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Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Using Firn Air for Facility Cooling at the WAIS Divide Site

Jason Weale, Mary Albert, and Gary Phetteplace

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Abstract

The National Science Foundation's United States Antarctic Program (USAP) is constantly striving to introduce materials and methods that will increase efficiency and reduce costs of their logistics and operations activities. Heating and cooling air in the polar regions consumes a high percentage of available energy resources. Polar firn contains a large natural repository of cold air, and accessing this cooling capacity could save fuel and reduce logistics costs at remote field camps where it is critical to maintain proper temperatures to preserve sensitive deep ice cores.

We assessed the feasibility of using firn air for cooling at the West Antarctic Ice Sheet (WAIS) Divide ice core drilling site as a means to adequately and efficiently refrigerate ice cores during storage and processing. We used estimates of mean annual temperature, temperature variations, and firn permeability measured at adjacent sites in West Antarctica to predict firn air cooling efficiencies. With a coefficient of performance (COP) of 5.9, the most conservative scenarios indicated cooling with firn air at the WAIS Divide site is almost twice as efficient as with conventional systems (COP 2.5). This report recommends conducting tests at the WAIS Divide site to verify our estimates of physical properties and cooling efficiency to properly design a full-scale cooling system.

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Preface

This study was conducted for the National Science Foundation (NSF), Division of Polar Programs (PLR), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-07-16, “Firn Air Cooling at WAIS Divide.” The technical monitor was George Blaisdell, Chief Program Manager, NSF-PLR, U.S. Antarctic Program.

The work was performed by Jason Weale and Dr. Gary Phetteplace (Force Projection and Sustainment Branch, Dr. Edel Cortez, Chief) and Dr. Mary Albert (Terrestrial and Cryospheric Sciences Branch, Dr. John Weatherly, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Janet Hardy was the program manager for EPOLAR. Dr. Justin Berman was Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

COL Jeffrey R. Eckstein was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	Coefficient of Performance
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics and Research
ERDC	Engineer Research and Development Center
ICDS	Ice Coring and Drilling Services
ITASE	International Trans-Antarctic Science Expedition
NICL	National Ice core Laboratory
NSF	National Science Foundation
PLR	Division of Polar Programs
USAP	United States Antarctic Program
WAIS	West Antarctic Ice Sheet

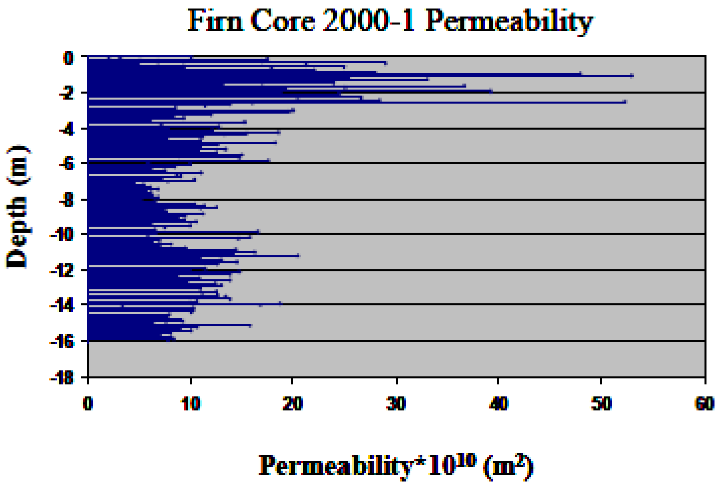
1 Introduction

Polar firn contains a large natural repository of air. At cold polar sites with little or no melt, the firn as a whole is much more permeable than any soil or sand and is amenable to pumping of interstitial air for possible use in cooling. Yen and Bender (1962) documented efforts to cool an under-snow structure at Camp Century, Greenland, making the first attempts at using the firn for cooling. They found that the cold air could provide a local cooling effect for the structure, but they stopped short of quantitative recommendations. During the construction of the under-snow Byrd camp, Mellor and Hendrickson (1965) noted in rooms of the camp unexpected drafts and sublimation from interstitial firn air movement coming from the walls of firn. These field endeavors show that there is hope for using cold firn air for cooling in camp operations. However, there is not a paradigm for designing a cooling system using firn air. Therefore, this report assesses the feasibility of using firn air for cooling at the West Antarctic Ice Sheet (WAIS) Divide ice core drilling site. USAP hopes that cold firn air can adequately refrigerate ice cores during storage and processing so that expensive fuel will not be required to generate power to run mechanical chillers at the drill site.

2 Firn Permeability

The intrinsic permeability of a porous medium is a measure of the ease or difficulty of moving interstitial fluid due to pressure differences and is a reasonable bulk indicator of the nature of the interconnected pore space. Our measurements from the International Trans-Antarctic Science Expedition (ITASE) in West Antarctica show that the firn exhibits large site-to-site differences in the permeability profile with depth; also at any given site, the firn permeability varies with depth due to layering and temporal variations in climate (snow, wind, etc.) that results in climate bands (Rick and Albert 2004a, 2004b). The ITASE 00-1 site (111°14′ W, 79°23′ S) (temperature: –31°C; accumulation: 22 cm/year water equivalent) is the site closest to the WAIS Divide site for which we have permeability measurements. Figure 1 shows the permeability profile for the 00-1 site. The profile was obtained from measurements taken along a core drilled with an electromechanical drill and shipped to the Cold Regions Research and Engineering Laboratory (CRREL) for analysis. We measured permeability using a custom-made "permeameter" (Albert et al. 2000) based on the double-head sampling design of Shimizu (1970) in which paired pressure and flow rates are measured; and permeability is then determined using Darcy's law, assuming linear flow throughout the sample.

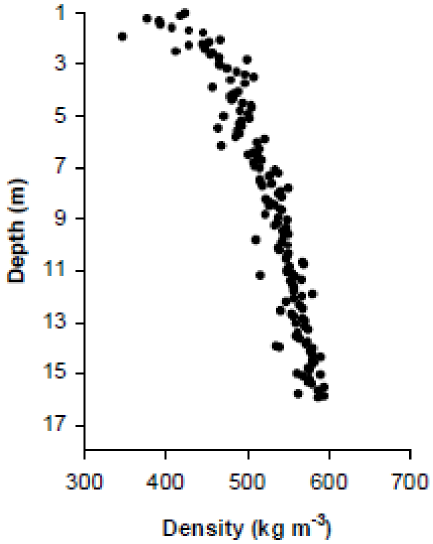
Figure 1. Measured permeability in the top 16 m of firn on December 2000 at 111°14′ W, 79°23′ S, a site not far from the WAIS Divide site in West Antarctica (Rick and Albert 2004a, 2004b).



The firn is very permeable to a depth of at least 16 m. It is least permeable in the top meter, and is most permeable in the several meters below the top meter. Usually, the windpack at the snow surface is fine-grained and has a lower permeability than the underlying firn from the preceding year or two, which typically has increased permeability due to crystal metamorphism from near-surface temperature gradients. Permeability below the top several meters is generally expected to decrease due to compaction but occasionally has bands of increased subsurface permeability, which are due to years with relatively lower snow accumulation compared to the years above it. At this site, the microstructure in the region between approximately the 7 to 10 m depth revealed smaller crystals and lower permeability due to a higher accumulation rate at that site during the El Nino years in the early 1990s (Rick and Albert 2004b). Bands of buried high-permeability layers will be beneficial to locate when choosing specific depths for withdrawing air from the firn because it requires less power to draw air from high permeability bands. Note that the core shown in Figure 1 was drilled in 2000. If the accumulation rate has been constant since that time, we would expect that 6 years after the measurements were made that the high-permeability region in the plot between approximately 11 to 14 m depth would be reduced due to compaction and also would be located about 132 cm deeper in the firn because of snow accumulation. It would help the design of the cooling system for WAIS Divide to know what the permeability profile in the firn is at the time and site of installation as the permeability has a first-order effect on pumping air out of the firn.

The measured density of the same firn whose permeability appears in Figure 1 is shown in Figure 2. It follows the familiar increase with depth, and the standard deviation of density is more variable in the near surface than deeper in the firn.

Figure 2. Measured density in the top 16 m of firn in December 2000 at 111°14′ W, 79°23′ S, (Rick and Albert 2004a, 2004b). These density measurements were made on the same samples as the permeability measurements shown in Figure 1.



3 Estimated Temperature Profile in the Firn

The temperature profile in the firn at the WAIS Divide site has not been measured and, therefore, is unknown. The mean annual surface temperature at the site is estimated to be −31°C (Morse et al. 2002). As an estimate of the temperature distribution in the firn at the future drilling site, we solve the heat conduction equation, assuming that the surface temperature varies sinusoidally through the year, oscillating about the mean annual temperature of −31°C. The diffusion equation is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}. \tag{1}$$

Here, T is the firn temperature; and t is time. In the absence of measurements of thermal conductivity and density at the WAIS Divide site, to determine the temperature profile, we assume that the thermal diffusivity, α, is spatially and temporally uniform in the firn. The thermal diffusivity is the ratio of the thermal conductivity to the heat capacity,

$$\alpha = \frac{k}{\rho C_p}, \tag{2}$$

where k is the thermal conductivity of the firn, ρ is the firn density, and C_p is the volumetric heat capacity.

We define the sinusoidally-varying surface temperature to be

$$T = T_a \cos(\frac{2\pi p}{p}) \tag{3}$$

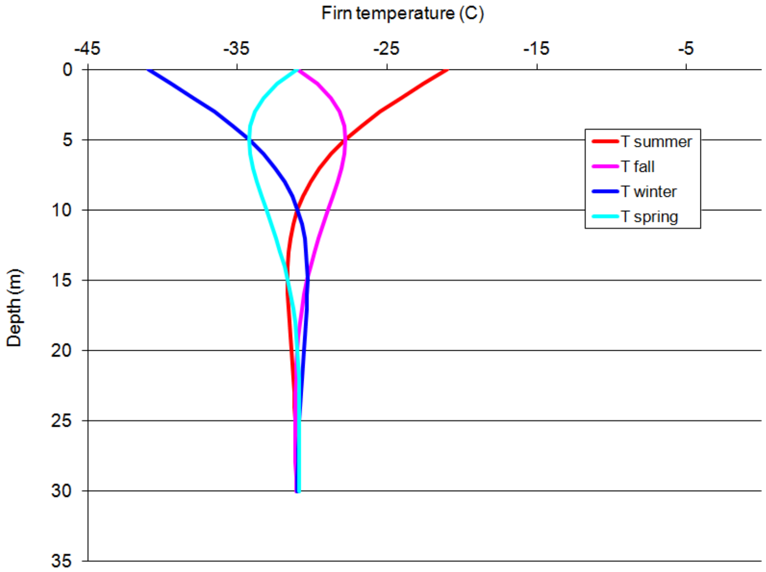
where T_a is the amplitude of the surface temperature change and p is the period. The solution to equations (1) and (3) is determined by using separation of variables. The result is

$$T = T_S + T_a \exp[-(\frac{\pi}{p\alpha})z] \cdot \cos[\frac{2\pi t}{p} - \sqrt{\frac{\pi}{p\alpha}} z]. \tag{4}$$

At $z = 0$ (surface), time starts at $t = 0$ when $T = T_s$, the warmest day of the year. To estimate the amplitude of the surface temperature oscillation about the mean, we used the measured temperatures at Byrd Station

(Shuman and Stearns 2001), which show a 10°C amplitude swing about the mean at that station. These data were the most recent and closest available for comparison to the WAIS divide. Therefore, we take $T_a = 10°C$. Figure 3 shows the theoretical temperature distribution in the firn on the warmest (summer) and coldest (winter) days of the year and in the spring and fall.

Figure 3. Theoretical temperature distributions in the firn for several times of year. We assumed the following values for these calculations: firn density = 450 kg/m^3, thermal conductivity = 0.17 W/m-K, $T_s = -31°C$, and $T_a = 10°C$.



The near-surface temperature profile (approximately 0–3 m) exhibits a 20°C shift between the summer and winter. The drilling at the WAIS Divide site will occur November through January, the warmest part of the year. To maintain a cooled room at temperatures of −20°C or lower for three to four months, we seek a large reservoir of cold firn air. Below approximately 11 m in the firn, we predict it to be between −29.5 and −32.5°C at any time of year. At 25 m depth, the temperature varies by less than half a degree over the year. Permeability measurements with depth at nine different sites in West Antarctica have shown that the permeability is usually significantly lower at 25 m than at 11 m, so the trade-off for colder air is a greater power requirement to reach it. Our preliminary calculations simulating the air flow and temperature distribution through an inlet pipe indicate that withdrawing air at 12 m does not significantly alter the natural temperature distribution in the firn more than a degree or two over a time span of several months. We will be conducting sensitivity investigations to try to put bounds on the effects.

Note that the thermal conductivity, density, and amplitude of the annual temperature variation shown in Figure 3 were all assumptions based on data from other sites. The temperature profile is not very sensitive to density but is fairly sensitive to thermal conductivity. If the actual thermal conductivity is higher than our estimate, the depth to constant annual temperature will be deeper than estimated here.

As seen in Figure 3, a smaller reservoir of very cold air (approximately −34°C) may exist in the spring at 5 m depth; however, by the end of summer, the temperature at 5 m is almost −28°C even without induced ventilation. Considering this, one might consider designing two source regions for cold air, with some boreholes at 5 m and others at 11–12 m depth. One could draw air from the 5 m borehole from the start of operations in the spring until the incoming firn air is warmer than −29°C, at which point one switches to drawing air from the 11 m depth. The firn at 5 m is more permeable and so will require less power for firn air removal, and it is nearer to the surface so will be more easily “recharged” with cold temperatures over the winter between drilling seasons. While it may offer opportunities for short term use, the air at a 5 m depth is in a transient zone and so does not offer the more stable supply of cold air that is available deeper in the firn.

4 Configuration

The primary goal of this work is to devise a logistically light, rapidly deployed method of extracting cold air from firn for use in cooling structures associated with ice core drilling. The largest and most stable source of cold air at the site is in the firn at a depth where the annual temperature oscillations are greatly damped, so the firn exists at a relatively constant and cold temperature. From Figure 3, we see that the theoretical temperature is very constant at a 25 m depth. However, because the firn permeability generally decreases with depth on a scale of meters (making it harder to withdraw air the deeper you go in the firn), it is advantageous to find the shallowest depth for which the temperature oscillations are sufficiently small to be acceptable. There will be a trade-off between power needed to pump the air out of the firn and the temperature of the firn air.

Two fast and easy ways to reach colder air in the firn are to drill a vertical hole and to dig a trench. This report investigates the use of vertical holes as it may be easier to reach deep and cold air with holes drilled and reamed than with trenches dug or dozed.

4.1 Calculated firn air flow from vertical boreholes in the firn

The power needed for a fan to withdraw cold air from the firn depends on the permeability of the firn. Because the permeability at the WAIS Divide site is unknown, we conducted calculations using several different permeability profiles: (1) a reasonably likely scenario using permeability measurements from the ITASE 00-1 site, (2) a worst-case scenario using uniformly low permeability values, and (3) the ITASE 00-1 scenario with the addition of the top meter mechanically packed to a very low permeability, such as may be the case very near to some of the buildings to be erected at the site.

Using holes from shallow cores enables a logistically light way to access subsurface cold firn air. The larger the hole, the greater the firn area from which to draw cold air in at depth and also the less the pressure drop in the pipe due to wall resistance to flow; so, larger holes are desirable rather than smaller holes. In order not to lose pressure to the firn at shallower depths than the sampling depth, the hole should be cased by inserting a PVC or other pipe down to the depth of firn air retrieval.

A larger pipe will allow more airflow; but if it is too large, installation becomes a problem. As per discussion with Charlie Bentley of Ice Coring and Drilling Services (ICDS), a 15 m deep hole created with a 10 cm ice-coring barrel typically used in the field can easily be reamed to become a 23 or 30 cm diameter hole. For the current calculations, we assume that the pipe inner diameter is 30 cm. We also assume that an inlet pressure difference of 800 Pa exists in the pipe. A pressure difference this size is achievable using a fan. We should note that the above diameter of the pipe and pressure drop are sample values to examine feasibility of the technique; other values could be chosen.

We ran a multidimensional, finite-element firn air model (Albert et al. 2000) to examine the flow field and flow rates under several different assumed firn permeability profiles and two different pipe inlet treatments (Table 1). In simulations for cases 1, 2, and 3, the deepest meter of the simulated pipe had voids in the pipe wall to act as a manifold to draw air in radially for the last meter, rather than only at the end of the pipe. In simulations for cases 4, 5, and 6, the pipe inlet was taken simply as the cross-section of the end of the pipe. In practice, the bottom meter of such a pipe would be engineered to maintain its strength structurally but would have large mesh or other adaptation to allow the free flow of air through the wall of the pipe in the last meter for increased exposure to the targeted temperature area of firn.

Table 1. Flow field results of the multidimensional, finite-element firn air model.

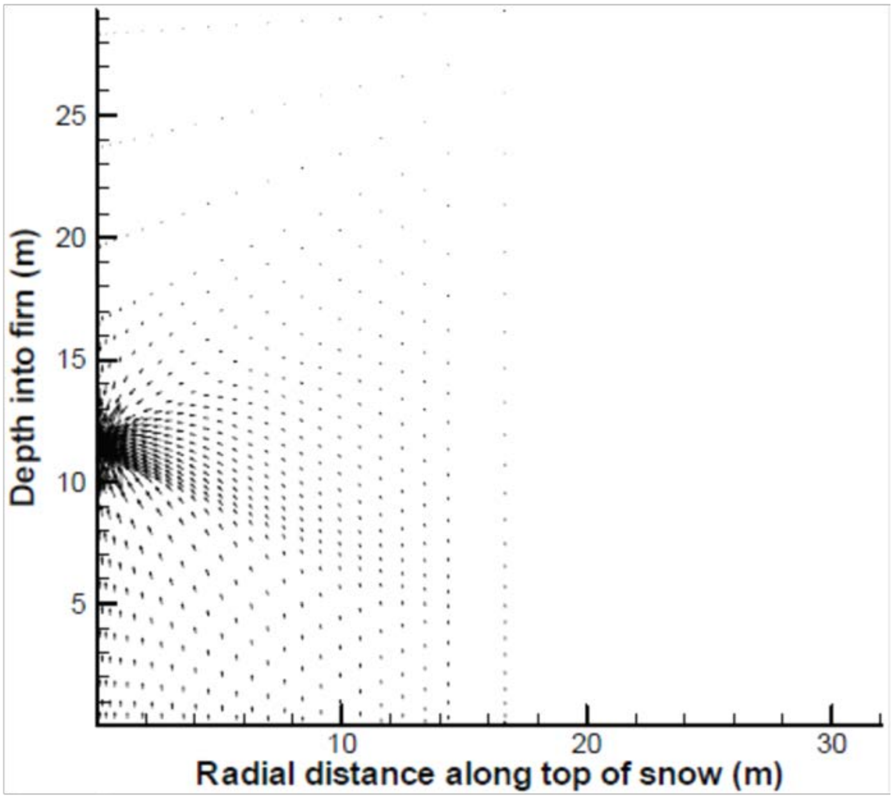
Case ID	Permeability Profile	V_{in} (cm/s)	Nature of Air Inlet in Pipe	Q_{in} (cm^3/s)
1	Uniform and low (10×10^{-10} m^2)	20	Side holes in the deepest meter	188,500
2	Similar to ITASE 00-1 site	25	Side holes in the deepest meter	235,625
3	No. 2 but top 2 m compacted firn	20	Side holes in the deepest meter	188,500
4	Uniform and low (10×10^{-10} m^2)	50	Solid pipe, inlet at end	35,350
5	Similar to ITASE 00-1 site	65	Solid pipe, inlet at end	45,955
6	No. 2 but top 2 m compacted firn	52	Solid pipe, inlet at end	36,057

It is evident that having the last meter of pipe act as a manifold, rather than a simple pipe opening inlet, allows for much greater flow (Q_{in}) due to the larger firn area exposed to the pressure difference.

The calculations are sensitive to the permeability of the firn. The surface permeability of the firn matters as much as the subsurface layering in this case as compacting the top 2 m of firn (to 3×10^{-10} m^2 resulting permeability) at a site with larger subsurface permeabilities (like the ITASE 00-1 site) gives the same or very similar Darcy flow and flux as the uniformly low-permeability profile. For example, cases 4 and 6 yield similar results for the pipe with solid walls, and cases 1 and 3 give similar results for the pipe with holes in the walls of the deepest meter of pipe. In all cases, relatively little contribution to air withdrawn from the firn will come from deeper than a meter or two below the pipe opening in the firn; and so it is unnecessary to drill much deeper than the depth of the cased section of pipe.

The firn most affected by the flow in a lateral distance from the inlet is within the nearest 10 m of the centerline of the pipe, and the induced flow 15 m or more away from the centerline of the pipe is negligible. Hence, if more than one pipe is installed, they should be spaced apart 30 m or more from center to center of the two pipes. Figure 4 shows the flow lines for the pipe with holes in the last meter. Note that the vertical axis, “Depth,” in this case is shown as positive upwards in the plot; this places the surface of the snow at the bottom of the plot.

Figure 4. Air flow vectors into the subsurface manifold. Note that the air–snow interface is at the bottom of the plot due to the coordinate system in this graphing technique. The 30 cm diameter hole is cased with a solid pipe down to 11 m depth and has holes in the pipe between 11 and 12 m to draw air in radially.



4.2 Trenching for firn air retrieval

Another approach that could be used to retrieve firn air, instead of using boreholes, is to use covered but unlined trenches. This would most likely involve using a bulldozer or other machine for moving large masses to dig down as many meters in the firn as possible and then covering the trench with a solid roof that is buried at several meters under the surface snow. Cold air can be piped out of this empty “room.” We have not explored this option in any detail yet, but certainly the geometry and the depth of the trench would be important, with a narrow, long, deep cavity being preferable to maximize wall surface area and to minimize required pumping power.

5 Cooling Performance

Comparing the cooling performance of a firn-based scheme requires that we compute the power necessary per unit of cooling and compare that to the performance that we could expect from conventional mechanical refrigeration. To calculate the power requirements for firn-based cooling, we take the pressure differential required to extract the air from the firn, add an allowance for duct losses (25% in this preliminary analysis) to deliver that air, and then multiply the total pressure differential required by the flow rate to find the required fan power. For the purposes of these calculations, we assumed a combined fan and motor efficiency of 65% in conversion of electrical power into the theoretical fan power calculated as described above.

The gross cooling effect delivered is simply the flow rate multiplied by the enthalpy difference between the conditions of the air required for the National Ice Core Laboratory (NICL) facility at WAIS Divide (required to be –20°C) and the air delivered from the firn. The potential air temperature delivered from the firn was discussed earlier; and for the purposes of the cooling effect calculations, we used a conservative assumption of –28°C. Dependent on the actual configuration of the firn-based cooling system, some portion of the fan energy will ultimately become heat in the very air the system is designed to cool. In keeping with our convention of conservative assumptions, we have assumed that all of the fan power will become heat, which must be removed by the firn-based cooling system because we do not know the final system configuration. Should the system be located away from the area that requires cooling, then the overall system efficiency will improve.

The cooling performance of a conventional cooling system is often expressed as a coefficient of performance, or COP. This criterion is equally valid for the firn-based cooling system. The COP is a dimensionless quantity formed by dividing the net cooling effect by the power consumed. Following the logic outlined above, we have calculated the COP for the firn-based cooling system based on the flow-pressure responses calculated as described earlier; Table 2 below shows these results.

Table 2. Firn-based cooling calculations.

Case ID	Nature of Air Inlet in Pipe	Permeability Profile	Q^{in} (cm^3/s)	Gross Cooling Effect (kW)	Ideal Fan Power (kW)	Fan Power with Combined Efficiency of 65%	Net Cooling Effect (W)
1	Side holes in the deepest meter	Uniform and low (10×10^{-10} m^2)	188,500	1.99	0.189	0.290	1.70
2	Side holes in the deepest meter	Similar to ITASE 00-1 site	235,625	2.49	0.236	0.363	2.13
3	Side holes in the deepest meter	No. 2 but top 2 m compacted firn	188,500	1.99	0.189	0.290	1.70
4	Solid pipe, inlet at end	Uniform and low (10×10^{-10} m^2)	35,350	0.374	0.035	0.054	0.32
5	Solid pipe, inlet at end	Similar to ITASE 00-1 site	45,955	0.486	0.046	0.071	0.42
6	Solid pipe, inlet at end	No. 2 but top 2 m compacted firn	36,057	0.382	0.036	0.055	0.33

For the performance of conventional mechanical cooling systems, we can refer to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2004). If we look at the expected performance based on ASHRAE (2004), Chapter 45, when the source and the sink temperatures are essentially equal, as will be expected for the summer cooling situation in the NICL facility, we expect a cooling COP of approximately 2.5. This result agrees with measured results by Phetteplace et al. (1992).

If we calculate the COP of the firn-based systems based on the results shown in Table 2, we find a COP of 5.9 for each of the alternatives examined. Note the COP is constant across all firn-based alternatives because both the fan power and the cooling effect are linear functions of the flow rate; and, hence, those effects cancel each other in the COP calculation. Thus, based on this preliminary analysis, we expect the firn-based cooling system to achieve much better performance than conventional refrigeration systems and to reduce the energy consumption by a factor of two or more.

6 Conclusions

Based on estimates of mean annual temperature and temperature variations, permeability measured at other sites in West Antarctica, and educated guesses of the thermal conductivity, it is evident that even in worst-case, conservative scenarios, cooling using firn air at the WAIS Divide site will be almost twice as efficient as using a conventional mechanical cooling system, reducing the energy consumption by a factor of two or more.

Because there is no data from the WAIS Divide site on any of the parameters used in the study, we strongly advise conducting a test season in a subsequent winter (1) to measure the permeability, temperature, density, and thermal conductivity from a firn core and (2) to put in a test borehole using simple PVC pipe and an attached fan to measure the pressure drop, flow rate, and temperatures from a single borehole. This will provide quantitative proof of concept and enable rapid deployment of a proven system later that year or early in the following year.

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14. ABSTRACT

The National Science Foundation's United States Antarctic Program (USAP) is constantly striving to introduce materials and methods that will increase efficiency and reduce costs of their logistics and operations activities. Heating and cooling air in the polar regions consumes a high percentage of available energy resources. Polar firn contains a large natural repository of cold air, and accessing this cooling capacity could save fuel and reduce logistics costs at remote field camps where it is critical to maintain proper temperatures to preserve sensitive deep ice cores.

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