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Cold Regions Research and Engineering Laboratory

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Potable Water Supply Feasibility Study for Summit Station, Greenland

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Program

Abstract: This study reviews potable water production methods that may be applicable for use at Summit Station, Greenland. The two methods that are most widely used at polar field sites are melting surface snow and melting subsurface ice to form a well. There are limited published data on the energy usage for melting surface snow. Based on the data obtained from operations at Summit we determined that the basic energy requirement to melt the snow is about 2300 Btu/gal. This method, as currently implemented at Summit, is also a labor-intensive activity; there are opportunities to reduce the labor in this process with a new design of the system. The feasibility of using a subsurface well established in the glacial ice (Rodwell) at Summit was also analyzed. The approximate sustained energy requirement for this would be 30–40,000 Btu/hr, with an initial requirement of 142,000 Btu/hr for start-up. This feasibility study shows that a Rodwell can provide *at least* 10 years of service before it will need to be relocated. The specific energy requirement for this system ranges from 4100–7000 Btu/gal. or 1.8 to 3.0 times higher than the current system of melting surface snow. This study also shows that the Rodwell is more energy efficient when it is designed to supply more water to support a large population.

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Preface

This study was conducted for the National Science Foundation, Office of Polar Programs, Arctic Research Support and Logistics Program under Engineering for Polar Operations, Logistics And Research (EPOLAR) Program. The technical monitor was Jennifer Mercer.

The work was performed by Robert B. Haehnel, Terrestrial & Cryospheric Sciences Branch (CEERD-RR-G), Janet Hardy, Chief; and Margaret A. Knuth, Force Projection & Sustainment Branch (CEERD-RR-H), James Buska, Chief; of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CEERL). At the time of publication, Dr. Justin B. Berman was Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen and the Director was Dr. Robert Davis.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
British thermal units (International Table)	1,055.056	joules
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412×10^{-3}	cubic meters
hectares	1.0×10^{4}	square meters

Executive Summary

This study reviews potable water production methods used in Polar Regions that may be applicable for use at Summit Station, Greenland. The two predominant methods currently in use are melting surface snow and melting subsurface ice to form a well and then extracting the melt water to the surface (a Rodriguez well or Rodwell).

There are limited published data on the energy used for melting surface snow. For this analysis, we rely mainly on the data from the existing Summit Station. The basic energy requirement to melt the snow is about 2300 Btu/gal. This does not include the energy associated with harvesting the snow or transporting the water after it is melted, which is found to be negligible. However, this is also a labor-intensive activity requiring regular use of personnel and heavy equipment. There are opportunities to reduce the labor in this process with a new design of the system (e.g., piping water from the melt tank to the service locations).

The feasibility of using a Rodwell at Summit was also analyzed. In this case, a subsurface well would be established in the glacial ice and melt water from the well would be pumped to the surface for treatment and distribution to point-of-use locations. The approximate sustained energy requirement for this system would be 30–40,000 Btu/hr, with an initial requirement of 142,000 Btu/hr for bulb start-up. These energy requirements are well within the waste heat quantities available at the current Summit Station. This feasibility study shows that a Rodwell can provide *at least* 10 years of service before it will need to be re-located. The specific energy requirement for this system ranges from 4100–7000 Btu/gal. or 1.8 to 3.0 times higher than the current system of melting surface snow. Also that the lower the population is at Summit, the higher the specific energy requirement is for producing water with a Rodwell. In other words, the Rodwell is more energy efficient when it is designed to supply more water. Additional considerations, including manpower to create and maintain the Rodwell, ancillary equipment needed for operation, potential subsurface obstructions and contingency planning, are also briefly discussed.

1 Introduction

Summit Station is a year-round science support facility located on the Greenland ice sheet at an elevation of approximately 10,500 ft. Weather can range from mild in the summer at 32°F (0˚C) with light winds to lower than –100°F (–73˚C) with strong windstorms in the winter. Currently, the population at the station varies widely from winter to summer, going from about 4 station personnel up to 50 support staff and scientists, respectively. On average, based on data from January of 2006–August of 2009, this population uses 15–18 gal. of water per person per day.

There are a variety of buildings at Summit Station. The primary facility, the "Big House" contains a kitchen, dining hall, communications office, and bathroom and laundry facility. Other major facilities include the Greenhouse (laboratory space, bathrooms, lounge, etc.), and the Berthing Module (the main living quarters). There are a variety of other small buildings around station.

Currently, to create potable water at Summit Station, snow is harvested from a designated area on station then driven to the dump location in the shop some 600–800 ft away. The snow is dumped down a chute into the building (Fig. 1) and through a trap door into a tank where waste heat is used to melt the snow before it is piped to treatment (filter and UV). Water is piped to the Green House and is also pumped into a tank on a sled to transport it to a storage tank in the Big House. This system requires extensive manual labor. It is hoped that the new station, dubbed Model 5, which is currently in design stages, will produce potable water via a less labor-intensive means.

Just as important as being less labor-intensive for station personnel, this new design should also be more energy efficient. There are a variety of energy efficiency measures currently being considered to enhance the station before the Model 5 design is complete and extending the waste heat system to the Big House is a main one (Armstrong 2010).

Figure 1. Caterpillar 933, used for snow mining at Summit Station, dumping snow into the chute leading to the melt tank.

The objectives of this study are two-fold. The first is to review the current approaches for providing potable water in Polar Regions. The second is to initially assess the feasibility of these methods for the Model 5 design, including assessing use of a Rodriguez well to serve the potable water needs at Summit.

2 Review of existing methods

As part of this study, a literature survey was done to assess the current state of knowledge for potable water production in Polar Regions. Though over 60 references were found, many did not provide sufficient detail about actual potable water production. Of the remaining methods found, many, such as desalination or reservoir systems, are not feasible at Summit Station. This left approximately 18 relevant references. These are listed in Appendix A.

Twenty-three different station systems were discussed in these references. A listing of data relating to station name, years active, type of system, station population, water production, treatment, transport system to production, transport system once potable, and then any other pertinent information was compiled and is given in Appendix A; unfortunately, for some stations the data are sparse. A summary of these data is provided here. The stations reviewed were active from 1952 to present. The most common way to produce potable water is snow melting, primarily using waste heat; this has been used since the 1950s. It has been used at stations with as few as 8 people and at others with more than 100. As is currently done at Summit Station, these snow melters are most often fed by manual labor, i.e., shovels and dozers. In other cases, the systems have been augmented by strategic placement of the melting tank (as in Halley VI or Princess Elisabeth Station), snowdrift collection (Neumayer Station III), or mechanical dragline (DYE 2 and 3).

Another well-known technique for potable water production is using a Rodriguez well (Schmitt and Rodriguez 1960) or “Rodwell.” This was first done at Camp Century in the late 1950s and most recently at the U.S. Antarctic Program’s Amundsen-Scott South Pole station and, if feasible, is generally preferred over snow melting as it provides higher-quality water. Figure 2 shows the progression of the Rodwell used at the South Pole station over 6 years; the well was started in January of 2002. A Rodwell system requires deep glacial coverage for the subsurface water bulb to form and a continuous energy input to maintain the bulb. This technology will be discussed as an option for Summit Station in more detail in section 3. Sketches and photos of the Rodwell system configuration at South Pole are included in Appendix E. Many recent efforts to produce potable water have also focused on water recycling systems. In particular, the Belgian Antarctic station Princess Elisabeth relies on this heavily, where 75% of water is used a second time, though all recycled water is used for non-potable applications.

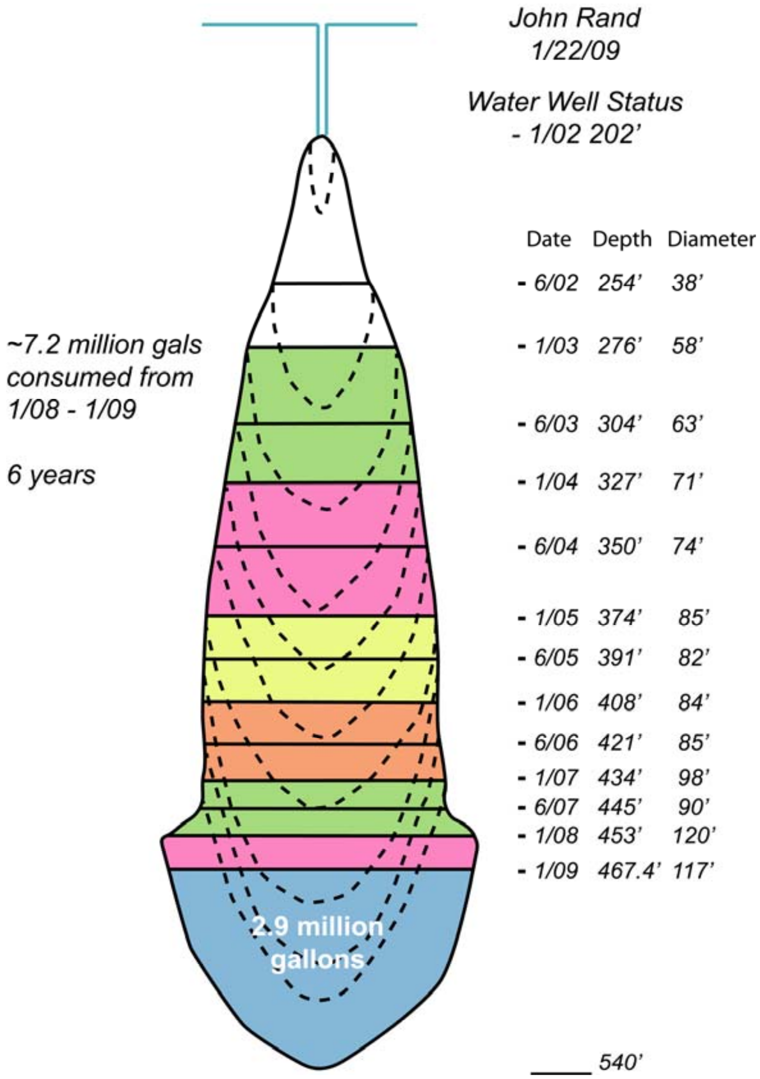
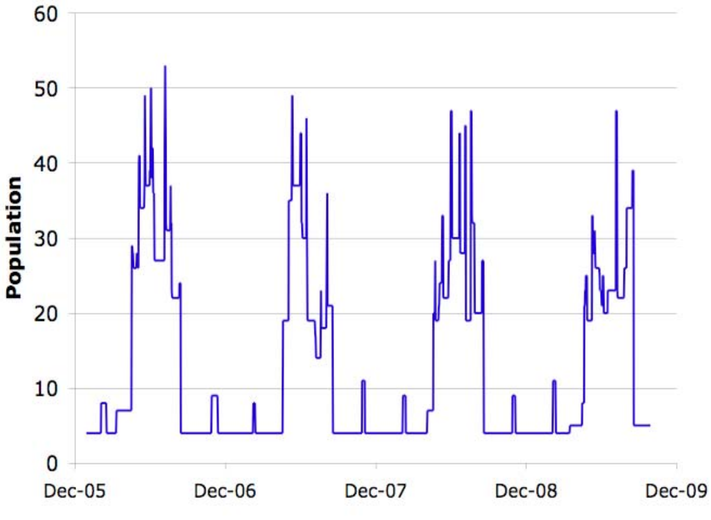


Figure 2. Progression of the Rodwell established at South Pole, starting in January of 2002 (drawing obtained from NSF/RPSC South Pole Project files).

3 System analysis

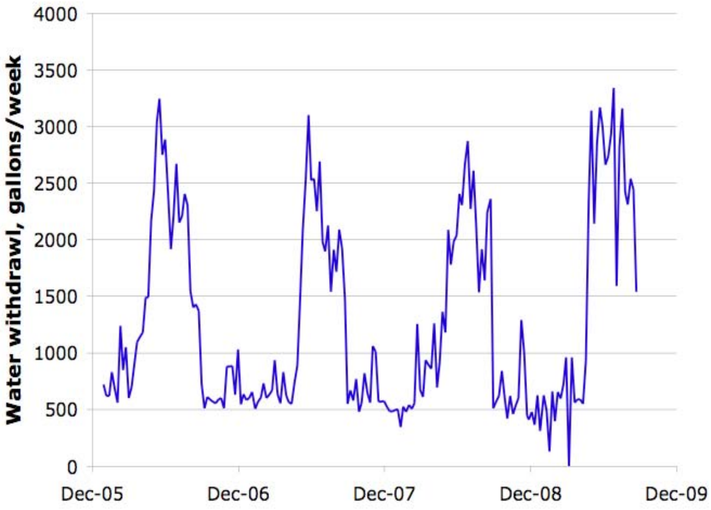
We will consider two scenarios for analysis. The first will be the current water demand based on the current population at Summit. The second will be the projected water demand based on the anticipated population that the Model 5 design is intended to support.

The baseline data for scenario 1 is determined as follows. The water demand and population at Summit over the recent past (January 2006–August 2009) are summarized in Figure 3. These data show that during the winter the population is typically 4, with peak of 8–11 persons. The summer population varies between about 20–50 persons. The water demand reflects these trends, with peak winter demand at about 1400 gal./week, and peak summer demand at about 3400 gal./week. Based on the data presented in Figure 3, it appears the summer "season" lasts from about 1 May to 30 September (153 days) and the winter season then goes from 1 October to 30 April and lasts 212 days. The average annual water consumption for the 3 full years of recorded data is 62,124 gal., with a peak of 68,236.



a. Recent population for Summit, Greenland.

Figure 3. Recent population and water demands for Summit, Greenland (Starkweather 2009).



b. Recent water demand for Summit, Greenland.

Figure 3 (cont'd). Recent population and water demands for Summit, Greenland (Starkweather 2009).

Scenario 2 is based on the anticipated population at Summit under Model 5 operation, which is 6 people year-round, except for 2 weeks during each of the months of April, August, November, and February, during which the population is 12. The current water consumption at Summit is 15–18 gal. of water per person per day (this may be reduced under the Model 5 design, but for the present it is the best available estimate). From a water usage standpoint, this creates a yearly demand of 45,468 gal. (based on the conservative number of 18 gal. per person per day). This is about 75% of the current amount of water used annually.

The available heat to provide this water supply currently comes from station waste heat produced by on-site generators. The amount of waste heat currently available is as follows. The current snow melter system uses up to 60,000 Btu/hr (60 MBH) of waste heat over a 48-hour period to melt enough snow into water to supply 6 people for 2 weeks. As much as 142 MBH can be made available if the medium sized generator is brought on-line. The glycol temperature for the waste heat recovery system ranges from 150–190°F (Sever 2010).

The planned heating system proposed in the Model 5 Concept Design includes a placeholder for 60 MBH dedicated to snow melting. This heating output is available for use in either a Rodwell or a manually filled batch-type snow melter, and, consistent with current performance, is estimated to produce 2 weeks' worth of water for 6 people in 48 hours. Assumptions include waste heat being available from the smallest generator operating at part load. In the event that larger generators are operated, or outside temperatures are higher than the design condition of –76°F, additional heat would be available (up to 200 MBH from the boiler plant alone). The glycol temperature delivered to the snow melt system ranges from 150–190°F.

3.1 Requirements

3.1.1 Scenario 1

Based on the above information for scenario 1 the following requirements for a water system are:

- Summer duration: 153 days (1 May–30 September).
- Summer water demand:[*] 3000 gal./week.
- Winter duration: 212 days.
- Winter water demand:[*] 700 gal./week.
- Minimum annual water withdrawal: 68,000 gal.
- Heat demand (continuous): ≤ 60 MBH.
- Heat demand (peak): ≤ 142 MBH.

3.1.2 Scenario 2

Based on the above information for scenario 2, the following requirements for a water system are:

- Baseline withdrawal duration: 309 days.
- Baseline water demand: 756 gal./week.
- Peak withdrawal duration: 56 days (broken into four time intervals of 14 days each)
- Peak water demand: 1512 gal./week.
- Annual water withdrawal: 45,468 gal.
- Heat demand (continuous): ≤ 60 MBH.
- Heat demand (peak): ≤ 142 MBH (though as much as 200 MBH is available).

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[*] These water demand requirements are based on a high estimate of the average weekly water demand shown in Figure 3. This would produce an annual withdrawal of 86,771 gal., 25% higher than the minimum requirement.

Furthermore, the Model 5 Station is planned so that it minimizes reliance on fossil fuels and uses renewable energy sources (e.g., solar heating and wind power) as much as possible. Thus, a further requirement for the final design is to minimize energy use with the aim of reducing the carbon footprint.

3.2 Analysis

As discussed in section 2, there are two basic methods for obtaining water at inland Polar Regions: melting surface snow and forming a subsurface water well in the glacial ice (a Rodwell). First, we review the performance of existing surface snow melting systems in terms of their energy requirements and other demands and their suitability for meeting the above system requirements. Then, we conduct a feasibility study for use of a Rodwell that would meet the above requirements.

3.2.1 Melting surface snow

As discussed above, the energy requirement to supply 2 weeks of water for 6 people using the existing snow melting system is 60,000 Btu/hr × 48 hours = 2.88×10^6 Btu and the water demand is 15–18 gal. of water per person per day. A conservative estimate of the energy required would be based on the lesser value (15 gal. per person per day) requiring at least 1300 gallons for a 2-week period, resulting in an energy requirement of about 2300 Btu/gal. of water. This is the “average” energy requirement only associated with melting the harvested snow. The additional energy associated with harvesting the snow is only about 1 Btu/gal. of water and transporting the water is 0.5 Btu/gal. of water (see Appendix C) and is, therefore, negligible. We contrast this to the latent heat of water that is about 17.3 Btu/gal. This is the minimum amount of energy required to melt the snow into water provided there are no heat transfer losses going from the waste heat glycol loop to the snow. This illustrates that there are significant heat losses in the current system.

3.2.2 Rodwell

To estimate the performance of a Rodwell at Summit, we used computer code developed to design the water well used at the South Pole station (Lunardini and Rand 1995). The input parameters for the original code were tailored for the South Pole. To use this for Summit, the correct inputs for the region needed to be determined, including the firn temperature, firn density with depth, water usage schedule, etc. We enumerate the parameters used in this simulation that apply to the Summit case in Table 1.

Table 1. Input parameters for Rodwell simulations for Summit, Greenland.

Firn Temperature (°F)	–20
Maximum heat flow rate (MBH)	142
Glycol temperature from boiler (°F)	150–190
Volume flow rate through boiler (gal./minute)	104
Target initial bulb volume (gal.)	12,000–13,000
Design lifespan (years)	10
Well depth range (ft)	100–600

In addition to the parameters in Table 1, we need to know the change in firn density with depth. This controls the volume of water created from the melted void in the firn and determines the depth at which the firn is non-porous, i.e., where melt water is no longer lost into the surrounding firn. We performed a piecewise fit to the available data that gives an adequate estimate of the variation at Summit (see Appendix B):

$$\rho_i \text{ (lbm/ft}^3\text{)} = 20.18 + 2.4996\, Z^{0.45};\ Z \leq 394 \text{ ft} \qquad (1)$$

$$\rho_i = 57.54 \text{ lbm/ft}^3;\ Z > 394 \text{ ft.}$$

This was entered as a condition into the computer code, replacing the curve fit used for the South Pole data.

3.2.2.1 Scenario 1

The input conditions for the first scenario are given in Table 2. Several cases were run to capture the design space for operating a Rodwell at Summit. Once we established an initial case that would quickly produce initial target bulb volumes, and also operate for a minimum of 10 years, we then varied the parameters to minimize energy use while still meeting target performance metrics. In Table 3 the results of the most informative cases are summarized.

Table 2. Input conditions for scenario 1.

Duration of summer season (days)	153
Water withdrawal during summer season (gal./day)	430
Duration of winter season (days)	212
Water withdrawal during winter season (gal./day)	100

Case 6, in Table 3, is a basic design case that will meet the requirements stated above. This assumes a lower boiler temperature of 150°F, and an initial start-up of 9 days to reach an initial bulb water volume greater than 12,000 gal. To minimize water loss to the firn, the initial well depth is established at 160 ft below the surface. For this case, start-up and initial operation of the Rodwell takes 95 days. We anticipate that this start-up period would be during the last part of a summer season. As the summer season is about 153 days long, this allows 58 days at the beginning of the first summer to install the equipment for the Rodwell and drill and melt the initial hole. The balance of the summer would then be consumed with well start-up. If the installation period needs to be lengthened, further refinements on the calculations can be made at a later time. This first case demonstrates that a Rodwell installation should be feasible at Summit with the available waste heat.

Cases 7–9 explore the viability of operating with lower energy requirements than baseline case 6. Case 7 required the same heat demand as case 6 to establish the initial well, after that the heat is cut back to require no more energy than the current snow melter system. Based on the melter requiring 2300 Btu/gal. (see section 3.2.1), and using the withdrawal rates given in Table 2, we see that during the summer the melter would require about 41.2 MBH and during the winter it would draw about 9.58 MBH. This case does not provide enough heat to sustain the bulb beyond the first full winter. There is not enough meltwater left in the bulb at the end of the winter to satisfy the summer withdrawal rate and the well "collapses" at the beginning of the summer season, that is, the amount of water withdrawn exceeds the amount produced, and the bulb is not sustainable.

Table 3. Summary of Rodwell performance calculations for scenario 1. Bold table entries indicate a change in conditions from the previous case.

	Case 6	Case 7	Case 8	Case 9	Case 10
Bulb formation					
Duration (days)	9	9	9	9	9
Boiler heat flow rate (MBH)	142	142	142	142	142
Boiler water temperature (°F)	150	150	150	150	**190**
Initial well depth (ft)	160	160	160	160	160
Bulb water loss volume (gal.)	12,186	12,186	12,186	12,186	12,254
Water loss to firn (gal.)	0	0	0	0	0
Initial water withdrawal					
Duration (days)	86	86	86	86	86
Boiler heat flow rate (MBH)	60	60	60	60	60
Withdrawal (gal./day)	430	430	430	430	430
Bulb water volume (gal.)	15,923	15,923	15,923	15,923	15,979
Total water loss to firn (gal.)	657	657	657	657	3339
First summer operation (days)	95	95	95	95	94
First winter operation					
Duration (days)	212	212	212	212	212
Boiler heat flow rate (MBH)	60	**9.58**	**20**	**40**	40
Withdrawal (gal./day)	100	100	100	100	100
Bulb water volume (gal.)	73,908	127	11,158	40,953	40999
Total water loss to firn (gal.)	657	657	657	657	659
Well depth (ft)	218	218	206	212	212
Summary of operations					
Duration (years)	10	1	1.1	10	10

	Case 6	Case 7	Case 8	Case 9	Case 10
Summer heat flow (MBH)	60	41.2	41.2	40	40
Summer withdrawal (gal./day)	100	100	100	100	100
Duration (days)	153	Collapse at the beginning of second summer	Collapse at the beginning of second summer	153	153
Winter heat flow (MBH)	60			40	40
Winter withdrawal (gal.day)	100			100	100
Duration (days)	212			212	212
Bulb water volume (gal.)	76,411	0	0	30,337	30,339
Total water loss to firn (gal.)	657	657	657	657	659
Well depth (ft)	341	218	244	588	588
Total water withdrawal (gal.)					
Total water withdrawal (gal.)	841,369	58,490	123,940	841,370	841,370

In Case 8 the available winter heat is increased to 20 MBH, which delays the bulb collapse to partway through the second summer season. In Case 9 we level the summer and winter available heat to 40 MBH, and a sustainable bulb is maintained for 10 years. The final well depth after 10 years is 588 ft. The average power requirement over this 10-year period is 40.29 MBH. This includes start-up and continuous operation. The average amount of energy per gal. is 4130 Btu/gal.

A final condition, Case 10, is a sensitivity study on the effect of boiler temperature. In this case the boiler temperature is increased to the maximum of 190°F. This has minimal impact on the bulb formation and no impact on the final bulb depth. Thus, Cases 9 and 10 demonstrate a viable Rodwell design with energy consumption minimized. Though further refinements and optimizations in this design are possible, this gives an initial operational design.

With this design (cases 9 and 10), the energy demand on the available waste heat is about 1.8 times higher than the current snowmelt configuration. Whether or not this additional energy can be justified because of its reduction in labor to provide water via snow melting methods is outside the scope of this effort.

3.2.2.2 Scenario 2

In this second scenario, we determine the feasibility of using a Rodwell for the projected population under Model 5 operations. In this simulation, we lump the withdrawals into two categories: baseline (population of 6) and peak (population of 12). To simplify the simulation, we implement these as step functions that cycle once per year. Based on the calculations run in scenario 1, we conclude that this simplification is justified. In particular, we find that we maintain the same heat flow both during the summer and winter once the initial well is established, and the bulb that is formed after about 1 year of service is enough to satisfy about a half year of operation (see Table 3, cases 9 and 10). As a result, increased withdrawal rates that occur intermittently throughout the year have roughly the same effect as one continuous, increased withdrawal period, and there is enough storage in the system to accommodate these fluctuations. Actual physical operation of the well would require detailed adjustments to accommodate these periodic withdrawals, but these are not captured in the physics of the computer code and, therefore, would have no effect on the model outcome. In Table 4 we provide a summary of the duration and withdrawal rates for the baseline and peak "lumped" periods.

Table 4. Input conditions for scenario 2.

Duration of start-up (days)	95
Start-up withdrawal (gal./day)	430
Duration of baseline withdrawal (days)	309
Baseline withdrawal (gal./day)	108
Duration of winter season (days)	56
Water withdrawal during winter season (gal./day)	216

Another consideration in this scenario is the start-up period. We assume that the population during well start-up is elevated to accommodate the crew needed to start the well and that this operation will take place during the transition from the existing station to the Model 5 operation. As such, we have the same start-up conditions as for scenario 1 (e.g., water withdrawal rate and period, heat flow rate, etc.).

Five cases were run for this scenario and they are summarized in Table 5. The first case (2.1) is essentially the same as case 9, scenario 1, except that the withdrawal rates and durations after the well is established are changed to meet the demands for the projected population for Model 5 operation. The remaining four cases explore the effect of reducing the heat flow on well performance. Table 5 shows that, in all five cases, a Rodwell can be established and maintained for a full 10 years, even with reduced heat flow (from 40 to 20 MBH). However the "steady" bulb water volume for the cases 2.4 and 5 once "steady" operations are established is very small, leaving very little buffer if the well water production needs to be stopped for a short period. For example, at baseline withdrawal and a heat rate of 20 MBH (Case 2.5), the amount of water stored in the bulb at the end of the first year of operation would last less than 80 days if there were no freeze-back (progressive freezing of the water bulb attributable to loss of heat flow to the well). Because of freeze-back, the usable water amount would be significantly less.

Table 5. Summary of Rodwell performance calculations for scenario 2. Bold table entries indicate a change in conditions from the previous case.

	Case 2.1	Case 2.2	Case2.3	Case 2.4	Case 2.5
Bulb formation					
Duration (days)	9	9	9	9	9
Boiler heat flow rate (MBH)	142	142	142	142	142
Boiler water temperature (°F)	150	150	150	150	190
Initial well depth (ft)	160	160	160	160	160
Bulb water loss volume (gal.)	12,186	12,186	12,186	12,186	12,254
Water loss to firn (gal.)	488	488	488	488	488
Initial water withdrawal					
Duration (days)	86	86	86	86	86
Boiler heat flow rate (MBH)	60	60	60	60	60
Withdrawal (gal./day)	430	430	430	430	430
Bulb warter volume (gal.)	15,923	15,923	15,923	15,923	15,923

	Case 2.1	Case 2.2	Case2.3	Case 2.4	Case 2.5
Total water loss to firn (gal.)	657	657	657	657	657
First summer operation (days)	95	95	95	95	95
Completion of first years' operation					
Duration (days)	309	309	309	309	309
Boiler heat flow rate (MBH)	40	**30**	**35**	**25**	**20**
Withdrawal (gal./day)	108	108	108	108	108
Bulb water volume (gal.)	46,346	25,953	35,897	16,706	8530
Total water loss to firn (gal.)	657	657	657	657	657
Well depth (ft)	217	214	215	212	212
Summary of operations					
Duration (years)	10	10	10	10	10
Peak withdrawal heat flow (MBH)	40	**30**	**35**	**25**	**20**
Peak withdrawal (gal./day)	216	216	216	216	216
Duration (days/yr)	56	56	56	56	56
Baseline heat withdrawal flow (MBH)	40	**30**	**35**	**25**	**20**
Baseline withdrawal (gal.day)	108	108	108	108	108
Duration (days)	309	309	309	309	309
Bulb water volume (gal.)	43,754	19,035	29672	11,162	5495
Total water loss to firn (gal.)	657	657	657	657	659
Well depth (ft)	301	362	324	433	632
Total water withdrawal (gal.)					
	477,442	477,442	477,442	477,442	477,442

Thus, we do not recommend operation with such small water bulb volumes. Furthermore, the final well depth for lower heat flows is much deeper (632 ft for a sustained 20 MBH vs. 301 ft for 40 MBH). Thus, these low heat flow rates produce a deep, narrow well, rather than the preferred wide, shallow well. From an operational point of view, the narrow deep wells require more attention as more piping needs to be fed down the well hole and the frequency of lowering the pump assembly increases. Also with the increased depth, annual pump changes are more labor-intensive as more pipe is required. Therefore, the optimal heat flow rate is likely in the range of 30–40 MBH. Further design work will be required once the detailed requirements for the Model 5 design operation are established to determine a final optimal well design.

Using the results for cases 2.1–2.3 (30–40 MBH), we find that the average heat required per gal. of water is 6600–7500 Btu/gal. This is 1.7 times higher than scenario 1 and 3.0 times higher than the current method used to harvest and melt snow. This increase in specific heat usage for scenario 2 over scenario 1 is a result of more heat loss to the surrounding firn and air per unit volume of the water bulb for the smaller water bulb established in scenario 2 in comparison to scenario 1. This shows that the Rodwell is better suited to handling large populations, and as the population shrinks, the efficiency of the Rodwell declines.

3.2.3 Other considerations

The above discussions show that a Rodwell could be established and successfully operated based on the existing available heat at Summit Station and the assumptions provided in Table 1 are met. Additional considerations that need to be addressed in the design of a Rodwell for this application are available electrical power, resources, and contingency. We will discuss each of these in turn.

First, based on the Rodwell design used at South Pole, the electrical power system to support the operation of the pumps, heat tape, and other electrical components to support the Rodwell is about 20 kW. The actual power draw for these systems is 17.7 kW peak, 12.1 kW average, and 6.3 kW low power draw (Dial 2010). This is likely higher than what is needed for the smaller installation required at Summit; a rough estimate of the power requirements for a Rodwell at Summit are 11 kW peak for the heaters only (the details of this estimate are given in Appendix D). Though this does not include the power for the pumps and other electrical components, the heaters make up the bulk of the power requirements, and this estimate should indicate the order of magnitude of the overall power requirements. Clearly, such power requirements will need to be factored into the overall design of the Model 5 station if the Rodwell is to be considered.

Establishing a Rodwell requires that resources and personnel be available specifically to support that operation. The time to install the equipment and establish the initial bulb will be at least a month. We recommend that there be an overlap in systems during the initial year of operation so that a sufficient reserve of water is generated in the well before cutting over to Rodwell-only use. Once the well is established, daily monitoring of the well is required to maintain proper performance (Rand 2010). The daily time commitment is small, but regular monitoring of well depth and diameter, water surface and pump depth, circulation flow rate, heat tape status, etc., is required, and regular adjustments in pump depth need to be made to maintain proper submerged depth (3–4 ft below the water surface). Annually, the pump assembly should be swapped out. This should be done during the summer months when there is sufficient crew to support this effort: 2–4 days and a crew of 3–4 people.

Another factor to consider is placement of the Rodwell. The locations of subsurface waste (including old sewage outflows) or debris (including buried buildings and equipment) must be determined so the Rodwell can be established in an area free of waste or debris over its entire life cycle. Determining the location of subsurface waste and debris may be possible through a ground penetrating radar (GPR) survey. Further work is required to determine the feasibility of this.

In the event that the heat supply is cut off for the Rodwell, a backup boiler needs to be available to maintain the heat circulation to the bulb. If no heat is available for an extended time, the pump unit will need to be drawn up out of the water bulb to prevent it freezing into the resulting ice that would form. This requires 3–4 people to be on hand to draw the pump up 8–10 ft out of the water and into the air (Rand 2010).

4 Conclusions

In this study we reviewed methods used in Polar Regions to provide potable water that may be used at Summit, Greenland. We found that two predominant methods are used: melting surface snow and melting subsurface ice to form a well and extracting the melt water to the surface (a Rodwell). Of these two methods, melting surface snow is most widely used and is currently used at Summit Station.

There are limited published data on the energy use for melting surface snow. For this analysis we rely mainly on data from the existing Summit Station. The basic energy requirement to melt snow is about 2300 Btu/gal. This does not include the energy associated with harvesting the snow or transporting the water after it is melted, both of which are labor-intensive activities requiring use of heavy equipment. Also, there is additional labor associated with transfer of the melt water from the melt tank to the transportation tank and then to the final storage tank. There are opportunities to reduce the labor in this process with a new system design (e.g., piping water from the melt tank to the point-of-use locations).

We also reviewed the feasibility of using a Rodwell at Summit. There is sufficient ice depth to support such a system, thus providing opportunities to reduce the labor associated with acquiring the “feed stock” for the meltwater and to improve the water quality at Summit Station. In this case, a subsurface well would be established in the ice sheet and meltwater from the well would be pumped to the surface for treatment and distribution to point-of-use locations. The approximate sustained energy requirement for this system would be 30–40,000 Btu/hr, with an initial requirement of 142,000 Btu/hr for bulb start-up. These energy requirements are well within the available waste heat at the current Summit Station; however, we should consider the anticipated decrease in available waste heat with the construction and implementation of Model 5. This feasibility study shows that a Rodwell can provide at least 10 years of service before it will need to be relocated. Depending on the population that the well will need to support, the energy requirement for this system is about 4100 to 7000 Btu/gal. or 1.8 to 3.0 times higher than the current system of melting surface snow. The lower the population is, the higher the specific energy required to generate water is, thus the Rodwell becomes less attractive from an energy consumption point of view as the population gets smaller.

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Appendix A: Summary of existing methods for providing potable water at polar stations

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Data

Location	Years active	Type of system	Population	Production level	Treatment	Transport System To Production	Water Transport once Potable	Other	References
Neumayer Station III	2009-present	snow melting	10 winter; 58 summer	117 L/person/day	??	Taken from surface to the east of the station and pushed through a chute into the melting vessel. An 'automatic' drift snow collector has been devised and may prove helpful in reducing the effort for snow transport.	piped	Melter will be driven by excess heat from the diesel generators; Nominal capacity of the melter will be in the range of 25 kW	18, various web
Halley VI, Antarctica	2008 - present	snow melting	16 winter; 52 summer	??	??	Vehicles will be used to fill the station melt tanks with snow	piped	Both energy modules will include solar thermal panels to supplement the waste heat collected from CHP generator engines for water heating. Evacuated tube solar panels will be positioned on the vertical surfaces of the energy modules.	17, various web
Princess Elisabeth Antarctica, Dronning Maud Land, Antarctica	2008 - present	snow melting	12 winter; 48 summer	??	anaerobic reactor, filtration, aerobic bio-reactor, active carbon, chlorination unit, and finally a regeneration system using UV treatment for conservation of drinking water inside the tank	utilization of snow drifting around station and ridge; collected snow will be automatically dumped into the (lower positioned) snow collector; When snow accumulation is low a tractor will be used	piped	100% of used water is recycled, 75% is used a second time, all recycled water is used for non-potable applications; use solar thermal panels for snow melt	2,16
Troll Station	2005-present	snow melting (winter) and fresh water reservoir (summer)	8 winter; 40 summer	??	??	??	??	During summer use reservoir of freshwater melted below blue ice	18,
Concordia, Dome C	2004-present	snow melting	15 winter; 70 summer	400 L/day in recycling system; 1188 L/day snow melting	various	??	??	energy to melt snow is produced by using a cogeneration system connected to the main electrical diesel generators	various web
Vostok Station	1999/2000	solar heating facility	n/a	~2 gal/hour	??	Snow is loaded into the collector via tractor	??	The concentrator is automatically oriented towards the sun where the rays are concentrated on the absorber and the solar heat is effectively transported from the absorber to snow through the heat transferring system.; Production is max based on tests done at -35 C and 3-4m/s winds	13,
South Pole Station, Antarctica	post 1995	Rodwell	28 winter; 140 summer	530,000 gal/yr	yes	melted in-situ - NO TRANSPORT NEEDED	??	Rodwell started to be tested in 1993 and took a few years to move completely to this system	14,

South Pole Station, Antarctica	pre 1995	snow melting	??	25 gal/man-day summer;	filtered through diatomaceous earth and treated with baking soda to combat oily taste	Front end track loader made continuous 45 min. round trips to four snow melters	??	heated by exhaust gases from the diesel generators (required 14.6 tons of snow/day)	1,14
Hallett Station	pre 1969	natural melting	??	??	??	melted in-situ - NO TRANSPORT NEEDED	water is collected in basin and piped down a slope till it fills waiting water wagons - wagons haul the water to various buildings and pump into storage tanks	In the winter they use distillation	12,
McMurdo Station	pre 1965	snow melting	250 winter; 1100 summer	20 gal/person/day	filtration using a vacuum diatomite filter then chlorinated	tractor and scoop goes out 1/2 mile from station	Water is distributed to storage tanks in buildings through a 1" hose, once/day; Buildings more than 150' away use bottled drinking water; each building has its own melter for water for other uses		12,
NCEL camp, Ross Ice Shelf, Antarctica	winter 1964/65	snow melting	20	12 gal/man-day	2, 5-micron particle filter elements of resin-bonded cellulose fiber; 18 activated carbon cartridge elements for removing taste and odor	loaded with a 2 yd3 bucket on a front-end loader	Pneumatic pressure system distributed the water to the fixtures; Storage tanks has 350 gallon capacity	water from the melter tank was circulated through an oil-fired water heater and returned to the melter reservoir	1,3,
DYE 2 and DYE 3, Greenland	~1960-1980	snow melting	30	2000 gal/day	??	snow is hauled up to the building (19 ft elevation) by remote control using a fixed dragline which tips into a projecting hopper; requires about 1 hr operation per day to fill the melter tank with enough snow	transfer pump takes usable water from the tank for distribution inside the heated composite building by a hydropneumatic system	Snow is sprayed with warm water from nozzles; spray water is heated by waste heat from the generating engines	1,7,
"New" Byrd Station, Antarctica	1960s	snow melting	??	25 gal/man-day summer; 10 gal/man-day winter	filtered through diatomaceous earth	carted by sled (from 1/4 mile upwind); then loaded by an inclined conveyor belt	distributed from a loop circulating continuously	heat exchanger on the cooling system provides energy for melting	1,12
Tuto under ice camp, Greenland	1960s	snow melting	??	??	??	melted in-situ - NO TRANSPORT NEEDED	??	continuous circulation of water from the well and through heat exchangers fitted to the station power plant	1,
Point Barrow Camp	1960s	fresh-water lake	??	26,000 gal/day for Aug. 1963	3, Army-type pressure filters and chlorination (Drinking water only)	Pumped to camp	Pumped to individual buildings		12,
Camp Century, Greenland	1959/1960	water well	??	10,000 gal/week	chlorination of 1 ppm	n/a	piping	vertical shaft steamed through snow to ~140-160' down where ponding occurred	1,
Syowa Base	1956-62	snow melting	11 winter; 40 summer	~5.25 gal/person/day	none	Pure ice dug out of an iceberg	originally by hand then later by pump	uses recovered exhaust-gas heat of the diesel engines and a steel walled melting tank	4,
NCEL camp, Ross Ice Shelf, Antarctica	1963	electric immersion heaters	25	??	??	??	??		1,3,

Camp Fistclench (Site II), Greenland	1957	snow melting	??	??	??	10-ton sleds; system was underground so just had a hopper	piped and 5 gal cans	Melted in 2 tanks heated by kerosene burners	1,
Camp Fistclench, Greenland	1957	water well	??	??	??	n/a	??	vertical shaft steamed through snow to ~130' down	1,
Little America V, Ross Ice Shelf, Antarctica	1956	snow melting	??	??	??	shoveled manually	pumped to overhead storage; some pipe distribution	melted in the tank by circulating warm water	1,
USAF ice cap radar station N-33	1952	snow melting	118 max	15-25 gal/day/man	??	bladed into a 5ft diam. Chute	snowmelter was 500 yards from camp - barrels mounted on sleds to take water to storage tanks	Cleaver Brooks snowmelter; Water samples taken to Thule regularly for testing	4,
USAF ice cap radar station N-34	1952	snow melting	20	450 gal/hour	??	bladed into a 5ft diam. Chute	snowmelter was 500 yards from camp - barrels mounted on sleds to take water to storage tanks	Cleaver Brooks snowmelter; Water samples taken to Thule regularly for testing; independently heated melt tank; fire tubes passed through melter and warm water was sprayed over the snow from header tubes above; passed to storage tank	1,4

Appendix B: Method for predicting performance of Rodwell at Summit, Greenland

Model description

We adapted the computer code developed by Lunardini and Rand (1995) to compute the performance of a proposed Rodwell for Summit station. This code assumes that a bulb formed in the firn is a paraboloid below the water line and a cone above the water line up to the starting depth of the well. This approximately describes the shape seen in Figure 1. The shaft for the well is a cylinder from the starting point to the surface. The melting of the firn is a result of warm water being pumped down to the bottom of the initial shaft. The bulb grows laterally and in depth as the melting proceeds. The program tracks the following energy balance

$$E_m = E_w - E_{cf} - E_{wa} \tag{B.1}$$

Where

E_m = energy that goes into melting and producing water from the firn
E_w = energy available in the warm water
E_{cf} = energy loss due to conduction into the firn
E_{wa} = energy lost due to convection from the free water surface into the air in the bulb or shaft.

The amount of energy that remains melts ice (firn) and produces water. However some of the water is lost to the surrounding porous firn; thus, not all of the water generated is available to be withdrawn from the well. The rate of water loss to the surrounding firn is a function of the firn porosity, which is also a function of depth.

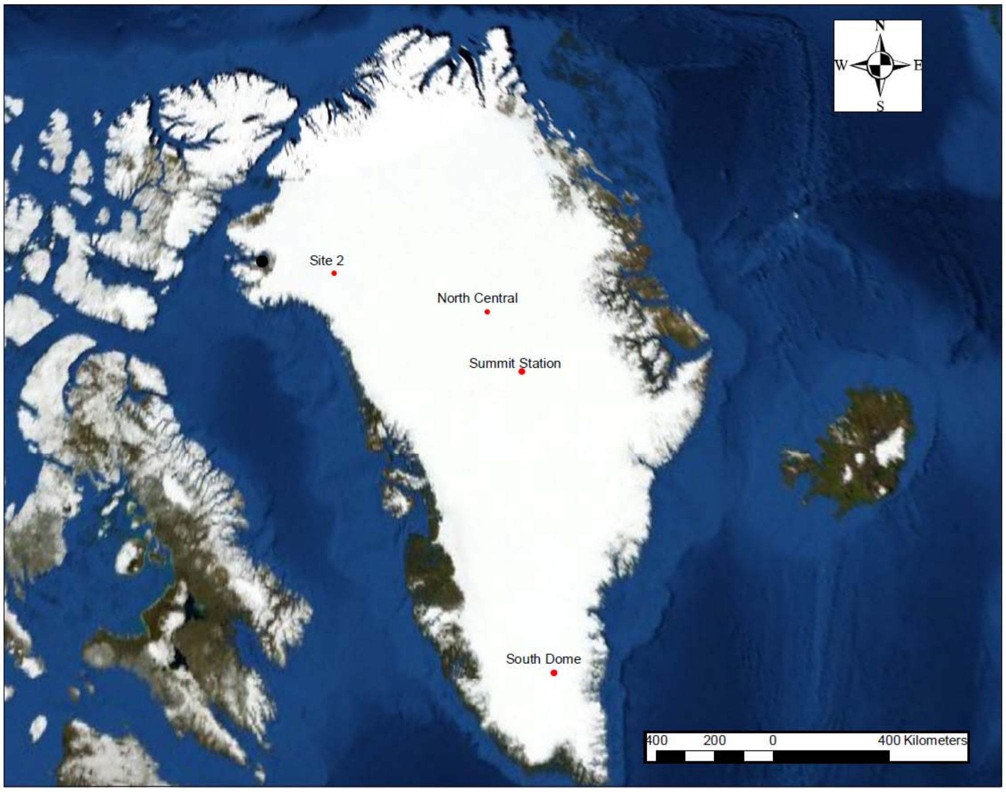

Figure B.1. Map of Greenland with approximate locations of measurements of firn density down to a depth of 30 m or more.

According to Lunardini and Rand (1995), the density at which all water loss is stopped is 45 lbm/ft^3 (0.72 g/cm^3). The surface snow density near Summit reported by several sources is around 0.25–0.35 g/cm^3 (Herron and Langway 1980; Dibb and Fahnestock 2004; Hawley et al. 2008). Consequently, information about the variation of firn density with depth is required to compute the water lost to the surrounding firn until the well reaches the depth at which the firn is impervious (density of 45 lbm/ft^3). Herron and Langway (1980) provide density/depth data down to about 70 m for three locations in Greenland named "Site 2," "South Dome," and "North Central." Their approximate locations are shown in Figure B.1. The depth at which the firn density was 45 lbm/ft^3 at these three sites ranged from 130–160 ft (40–50 m), so there is some variability in the density with depth at the various sites. Thus, it is desirable to get the depth/density information at Summit.

Hawley et al. (2008) measured the density to a depth of 98 ft (30 m) at Summit Station. Unfortunately, this depth was not enough to reach a density of 45 lbm/ft^3. Thus, to determine an approximate depth/density relationship, we used information from both the Herron and Langway

(1980) and Hawley et al. (2008). This is provided as eq 1. This is adequate for this feasibility study, though better data would be desirable if a detailed analysis is warranted.

The complete computer code used for this simulation is printed out at the end of this appendix.

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Computer Code “Summit.f”

```
      program main

c Original program written for
c     Lunardini, V. J. and J. Rand (1995) Thermal Design of an Antarcti
c Water
c     Well, CRREL Special Report 95-10, Cold Regions Research and Engin
eering
c     Laboratory, Hanover, NH.

      IMPLICIT DOUBLE PRECISION (A-H,K-M,O-Z)
      character PRNTR*12
      integer i,j,n

      integer jj

      read(*,*) PRNTR
      OPEN(9,FILE=PRNTR, STATUS='unknown')

c
c Modified to run for Summit, Greenland

CCC   FORMATION DELT = TZ3
      read(*,*) TZ3  ! hrs
      read(*,*) MG0 ! gallons, initialized bulb volume
      read(*,*) QBC
      read(*,*) MF !lbm/hr, Boiler mass flow rate
CCC   PHASE 1 1ST SUMMER DELT = TZ4+24
      read(*,*) TZ4 !hrs
      read(*,*) QBC1 ! btu/hr
      read(*,*) MUG1  ! gal/day, initial withdrawal
      read(*,*) MF1 ! lbm/hr, boiler mass flow rate
      TZ3E = 88000.0 ! ten years
CCC   PHASE 2 1ST SUMMER DELT = TZ5
      read(*,*) TZ5 ! hrs
      MUG2 = MUG1 ! gal/day
      read(*,*) QBC2
      read(*,*) MF2
CCC   PHASE 3 1ST WINTER DELT = TZ6
      read(*,*) TZ6
      read(*,*) QBC3
CCC   2ND & SUB SUMMERS
      read(*,*) QBC4
CCC   2ND & SUB WINTERS
      read(*,*) QBC5

      AL = 0.30 ! Firn loss parameter
      ALPHAI = .0446 ! ft2/hr
      BO = 1.1
      CPA = .24 ! BTU /lb-F, Cp air
      CPI = .5  ! Cp ice
```

```
      CPW = 1.0 ! Cp water
      read(*,*) DEPTH ! ft, initial depth to top of water
      DT = 8.333001E-03 ! hrs (30 secs)
      EIT = 0.0
      E = 0.0
      FI = 0.90
      GAM = 1.0
      H = 10.0
      HA = 1.0
      HB = 60.0
      HI = 1.0
      HS = 32.5 ! BTU/hr-ft2-F
      HBN = 24.0
      HSN = 32.5
      HSO = 32.5
      J = 1
      KI = 1.28 !BTU/hr-ft-F, ice/firn conductivity

      MU = 0.0
      MUD = 7549.5
      MWG = 0.0 ! gallons, bulb water volume in gallons
      read(*,*) MFS ! summer boiler flow rate. lbm/hr
      read(*,*) MFW ! winter flow rate
      read(*,*) MUGS ! summer withdrawal, gal/day
      read(*,*) MUGW ! winter withdrawal, gal/day
      MGW = 1106533.0 !
      N = 1
      OMEGA = 5.399
      PI = 3.141593
      PL = 0.0
      PM = 0.0
      PLT = 0.0
      PMT = 0.0
      PRWT = 0.0
      QS = 0.0
      QT = 0.0
      QTT = 0.0
      QIT = 0.0
      RA = 1.5 !ft, drill radius
      RHOIS = 45.0 !lbm/ft3, start close-off density of firn
      RHOIM = 57.54 !lbm/ft3, max firn density
      RHOW = 62.6 ! lbm/ft3, water density
      RO = RA ! ft

CCC   TIME PARAMETERS

      TAUP = 0.0
      TI = 0.0
      TIS = 0.0
      TP = 24.0
      TPI = 24.0
```

```
      TPIW = 24.0
      TZ1 = 8760.0 ! 8760 days is one year
      TZ2 = 8760.0
      TZS = TZ1 - TZ6 ! Summer duration (days)

CCC   TEMPERATURES

      TF = 32.0
      read(*,*) TICE ! F, Firn Temperature
      read(*,*) TWB ! F, Boiler water temperture
      TA = TICE
      TS = TICE
      TW = TWB

      ! depth at which shut-off starts in firn.
      ZS = ((RHOIS - 20.18)/2.4996)**(1/0.45) ! Greenland data
ccc
      D = 2.82843*RO !ft, diameter of bulb
      MFA = MF
      MW = PI * RA * RA * H * RHOW !lbm, water mass
      MWO = MW
      HWB = DEPTH + H !ft, depth to well bottom
      MWGA = MW / (.134 * RHOW) ! gallons, convert bulb water mass to v
olume in gallons
      LE = 144.0 + CPI * (TF - TICE) * OMEGA
      AB = PI * D**2./4.0        ! ft2, air-water interface area
      HW = H                     ! ft, water depth
      AS = 2.0*PI*D*H/3.0        ! ft2, water-ice contact area
      VW = PI*D**2.*H/8.0        ! ft3, water volume in bulb
      AI = 2.0 * PI * RA * DEPTH ! ft2, air-ice contact area
      VA = PI * RA * RA * DEPTH  ! ft3, air volume

130   Write(9,3000)
3000  format(1x,'          ANTARCTIC PARABOLIC ICE RESEVOIR FORMATION '
)
140   Write(9,3001) TWB
3001  format(1x,' BOILER WATER TEMP DEG F                   = ',F9.2)
150   Write(9,3002) MF
3002  format(1x,' BOILER WATER FLOW RATE lbm/hr             = ',F9.2)
160   Write(9,3003) HS
3003  format(1x,' CONVECTIVE COEFFICIENT BTU/HR-FT2-F       = ',F9.2)
      Write(9,3013) RA
3013  format(1x,' INITIAL DRILL RADIUS FT                   = ',F9.2)
      Write(9,3014) DEPTH
3014  format(1x,' DEPTH TO TOP OF WATER AT START FT         = ',F9.2)
180   Write(9,3005) D
3005  format(1x,' INITIAL PARABOLIC WATER DIAMETER D FT     = ',F9.2)
191   Write(9,3007) HW
3007  format(1x,' INITIAL PARABOLIC WATER HEIGHT HW FT      = ',F9.2)
200   Write(9,3008) TW
3008  format(1x,'INITIAL WATER TEMP TW DEG F                = ',F9.2)
```

```
201   Write(9,3009) TA
3009  format(1x,' INITIAL AIR TEMP TA DEG F                   = ',F9.2)
202   Write(9,3010) TS
3010  format(1x,' INITIAL ICE SURFACE TEMP TS DEG F           = ',F9.2)
210   Write(9,3011) TICE
3011  format(1x,'AMBIENT ICE TEMP DEG F                       = ',F9.2)
220   Write(9,3012) LE
3012  format(1x,'EFFECTIVE LATENT HEAT BTU/LB                 = ',F9.2)

221   Write(9,*) 'TIME IN HRS, WATER VOL MW GALLONS, ICE AREA AI FT2,
     &  AIR VOL VA FT3 '
222   Write(9,*)
252   Write(9,*) '   TIME    TW     TA     TS        MW      D    HW   H
WB
     &         AI          VA'
253   Write(9,2001) TI, TW, TA, TS, MWGA, D, HW, HWB, AI, VA
3030  format(1x,F8.2, 3F7.2,F9.2,2F6.2,F7.2,2F7.2)

260   DO I=1,112500000
         IF (MWG .GT. MGO) GOTO 1220 ! bulb water volume .gt. initilaiz
e volume
         IF (TI .GT. TZ3) GOTO 1220  ! time .gt. formation period
         IF (J .EQ. 1) GOTO 280      ! not sure why we branch here, bul
b formation?

 400     IF (TI .LT. TAUP) then      ! not sure what taup is
            MF = 0.0
            MUG = MUGA
            MU = MUD
         else
            MF = MFA
            MUG = 0.0
            MU = 0.0
         end if

         ! determine firn density
 280     ZP = HWB-H/2.0         ! ft, average bulb depth
         ! This is for Greenland data at Summit
         RHOI = 20.18 + 2.4996 * ZP**0.45 ! shallow: ZP .le. 394 ft
         IF(ZP .GT. 394) then
            RHOI = RHOIM
         end if

         ! compute the change in water depth, h (eq. 7)
 291     DELH = 16.0*H*(HS*(TW-TF)-QS)*DT/(RHOI*LE*3.0*(2.0*GAM*H+D))
         HP = H+DELH
         DP = D+GAM*DELH
         HWBP = HWB+DELH

         ! assumes full shut-off of water leakage into firn at ZS.
         ZPS = HWB-ZS
```

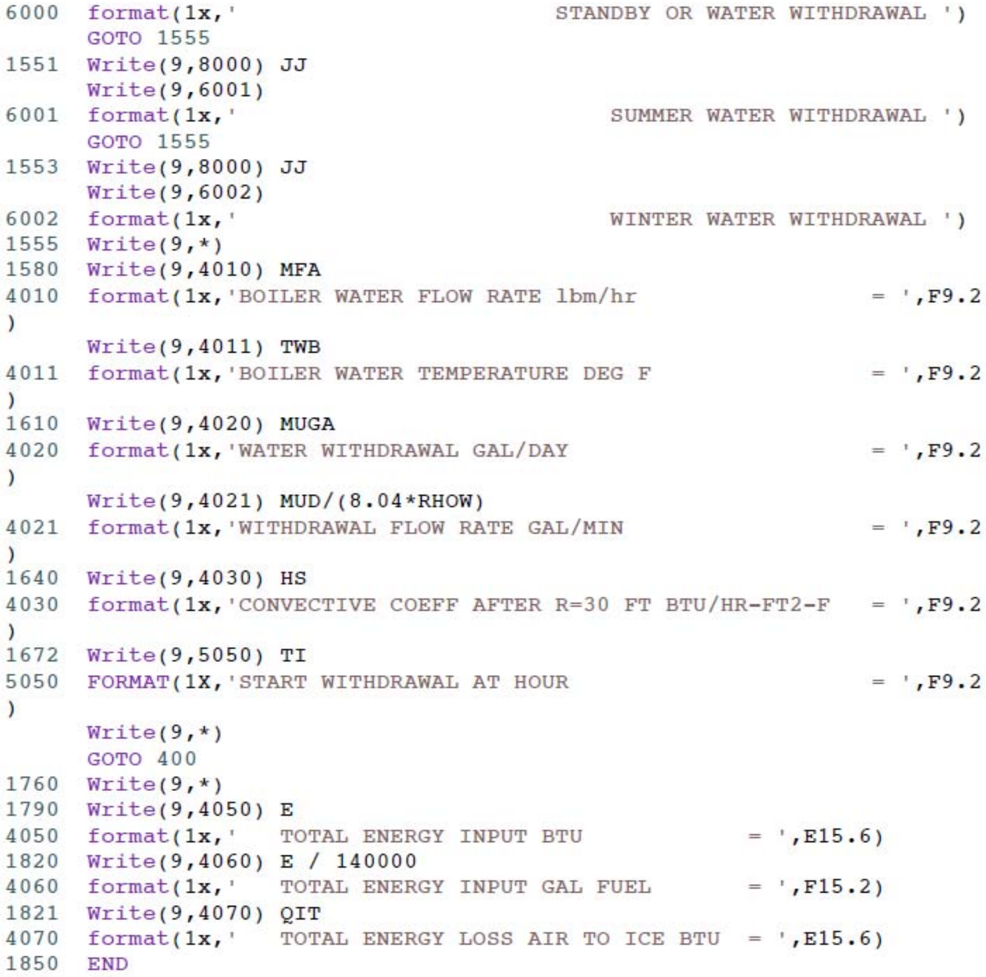
```
         ASP = 2.0*PI*D*H/3.0   ! all of surface area in fully porous f
irn
         IF(ZPS .GT. H) then    ! bulb below firn shut-off
            ASP = 0.0           ! none of bulb surface area in fully po
rous firn
         else IF(HWB .GT. ZS) then ! well bottom is deeper than firn sh
ut-off
            ZPP = (ZS+HWB-H)/2.0 ! average depth of portion of bulb in
porous firn
            ASP = 2.0*PI*D*H*(1.0-(ZPS/H)**1.5)/3.0 ! portion of bulb i
n porous firn
            RHOI = 20.18 + 2.4996 * ZPP**0.45 ! firn density
         endif
 283     MUL = AL*ASP*(RHOIS - RHOI) ! water mass lost to firn

         IF(MF .EQ. 0.0) GOTO 284
         TWB = QBC/(CPW*MF) + TW
 284     TWP = TW+(MF*(TWB-TW)-HS*AS*(TW-TF)*(1.0/CPW+(TW-TF)/LE-QS/
     &        (LE*HS))-HA*AB*(TW-TA)/CPW)*DT/MW
         MWP = MW+(((TW-TF)*HS-QS)*AS/LE-MU-MUL)*DT
         MWG = MWP / (.134 * RHOW)
         VWP = MWP / RHOW
         HF = SQRT(8.0*VWP*HP/PI)/DP
         DF = DP*SQRT(HF/HP)
         HW = HF
         EP = CPW * (TWB - TWP) * MF * DT
         E = E + EP
         PMP = MU*DT
         PM = PM + PMP
         PLP = MUL*DT
         PL = PL + PLP
         AIP = AI+PI*(DP**2-D**2)/4.0 + PI*DP*(HP-HF)
         VAP = VA + PI*(DP**2*HP-DF**2*HF)/8.0
         H = HF
         D = DF
         TI = DT + TI
         Q = HI * (TA - TS)
         QI = Q * DT * AI
         QT = QT + Q * DT
         QIT = QIT + QI
         QB = QT / TI
         TAU = ALPHAI * TI / (RO ** 2)

         RHOA = 39.685 / (TA + 460.0)
         TAP = TA+(HA*AB*(TW-TA)+HI*AI*(TS-TA))*DT/(RHOA*VA*CPA)


 418     FB = 5.0*BO**3.0/36.0-BO/4.0+1.0/9.0+(1.0/3.0-BO/2.0)*LOG(BO)-
     &        TAU*(BO-1.0+LOG(BO))
         FBP = 5.0*(BO**2)/12.0 - .25-LOG(BO)/2.0+(1.0/3.0-BO/2.0)/BO-
     &    TAU*(1.0+1.0/BO)
```

```
         BP = BO - FB /FBP
         BZ = ABS(BP - BO)
         IF(BZ .lt. .0001) GOTO 425
         BO = BP
         GOTO 418
 425     B = BP
         BO = BP +.1
         TS = TICE+QB*RO*(B-1.0)*LOG(B)/(KI*(B-1.0+LOG(B)))
         IF(J .EQ. 1) GOTO 1031
         IF(TI .gt.TPW) GOTO 1130
 1028    IF(TI .gt. TP) GOTO 1131
         GOTO 560
 1031    IF(TI .gt. TP) GOTO 1128
 560     continue
         HWB = HWBP
         TW = TWP
         TA = TAP
         MW = MWP
         AS = 2.0*PI*D*H/3.0
         AB = PI*D**2/4.0
         AI = AIP
         VA = VAP
         IF (D .GT. 60.0) GOTO 1010
         HS = HSO
         GOTO 1040
 1010    HS = HSN
 1040    IF(TW .LT. 32.0001) GOTO 1075
 1041    IF(TI .GT. TZ2) GOTO 1220
         IF(TI .GT. TZ1) GOTO 1220

1070  end do
      GOTO 1760
1075  TW = 32.0
      GOTO 1041
1128  Write(9,2001) TI, TWP, TAP, TS, MWG, D, HW, HWBP, AIP, VAP
      TP = TP + TPI
      TPW = TP
      GOTO 560
1130  Write(9,2001) TI, TWP, TAP, TS, MWG, D, HW, HWBP, AIP, VAP
2001  format(1x, F8.1, 3F7.2, F9.1, 2F6.2, F7.2, 2F11.2)
      TPW = TPW + TPIW
      GOTO 1028
1131  TP = TP + TPI
      TAUP = TP+MUGA*.134*RHOW/MUD-TPI
      GOTO 560
1220  Write(9,2001) TI, TWP, TAP, TS, MWG, D, HW, HWBP, AIP, VAP
2000  format(1X,6F9.2)
1280  Write(9,*)
      EI = E - EIT
      ESR = EI/(TI-TIS)
      EIT = E
```

```
      PRW = MW-MWO + PM
      PRWT = PRWT+PRW
      PLT = PLT+PL
      PMT = PMT+PM
      EKT = PRWT*19500.0/E
      EK = PRW * 19500.0 / EI
      PMG = PM/(.134*RHOW)
      PM = 0.0
      PLG = PL/(.134*RHOW)
      PL = 0.0
      MWO = MW
      EF = E / 140000.0
      EFI = EI / 140000.0
      QITI = QIT - QTT
      QTT = QIT
1340  Write(9,3040) E
3040  format(1x, '   TOTAL ENERGY INPUT BTU               = ',E15.6)
      Write(9,3041) EI
3041  format(1x, '   SEASONAL ENERGY INPUT BTU            = ',E15.6)

      Write(9,3051) EFI
3051  format(1x, '   SEASONAL ENERGY INPUT GAL FUEL       = ',F15.2)
      Write(9,3042) ESR
3042  format(1x, '   SEASONAL ENERGY RATE BTU/HR          = ',F15.2)
1370  Write(9,3050) EF
3050  format(1x, '   TOTAL ENERGY INPUT GAL FUEL          = ',F15.2)
      Write(9,3063) EKT
3063  format(1x, '   AVERAGE LB. WATER PER LB. FUEL       = ',F15.2)
1400  Write(9,3060) EK
3060  format(1x, '   SEASONAL LB. WATER PER LB. FUEL      = ',F15.2)
1401  Write(9,3070) QIT
3070  format(1x, '   ENERGY FROM AIR TO ICE BTU           = ',E15.6)
      Write(9,3071) QITI
3071  format(1x, '   SEASONAL ENERGY LOSS, AIR TO ICE BTU = ',E15.6)
      Write(9,3064) PMT/(.134*RHOW)
3064  format(1x, '   TOTAL WATER WITHDRAWN GAL            = ',F15.2)
      Write(9,3061) PMG
3061  format(1x, '   SEASONAL WATER WITHDRAWN GAL         = ',F15.2)
      Write(9,3065) PLT/(.134*RHOW)
3065  format(1x, '   TOTAL WATER LOSS GAL                 = ',F15.2)
      Write(9,3062) PLG
3062  format(1x, '   SEASONAL WATER LOSS GAL              = ',F15.2)

1430  Write(9,*)



      IF(N .EQ. 1) GOTO 1490
      IF(N .EQ. 2) GOTO 1204
      IF(N .EQ. 3) GOTO 1540
```

```
CCC **** END OF YEAR 1 ****

      IF(N .EQ. 4) GOTO 1520
      IF(N .EQ. 5) GOTO 1500
CCC **** END OF YEAR 2 ****

      IF(N .EQ. 6) GOTO 1520
      IF(N .EQ. 7) GOTO 1500
CCC **** END OF YEAR 3 ****

      IF(N .EQ. 8) GOTO 1520
      IF(N .EQ. 9) GOTO 1500
CCC **** END OF YEAR 4 ****

      IF(N .EQ. 10) GOTO 1520
      IF(N .EQ. 11) GOTO 1500
CCC **** END OF YEAR 5 ****

      IF(N .EQ. 12) GOTO 1520
      IF(N .EQ. 13) GOTO 1500
CCC **** END OF YEAR 6 ****

      IF(N .EQ. 14) GOTO 1520
      IF(N .EQ. 15) GOTO 1500
CCC **** END OF YEAR 7 ****

      IF(N .EQ. 16) GOTO 1520
      IF(N .EQ. 17) GOTO 1500
CCC **** END OF YEAR 8 ****

      IF(N .EQ. 18) GOTO 1520
      IF(N .EQ. 19) GOTO 1500
CCC **** END OF YEAR 9 ****

      IF(N .EQ. 20) GOTO 1520
      IF(N .EQ. 21) GOTO 1500
CCC **** END OF YEAR 1o ****

      IF(N .EQ. 22) GOTO 1760

1490  MGO = MGW
      MF = MF1
      MUGA = MUG1
      N = N + 1
      J = J + 1
      JJ = 1 ! year
      MFA = MF
      TIS = TI
      TP = INT(TI/24.0)*24.0+TPI
      TZ1 = TP+TZ4
      TZ2 = TZ1+TZ5
```

```
      TZ3 = TZ3E
      QBC = QBC1
      GOTO 1210
1500  MGO = MGW
      MUGA = MUGW
      MFA = MFS
      N = N+1
      MU = MUD
      TZ2 = TZ1+TZS
      TIS = TI
      QBC = QBC5
      GOTO 1553
1520  MGO = MGW
      MUGA = MUGS
      MFA = MFS
      N = N+1
      MU = MUD
      JJ = JJ+1
      TIS = TI
      TZ1 = TZ2+TZ6
      QBC = QBC4
      GOTO 1551
1540  MGO = MGW
      MUGA = MUGW
      MFA = MFS
      N = N+1
      JJ = 1
      MU = MUD
      TIS = TI
      QBC = QBC3
      TZ2 = TZ1+TZS
      GOTO 1550


1204  MGO = MGW
      MF = MF2
      MUGA = MUG2
      N = N+1
      JJ = 1
      MFA = MF
      MU = MUD
      TIS = TI
      TZ1 = TZ2+TZ6
      QBC = QBC2
      GOTO 1550
1210  MU = MUD
      TAUP = TP+MUGA*.134*RHOW/MUD-TPI
      TPIW = 168.0
1550  Write(9,8000) JJ
8000  format(1x,' YEAR ',I3)
      Write(9,6000)
```



```
6000  format(1x,'                       STANDBY OR WATER WITHDRAWAL ')
      GOTO 1555
1551  Write(9,8000) JJ
      Write(9,6001)
6001  format(1x,'                           SUMMER WATER WITHDRAWAL ')
      GOTO 1555
1553  Write(9,8000) JJ
      Write(9,6002)
6002  format(1x,'                           WINTER WATER WITHDRAWAL ')
1555  Write(9,*)
1580  Write(9,4010) MFA
4010  format(1x,'BOILER WATER FLOW RATE lbm/hr                 = ',F9.2
)
      Write(9,4011) TWB
4011  format(1x,'BOILER WATER TEMPERATURE DEG F                = ',F9.2
)
1610  Write(9,4020) MUGA
4020  format(1x,'WATER WITHDRAWAL GAL/DAY                      = ',F9.2
)
      Write(9,4021) MUD/(8.04*RHOW)
4021  format(1x,'WITHDRAWAL FLOW RATE GAL/MIN                  = ',F9.2
)
1640  Write(9,4030) HS
4030  format(1x,'CONVECTIVE COEFF AFTER R=30 FT BTU/HR-FT2-F   = ',F9.2
)
1672  Write(9,5050) TI
5050  FORMAT(1X,'START WITHDRAWAL AT HOUR                      = ',F9.2
)
      Write(9,*)
      GOTO 400
1760  Write(9,*)
1790  Write(9,4050) E
4050  format(1x,'   TOTAL ENERGY INPUT BTU            = ',E15.6)
1820  Write(9,4060) E / 140000
4060  format(1x,'   TOTAL ENERGY INPUT GAL FUEL       = ',F15.2)
1821  Write(9,4070) QIT
4070  format(1x,'   TOTAL ENERGY LOSS AIR TO ICE BTU  = ',E15.6)
1850  END
```

Appendix C: Energy usage for harvesting and transporting snow

Harvesting snow

The amount of energy associated with harvesting snow from the field and transporting it to the melt tank is as follows. Equipment logs for March 2010 (Burnside 2010) show that the number of hours the CAT 933 front loader was operated to harvest snow during 1 week was 12 hours to deliver 10 buckets of snow, and during a following week it took 10 hours to deliver 12 buckets of snow. Thus, on average it is about 1 hour of CAT 933 operation per bucket load of snow. This is about twice the previous estimates of ½ hour per bucket load (Helkenn 2010).

Also from equipment logs, we obtained a record of how many buckets of snow were delivered each day for the period of 10 May–23 June 2010. The total number over that period was 171 bucket loads. We also have the water usage during that same time period (Starkweather 2009) averaged over 3 years (2007–09), which is 15,326 gallons. This gives an average of 93 gallons per bucket load. This is consistent with the bucket capacity and snow density. The bucket capacity for the CAT 933 loader is 1.26 yards^3 or 252 gallons. The specific gravity of the surface snow at Summit is about 0.34 (see Appendix B). Thus, a bucket of snow should contain about 252 gal. × 0.34 = 86 gal. of water once melted. For this estimate, we use 90 gal. of water obtained per bucket load of snow.

From the above, the loader delivers 90 gal. of water per hour. The fuel usage of the CAT 933 (Nordby 2010) is about 0.72 gal. of diesel per hour. Thus, about 125 gal. of water are transported for 1 gal. of diesel fuel used. The lower heating value of diesel fuel is about 126 Btu/gal. (Heywood 1988). Thus, about 1 Btu of energy is needed to harvest a gallon of water and deliver it to the snow melt tank.

Water delivery

The water is transported using an Argo vehicle. It takes 45 minutes round trip for the Argo to shuttle 220 gal. of water to the Big House. Per the manufacturer's specifications, the Argo consumes approximately 0.9

gal. of gasoline per hour. This equates to 245 gal. of water transported per gal. of fuel. The lower heating value of gasoline is about 118 Btu/gal. (Heywood 1988). Thus, about 0.5 Btu of energy is required to transport a gal. of water from the shop to the Big House.

References

Burnside, J.2010. E-mail correspondence on 24 June 2010.

Helkenn, G. 2010. Personal communication, 24 June 2010.

Heywood, J. B. 1988. *Internal combustion engine fundamentals.* McGraw-Hill, New York, NY.

Nordby, L. 2010. Equipment records 28 June 2010.

Starkweather, S. 2009. E-mail correspondence, 26 Oct 2009.

Appendix D: Estimate of power requirements for the heaters on the Rodwell down-hole pipes

Calculation

The following assumptions were made in this calculation:

- The piping needs to be maintained at a minimum of 35°F (1.7°C).
- The air temperature in the void space when the well is shut down is the same as the firn temperature (–20°F or 244 K).
- The length of piping that needs to be heated is 600 ft (183 m). This is based on the final well depth being approximately 600 ft (see scenarios 1 and 2).

This provides a conservative estimate of the heat requirements and will provide adequate performance if the well is shut down for a long period (long enough for the air to cool to the firn temperature).

The heat loss, q(W/m^2), is computed from $q = h\Delta T$ and the required heating power, P(W), is

$$P = q\pi DL$$

where

D = approximate diameter of the pipe assembly
L = length of the pipe that extends into the well
h = heat transfer coefficient
ΔT = temperature difference between the pipe and the air temperature in the void.

To estimate the heat loss, we need to know h for the system. This can be estimated from the equations for free convection from a vertical surface (Incropera and DeWitt 1985):

$$h = \frac{k}{L}\left\{0.825 + \frac{0.387Ra^{1/6}}{\left[1+\left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{8/27}}\right\}^2$$

$$Ra = \Pr\frac{g\beta\Delta TL^3}{\nu^2}$$

At 244 K, the Prantl number, Pr = 0.72, the coefficient of thermal expansion for air is $\beta = 3.12 \times 10^{-3}$/K, and the kinematic viscosity of air, $\nu = 11.4 \times 10^{-6}$ m²/s. g is the gravitation constant: 9.81 m/s².

Applying the above equations we find h = 4.1 W/m² K, q = 126 W/m² and P = 11 kW.

Reference

Incropera, F. P. and D. P. DeWitt. 1985. *Introduction to heat transfer*. John Wiley & Sons. New York.

Appendix E: Rodwell system configuration at South Pole

The configuration of the surface systems needed to support the Rodwell is shown in Figure E.1 with the basic components labeled. The supply and return water lines are bundled together with supply power for the submersible pump and the heat tape used to prevent freeze-up. The configuration of this bundle is shown in Figure E.2. The weight of the bundle is structurally supported by the 3/8-in. cable shown in Figure E.2. The entire length of the bundle is wrapped in 4-in. pipe insulation and is lowered down the well shaft using the winch shown in Figure E.1 as the hose and heat tape are played out from the reels on which they are stored.

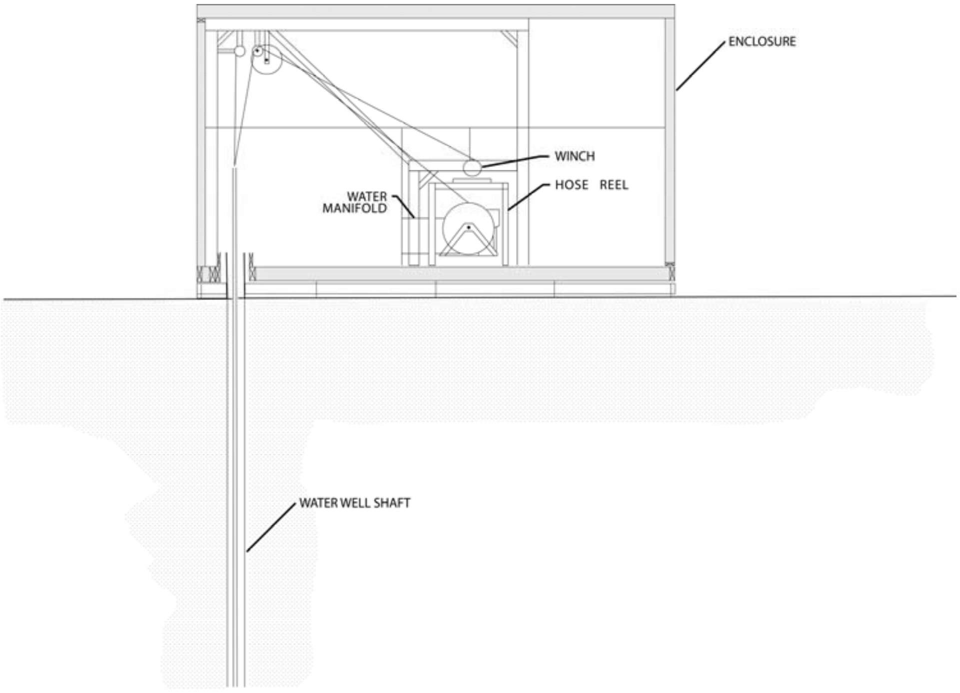


Figure E.1. Surface enclosure used to house the support systems for the Rodwell at South Pole, Antarctica (drawing extracted from the approved for construction drawings for South Pole Water Well #3, NSF).

Figure E.3 shows the pump head assembly before it is inserted into the well shaft. To establish the well, an initial shaft needs to be melted into the firn. The initial shaft depth is on the order of 202 ft for well number

3 at South Pole. This shaft is established using a hot point drill as shown in Figure E.4.

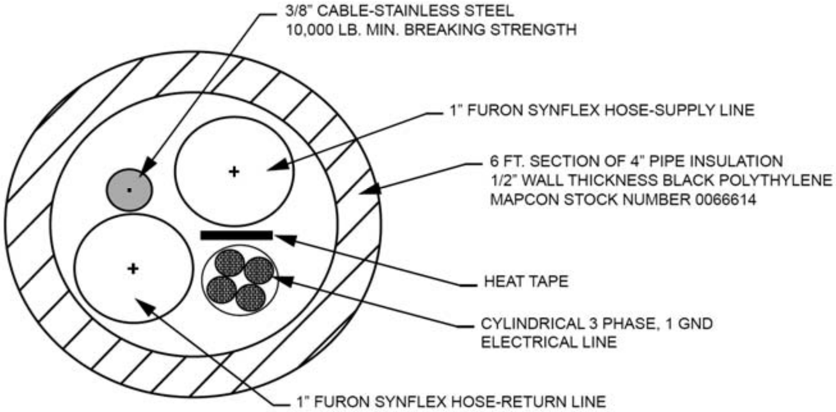


Figure E.2. Power cable and water lines that are bundled together and fed down the well shaft (drawing obtained from NSF/RPSC South Pole Project files).

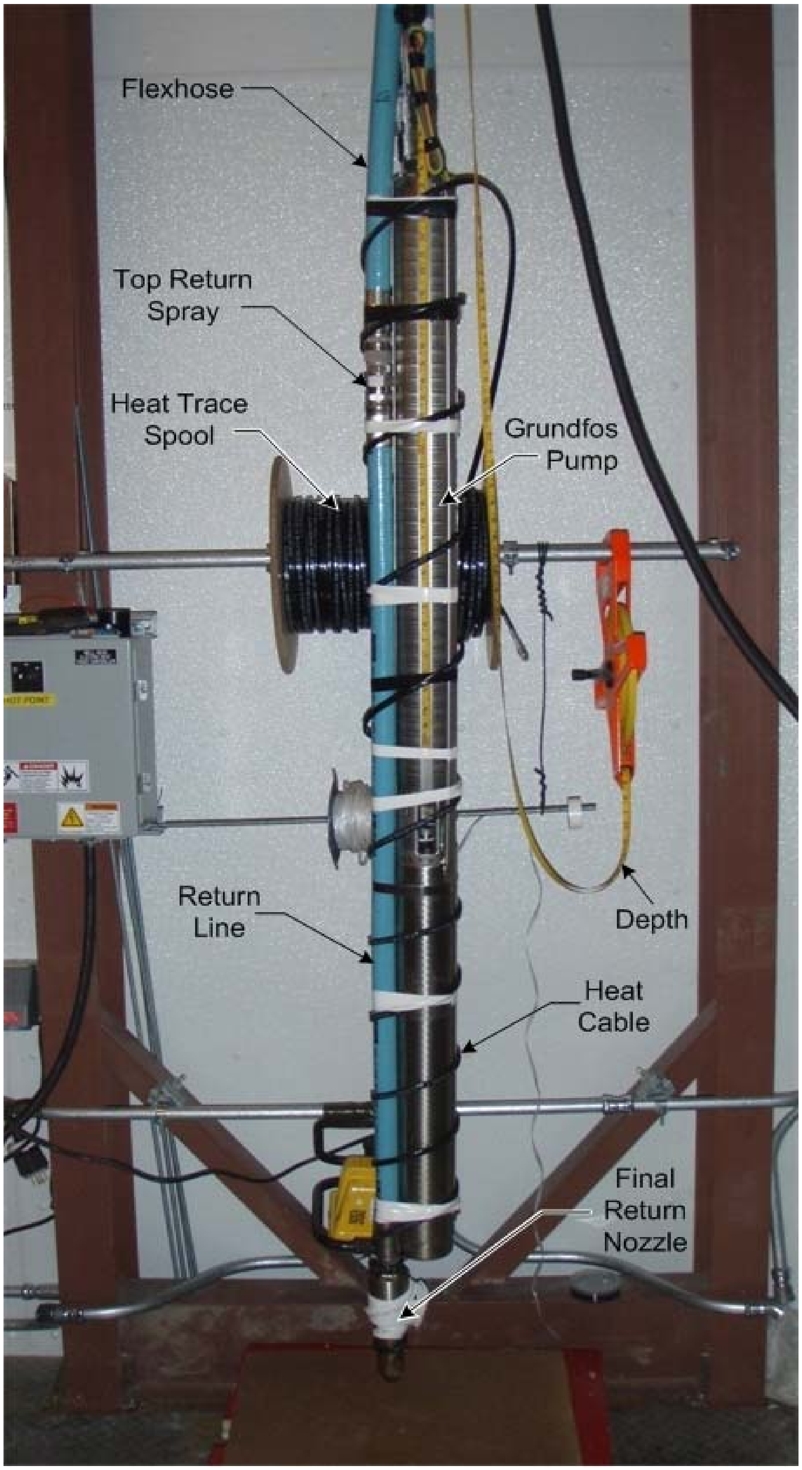


Figure E.3. Pump head prior to being lowered down into the well. Components of the head are labeled (photo obtained from NSF/RPSC South Pole Project files).

Figure E.4. Hot point drill used to establish the initial well shaft for the Rodwell at South Pole (photo obtained from NSF/RPSC South Pole Project files).

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14. ABSTRACT

This study reviews potable water production methods that may be applicable for use at Summit Station, Greenland. The two methods that are most widely used at polar field sites are melting surface snow and melting subsurface ice to form a well. There are limited published data on the energy usage for melting surface snow. Based on the data obtained from operations at Summit we determined that the basic energy requirement to melt the snow is about 2300 Btu/gal. This method, as currently implemented at Summit, is also a labor-intensive activity; there are opportunities to reduce the labor in this process with a new design of the system. The feasibility of using a subsurface well established in the glacial ice (Rodwell) at Summit was also analyzed. The approximate sustained energy requirement for this would be 30–40,000 Btu/hr, with an initial requirement of 142,000 Btu/hr for start-up. This feasibility study shows that a Rodwell can provide *at least* 10 years of service before it will need to be relocated. The specific energy requirement for this system ranges from 4100–7000 Btu/gal. or 1.8 to 3.0 times higher than the current system of melting surface snow. This study also shows that the Rodwell is more energy efficient when it is designed to supply more water to support a large population.

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