.

Figure 11. A 2-D model setup for a simulation (a) without thermopiles and (b) with thermopiles.

For the top boundary, air temperature and a snow-depth layer were applied to the model boundary condition (Figure 11). The snow depth on the sea ice varies from 0.02 m to 0.60 m (Paige and Lee 1967). As a simplification, the model used a constant snow depth with an average snow density of 300 kg/m³. For this snow density, Sturm et al. (1997) reported a thermal conductivity of 0.2 W/mK, so this is also what was applied in this study. For multiyear ice, we know that sea-ice thickness at the mouth of WQB is about 9 m after 15 years*. At the beginning of the study, we performed a calibration and sensitivity analysis to determine a snow-depth thickness that would yield a sea-ice thickness of 9 m after 15 years. The total snow depths applied in several scenarios were varied with a 0.10 m increment from 0.10 to 0.40 m. A constant temperature of -1.9°C was used for the bottom boundary. No-flow boundaries were applied to the vertical boundaries.

The general shape of the 3-D model was a 6 m wide wedge extending in depth (from 6 m at the bottomfast-ice edge to 15 m seaward) with existing bottomfast ice ($y = 0$ m to $y = 10$ m) and seawater ($y = 10$ m to $y = 50$ m) as shown in Figure 12. To decrease the computer processing time, we selected a 6 m width for the model. This width also eliminated edge effects. The same boundary conditions that were applied in the 2-D models were used for the 3-D models, also. Because all 3-D simulations started in the

* From 2002 to 2005, 4-year-old (1998–2002) sea ice fast to the McMurdo Ice Shelf was trapped in southern McMurdo Sound by the presence of iceberg B-15 more than 50 km north. It was not until 2011 that this multiyear sea ice broke free. Measurements of ice thickness at that time were over 8 m. We selected 9 m thickness over 15 years for calibration since it represented an established growth rate and a long time period over which any errors in the model would accumulate and become obvious.

winter, the only difference from the 2-D simulation was that a 1 m sea-ice layer was applied for all simulation starting times.

Figure 12. A 3-D Model setup.

We simulated thermopiles aligned in rows (two rows or four rows) at a 1.5 m distance between thermopiles. The thermopiles were offset 0.75 m for each row as indicated in Figure 4a. The depth at the bottomfast-ice edge ($y = 10$ m) was simulated at 6 m. During the first simulation, the evaporator extended the full water depth, which resulted in an effective evaporator length of 6 m being used in all simulations. After 30 days (30 time steps), we evaluated the model output to determine if freezing-to-closure had been completed. If freezing was complete, the thermopiles were moved in the seaward direction and a new simulation was started with a thermopile advancement distance of 1.5 m (in the y -direction in Figure 12). The starting temperatures of this new simulation were the temperatures from the end of the prior simulation. For the simulations where freezing-to-closure was not yet complete, the simulations were continued until they were. For example, a two-row (2R) simulation started with one row (four thermopiles) located at $y = 10$ m (with the bottomfast-ice edge ending at 10 m) and the second row (three thermopiles) with a thermopile offset of 0.75 m at $y = 11.5$ m. The setup of the next simulation was with one row of thermopiles at $y = 13$ m and one row at 14.5 m. A total of fourteen simulations was completed for each 2R scenarios and seven simulations for the four-row (4R) scenarios.

2.4 Model scenarios

Our study ran model scenarios with and without thermopiles. The total calculated sea-ice thickness in the simulations without thermopiles became a validation dataset for this study.

This report discusses fifteen 2-D scenarios and details them in Table 1. Simulations were carried out for 15 years with most scenarios starting 1 July. Only one scenario started in the middle of the austral summer (1 January).

Nine 3-D scenarios were simulated until a total width of 40 m (seaward from the bottomfast-ice edge) was completed. Table 2 details these scenarios. Six scenarios simulated two rows of thermopiles, and the remaining three scenarios simulated four rows of thermopiles. The start date of the simulations varied from early July (Jul) and late February (Feb). We also investigated the difference in freezing between the maximum (Max) and average (Ave) air temperatures and investigated two different fin areas (6.5 and 15.8 m²).

Table 1. Parameters for each 2-D simulation scenario. The AFI thermopile total performance (Fig. 7) was applied in all thermopile (TP) simulations except for the simulations noted “Low.” The total estimated “McMurdo” thermopile (freezing cells) performance was applied in those simulations.

Scenario	Snow Depth, SD (m)	Number of Thermopiles	Thermopile Spacing (m)	Evaporator Length (E, m)	Total Performance (W/°C)
1: Natural Freezing	0.1	None	N/A	N/A	N/A
2: Natural Freezing	0.2	None	N/A	N/A	N/A
3: Natural Freezing	0.3	None	N/A	N/A	N/A
4: Natural Freezing	0.4	None	N/A	N/A	N/A
5: TP ^a SD 0.1 m	0.1	6	1.5	9	117.4
6: TP ^a SD 0.2 m	0.2	6	1.5	9	117.4
7: TP ^a SD 0.3 m	0.3	6	1.5	9	117.4
8: TP ^a SD 0.4 m	0.4	6	1.5	9	117.4
9: TP ^a 2 m	0.1	6	2.0	9	117.4
10: TP ^a 3 m	0.1	6	3.0	9	117.4
11: TP Low ^b	0.1	6	1.5	9	11.74
12: TP Low ^b 2 m	0.1	6	2.0	9	11.74
13: TP Low ^b 3 m	0.1	6	3.0	9	11.74
14: TP ^a EL ^c Half	0.1	6	1.5	4.5	117.4
15: TP ^a Jan Start ^d	0.1	6	1.5	9	117.4

^a AFI thermopiles.

^b McMurdo thermopiles.

^c EL = evaporator length.

^d This simulation started 1 January with a sea-ice thickness of 2 m. All other simulations started 1 July with a sea-ice thickness of 1 m.

Table 2. Parameters for each 3-D simulation scenario.

Scenario	Start Date	Temperature	Total Performance (W/°C)	Fin size (m ²)
2R 70 ^a Jul Max	Jul	Max	117.4	6.5
2R 70 Feb Max	Feb	Max	117.4	6.5
2R 70 Feb Ave	Feb	Ave	117.4	6.5
2R 170 ^b Jul Max	Jul	Max	285.1	15.8
2R 170 Feb Max	Feb	Max	285.1	15.8
2R 170 Feb Ave	Feb	Ave	285.1	15.8
4R 70 Jul Max	Jul	Max	117.4	6.5
4R 170 Feb Max	Feb	Max	285.1	15.8
4R 170 Feb Ave	Feb	Ave	285.1	15.8

^a This scenario is called “70” because it uses a 70 ft² (6.5 m²) fin size, which is one of the commonly used fin sizes.

^b This scenario is called “170” because it uses a 170 ft² (15.8 m²) fin size, which is one of the commonly used fin sizes.

3 Model Results

3.1 Natural vs. artificial freezing of the seawater

During calibration, several snow depths (0.1, 0.2, 0.3, and 0.4 m) were applied to the upper boundary condition (Scenarios 1–4, Table 1). The sea-ice surface temperature was about 6°C colder for the 0.1 m snow-depth scenario compared to the 0.4 m scenario (Figure 13). At depth, this difference was slightly less where, for example at a depth of 1 m, the difference was only 2.5°C. As discussed in Section 2.3, our calibration was directed by achieving a sea-ice thickness of 9 m after 15 years. The 0.1 m scenario reached a sea-ice thickness of about 7.5 m after 15 years (Figure 13). A greater sea-ice depth could be refined further by changing the snow thermal conductivity and snow-depth thickness.

When comparing the natural freezing with artificial freezing (Scenarios 5–8), artificial freezing causes a much deeper freeze (Figure 14). In 15 years, the freezing is 18 m; and at deeper depths (>6 m), almost no difference between the 0.1 m and 0.4 m snow depth is seen. The remaining simulations used a snow depth of 0.1 m, the scenario that reached a sea-ice depth of 7.5 m.

Figure 13. Temperatures at several depths for a snow-depth (*SD*) simulation of 0.1 m (*upper*) and 0.4 m (*lower*).

Figure 14. Temperatures at varying depths (2, 3, 6, and 9 m) for 15-year scenarios without thermopiles (*left*) and with thermopiles (*right*) with a spacing of 1.5 m and where the top boundary condition includes a varying snow-depth cover of 0.1 m (*black*), 0.2 m (*red*), 0.3 m (*green*), and 0.4 m (*blue*).

3.2 Frozen sea-ice barrier

3.2.1 Thermopile spacing and total thermopile performance

Thermopile spacing greatly affects the rate and depth of freezing. We investigated this by simulating different thermopile spacings of 1.5, 2, and 3 m (Scenarios 5, 9, and 10). For a 1.5 m thermopile spacing, it takes 21 days for the seawater to freeze to a depth of 2 m (Figure 15). In comparison, it takes 33 days for a thermopile spacing of 2 m and 53 days for a thermopile spacing of 3 m. At a depth of 9 m, this difference in freezing time for a 2 m thermopile spacing is almost 2 months (57 days); and for a 3 m thermopile spacing, the difference in freezing time is almost 3 months (114 days) compared to about a month for the 1.5 m thermopile spacing

(32 days). After two years, the freezing rate difference between the thermopile spacing scenarios is almost negligible.

Figure 15. Temperature response at varying depths (2, 3, 6, and 9 m) for 2-year scenarios with different thermopile spacing (1.5, 2, and 3 m) and different thermopile performance (P = Average and P = Low). As a comparison between the artificial freezing and natural freezing, the “no thermopile” scenario at each specified depth is shown as a reference (*turquoise*).

The difference in freezing is also greatly affected by the total performance of the thermopile. We investigated this by comparing the AFI thermopile performance simulations (Scenarios 5, 9, and 10) to the lower performing McMurdo piles (Scenarios 11–13). At a depth of 2 m, the AFI thermopiles (spacing of 1.5 m) freeze 41 days faster than the McMurdo piles. For a thermopile spacing of 3 m, this difference is 68 days. At a depth of 9 m, the difference between the time to freeze for the AFI and McMurdo piles is even bigger—the AFI thermopiles freeze seawater about 10 months (297 days) faster than the McMurdo piles. At a spacing of 3 m, the difference between the two thermopiles is close to 2 years (671 days).

3.2.2 Evaporator length scenarios for 2-D frozen barrier scenario

The 2-D scenarios investigated two evaporator lengths: 9 m, the length used for most scenarios, and half this length (4.5 m) (Scenario 14). Figure 16 compares the two evaporator lengths (Scenarios 5 and 14). There is not much temperature difference between the two evaporator lengths at shallow depths (down to about 4 m), but by 5 m (not shown), a temperature difference of about 6.2°C (colder for the 9 m evaporator length) is seen after 1 year. At this time, the 4.5 m evaporator length scenario freezes down to only about 6.5 m, and the 9 m evaporator length scenario freezes 5 m

deeper (11.5 m). Both evaporators yield a freezing bulb of about 2 to 2.5 m below the bottom of the evaporator.

Figure 16. Temperature response at varying depths (2, 3, 6, and 9 m) for 1-year scenarios with different evaporator (E) lengths (4.5 and 9 m) and a thermopile spacing of 1.5 m. As a comparison between the artificial and natural freezing scenarios, each depth includes the “no thermopile” scenario (Scenario 1).

3.2.3 Installation timing

This study started most scenarios on 1 July to maximize the cold air temperatures during the austral winter. In one scenario (Scenario 15), we started the simulation on 1 January to take advantage of the thickest sea ice (about 2 m). Installation timing was crucial in the first year of simulation; but by Year 2, the two different start dates yield similar temperatures (Figure 17).

Figure 17. Simulation scenarios with a thermopile spacing of 1.5 m and a starting date of 1 July (day 1) and 1 January (day 185).

At shallow depths (2 m), freezing takes place 20 days after the installation (20 July); and at a depth of 9 m, the freezing takes place about a month after the simulation starts (33 days). For the austral summer simulation, it takes 48 days to freezing (17 February) at a depth of 2 m; and at a deeper depth (9 m), freezing takes about 3 months (94 days).

3.2.4 Freezing-to-closure

For the AFI thermopile simulations (Scenarios 5, 9 and 10), freezing-to-closure to a depth of 8 m occurs at about the same time throughout the length of the evaporator (Figure 18). At a depth of 9 m, freezing-to-closure for the 1.5 m spaced AFI thermopile takes place at 32 days and for the 3 m thermopile spacing at 114 days. There is a greater variance in freezing time by depth for the lower-performance (McMurdo piles) scenarios (Scenarios 11–13). Here, the freezing-to-closure occurs after almost a year (328 days) for the 1.5 m spaced thermopile scenario and slightly more than two years (786 days) for the 3 m spaced thermopile scenario. The freezing-to-closure for the thermopile spacing scenarios also varies more with McMurdo piles compared to the AFI scenarios.

Figure 18. Time to closure (freezing) of simulation scenarios with different thermopile spacing (1.5, 2, and 3 m), evaporator length (E), and different thermopile performance (P = Average and P = Low). The solid gray field indicates the desired depth of the ice pier (9 m).

3.3 Ice-pier extension

For our nine 3-D scenarios, we estimated the time to freezing fronts at 10, 20, and 40 m seaward from the existing bottomfast-ice face. Our results indicate that using AFI thermopiles, the 40 m ice pier would be completed after approximately 255* to 820† days (see Figure 19). Figure 20 illustrates the advancing freezing front at different distances from the current bottomfast-ice edge (10, 20, and 40 m) using four 1.5 m spaced higher-performing thermopiles at three different time steps for the “4R 170 Feb Ave” simulation (Table 2).

Figure 19. Time to freezing fronts at 10 m (*blue*), 20 m (*red*), and 40 m (*black*) for the 3-D scenarios (see Table 2) with 1.5 m spaced AFI thermopiles.

* February start with four 1.5 m spaced higher-performing thermopile rows and average expected McMurdo air temperatures.

† February start with two 1.5 m spaced lower-performing thermopile rows and the highest expected McMurdo temperatures.

Figure 20. Freezing front for the 4R scenario where 1.5 m spaced thermopiles with a fin size of 15.8 m² were used and an average air temperature boundary condition was applied (4R 170 Feb Ave). The simulation steps shown are (a) 90 days, (b) 155 days, and (c) 245 days.

4 Economic Considerations

Using the concept outlined earlier in this report and the model outputs, we can estimate the time and resources likely required to construct the envisioned bottomfast-ice extension that would allow direct ship docking at McMurdo. Table 3 provides an AFI thermopile cost estimate for the scenarios with two and four rows to freeze a 140 m by 40 m bottomfast-ice extension. This estimate was based on a current cost (2019 U.S. dollars) of \$3,120 for a 0.089 m pipe evaporator with a 12 m working length (fin size = 6.5 m²) and \$4,396 for the same size pipe evaporator with a 21 m working length (fin size = 15.8 m²).

Table 3. Cost and performance of selected thermopile installation scenarios. Three scenarios assume average McMurdo temperature conditions and February installation of AFI thermopiles. One scenario assumes maximum McMurdo temperature conditions.

Fin size (m ²)	Number of Rows	Number of Thermopiles	Capital Cost (2019 U.S. dollars)	Approximate Days to Produce Bottomfast-Ice Extension
6.5	2	187	582,400	580
15.8	2	187	820,587	550
6.5	4	373	1,164,800	455 ^a
15.8	4	373	1,641,173	255

^a Maximum McMurdo temperature conditions with a start date of July applied.

Not surprisingly, the 4R scenarios have double the capital cost of a 2R configuration. The benefit for a 4R setup is that the bottomfast-ice extension can be completed within a year (Table 3). This is very attractive since it would allow thermopiles to be installed shortly after the conclusion of one season's vessel resupply operations from a traditional ice pier and have the next season's resupply take place from a completed extended bottomfast-ice edge. This would lessen the conflict between thermopiles and ship operations that would occur with either of the 2R scenarios that require about 18 months to complete (Table 3).

The models do not show a dramatic improvement in freeze-up with a larger condenser for the 2R simulations (Table 3). One reason for this is that the advancement of thermopiles was chosen at a constant 30 day time step (to simplify the modeling effort) rather than at the exact time step of freezing-to-closure. Most of the time, the freezing-to-closure occurred at a faster rate than the 30 day time step for the higher-performing thermo-

piles. It is therefore also possible that the completion of the 40 m bottomfast-ice extension can be completed faster than 255 days for the 4R scenario with a larger-fin-size thermopile (last row in Table 3).

Given the operational advantage of a less-than-12-month construction period, the 4R scenario with a larger-fin-size thermopile in Table 3 is the most attractive. It is possible that the smaller-fin-size thermopile (not simulated) would also fall within the 12 month completion timeframe for an average temperature scenario, making that worth exploring as well. However, if, for the year of actual installation, temperatures are warmer than average (as modeled in the “Max” scenario), the higher-performing thermopile would be a better choice. Other possible solutions to advance the freezing front at a faster rate would be to install thermopiles at a closer spacing or to use an even higher-performing thermopile.

With a capital cost of \$1.6 million, this bottomfast-ice extension configuration compares very favorably with a recent study of McMurdo vessel resupply infrastructure options (R&M Consultants and Glosten 2017). That analysis used the current ice pier as its baseline, and assigned it a capital cost of \$2.2 million. The baseline was compared to a sheet pile bulkhead (\$22.9 million capital cost), a platform dock (\$34.3 million), a barge-based floating dock (\$36.7 million), and a modular floating dock (\$17.2 million).

The R&M Consultants and Glosten (2017) study also identified annual maintenance costs for each option; they ranged from \$1.5 million for the existing ice pier to \$10.1 million for the barge-based floating dock if it needed to be towed to a wintering site every season. While we have not estimated annual maintenance costs for the thermopile-generated bottomfast-ice wharf extension, it will certainly not be zero. We expect that close monitoring of the base and face of the bottomfast-ice extension will be required each year and that thermopiles will need to be installed occasionally along the borders (and perhaps at “hot spots” internally) to preserve and mitigate erosion of the extended bottomfast-ice edge. An initial estimate at annual costs might be the same as currently assumed for the ice pier (\$1.5 million) but could be less. Certainly, over time, the ongoing maintenance for the extended ice wharf will provide a resupply platform that avoids the periodic complete rebuilding now experienced unpredictably with the ice pier (Figure 3), which eliminates the estimated capital cost of pier rebuilding (\$2.2 million).

Further, as stated at the outset of this report, an extended bottomfast-ice ship-docking facility would significantly reduce the overall risk to resupply and shipping operations. Such an infrastructure change removes the single-point failure present with the floating ice pier and its Baily bridge connection to Ross Island. The economic impact of this risk reduction cannot easily be calculated but is certainly real.

5 Conclusions and Recommendations

5.1 Conclusions

The main objective of this work was to determine the feasibility of using thermopiles to artificially freeze seawater in WQB to secure the ice wharf. We modeled different configurations of thermopiles, varying spacing between thermopiles, total thermopile performance, evaporator length, and timing of installation.

Overall, our results indicate that using thermopiles to artificially freeze the seawater at WQB has the potential to create a much more reliable and robust ship docking and loading platform. It is a feasible concept where freezing-to-closure to a depth of 9 m could be achieved in about a month for each 1.5 m wide vertical slab of bottomfast ice if installed on 1 July with an initial sea-ice thickness of 1 m. From our selected scenarios, a 40 m seaward extension of the existing bottomfast-ice wharf would be completed in 255 to 820 days. The timing of freezing-to-closure depends significantly on the total performance of the thermopile and the spacing between the thermopiles. It is also dependent on the number of rows of thermopiles, where multiple rows will complete the ice pier at a faster rate, albeit resulting in a greater capital cost. These results depend heavily on modeling-parameter assumptions but serve as a preliminary feasibility study of successfully using thermopiles for reducing the level of risk to McMurdo resupply associated with the current ice-pier infrastructure. The total capital cost of the solution we recommend (four rows of 15.8 m² fin area AFI thermopiles spaced 1.5 m apart) is \$1.6 million. This cost is about 70% of the estimate for constructing a traditional ephemeral ice pier and only 4% of the most costly alternative considered in a recent study of resupply infrastructure solutions (R&M Consultants and Glosten 2017).

5.2 Recommendations

We believe this study shows that creating and sustaining a bottomfast-ice edge capable of directly supporting ship offloading at McMurdo will be less costly than the current construction and maintenance of an ice pier and Bailey bridge and other alternative infrastructure solutions. Further, we believe that such an off-load wharf face will be more predictable and reliable than the current situation.

Using thermopiles to artificially freeze seawater has not yet been carried out in a laboratory or natural environment. Therefore, we have a limited number of validation datasets available for this modeling effort. The only validation of the conceptual model available was the sea-ice thickness as referenced by McFeters et al. (1993) and an estimated multiyear ice thickness of about 9 m in 15 years. Our study used these assumptions for the seawater freezing scenario and yielded reasonable results of sea-ice thickness after 15 years of simulation.

Since no direct validation data sets exist, we recommend performing laboratory simulations for artificial freezing using thermopiles in a seawater environment. In addition, the total performance of the McMurdo thermopiles (freezing cells) has not been tested. We therefore recommend testing their performance if they are to be considered for the extending bottomfast ice. For future modeling efforts, we recommend performing laboratory studies artificially freezing seawater with thermopiles. Recommended testing for a more precise artificial seawater freezing model would include varying several parameters:

- Air temperature
- Wind velocity
- Evaporator length of thermopiles
- Fin areas of thermopiles
- Hybrid thermopiles

These parameters could be tested in a deep standing tank with several different-size thermopiles. Testing for the wave and tide effects would be more difficult to do in a laboratory environment. Therefore, testing this in a natural environment would be preferable.

This study has shown that thermopiles are a potential way forward for securing the ice wharf at WQB. The ideal test would be in the actual physical environment in Antarctica. This study demonstrates that for the McMurdo WQB setting, commercially available thermopiles can significantly accelerate natural freezing to achieve thick sea ice. Therefore, applying this technology at WQB has the potential to reduce the cost of McMurdo resupply and greatly reduce the risk associated with an ice pier failure.

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